Palaeoclimatology 2025

Modelling climate change since the Devonian

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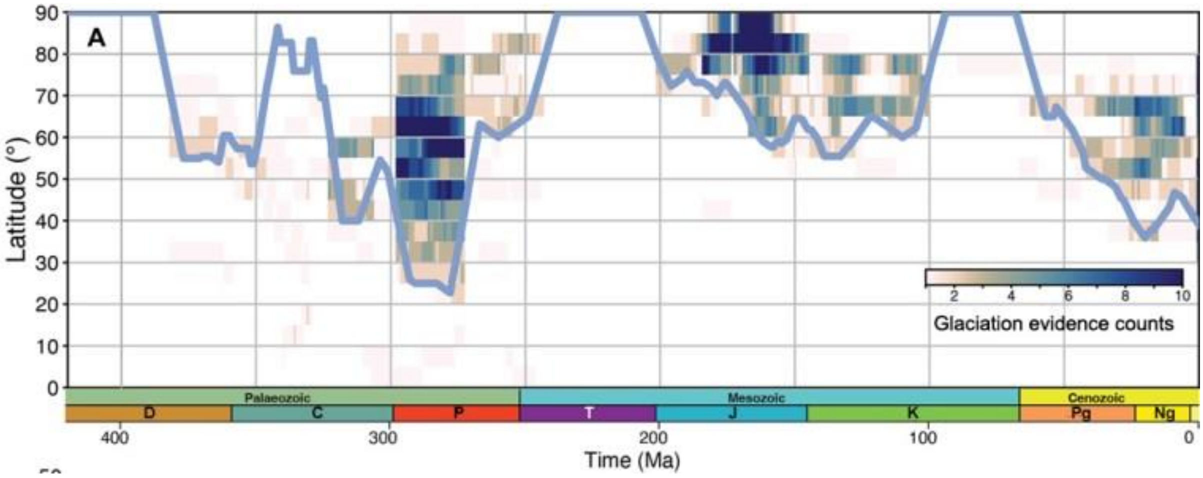
A consortium of geoscientists from Australia, Britain and France, led by Andrew Merdith of the University of Adelaide examines the likely climate cooling mechanisms that may have set off the two great 'icehouse' intervals in the last 541 Ma (Merdith, A.S. *et al*. 2025. Phanerozoic icehouse climates as the result of multiple solid-Earth cooling mechanisms. *Science Advances*, v. 11, article eadm9798: DOI: 10.1126/sciadv.adm9798). They consider the first to be the global cooling that began in the latter part of the Devonian culminating in the Carboniferous-Permian icehouse. The second is the Cenozoic global cooling to form the permanent Antarctic ice cap around 34 Ma and culminated in cyclical ice ages on the northern continents after 2.4 Ma during the Pleistocene. They dismiss the 40 Ma long, late Ordovician to early Silurian glaciation that left its imprint on North Africa and South America – then combined in the Gondwana supercontinent. The data about two of the parameters used in their model – the degree of early colonisation of the continents by plants and their influence on terrestrial weathering are uncertain in that protracted event. Yet the Hirnantian glaciation reached 20°S at its maximum extent in the Late Ordovician around 444 Ma to cover about a third of Gondwana: it was larger than the present Antarctic ice cap. For that reason, their study spans only Devonian and later times.



Fluctuation in evidence for the extent of glacial conditions since the Devonian: the 'ice line' is grey. The count of glacial proxy occurrences in each 10° of latitude through time is shown in the key. Credit: Merdith et al., Fig 2A.

Merdith *et al*. rely on four climatic proxies. The first of these comprises indicators of cold climates, such as glacial dropstones, tillites and evidence in sedimentary rocks of crystals of hydrated calcium carbonate (ikaite – $CaCO_3.6H_2O$) that bizarrely forms only at around 0°C . From such occurrences it is possible to define an 'ice line' linking different latitudes through geological time. Then there are estimates of global average surface temperature; low-latitude sea surface temperature; and estimates of atmospheric CO_2. The 'ice-line' data records an additional, long period of glaciation in the Jurassic and early Cretaceous, but evidence does not extend to latitudes lower than 60°. It is regarded by Merdith *et al*. as an episode of ‘cooling’ rather than an ‘icehouse’. Their model assesses sources and sinks of CO_2 since the Devonian Period.

The main natural source of the principal greenhouse gas CO_2 is degassing through volcanism expelled from the mantle and breakdown of carbonate rock in subducted lithosphere. Natural sequestration of carbon involves weathering of exposed rock that releases dissolved CO_2 and ions of calcium and magnesium. A recently compiled set of plate reconstructions that chart the waxing and waning of tectonics since the Devonian Period allows them to model the tectonically driven release of carbon over time, with time scales on the order of tens to hundreds of Ma. The familiar Milanković forcing cycles on the order of tens to hundreds of ka are thus of no significance in Merdith *et al*.’s broader conception of icehouse episodes Their modelling shows high degassing during the Cretaceous, modern levels during the late Palaeozoic and early Mesozoic, and low emissions during the Devonian. The model also suggests that cooling stemmed from variations in the positions and configuration of continents over time. Another crucial factor is the tempo of exposure of rocks that are most prone to weathering. The most important are rocks of the ocean lithosphere incorporated into the continents to form ophiolite masses. The release of soluble products of weathering into ocean basins through time acts as a fluctuating means of ‘fertilising’ so that more carbon can be sequestered in deep sediments in the form of organisms’ unoxidised tissue and hard parts made of calcium carbonates and phosphates. Less silicate weathering results in a boost to atmospheric CO_2.

Only two long, true icehouse episodes emerge from the empirical proxy data, expressed by the ‘ice-line’ plots. Restricting the modelling to single global processes that might be expected to influence degassing or carbon sequestration produces no good fits to the climatic proxy data. Running the model with all the drivers “off” produces more or less continuous icehouse conditions since the Devonian. The model’s climate-related outputs thus imply that many complex processes working together in syncopation may have driven the gross climate vagaries over the last 400 Ma or so. A planet of Earth’s size without such complexity would throughout that period have had a high-CO_2 warm climate. According to Andrew Merdith its fluctuation from greenhouse to icehouse conditions in the late Palaeozoic and the Cenozoic were probably due to “coincidental combination of very low rates of global volcanism, and highly dispersed continents with big mountains, which allow for lots of global rainfall and therefore amplify reactions that remove carbon from the atmosphere”.

Geological history is, almost by definition, somewhat rambling. So, despite despite the large investment in seeking a computed explanation of data drawn from the record, the outcome reflects that in a less than coherent account. To state that many complex processes working at once may have driven climate vagaries over the last 400 Ma or so, is hardly a major advance: palaeoclimatologists have said more or less the same for a couple of decades or more, but have mainly proposed single driving mechanisms. One aspect of Merdith *et al*.’s results seems to be of particular interest. ‘Icehouse’ conditions seem to be rare events interspersed with broader ice-free periods. We evolved within the mammal-dominated ecosystems on the continents during the latest of these anomalous climatic episodes. And we and those ecosystems now rely on a cool world. As the supervisor of the project commented, ‘Over its long history, the Earth likes it hot, but our human society does not’.

Readers may like to venture into how some philosophers of science deal with a far bigger question; ‘Is intelligent life a rare, chance event throughout the universe?’ That is, might we be alone in the cosmos? In the same issue of *Science Advances* is a paper centred on just such questions (Mills, D.B. *et* al. 2025. A reassessment of the “hard-steps” model for the evolution of intelligent life. *Science Advances*, v. 11, article eads5698; DOI: 10.1126/sciadv.ads5698). It stems from cosmologist Brandon Carter’s ‘Anthropic Principle’ first developed at Nicolas Copernicus’s 500th birthday celebrations in 1973. This has since been much debated by scientists and philosophers – a gross understatement as it knocks the spots off the Drake Equation. To take the edge off what seems to be a daunting task, Mills *et al*. consider a corollary of the Anthropic Principle, the ‘hard steps model’. That, in a nutshell, postulates that the origin of humanity and its ability to ponder on observations of the universe required a successful evolutionary passage through a number of hard steps. It predicts that such intelligence is ‘exceedingly rare’ in the universe. Icehouse conditions are respectable candidates for evolutionary ‘hard steps’, and in the history of Earth there have been five of them.

Direct measurements of ancient atmospheric composition

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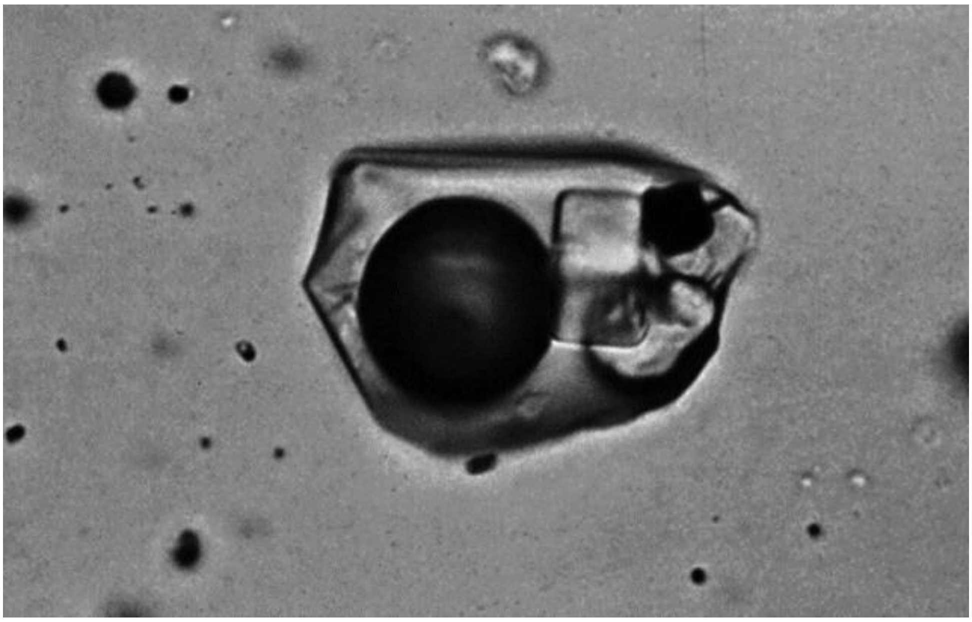
For decades, research into the composition of the Earth’s early atmosphere depended on indirect means. An example is the preservation of water-worn grains of sulphides and uranium oxides in coarse terrestrial sediments older than about 2,200 Ma. Their survival on the continental surface suggested that the atmosphere before then had vanishingly low O_2. Such grains would have otherwise been broken down by oxidation reactions. Younger sediments simply do not contain such detrital grains. This suggested the appearance of an oxidising atmosphere around 2.2 Ga ago: the Great Oxygenation Event. The greenhouse gases – carbon dioxide and methane – are also difficult to estimate directly, especially in the Precambrian. Once plants colonised the land surface, their photosynthesis depended on inhaling and exhaling air through stomata on the surface of leaves (**see:** Ancient CO_2 estimates worry climatologists; January 2017). The number of stomata per unit area of a leaf surface is expected to increase with lowering of atmospheric CO_2 and vice versa, which has been observed in plants grown in different air compositions. By comparing stomatal density in fossilised leaves of modern plants back to 800 ka allows the change to be calibrated against the record of CO_2 inside air bubbles trapped in ice-cores. This proxy method has given a guide to CO2 variations through the Cenozoic, Mesozoic and upper Palaeozoic Eras. However, the reliability of extinct plant leaves as proxies is suspect.



A fluid inclusion (about 0.2 mm) containing a spherical gas bubble trapped in a crystal of halite (NaCl). Credit: alchetron.com

Is it possible to find air trapped by other means than in glacial ice? It may be. Tiny pockets of liquid and gas – fluid inclusions – are often found in minerals that crystallised at the Earth's surface. The most common are crystals of salt (NaCl) and carbonates from ancient lake deposits. A 2019 study revealed that Late Triassic carbonates from Colorado, USA record an increase of atmospheric oxygen levels from 15 to 19% about 215 Ma ago over a period of just 3 million years as dinosaurs first spread into North America, then at equatorial latitudes in the Pangaea supercontinent. This sudden increase in the availability of oxygen may also be linked to the trend towards larger and larger dinosaurs worldwide. Going further back in time trace-metal chemistry of 1,400 Ma old marine sediments from China indicates oxygenated water that suggests an atmospheric oxygen level greater than 4% of that at present. Small as that might seem, it would have been sufficient to sustain animal respiration about half a billion years before the first evidence for the earliest animals. Further work on ancient salt and carbonate deposits confirms much higher oxygen levels than geochemists have expected previously.

Source: Voosen, P, 2025. Earth's rocks hold whiffs of air from billions of years ago. *Science*, v.**387**, articlezhst73x; DOI: 10.1126/science.zhst73x