

Climate change and palaeoclimatology

The mid-Pleistocene transition (March 2019)

As shown by oxygen-isotope records from marine sediments, before about 1.25 Ma global climate cycled between cold and warm episodes roughly every 41 ka. Between 1.25 to 0.7 Ma these glacial-interglacial pulses lengthened to the ~100 ka periods that have characterised the last seven cycles that were also marked by larger volume of Northern Hemisphere ice-sheet cover during glacial maxima. Both periodicities have been empirically linked to regular changes in the Earth's astronomical behaviour and their effects on the annual amount of energy received from the Sun, as predicted by Milutin Milankovich. As long ago as 1976 early investigation of changes of oxygen isotopes with depth in deep-sea sediments had revealed that their patterns closely matched Milankovich's hypothesis. The 41 ka periodicity matches the rate at which the Earth's axial tilt changes, while the ~100 ka signal matches that for variation in the eccentricity of Earth's orbit. 19 and 24 ka cycles were also found in the analysis that reflect those involved in the gyroscope-like precession of the axis of rotation. Surprisingly, the 100 ka cycling follows by far the weakest astronomical effect on solar warming yet the climate fluctuations of the last 700 ka are by far the largest of the last 2.5 million years. In fact the 2 to 8 % changes in solar heat input implicated in the climate cycles are 10 times greater than those predicted even for times when all the astronomical influences act in concert. That and other deviations from Milankovich's hypothesis suggest that some of Earth's surface processes act to amplify the astronomical drivers. Moreover, they probably lie behind the mid-Pleistocene transition from 41 to 100 ka cyclicity. What are they? Changes in albedo related to ice- and cloud cover, and shifts in the release and absorption of carbon dioxide and other greenhouse gases are among many suggested factors. As with many geoscientific conundrums, only more and better quality data about changes recorded in sediments that may be proxies for climatic variations are likely to resolve this one.

Adam Hazenfratz of ETH in Zurich and colleagues from several other European countries and the US have compiled details about changing surface- and deep-ocean temperatures and salinity – from $\delta^{18}\text{O}$ and Mg/Ca ratios in foraminifera shells from a core into Southern Ocean-floor sediments – that go back 1.5 Ma (Hazenfratz, A.P. and 9 others 2019. The residence time of Southern Ocean surface waters and the 100,000-year ice age cycle. *Science*, v. **363**, p. 1080-1084; DOI: 10.1126/science.aat7067). Differences in temperature and salinity (and thus density) gradients show up at different times in this critical sediment record. In turn, they record gross shifts in ocean circulation at high southern latitudes that may have affected the CO_2 released from and absorbed by sea water. Specifically, Hazenfratz *et al.* teased out fluctuations in the rate of mixing of dense, cold and salty water supplied to the Southern Ocean by deep currents with less dense surface water. Cold, dense water is able to dissolve more CO_2 than does warmer surface water so that when it forms near the surface at high latitudes it draws down this greenhouse gas from the atmosphere and carries it into long-term storage in the deep ocean when it sinks. Deep-water formation therefore tends to force down mean global surface temperature, the more so the longer it resides at depth. When deep water wells to the surface and warms up it releases some of its CO_2 content to produce an opposite, warming influence on global climate. So, when mixing of deep and

surface waters is enhanced the net result is global warming, whereas if mixing is hindered global climate undergoes cooling.



The Southern Ocean, where most dissolved and gaseous carbon dioxide are emitted and absorbed by seawater (Credit: British Antarctic Survey)

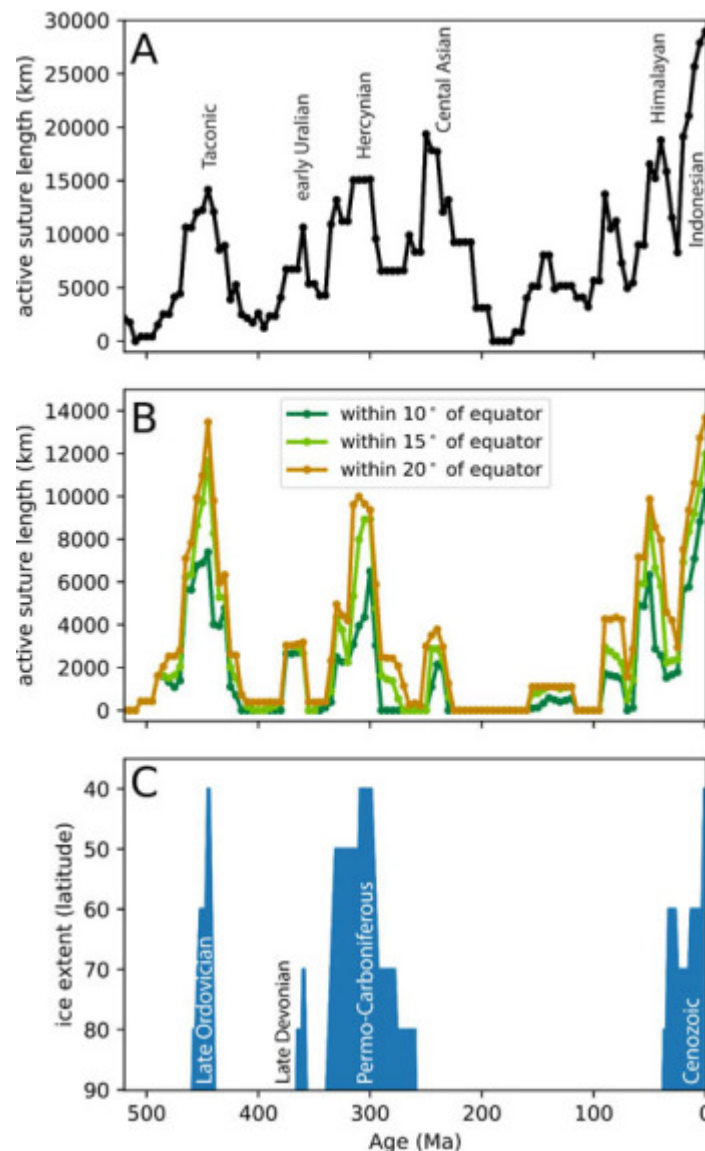
The critical factor in the rate of mixing deep with surface water is the density of that at the surface. When its salinity and density are low the surface water layer acts as a lid on what lies beneath, thereby increasing the residence time of deep water and the CO_2 that it contains. This surface ‘freshening’ in the Southern Ocean seems to have begun at around 1.25 Ma and became well established 700 ka ago; that is, during the mid-Pleistocene climate transition. The phenomenon helped to lessen the greenhouse effect after 700 ka so that frigid conditions lasted longer and more glacial ice was able to accumulate, especially on the northern continents. This would have made it more difficult for the 41 ka astronomically paced changes in solar heating to have restored the rate of deep-water mixing to release sufficient CO_2 to return the climate to interglacial conditions. That would lengthen the glacial-interglacial cycles. The link between the new 100 ka cyclicity and very weak forcing by the varying eccentricity of Earth’s orbit may be fortuitous. So how might anthropogenic global warming affect this process? Increased melting of the Antarctic ice sheet may further freshen surface waters of the Southern Ocean, thereby slowing its mixing with deep, CO_2 -rich deep water and the release of stored greenhouse gases. As yet, no process leading to the decreased density of surface waters between 1.25 and 0.7 Ma has been suggested, but it seems that something similar may attend global warming.

Related articles: Menviel, L. 2019. The southern amplifier. *Science*, v. **363**, p. 1040-1041; DOI: 10.1126/science.aaw7196; [The deep Southern Ocean is key to more intense ice ages](#) (Phys.org)

Tectonics and glacial epochs (March 2019)

Because the configuration of continents inevitably affects the ocean currents that dominate the distribution of heat across the face of the Earth, tectonics has a major influence over climate. So too does the topography of continents, which deflects global wind patterns, and that is also a reflection of tectonic events. For instance, a gap between North and South America allowed exchange of the waters of the Pacific and Atlantic Oceans throughout the Cenozoic Era until about 3 Ma ago, at the end of the Pliocene Epoch, although the seaway had long been shallowing as a result of tectonics and volcanism at the destructive margin of the eastern Pacific. That seemingly minor closure transformed the system of currents in the Atlantic Ocean, particularly the Gulf Stream, whose waxing and waning were instrumental in the glacial-interglacial cycles that have persisted for the last 2.5 Ma. This was partly through its northward transport of saltier water formed by tropical evaporation that cooling at high northern latitudes encouraged to sink to form a major component of the global oceanic heat conveyor system. Another example is the rise of the Himalaya following India's collision with Eurasia that gave rise to the monsoonal system dominating the climate of southern Asia. The four huge climatic shifts to all-pervasive ice-house conditions during the Phanerozoic Eon are not explained so simply: one during the late-Ordovician; another in the late-Devonian; a 150 Ma-long glacial epoch spanning much of the Carboniferous and Permian Periods, and the current Ice Age that has lasted since around 34 Ma. Despite having been at the South Pole since the Cretaceous Antarctica didn't develop glaciers until 34 Ma. So what may have triggered these four major shifts in global climate?

Five palaeoclimatologists from the University of California and MIT set out to find links, starting with the most basic parameter, how atmospheric greenhouse gases might have varied. In the long term CO₂ builds up through its emission by volcanoes. It is drawn down by several geological processes: burial of carbon and carbonates formed by living processes; chemical weathering of silicate minerals by CO₂ dissolved in water, which forms solid calcium carbonate in soil and carbonate ions in seawater that can be taken up and buried by shell-producing organisms. Rather than comparing gross climate change with periods of orogeny and mountain building, mainly due to continent-continent collisions, they focused on zones that preserve signs of subduction of oceanic lithosphere – suture zones (Macdonald, F.A. *et al.* 2019. [Arc-continent collisions in the tropics set Earth's climate state](#). *Science*, v. **363** (in press); DOI: 10.1126/science.aav5300). Comparing the length of all sutures active at different times in the Phanerozoic with the extent of continental ice sheets there is some correlation between active subduction and glaciations, but some major misfits. Selecting only sutures that were active in the tropics of the time – the zone of most intense chemical weathering – results in a far better tectonic-climate connection. Their explanation for this is not tropical weathering of all kinds of exposed rock but of calcium- and magnesium-rich igneous rocks; basaltic and ultramafic rocks. These dominate oceanic lithosphere, which is exposed to weathering mainly where slabs of lithosphere are forced, or obducted, onto continental crust at convergent plate margins to form ophiolite complexes. The Ca- and Mg-rich silicates in them weather quickly to take up CO₂ and form carbonates, especially in the tropics. Through such weathering reactions across millions of square kilometres the main greenhouse gas is rapidly pulled out of the atmosphere to set off global cooling.



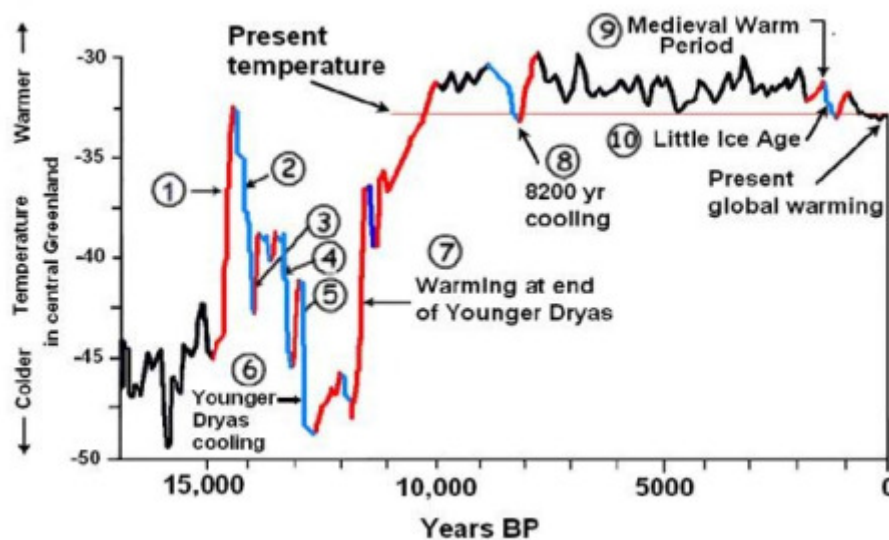
Top – variation in the total length of active, ophiolite-bearing sutures during the Phanerozoic; middle – length of such sutures in the tropics; bottom – extent of Phanerozoic glaciers. (Credit: Macdonald et al. 2019; Fig.2)

Rather than the climatic influence of tectonics through global mountain building, the previous paradigm, Macdonald and colleagues show that the main factor is *where* subduction and ophiolite obduction were taking place. In turn, this very much depended on the configuration of continents on which ophiolites can be preserved. The most active period of tectonics during the Mesozoic, as recorded by the global length of sutures, was at 250 Ma – the beginning of the Triassic Period – but they were mainly outside the tropics, when there is no sign of contemporary glaciation. During the Ordovician, late-Devonian and Permo-Carboniferous ice-houses active sutures were most concentrated in the tropics. The same goes for the build-up to the current glacial epoch.

Younger Dryas impact trigger: evidence from Chile (May 2019)

A sudden collapse of global climate around 12.8 ka and equally brusque warming 11.5 ka ago is called the Younger Dryas. It brought the last ice age to an end. Because significant

warming preceded this dramatic event palaeoclimatologists have pondered its cause since it came to their attention in the early 20th century as a stark signal in the pollen content of lake cores (*Dryas octopetala* a tundra wild flower), then shed more pollen than before or afterwards; hence the name. A century on, two theories dominate: North Atlantic surface water was freshened by a [glacial outburst flood](#) that shut down the Gulf Stream [June 2006]; a [large impact event](#) shed sufficient dust to lower global temperatures [July 2007]. An oceanographic event remains the explanation of choice for many, whereas the evidence for an extraterrestrial cause – also suggested to have triggered megafaunal extinctions in North America – has its supporters and detractors. The first general reaction to the idea of an impact cause was the [implausibility of the evidence](#) [November 2010], yet the discovery by radar of a [major impact crater beneath the Greenland ice cap](#) [November 2018] resurrected the ‘outlandish’ notion. A recent paper in *Nature: Scientific Reports* further sharpens the focus.



Temperature fluctuations over the Greenland ice cap during the past 17,000 years, showing the abrupt cooling during the Younger Dryas. (credit: Don Easterbrook)

Since 2007, a team of Chilean and US scientists has been working on a rich haul of late Pleistocene fossil mammals from Patagonian Chile that turned up literally in someone’s suburban back garden in the town of Osorno. The stratigraphy has been systematically dated using the radiocarbon method. A dark layer composed of peat with abundant charcoal gave an age of about 12.8 ka, thereby marking both the local base of the Younger Dryas episode and a cap to the rich mammalian fossil assemblage. Similar beds have been found at more than 50 sites elsewhere in the world at this stratigraphic level, including the famous Clovis site in Arizona. Steadily, such ‘black mats’ have been yielding magnetised spherules, elevated concentrations of platinum-group metals, gold, native iron, fullerenes and microscopic diamonds, plus convincing signs of wild fires at some sites; the very evidence that most researchers had panned when first reported. The Chilean example contains much the same pointers to an extraterrestrial cause, attributed to air-burst impacts (Pino, M. and 14 others 2019. [Sedimentary record from Patagonia, southern Chile supports cosmic-impact triggering of biomass burning, climate change, and megafaunal extinctions at 12.8 ka](#). *Scientific Reports*, v. 9, article 4413; DOI: 10.1038/s41598-018-38089-y)

A larger team of researchers, to which several of the authors of the Chilean paper are affiliated, claim the evidence supports some kind of impact event 12.8 ka ago, possibly several produced by the break-up of a comet. Yet the criticisms persist. For instance, had there been wildfires on the scales suggested, then there ought to be a significant peak in the proportion of charcoal in lake bed sediments from any one region at 12.8 ka. In fact such data from North America show no such standalone peak among many from the age range of the Younger Dryas. The fossil record from the last few millennia of the Pleistocene does not support a sudden extinction, but a decline. The Clovis-point culture, thought by many to have wrought havoc on the North American megafauna, may have come to an end around 12.8 ka, but was quickly succeeded by an equally efficient technology – the Folsom point.

As regards the critical evidence for impacts, shocked mineral grains, none are reported, and some of the reported evidence of microspherules and nanodiamonds is not strongly supported by independent analysis – and nor are they unique to impact events. How about the dating? The evidence from ice cores strongly suggests that the Younger Dryas began with an 8° C temperature decline over less than a decade, and the end was equally as sudden. Is radiocarbon dating capable of that time resolution and accuracy? Certainly not.

Related articles: Gramling, C. 2018. [Why won't this debate about an ancient cold snap die?](#) (*Science News*); Easterbrook, D.L. 2012. [The Intriguing Problem Of The Younger Dryas—What Does It Mean And What Caused It?](#) (Watts Up With That); Wolbach, W.S. and 26 others 2018. [Extraordinary Biomass-Burning Episode and Impact Winter Triggered by the Younger Dryas Cosmic Impact ~12,800 Years Ago. 1. Ice cores and Glaciers.](#) *Journal of Geology*, v. **126**, p. 165-184; DOI: 10.1086/695703; Wolbach, W.S. and 30 others 2018. [Extraordinary Biomass-Burning Episode and Impact Winter Triggered by the Younger Dryas Cosmic Impact ~12,800 Years Ago. 2. Lake, Marine, and Terrestrial Sediments.](#) *Journal of Geology*, v. **126**, p. 185-205; DOI: 10.1086/695704.

Soluble iron, black smokers and climate (June 2019)

At present the central areas of the oceans are wet deserts; too depleted in nutrients to support the photosynthesising base of a significant food chain. The key factor that is missing is dissolved divalent iron that acts as a minor, but vital, nutrient for phytoplankton. Much of the soluble iron that does help stimulate plankton 'blooms' emanates from the land surface in windblown dust ([Palaeoclimatology](#) September 2011) or dissolved in river water. A large potential source is from hydrothermal vents on the ocean floor, which emit seawater that has circulated through the basalts of the oceanic crust. Such fluids hydrate the iron-rich mafic minerals olivine and pyroxene, which makes iron available for transport. The fluids originate from water held in the muddy, organic-rich sediments that coat the ocean floor, and have lost any oxygen present in ocean-bottom water. Their chemistry is highly reducing and thereby retains soluble iron liberated by crustal alteration to emanate from hydrothermal vents. Because cold ocean-bottom waters are oxygenated by virtue of having sunk from the surface as part of thermohaline circulation, it does seem that ferrous iron should quickly be oxidised and precipitated as trivalent ferric compounds soon after hydrothermal fluids emerge. However, if some was able to rise to the surface it could fertilise shallow ocean water and participate in phytoplankton blooms, the sinking of dead organic matter then effectively burying carbon beneath the ocean floor; a '[biological pump](#)'

in the carbon cycle with a direct influence on climate. Until recently this hypothesis had little observational support.



Phytoplankton bloom in the Channel off SW England (Landsat image)

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The Southern Ocean surrounding Antarctica is iron-starved for the most part, but it does host huge phytoplankton blooms that are thought to play an important role in sequestration of CO₂ from the atmosphere. Oceanographic research now benefits from semi-autonomous buoys set adrift in the deep ocean. The most sophisticated (Argo floats) are able to dive to 2 km below the surface, measuring variations of physical and chemical conditions with depth for long periods. There are 4,000 of them, owned by several countries. Two of them drifted with surface currents across the line of the Southwest Indian Ridge through waters thought to be depleted in phytoplankton, despite having high nitrate, phosphate and silica contents – major ‘fertilisers’ in water. They showed up ‘spikes’ in chlorophyll concentrations in the upper levels of the Southern Ocean (Ardyna, M. and 11 others 2019. [Hydrothermal vents trigger massive phytoplankton blooms in the Southern Ocean](#). *Nature Communications*, 5 June 2019, online; DOI: 10.1038/s41467-019-09973-6). Their location relative to a large cluster of hydrothermal vents on the Southwest Indian Ridge was ‘downstream’ of them in the circum-Antarctic Current, but remote from any known terrestrial source of iron (continental shelves, dust deposition melting sea ice). Earlier oceanographic surveys that detected anomalous helium isotope, typical of emanations from the mantle, show that hydrothermal-vent water moves through the two areas. Although the Argo floats are equipped for neither helium nor iron measurements, it is likely that the blooms benefitted from hydrothermal iron. Modelling of the likely current dispersion of material in the hydrothermal plumes also outlines a large area of ocean where iron fertilisation may encourage regular blooms where they would otherwise be highly unlikely. Unfortunately, the study does not include any direct evidence for elevated soluble iron.

One thing that the study does foster is renewed interest in deliberate iron-fertilisation of the oceans to speed up the ‘biological pump’ as a means of managing global warming (Boyd, P. & Vivian, C. 2019. [Should we fertilize oceans or seed clouds? No one knows](#). *Nature*, v. **570**, p. 155-157; doi: 10.1038/d41586-019-01790-7). Small scale pilots of such ‘geoengineering’ have been tried, but raised outcries from environmental groups. Other than detecting, or hinting at, soluble iron from a deep natural source, scientific research has provided scanty evidence of what iron-seeding at the surface might do. There could be unexpected consequences, such as methane emission from decay of the blooms – a worse greenhouse gas than carbon dioxide.

See also: [An iron age for climate engineering?](#) (*Palaeoclimatology*, July 2007); [Dust in the wind: North Pacific Ocean fertilized by iron in Asian dust](#) (*National Science Foundation* 2019)

Ediacaran glaciated surface in China (July 2019)

It is easy to think that firm evidence for past glaciations lies in sedimentary strata that contain an unusually wide range of grain size, a jumble of different rock types – including some from far-off outcrops – and a dominance of angular fragments: similar to the boulder clay or till on which modern glaciers sit. In fact such evidence, in the absence of other signs, could have formed by a variety of other means. To main a semblance of hesitancy, rocks of that kind are now generally referred to as *diamictites* in the absence of other evidence that ice masses were involved in their deposition. Among the best such confirmation would be the discovery that a diamictite rests on a surface that has been scored by the passage of rock-armoured ice – a *striated pavement* and, best of all, that the diamictites contain fragments that bear flat surfaces that are also scratched. The Carboniferous to Permian

glaciation of the southern continents and India that helped Alfred Wegener to reconstruct the Pangaea supercontinent was proved by the abundant presence of striated pavements. Indeed, it was the striations themselves that helped clinch his revolutionising concept. On the Pangaea reconstruction they formed a clear radiating pattern away from what was later to be shown by palaeomagnetic data to be the South Pole of those times.



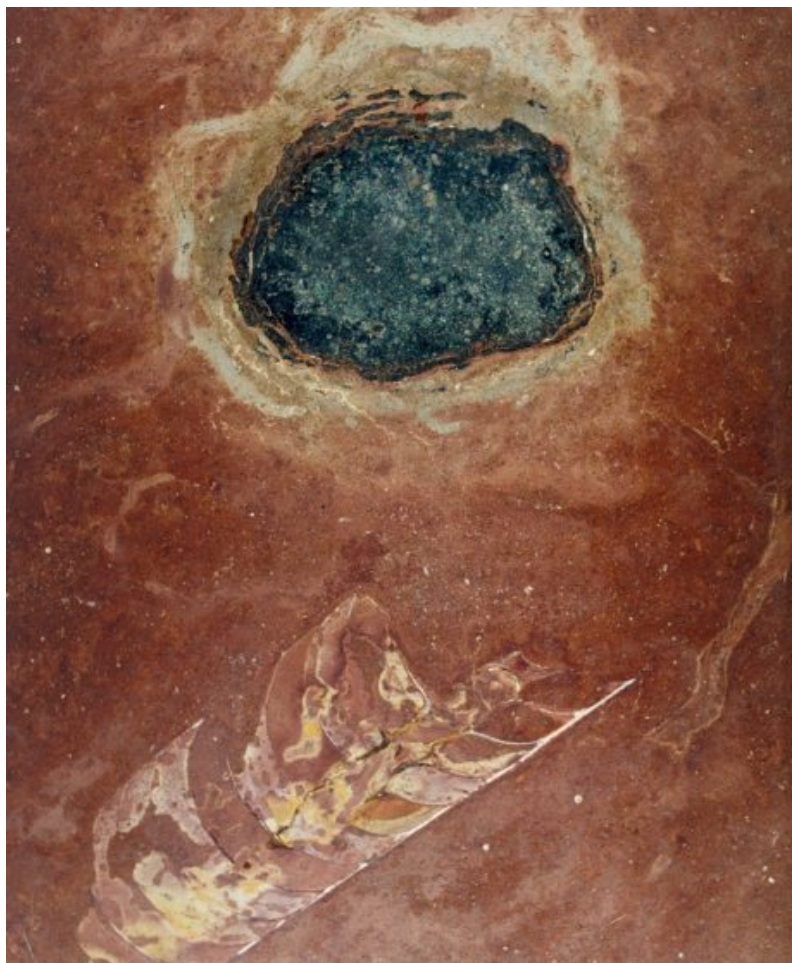
29 Ma old striated pavement beneath the Dwyka Tillite in South Africa (credit: M.J Hambrey)

The multiple glacial epochs of the Precambrian that extended to the Equator during Snowball Earth conditions were identified from diamictites that are globally, roughly coeval, along with other evidence for frigid climates. Some of them contain dropstones that puncture the bedding as a result of having fallen through water, which reinforces a glacial origin. However, Archaean and Neoproterozoic striated pavements are almost vanishingly rare. Most of those that have been found are on a scale of only a few square metres. Diamictites have been reported from the latest Neoproterozoic Ediacaran Period, but are thin and not found in all sequences of that age. They are thought to indicate sudden climate changes linked to the hesitant rise of animal life in the run-up to the Cambrian Explosion. One occurrence, for which palaeomagnetic date suggest tropical latitude, is near Pingdingshan in central China above a local unconformity that is exposed on a series of small plateaus (Le Heron, D.P. and 9 others 2019. [Bird's-eye view of an Ediacaran subglacial landscape](#). *Geology*, v. **47**, p. 705-709; DOI: 10.1130/G46285.1). To get a synoptic view the authors deployed a camera-carrying drone. The images show an irregular surface rather than one that is flat. It is littered with striations and other sub-glacial structures, such as

faceting and fluting, together with other features that indicate plastic deformation of the underling sandstone. The structures suggest basal ice abrasion in the presence of subglacial melt water, beneath a southward flowing ice sheet

Ordovician ice age: an extraterrestrial trigger (September 2019)

The Ordovician Period is notable for three global events; an explosion in biological diversity; an ice age, and a mass extinction. The first, colloquially known as the Great Ordovician Biodiversification Event, occurred in the Middle Ordovician around 470 Ma ago (see [The Great Ordovician Diversification](#), September 2008) when the number of recorded fossil families tripled. In the case of brachiopods, this seems to have happened in no more than a few hundred thousand years. The glacial episode spanned the period from 460 to 440 Ma and left tillites in South America, Arabia and, most extensively, in Africa. Palaeogeographic reconstructions centre a Gondwanan ice cap in the Western Sahara, close to the Ordovician South Pole. It was not a Snowball Earth event, but covered a far larger area than did the maximum extent the Pleistocene ice sheets in the Northern Hemisphere. It is the only case of severe global cooling bracketing one or the 'Big Five' mass extinctions of the Phanerozoic Eon. In fact two mass extinctions during the Late Ordovician rudely interrupted the evolutionary promise of the earlier threefold diversification, by each snuffing-out almost 30% of known genera.



L-chondrite meteorite in iron-stained Ordovician limestone together with a nautiloid (credit: Birger Schmitz)

A lesser-known feature of the Ordovician Period is a curious superabundance of extraterrestrial debris, including high helium-3, chromium and iridium concentrations, preserved in sedimentary rocks, particularly those exposed around the Baltic Sea (Schmitz, B. and 19 others 2019. [An extraterrestrial trigger for the mid-Ordovician ice age: Dust from the breakup of the L-chondrite parent body](#). *Science Advances*, v. 5, eaax4184; DOI: 10.1126/sciadv.aax4184). Yet there is not a sign of any major impact of that general age, and the meteoritic anomaly occupies a 5 m thick sequence at the best studied site in Sweden, representing about 2 Ma of deposition, rather than the few centimetres at near-instantaneous impact horizons such as the K-Pg boundary. Intact meteorites are almost exclusively L-chondrites dated at around 466 Ma. Schmitz and colleagues reckon that the debris represents the smashing of a 150 km-wide asteroid in orbit between Mars and Jupiter. Interestingly, L-chondrites are more abundant today and in post-Ordovician sediments than they were in pre-Ordovician records, amounting to about a third of all finds. This suggests that the debris is still settling out in the Inner Solar System hundreds of million years later. Not long after the asteroid was smashed a dense debris cloud would have entered the Inner Solar System, much of it in the form of dust.

The nub of Schmitz *et al*'s hypothesis is that considerably less solar radiation fell on Earth after the event, resulting in a sort of protracted 'nuclear winter' that drove the Earth into much colder conditions. Meteoritic iron falling the ocean would also have caused massive phytoplankton blooms that sequestered CO₂ from the Ordovician atmosphere to reduce the greenhouse effect. Yet the cooling seems not to have immediately decimated the 'booming' faunas of the Middle Ordovician. Perhaps the disruption cleared out some ecological niches, for new species to occupy, which may explain sudden boosts in diversity among groups such as brachiopods. Two sharp jumps in brachiopod species numbers are preceded and accompanied by 'spikes' in the number of extraterrestrial chromite grains in one Middle Ordovician sequence. One possibility, suggested in an earlier paper (Schmitz, B. and 8 others 2008. [Asteroid breakup linked to the Great Ordovician Biodiversification Event](#). *Nature Geoscience*, v. 1, p. 49-53; DOI: 10.1038/ngeo.2007.37) is that the undoubted disturbance may have killed off species of one group, maybe trilobites, so that the resources used by them became available to more sturdy groups, whose speciation filled the newly available niches. Such a scenario would make sense, as mobile predators/scavengers (e.g. trilobites) may have been less able to survive disruption, thereby favouring the rise of less metabolically energetic filter feeders (e.g. brachiopods).

See also: Sokol, J. 2019. Dust from asteroid breakup veiled and cooled Earth. *Science*, v. 365, pp. 1230; DOI: 10.1126/science.365.6459.1230, [How the first metazoan mass extinction happened](#) (Earth-logs, May 2014)

Chaos and the Palaeocene-Eocene thermal maximum (October 2019)

The transition from the Palaeocene to Eocene Epochs (56 Ma) was marked by an abrupt increase in global mean temperature of about 5 to 8°C within about 10 to 20 thousand years. That is comparable to a rate of warming similar to that currently induced by human activities. The evidence comes from the oxygen isotopes and magnesium/calcium ratios in the tests of both surface- and bottom dwelling foraminifera. The event is matched by a similarly profound excursion in the $\delta^{13}\text{C}$ of carbon-rich strata of that age, whose extreme negative value marks the release of a huge mass of previously buried organic carbon to the

atmosphere. The Epoch-boundary coincides with the beginning of rapid diversification among mammals and plants that had survived the end-Cretaceous mass extinction some 10 Ma beforehand. The most likely cause was the release of methane, a more potent greenhouse gas than CO₂, from gas hydrate buried just beneath the surface of sea-floor sediments on continental shelves. An estimated mass of 1.5 trillion tonnes of released methane has been suggested. Methane rapidly oxidizes to CO₂ in the atmosphere, which dissolves to make rainwater slightly acid so that the oceans also become more acid; a likely cause for the mass extinction of foraminifera species at the boundary.

Since the discovery of the [Palaeocene-Eocene Thermal Maximum](#) (PETM) in the late-1990s a range of possible causes have been suggested. Releasing methane suddenly from sea-floor gas hydrates needs some kind of trigger, such as a steady increase in the temperature of ocean-bottom water to above the critical level for gas-hydrate stability. The late-Palaeocene witnessed slow global warming by between 3 to 5°C over 4 to 5 Ma. There are several hypotheses for this precursor warming, such as a direct CO₂ release from the mantle by volcanic activity for which there are several candidates in the geological record of the Palaeocene. Such surface warming would have had to be transferred to the sea floor on continental shelves to destabilise gas hydrates, which implicates a change in oceanic current patterns. An extraterrestrial cause has also been considered (see [Impact linked to the Palaeocene-Eocene boundary event](#), Earth-logs October 2016). Sediment cores from the North Atlantic off the eastern seaboard of the US have revealed impact debris including glass spherules and shocked mineral grains at the same level as the PETM, together with iridium in terrestrial sediments onshore of the same age: there are no such global signatures). But apart from two small craters in Texas and Jordan (12 and 5 km across, respectively) of roughly the same age, no impact event of the necessary magnitude for truly global influence is known. However, there may have been an altogether different triggering mechanism.

Since the confirmation of the Milanković-Croll hypothesis to explain the cyclical shifts in climate during the Pleistocene Epoch in terms of changes in Earth's orbital characteristics induced by varying gravitational forces in the solar system, the findings have been used as an alternative means of dating other stratigraphic events that show cyclicity. In essence, the varying forces at work are [inherently chaotic](#), in a formally mathematical sense. Although Milanković cycles sometimes pop-up when ancient, repetitive stratigraphic sequences are analysed, consistently using the method as a tool to calibrate the geological record to an astronomical timescale breaks down for sediments older than about 50 Ma. Calculations disagree markedly beyond that time. Richard Zeebe and Lucas Lourens of the Universities of Hawaii and Utrecht tried an opposite approach, using the known geological records from deep-sea cores to calibrate the astronomical predictions and, in turn, used the solution to take the astronomical time scale further back than 50 Ma (Zeebe, R.E. & Lourens, L.J. 2019. Solar System chaos and the Paleocene–Eocene boundary age constrained by geology and astronomy. *Science*, v. **365**, p. 926-929; DOI: 10.1126/science.aax0612). They reached back about 8 Ma, so putting the PETM in focus. As well as refining its age (56.01 ± 0.05 Ma) they showed that the PETM coincided with a 405 ka maximum in Earth's orbital eccentricity lasting around 170 ka: a possible orbital trigger for the spike in temperature and δ¹³C together, with evidence for a period of chaos in the Solar System about 50 Ma ago. But, what did that chaos actually **do**, other than mess up orbital dating? To me it seems to

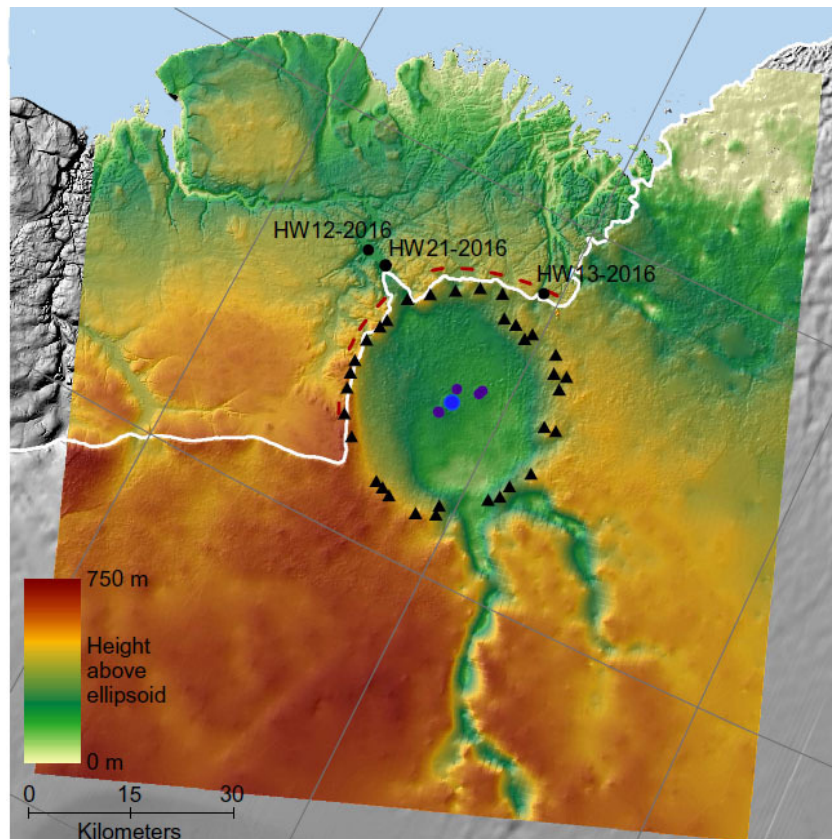
suggest something nasty happening to the behaviour of the Giant Planets that are the Lords of the astronomical dance...

See also: Grabowski, M. 2019. [Deep-sea sediments reveal solar system chaos: an advance in dating geologic archives](#). SOEST News

More on the Younger Dryas causal mechanism (November 2019)

The divergence of opinion on why a millennium-long return to glacial conditions began 12.8 thousand years recently deepened. The Younger Dryas stadial was an unprecedented event that halted and even reversed the human recolonisation of mid- to high northern latitudes after the end of the last ice age. Its inception was phenomenally rapid, taking a couple of decades to as little as perhaps a few years. The first plausible explanation was put forward by Wallace Broecker in 1989, who looked to explosive release of meltwater trapped in glacial lakes astride the Canadian-US border along the present St Lawrence River Valley, effectively flooding the source of NADW with a surface layer of low-density, low-salinity water. This, he suggested, would have shut down the thermohaline circulation in the North Atlantic. This is currently driven by cooling of salty surface water brought from the tropics to the Arctic Ocean by the Gulf Stream so that the resulting increase in density causes it to sink and thereby drive this part of the ocean water 'conveyor' system. A massive freshwater influx would prevent sinking and shut down the Gulf Stream, with the obvious effect of cooling high northern latitudes allowing ice caps to return to the surrounding continents. Yet [Broecker's St Lawrence flood mechanism](#) was flawed by lack of evidence and the knowledge that a well-documented flood along that valley a thousand years before had raised sea level by 20 m with no climatic effect. In 2005 clear evidence was found for a huge glacial outburst flood directly to the Arctic Ocean at around 12.8 ka that had followed Canada's MacKenzie River; a route that would force low-density seawater to the very source of North Atlantic Deep Water through the Fram Straits, thereby stopping thermohaline circulation.

The year 2007 saw the emergence of a totally different account (see [Whizz-bang view of Younger Dryas](#), July 2007; [Impact cause for Younger Dryas draws flak](#), May 2008) centring on evidence for a 12.8 ka major impact in the form of excess iridium; spherules; fullerenes and evidence for huge wildfires in soils directly above the last known occurrences of the superbly crafted tools known as Clovis points – the hallmark of the earliest known humans in North America. Later (see [Comet slew large mammals of the Americas?](#), March 2009) the same team reported minute diamonds from the same soils along with evidence for extinction of the Pleistocene megafauna; a view that was panned unmercifully. Like the yet-to-be-found 'end-Permian impact' previously proposed by the same team, no crater of Younger Dryas age was then known. However, in 2018, ice-penetrating radar surveys revealed a convincing, 31 km wide [subglacial impact structure beneath the Greenland ice cap](#), that is directly overlain by ice of Holocene (<11.7 ka) age. This reopened the case for an extraterrestrial origin for the Younger Dryas, followed by [evidence from Chile for 12.8 ka wildfires](#) presented by a team that includes academics who first made claims of an impact cause.



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

Last week, the impact-hungry team provided further evidence in lake-bed sediments from South Carolina, USA, which they have dated using an advanced approach to the radiocarbon method (Moore, C.R. and 16 others 2019. [Sediment Cores from White Pond, South Carolina, contain a Platinum Anomaly, Pyrogenic Carbon Peak, and Coprophilous Spore Decline at 12.8 ka](#). *Nature Scientific Reports*, v. 9, online 15121; DOI: 10.1038/s41598-019-51552-8). This centres on a large spike in platinum and palladium, which they date to $12,785 \pm 58$ years before present; i.e. the start of the Younger Dryas. Preceding it is a peak in soot with a distinctive $\delta^{13}\text{C}$ value attributed to wildfires ($12,838 \pm 103$ years b.p), and is followed by a peak in nitrogen isotopes ($\delta^{15}\text{N}$), indicating environmental changes, and a sharp decline in spores ($12,752 \pm 54$ years b.p) attributed to fungi that consume herbivore dung – a sign of a decline in the local megafauna. In other words, a confirmation of previous findings at the Clovis site– but no diamonds. The variations in different parameters are based on 30 to 35 samples (each about 2 cm long) from about 0.8 m of sediment core, so it is curious that most of the data are presented as continuous curves. That issue may become the focus of criticism, as may the need for confirmation from other lake-bed cores from a wider number of localities. With such polarised views on a crucial episode in recent geological and biological history critical scrutiny is sure to come.

How permanent is the Greenland ice sheet? (November 2019)

Eighty percent of the world's largest island is sheathed in glacial ice up to 3 km thick, amounting to 2.85 million km^3 . A tenth as large as the Antarctic ice sheet, if melted it could add over 7 m to global sea level if it melted completely; compared with 58 m should

Antarctica suffer the same fate. Antarctica accumulated glacial ice from about 34 to 24 million years ago during the Oligocene Epoch, deglaciated to become largely ice free until about 12 Ma and then assumed a permanent, albeit fluctuating, ice cap until today. In contrast, Greenland only became cold enough to support semi-permanent ice cover from about 2.4 Ma during the late-Pliocene to present episode of ice-age and interglacial cycles. The base of the GRIP ice core from central Greenland has been dated at 1 Ma old, but such is the speed of ice movement driven by far higher snow precipitation than in Antarctica that it is possible that basal ice is shifted seawards. The deepest layers recovered by drilling have lost their annual layering as a result of ice's tendency to deform in a plastic fashion so do not preserve detailed glacial history before about 110 ka. In contrast, the more slowly accumulating and more sluggishly moving Antarctic ice records over 800 ka of climatic cyclicity in continuous cores and has yielded [2.7 Ma old blue ice](#) exposed at the surface with another 2 km lying beneath it.

However, sediments at the base of two ice cores from Greenland have raised the possibility of periods when the island was free of ice. One such example is from an early core drilled to a depth of 1390 m beneath the 1960's US military's nuclear weapons base, Camp Century. It helped launch the use of continental ice as a repository of Earth's recent climatic history at a far better resolution than do sediment cores from the ocean floors. It languished in cold storage after it was transferred from the US to the University of Copenhagen. Recently, samples from the bottom 3 m of sediment-rich ice were rediscovered in glass jars. A workshop centring on this seemingly unprepossessing material took place in the last week of October 2019 at the University of Vermont, USA (Voosen, P. 2019. [Mud in stored ice core hints at thawed Greenland](#). *Science*, v. 366, p. 556-557; DOI: 10.1126/science.366.6465.556.



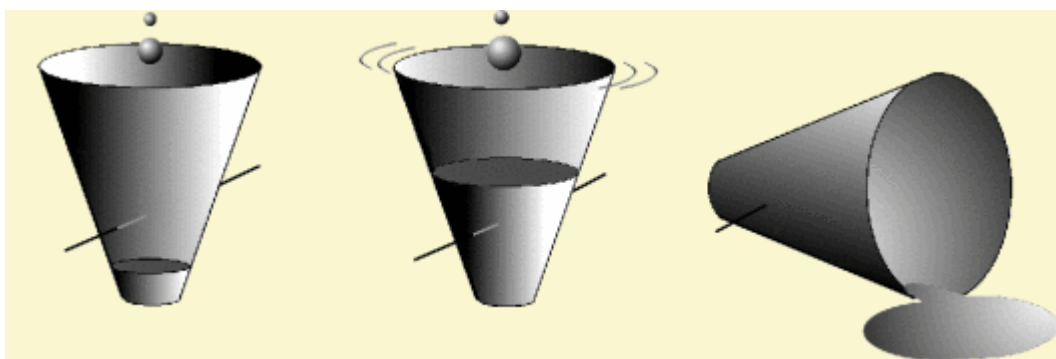
Sediment recovered from the base of the Camp Century core through the Greenland ice sheet (credit: Jean-Louis Tison, Free University of Brussels)

To the participants' astonishment, among the pebbles and sand were fragments of moss and woody material. It was not till, but a soil; Greenland had once lost its ice cover. Measurement of radioactive isotopes ^{26}Al and ^{10}Be , that form when cosmic rays pass through exposed sand grains, revealed that the once vegetated soil had formed at about 400 ka. Preliminary DNA analyses of preserved plant material indicates species that would have thrived at around 10°C . Samples have been shared widely for comprehensive analysis to reconstruct the kind of surface environment that developed during the 400 ka interglacial. Also, Greenland may have been bare of ice during several such relatively warm intervals. So other cores to the base of the ice may be in the funding pipeline. But most interest centres on the implications of a period of rapid anthropogenic climatic warming that may take Arctic temperatures above those that melted the Greenland ice sheet 400 ka ago.

See also: [Secrets under the ice](#). UVM Today 2019.

Risks of sudden changes linked to climate (December 2019)

The Earth system comprises a host of dynamic, interwoven components or subsystems. They involve processes deep within Earth's interior, at its surface and in the atmosphere. Such processes combine inorganic chemistry, biology and physics. To describe them properly would require a multi-volume book; indeed an entire library, but even that would be even more incomplete than our understanding of human history and all the other social sciences. Cut to its fundamentals, Earth system science deals with – or tries to – a planetary engine. In it, the available energy from inside and from the Sun is continually shifted around to drive the bewildering variety, multiplicity of scales and variable paces of every process that makes our planet the most interesting thing in the entire universe. It has done so, with a variety of hiccups and monumental transformations, for some four and half billion years and looks likely to continue on its roiling way for about five billion more – with or without humanity. Though we occupy a tiny fraction of its history we have introduced a totally new subsystem that in several ways outpaces the speed and the magnitude of some chemical, physical and organic processes. For example: shifting mass (see the previous item, *Sedimentary deposits of the 'Anthropocene'*); removing and modifying vegetation cover; emitting vast amounts of various compounds as a result of economic activity – the full list is huge. In such a complex natural system it is hardly surprising that rapidly increasing human activities in the last few centuries of our history have hitherto unforeseen effects on all the other components. The most rapidly fluctuating of the natural subsystems is that of climate, and it has been extraordinarily sensitive for the whole of Earth history.



Cartoon metaphor for a 'tipping point' as water is added to a bucket pivoted on a horizontal axis. As water level rises to below the axis the bucket becomes increasingly stable. Once the level rises above this pivot instability sets in until the system suddenly collapses

Within any dynamic, multifaceted system-component each contributing process may change, and in doing so throw the others out of kilter: there are 'tipping points'. Such phenomena can be crudely visualised as a pivoted bucket into which water drips and escapes. While the water level remains below the pivot, the system is stable. Once it rises above that axis instability sets in; an *external* push can, if strong enough, tip the bucket and drain it rapidly. The higher the level rises the less of a push is needed. If no powerful push upsets the system the bucket continues filling. Eventually a state is reached when even a tiny force is able to result in catastrophe. One much cited hypothesis invokes a tipping point in the global climate system that began to allow the minuscule effect on insolation from changes in the eccentricity of Earth's orbit to impose its roughly 100 ka frequency on the ups and downs of continental ice volume during the last 800 ka. In a recent issue of *Nature* a group of climate scientists based in the UK, Sweden, Germany, Denmark, Australia and China published a Comment on several potential tipping points in the climate system (Lenton, T.M. *et al.* 2019. [Climate tipping points — too risky to bet against](#). *Nature*, v. **575**, p. 592-595; DOI: 10.1038/d41586-019-03595-0). They list what they consider to be the most vulnerable to catastrophic change: loss of ice from the Greenland and Antarctic ice sheets; melting of sea ice in the Arctic Ocean; loss of tropical and boreal forest; melting of permanently frozen ground at high northern latitudes; collapse of tropical coral reefs; ocean circulation in the North and South Atlantic.

The situation they describe makes dismal reading. The only certain aspect is the steadily mounting level of carbon dioxide in the atmosphere, which boosts the retention of solar heat by delaying the escape of long-wave, thermal radiation from the Earth's surface to outer space through the greenhouse effect. An 'emergency' – and there can be little doubt that one of more are just around the corner – is the product of 'risk' and 'urgency'. *Risk* is the *probability* of an event times the *damage* it may cause. *Urgency* is the product of *reaction time* following an alert divided by the *time left to intervene* before catastrophe strikes. Not a formula designed to make us confident of the 'powers' of science! As the commentary points out, whereas scientists are aware of and have some data on a whole series of tipping points, their understanding is insufficient to 'put numbers on' These vital parameters. And there may be other tipping points that they are yet to recognise. Another complicating factor is that in a complex system catastrophe in one component can cascade through all the others: a tipping may set off a 'domino effect' on all the others. An example is the steady and rapid melting of boreal permafrost. Frozen ground contains methane in the solid form of gas hydrate, which will release this 'super-greenhouse' gas as melting progresses. Science 'knows of' such potential feedback loops in a largely untried, theoretical sense, which is simply not enough.

A tipping point that has a direct bearing on those of us who live around the North Atlantic resides in the way that water circulates in that vast basin. 'Everyone knows about' the Gulf Stream that ships warm surface water from equatorial latitudes to beyond the North Cape of Norway. It keeps NW Europe, otherwise subject to extremely cold winter temperatures, in a more equable state. In fact this northward flow of surface water and heat exerts controls on aspects of climate of the whole basin, such as the tracking of tropical storms and hurricanes, and the distribution of available moisture and thus rain- and snowfall. But the

Gulf Stream also transports extra salt into the Arctic Ocean in the form of warm, more briny surface water. Its relatively high temperature prevents it from sinking, by reducing its density. Once at high latitudes, cooling allows Gulf-Stream water to sink to the bottom of the ocean, there to flow slowly southwards. This thermohaline circulation effectively 'drags' the Gulf Stream into its well-known course. Should it stop then so would the warming influence and the control it exerts on storm tracks. It has stopped in the past; many times. The general global cooling during the 100 ka that preceded the last ice age witnessed a series of lesser climate events. Each began with a sudden global warming followed by slow but intense cooling, then another warming to terminate these stadials or Dansgaard-Oeschger cycles (see: [Review of thermohaline circulation](#), Earth-logs February 2002). The warming into the Holocene interglacial since about 20 ka was interrupted by a millennium of glacial cold between 12.9 and 11.7 ka, known as the Younger Dryas (see: [On the edge of chaos in the Younger Dryas](#), Earth-logs May 2009). A widely supported hypothesis is that both kinds of major hiccup reflected shut-down of the Gulf Stream due to sudden influxes of fresh water into North Atlantic surface water that reduced its density and ability to sink. Masses of fresh water are now flowing into the Arctic Ocean from melting of the Greenland ice sheet and thinning of Arctic sea ice (also a source of fresh water). Should the Greenland ice sheet collapse then similar conditions for shut-down may arise – rapid regional cooling amidst global warming – and similar consequences in the Southern Hemisphere from the collapse of parts of the Antarctic ice sheets and ice shelves. Lenton *et al.* note that North Atlantic thermohaline circulation has undergone a 15% slowdown since the mid-twentieth century...

See also: Carrington, D. 2019. [Climate emergency: world 'may have crossed tipping points'](#) (Guardian, 27 November 2019)

How marine animal life survived (just) Snowball Earth events (December 2019)



A Cryogenian glacial diamictite containing boulders of many different provenances from the Garvellach Islands off the west coast of Scotland. (Credit: Steve Drury)

Glacial conditions during the latter part of the Neoproterozoic Era extended to tropical latitudes, probably as far as the Equator, thereby giving rise to the concept of [Snowball Earth](#) events. They left evidence in the form of sedimentary strata known as [diamictites](#), whose large range of particle size from clay to boulders has a range of environmental explanations, the most widely assumed being glacial conditions. Many of those from the [Cryogenian Period](#) are littered with dropstones that puncture bedding, which suggest that they were deposited from floating ice similar to that forming present-day Antarctic ice shelves or extensions of onshore glaciers. Oceans on which vast shelves of glacial ice floated would have posed major threats to marine life by cutting off photosynthesis and reducing the oxygen content of seawater. That marine life was severely set back is signalled by a series of perturbations in the carbon-isotope composition of seawater. Its relative proportion of ^{13}C to ^{12}C ($\delta^{13}\text{C}$) fell sharply during the two main Snowball events and at other times between 850 to 550 Ma. The Cryogenian was a time of repeated major stress to Precambrian life, which may well have speeded up evolution, sediments of the succeeding Ediacaran Period famously containing the first large, abundant and diverse eukaryote fossils.

For eukaryotes to survive each prolonged cryogenic stress required that oxygen was indeed present in the oceans. But evidence for oxygenated marine habitats during Snowball Earth events has been elusive since these global phenomena were discovered. Geoscientists from Australia, Canada, China and the US have applied novel geochemical approaches to occasional iron-rich strata within Cryogenian diamictite sequences from Namibia, Australia and the south-western US in an attempt to resolve the paradox (Lechte, M.A. and 8 others 2019. [Subglacial meltwater supported aerobic marine habitats during Snowball Earth](#). *Proceedings of the National Academy of Sciences*, 2019; 201909165 DOI: 10.1073/pnas.1909165116). Iron isotopes in iron-rich minerals, specifically the proportion of ^{56}Fe relative to that of ^{54}Fe ($\delta^{56}\text{Fe}$), help to assess the redox conditions when they formed. This is backed up by cerium geochemistry and the manganese to iron ratio in ironstones.

In the geological settings that the researchers chose to study there are sedimentological features that reveal where ice shelves were in direct contact with the sea bed, i.e. where they were 'grounded'. Grounding is signified by a much greater proportion of large fragments in diamictites, many of which are striated through being dragged over underlying rock. Far beyond the grounding line diamictites tend to be mainly fine grained with only a few dropstones. The redox indicators show clear changes from the grounding lines through nearby environments to those of deep water beneath the ice. Each of them shows evidence of greater oxidation of seawater at the grounding line and a falling off further into deep water. The explanation given by the authors is fresh meltwater flowing through sub-glacial channels at the base of the grounded ice fed by melting at the glacier surface, as occurs today during summer on the Greenland ice cap and close to the edge of Antarctica. Since cold water is able to dissolve gas efficiently the sub-glacial channels were also transporting atmospheric oxygen to enrich the near shore sub-glacial environment of the sea bed. In iron-rich water this may have sustained bacterial chemo-autotrophic life to set up a fringing food chain that, together with oxygen, sustained eukaryotic heterotrophs. In such a case, photosynthesis would have been impossible, yet unnecessary. Moreover, bacteria that use the oxidation of dissolved iron as an energy source would have caused Fe-3 oxides to precipitate, thereby forming the ironstones on which the study centred. Interestingly, the hypothesis resembles the recently discovered ecosystems beneath Antarctic ice shelves.

Small and probably unconnected ecosystems of this kind would have been conducive to accelerated evolution among isolated eukaryote communities. That is a prerequisite for the sudden appearance of the rich Ediacaran faunas that colonised sea floors globally once the Cryogenian ended. Perhaps these ironstone-bearing diamictite occurrences where the biological action seems to have taken place might, one day, reveal evidence of the precursors to the largely bag-like Ediacaran animals