

## ***Climate change and palaeoclimatology***

### **Meltdown for Snowball Earth? (January 2002)**

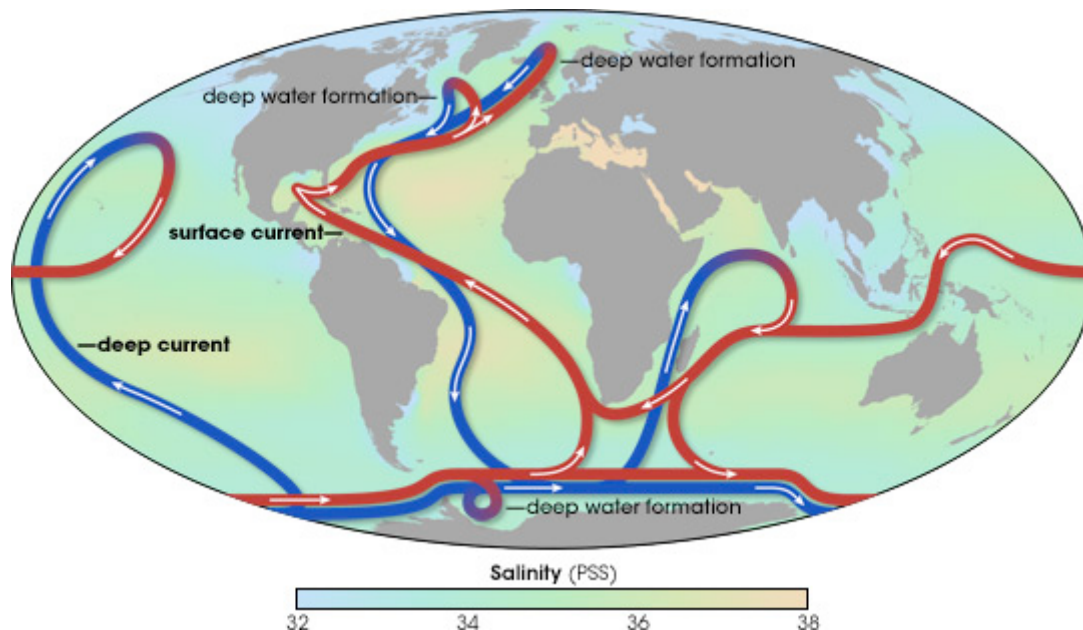
Following on from their linking carbon-isotope excursions associated with Neoproterozoic diamictite-cap carbonate sequences to methane release (see [Methane and Snowball Earth](#), December 2001), Martin Kennedy, Nicholas Christie-Blick and Anthony Prave turned to the  $\delta^{13}\text{C}$  values in the diamictites for which a glaciogenic interpretation forms the main plank of the Snowball Earth hypothesis (Kennedy, M.J. *et al.* 2001. [Carbon isotope composition of Neoproterozoic glacial carbonates as a test of paleoceanographic models for snowball Earth phenomena](#). *Geology*, v. **29**, p. 1135-1138; doi: 10.1130/0091-7613(2001)029<1135:CICONG>2.0.CO;2).

Complete ice cover of the oceans would chemically isolate ocean water from the atmosphere, and would effectively shut down the organic sinks for atmospheric carbon dioxide. While they operate, the exclusion of  $^{13}\text{C}$  relative to lighter carbon by organisms drives up  $\delta^{13}\text{C}$  in sea water, to be preserved in carbonate sediments. The Snowball Earth model predicts negative  $\delta^{13}\text{C}$ , approaching the -5‰ of the mantle, in carbonates deposited during all-enveloping glacial epochs. However, few researchers have made the measurements needed to test that part of the hypothesis.

Kennedy and co-workers show from three such diamictite sequences that the carbonate precipitated as cement in them has consistently positive  $\delta^{13}\text{C}$ . Although that does not disprove the existence of glaciation at tropical latitudes, it is not consistent with the dreadful scenario of totally ice-bound oceans devoid of life. Nor, for that matter, is there any evidence from strontium isotope variations in carbonate cap rocks for the massive continental weathering that the Snowball Earth devotees propose as a means of escape from the eventual hot-house that build up of volcanic  $\text{CO}_2$  emissions to release Earth from the mothers of all cold snaps would create. Expect interesting news in later *Earth Pages* of how the greatest Earth science debate of the 21<sup>st</sup> century develops.

### **Review of thermohaline circulation (February 2002)**

The central factor in abrupt climatic shifts during the last glacial period was change in thermohaline circulation (THC), particularly in the Atlantic Ocean. Two general processes underpin THC: differences in solar heating from low to high latitudes drive polewards flow of surface water; formation beneath sea-ice of dense brine that sinks to form an equatorwards flow of North Atlantic Deep Water (NADW). Freshwater influx at high latitudes suppresses the formation of NADW, which, together with enhanced low-latitude evaporation, slows polewards surface flow.. Currently, the thermal influence and NADW formation dominates heat transport northwards in the North Atlantic, by carrying about a petawatt at mid latitudes. THC is of little consequence in the North Pacific, partly because its fresher surface water hinders dense-brine formation, and partly because any deep water formed beneath sea ice in the Arctic cannot flow through the very shallow Bering Straits.



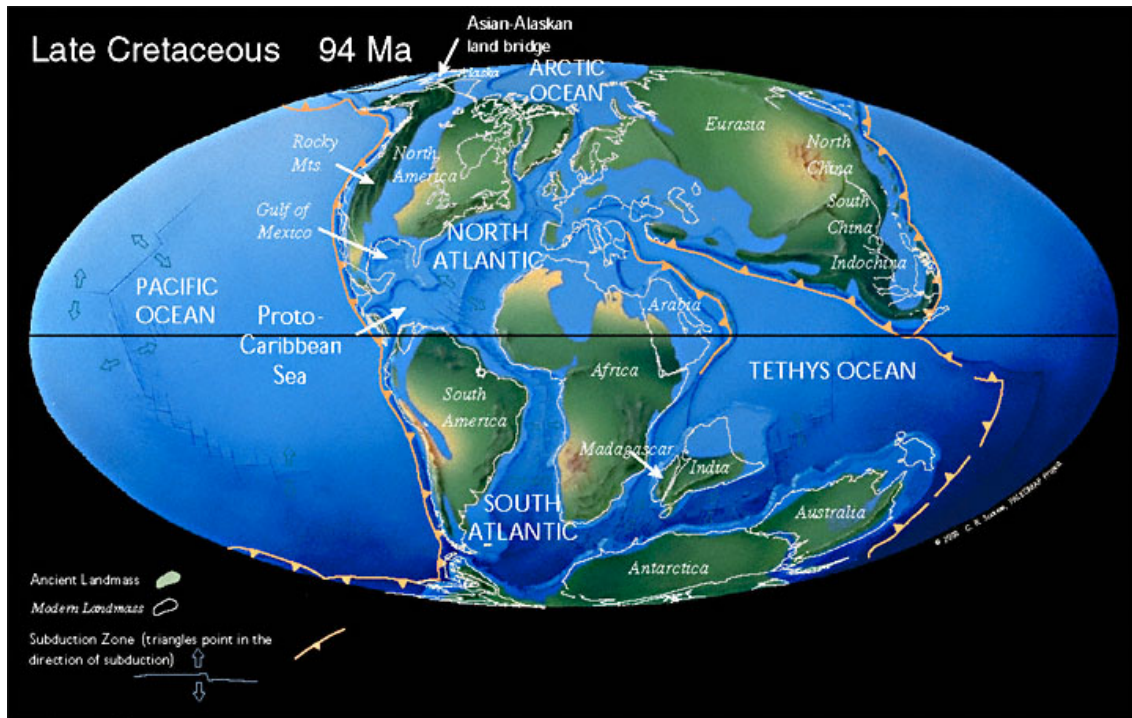
Simplified view of global thermohaline circulation (red – surface water; blue – bottom water) (Credit: Arstechnica)

Clearly THC is a sensitive mechanism, inseparable from other factors in climate forcing. Having such a vast influence on heat transport, if it changes there are likely to be dramatic outcomes for climate, particularly along the eastern flank of the North Atlantic where much of the transported heat arrives. Sea-ice formation around Iceland is decreasing, so a review article on THC and rapid climate change is essential reading (Clark, P.U. *et al.* 2002. [The role of thermohaline circulation in abrupt climate change](#). *Nature*, v. **415**, p. 863-869; DOI: 10.1038/415863a). It is now known that the last glacial period was punctuated by short-period (~ 1-2 ka) warming-cooling episodes, known as Dansgaard-Oeschger events, one aspect of which was the launching of “armadas” of icebergs to latitudes as far south as Portugal (known as Heinrich events), which left their mark as occasional gravel layers in the otherwise muddy sediments on the deep Atlantic floor. These episodes involved temperature changes over the Greenland icecap of as much as 15°C. They began with warming on this scale within a matter of decades followed by slow cooling to minimal temperatures, before the next turn-over. The deep cooling seems to have accompanied slowing and shut-down of THC. Current global warming is likely to do three things: increasing low-latitude evaporation, increasing freshwater influx to high-latitude Atlantic surface water and a decrease in sea-ice formation at the site of NADW formation. Because all three drive down polewards heat flux, anthropogenic warming may well result in contrary climate shift in Western Europe and Scandinavia - freeze rather than thaw. If it happens, chances are that it will be upon us with little warning.

### **Prolonged Cretaceous hothouse (March 2001)**

Hothouse conditions were forced by massive emission of CO<sub>2</sub> during the mid-Cretaceous superplume event that created huge submarine basalt plateaux and began the development of many island chains that litter the floor of the central Pacific. It was at this time that dinosaur-infested forests cloaked high latitudes, almost to both poles. Terrestrial evidence suggests that conditions cooled somewhat in the later Cretaceous, and sequence

stratigraphy indicates cyclic sea-level fluctuations, ascribed by some to the development of Antarctic ice sheets. Resolving later Cretaceous global mean temperatures, and the ice-sheet question relies on oxygen isotopes from sea-floor sediments. These are now available with sufficient precision and resolution to show that hothouse conditions lasted a great deal longer than suspected (Huber, B.T. *et al.* 2002. [Deep-sea paleotemperature record of extreme warmth during the Cretaceous](#). *Geology*, v. **30**, p. 123-126; doi: DOI: 10.1130/0091-7613(2002)030<0123:DSPROE>2.0.CO;2).



Tectonics of the mid-Cretaceous. Note high sea level and transgression onto the continents

The Pacific superplume's maximum activity was over a period of 15 Ma from 125 to 110 Ma (Barremian and Aptian), although it lasted until the early Campanian (80 Ma). Contrary to the supposed magnitude of CO<sub>2</sub> release by volcanism, heating reached a maximum from 94 to 80 Ma. Even at high southern latitudes, deep-ocean water remained at 14 to 19°C for these 14 Ma. Until the end of the Cretaceous it rarely fell below 10°C. The data rule out any circulation of cold, dense brines into the deep ocean basins from the formation of boreal sea ice, and consequently any influence by polar ice sheets. Sea level reached its highest during this period, almost certainly because the volume of the ocean basins shrank, being flooded by young, warm, low-density crust formed by the superplume. Mid to late-Cretaceous flooding of the continental margins created uniquely favourable conditions for an explosive development of carbonate-secreting organisms of many kinds. Despite the burial of vast carbonate platforms, as well as thick boreal coal seams, these limestone "factories" seem incapable of having kept pace with greenhouse warming. Was CO<sub>2</sub> the only means then of global warming?

### Glacial floods and climate change (May 2002)

One of the fundamental discoveries about climate change during the Plio-Pleistocene ice ages is how many climate fluctuations with periods too short to be ascribed to astronomical

forcing link to shifts in deep-ocean circulation. In the case of the North Atlantic Ocean, if high-latitude seas become diluted by fresh water cold, dense brines are less able to form. It is their sinking that helps drive the “ocean conveyor” and draws warmer water into the Arctic from the tropics. If they do not form, then the conveyor shuts down and high-latitudes cool. The most spectacular of these ocean-driven events was the Younger Dryas cooling from about 12.9 to 11.6 ka, and it may well have occurred because of the sudden drainage of a giant lake of glacial meltwater down the St Lawrence Seaway to dilute North Atlantic surface water. The waning of every major ice sheet covering North America would have generated vast amounts of freshwater, and because repeated glaciation created basins by erosion and sagging of the low-relief surface, drainage of such lakes would have been characteristic of every transition to interglacial warmth. Steven Colman of the US Geological Survey reviews recent attempts to model how flooding may have escaped from the ice-sheet margins (Colman, S.M. 2002. A fresh look at glacial floods. *Science*, v. **296**, p. 1251-1252; DOI: 10.1126/science.1073377).

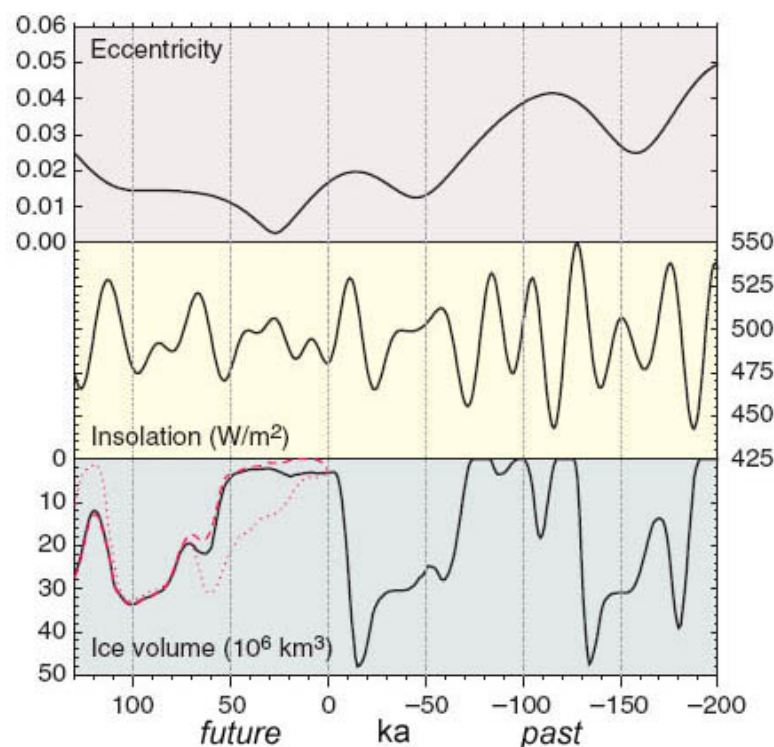
### **The Hadean was cool (May 2002)**

James Hutton’s observation that the geological history of Scotland had “no vestige of a beginning” applies everywhere, for no-one has dated rocks that are older than about 4.0 billion years (Ga) old, despite a great deal of effort. It seems that continental crust only became capable of remaining at the surface in large volumes almost 600 Ma after the Earth formed from the solar nebula. Indirect isotopic evidence and dating of meteorites do indicate that the Earth accreted from dust and planetesimals about 4.56 Ga ago. There are terrestrial materials that break the 4 Ga barrier, but they are so few and so tiny that they could be lost with one powerful sneeze. These are crystals of the highly resistant mineral zircon, found as detrital grains in mid-Archaean sandstones in Western Australia. The oldest of these is a single grain dated at 4.404 Ga. All of them formed in igneous rocks produced by partial melting of the mantle, which concentrates zirconium in magma. Following their liberation to sedimentary processes by weathering, the zircons have probably been through several sedimentary cycles since the formed. So the pre-Archaean history of our world has left relics, but they are minuscule. Because of the absence of pre-4Ga crust, that period was probably turbulent, partly through rapid convective turnover of the mantle and higher degrees of melting because of higher heat production, and partly due to far more large impacts that the lunar surface shows during those times. Dating of lunar cratering and impact glasses suggests that bombardment reached a crescendo around 4.0 to 3.9 Ga. It is now fairly certain that the Moon formed from incandescent material ejected from the Earth when it collided with a Mars-sized planet around 4.45 Ga. Earth and its companion would, in that likely scenario, have begun their geological evolution completely molten in the case of the Moon and with a deep magma ocean on Earth. “Hellish” is a barely adequate adjective for such conditions, and the period before 4 Ga has been termed the Hadean. A vital question concerns when such extreme conditions waned to become potentially supportive of biochemistry and the origin of life.

Minute as they are, the pre-4.0 Ga zircons provide useful oxygen-isotope data, and their  $\delta^{18}\text{O}$  is no different from that of more common zircons throughout the Archaean Aeon. The explanation for this is that the mantle and the magmas produced from it contained an  $\text{H}_2\text{O}$  phase. Either the mantle has always had a water content - no surprise as it still does - or the

magmas from which the zircons crystallized encountered near-surface water vapour, possibly as a result of hydrothermal exchange with a hydrosphere. Reviewing these data, John Valley and colleagues from the University of Wisconsin USA and Curtin University Australia pursue the second conjecture (Valley, J.W. *et al.* 2002. [A cool early Earth](#). *Geology*, v. **30**, p. 351-354; [https://doi.org/10.1130/0091-7613\(2002\)030<0351:ACEE>2.0.CO;2](https://doi.org/10.1130/0091-7613(2002)030<0351:ACEE>2.0.CO;2)), and argue for a surface temperature below the boiling point of water since 4.4 Ga, only 50 Ma years after geochemical “year zero”. The crux of their argument is that the high  $\delta^{18}\text{O}$  values of four Hadean zircons indicate their equilibration with water vapour at temperatures below water’s critical point (374°C). If crystallization at depth was below that temperature, then the Earth would have had surface oceans. But is this such a surprising conclusion? Loss of heat by radiation being proportional to the fourth power of absolute temperature, an incandescent Earth's surface at the time of Moon formation would have cooled below 100°C well within 50 Ma, unless it was blanketed by an opaque atmosphere. Impacts of the size of those which produced the lunar *maria* around 4.0-3.9 Ga could have boiled away any surface water from time to time, only for the surface to cool quickly once again. Conditions for bio-geochemistry could well have been present throughout the Hadean. The significance of that for the origin of life is hard to judge, because large impacts and ocean boiling would have extinguished any progress, so that the process may have had to restart again and again.

#### Long-range forecast: a prolonged interglacial (August 2002)



Recent and predicted variations in Earth’s orbital eccentricity, northern hemisphere insolation and ice volume. (Credit: Berger & Loutre, 2002)

Provided the Milankovich theory of astronomical influences on insolation is indeed behind the pacing of glacial-interglacial episodes of the near past, it should be easier to forecast future change in overall climate than that of weather. It turns out that the fluctuation of



Earth's orbital eccentricity (behind the roughly 100 ka periodicity of climate change for the past 1 Ma) is entering an historic low, due to the 400 ka period of one of its two cycles. Modelling future insolation at high northern latitudes results in a damping of its fluctuations over the next 100 ka (Berger, A. & Loutre, M.F. 2002. [An exceptionally long interglacial ahead?](#) *Science*, v. **297**, p. 1287-1288; DOI: 10.1126/science.1076120). Left to climate's own devices, the small changes in insolation may prolong the Holocene interglacial for as much as another 50 ka, instead of being now on the cusp of a descent into more frigid conditions, as previously believed. Until recently, many climatologists looked to the last, Eemian interglacial as the model for the current one, and that lasted only 10 ka.

Of course, climate is no longer at the whim of astronomical forces and the Earth's own circulation of energy, principally by the flow of energy in North Atlantic water, driven by deep water formed by sea-ice around Iceland. Atmospheric CO<sub>2</sub> stands about 30% higher than during previous interglacials, because of anthropogenic emissions. Berger and Loutre factor in the "greenhouse" influence of the additional CO<sub>2</sub>, to find an ominous possibility that the Greenland ice sheet might well melt, with the climate entering an irreversible warming. The climate, however, is not a model, and there is really no inkling of what surprises are in store from counter-intuitive behaviour of the many forces at work in it, under conditions that have no analogue during the whole of human evolutionary history.

### **Analogue of Archaean carbon cycle in Black Sea reefs (August 2002)**

The Archaean world almost certainly had an atmosphere and oceans that were more or less free of oxygen. Under such conditions the fate of dead organisms in the ocean, perhaps the remains of photosynthesizing cyanobacteria, would have been bacterial fermentation and the production of massive amounts of methane. Along with volcanic emissions of carbon dioxide, methane in the atmosphere would have helped warm the planet at a time when the Sun emitted considerably less energy than it does now. Methane is more strongly depleted in <sup>13</sup>C than any organic or inorganic carbon compound. So large falls in the δ<sup>13</sup>C composition of organic carbon in Archaean rocks, around 2700 Ma have been taken by some palaeobiologists to signify methane metabolism. Most methane-consuming bacteria today produce oxygen as a byproduct, so the negative excursions might indicate an early build up of more than a trace of oxygen in the Archaean atmosphere. Discovery of bacterial communities on the floor of the Black Sea, which consume methane without oxygen production (Michaelis, W. and 16 others 2002. [Microbial reefs in the Black Sea fuelled by anaerobic oxidation of methane](#). *Science*, v. **297**, p. 1013-1015; DOI: 10.1126/science.1072502), suggest strongly that there may be little reason to suppose that Archaean conditions did involve free oxygen.

Off the coast of Crimea there are numerous sea-bed methane seeps in shallow water. Surprisingly they are well-colonized by primitive bacteria, which produce thick mats held together by carbonate precipitates in completely anoxic conditions. Laboratory cultures of the communities reveal that they consist of archaea and bacteria that respectively consume methane and reduce sulphate ions to sulphide. The net result is that methane is oxidized by sulphate to produce calcium and magnesium carbonates, and lots of hydrogen sulphide (methane donates electrons for sulphate reduction, thereby becoming a source of carbon for cell metabolism). Since much of the methane's carbon ends up in stable carbonate -

perhaps ten times more than in organic matter, such a process in the Archaean would have helped stabilize the “greenhouse effect” then.

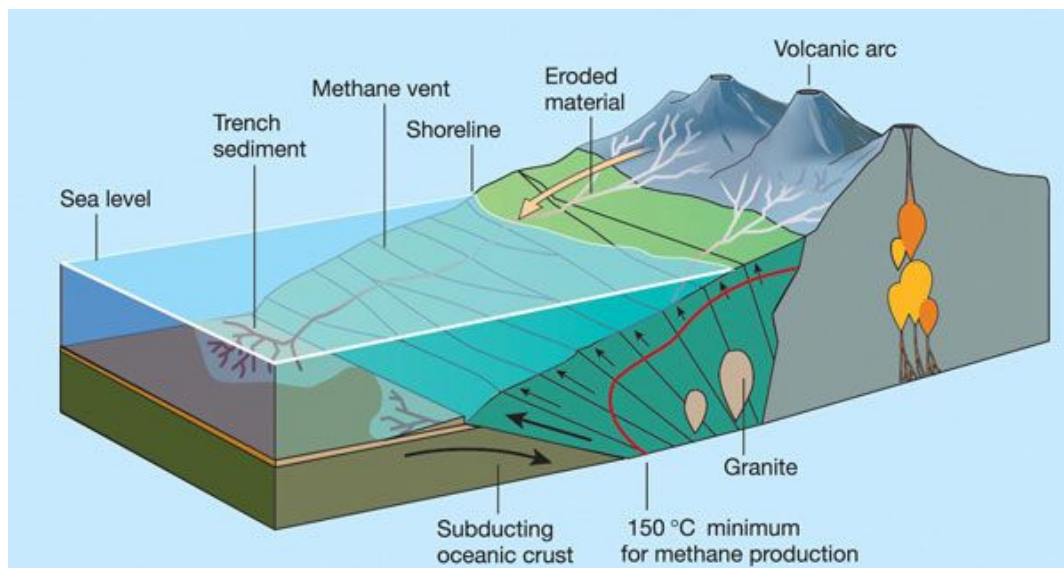
### **Reviews of climate and the hydrological cycle (September 2002)**

I have commented several times on developments in the connection between ocean currents and climate, over the last 3 years. The subject has many aspects, and these have been bundled and brought up to date in one of a series of review articles on the relationship between climate and the hydrological cycle in *Nature's* occasional Insight series (Rahmstorf, S. 2002. [Ocean circulation and climate during the last 120,000 years](#). *Nature*, v. **419**, p. 207-214; DOI: 10.1038/nature01090 · ). Stefan Rahmstorf covers the evidence to date that implicates changes in deep circulation in rapid and dramatic climate shifts, such as changed air temperatures over the Greenland ice cap and iceberg armadas in the North Atlantic. Another review outlines the longer-term perspective of links between atmosphere, oceans, ice sheets, solid-Earth processes and astronomical forcing in shifts of climate and sea level over the last 3 Ma. Central to this linked system is the transfer of tens of millions of cubic kilometres of water from tropics to poles, and from ice sheets to sea levels (Lambeck, K. *et al.* 2002. [Links between climate and sea levels for the past three million years](#). *Nature*, v. **419**, p. 199-206; DOI: 10.1038/nature01089).

### **Alaskan source proposed for end-Palaeocene warming (September 2002)**

Between 58 and 52 Ma, around the Palaeocene-Eocene boundary, Earth's climate bucked the long-term cooling trend during the Cenozoic, by warming considerably. Since the warming lasted for so long, it seems likely to have been caused by an enhanced atmospheric "greenhouse" gases rather than by either astronomical or oceanic causes. Carbon isotope data around the P-E boundary can be interpreted in terms of massive releases of biogenic methane, perhaps from gas hydrates on the sea floor. However, such releases are likely to have been sudden, and a more continual release of “greenhouse” gases fits the record better; but that begs the questions where and how? Catastrophic methane release has been invoked for the dramatic rise in deep-ocean and high-latitude temperatures within 10 thousand years exactly at the P-E boundary.

Lengthy climatic warming can stem from increased volcanism and sea-floor spreading, but there is scanty evidence for either during this period. Another possibility is production of gases as a result of tectonic activity, either by involvement of carbonate sediments in metamorphism, which releases CO<sub>2</sub>, or “stewing” organic matter in thick sedimentary sequences. Candidates for the last are the thick accretionary prisms at Pacific destructive margins, an especially appropriate example being that of the Gulf of Alaska which grew rapidly during this period (Hudson, T.I. & Magoon, I.B. 2002. Tectonic controls on greenhouse gas flux to the Paleogene atmosphere from the Gulf of Alaska accretionary prism. *Geology*, v. **30**, p. 547-550; DOI: [10.1130/0091-7613\(2002\)030<0547:TCOGGF>2.0.CO;2](#)).



Typical accretionary prism

Oceanic and continental margin sediments scraped off descending oceanic lithosphere contain buried organic matter. Increased heat flow, perhaps associated with rising magmas, can cause organic debris to break down to hydrocarbons. Over-maturation results in the formation of methane, potentially in vast volumes, that can leak continually to the atmosphere. Methane rapidly oxidizes to  $\text{CO}_2$ , decreasing the warming effect, but able to linger for considerable periods. Hudson and Magoo calculate such enormous releases, that even disputes over the amount of accreted sediment in the Gulf of Alaska do little to rule out its being a major source for climatically implicated gases. This first suggestion of a role for accretionary prisms in climate change may spur studies of such processes elsewhere, in an attempt to remove much of the load from the BLAG hypothesis that involves metamorphic release of  $\text{CO}_2$  in a difficult to verify process of lithospheric flatus.

**See also:** Clift, P. & Bice, K. 2002. Baked Alaska. *Nature*, v. **419**, p.129-130; doi: 10.1038/419129a

### Africa's first ice core record

Melting of low-latitude glaciers in Africa is so rapid that, unless they are cored soon, their content of long-term climate data may soon be gone forever. So the first detailed isotopic record from Africa's highest glacier on Kilimanjaro is cause for some relief. Intrepid glaciologist Lonnie Thompson welded a large team together for this important task (Thompson, L. 2002. [Kilimanjaro ice core records: evidence of Holocene climate change in tropical Africa](#). *Science*, v. **298**, p. 589-593; DOI: 10.1126/science.1073198). The annually layered ice goes back only about 12 ka, but nonetheless gives a precious account of climate change at the heart of the continent, far more detailed than sparse lake-bed cores from various places.

The core confirms a broad pattern of warm, wet conditions from 11 to 4 ka, before the long-term cooling and drying of historical times. These reflect likely weakening of monsoonal conditions in the late Holocene. However, assigning precise ages to depth in the cores is not as easy as in those from high-latitude ice sheets, because of a lack of good layering (presumably) and dateable carbon. At about 5200 years ago, the record shows an abrupt



fall in  $\delta^{18}\text{O}$ , a sign of drying and cooling that took place over perhaps a matter of decades. This correlates with disruption of early civilisations in India, Egypt and the Middle East, and probably stemmed from cooling in the North Atlantic. However, an equally rapid deterioration occurred around 6300 years bp, although not so extreme, to presage a millennium of arid conditions at the heart of Africa. Important as these data are, the team's estimates of current retreat rates of the Kilimanjaro glaciers are alarming. Quite probably, the white cap of Africa's highest mountain will have disappeared within the next 20 years.



Kilimanjaro glacier with layering (Credit: <https://www.jambo-kilimanjaro.com/>)

Lonnie Thompson is obviously both keyed- and clued up about extracting climatic data from ice at high elevations. So much so, that *Science* has printed a lengthy account of his exploits, mainly on low-latitude glaciers (Krajick, K. 2002. Ice man: Lonnie Thompson scales the peaks for science. *Science*, v. **298**, p. 518-522; DOI: 10.1126/science.298.5593.518).

### **Snowball Earth hypothesis challenged, again (November 2002)**

Palaeomagnetic data from localities famed for their Neoproterozoic glaciogenic rocks point persuasively to several epochs between 750 and 550 Ma when widespread continental glaciation took place at low latitudes. It is this evidence, along with theoretical consideration of drastic changes in the Earth's albedo that would result from tropical land ice, that encouraged the idea of pole to pole ice cover. Only a build-up of volcanogenic  $\text{CO}_2$  in the atmosphere could prevent such a "Snowball Earth" lasting indefinitely, and even with such relief it would have endured for millions of years. Much of the geological evidence cited by those who support and promote this neo-catastrophic idea comes from excellent, but geographically quite limited occurrences of tillites or glaciomarine sediments, such as those of Namibia. Some occurrences have never been seriously analysed, except as examples that

superficially support the hypothesis. One such sequence is that of Arabia, easily accessed in northern Oman and described by a British-Swiss team (Leather, J. *et al.* 2002.

[Neoproterozoic snowball Earth under scrutiny: Evidence from the Fiq glaciation of Oman.](#) *Geology*, v. **30**, p. 891-894; DOI: 10.1130/0091-7613(2002)030<0891:NSEUSE>2.0.CO;2).



The Port Askaig tillite on the Garvellach Isles, Scotland (Credit: author)

Isotopic studies of carbonates from glaciogenic sediments (see *Meltdown for Snowball Earth?* above) seriously undermined several arguments by “Snowball Earth” supporters, but are open to various interpretations. Hard geological evidence is less easy to rationalize. A growing number of Neoproterozoic glaciogenic sequences, such as the Port Askaig Tillite of the Scottish Dalradian Supergroup and others from the Congo and Kalahari cratons, and Laurentia, show dropstone-rich diamictites interbedded with sediments that show little if any sign of a glacial influence (Condon, D.J. *et al.* 2002. Neoproterozoic glacial-rainout intervals: Observations and implications. *Geology*, v. **30**, p. 35-38; doi: 10.1130/0091-7613(2002)030<0035:NGRIOA>2.0.CO;2). Such evidence can be explained by climatic change and a fully functioning hydrological cycle. The report on the Omani example by Leather and colleagues highlights splendid examples of sediments that mark cycles of glacial advance and retreat, reminiscent of those of the Pleistocene glacial epoch and more or less the same as in many Neoproterozoic occurrences. It can only be a matter of time before Australian geologists enter the fray decisively, for glaciogenic sediments comprise up to 30% of the many-kilometres thick Umberatana Group in the Neoproterozoic of the Flinders Range in South Australia, and there are several other stratigraphically distinct diamictite sequences.

It seems likely that the “Snowball Earth” hypothesis is waning; an embarrassment for those geologists who have promoted it so assiduously over the last several years. However, the enigma of low-latitude glaciation on a vast scale is likely to remain, unless, that is, all the diamictites can be shown to have non-glacial origins, which is not as unlikely as it might seem. The Fiq sequence of Oman, like the Dalradian example in Scotland, formed in an



actively extending basin. Repeated seismicity on rift-bounding faults could have launched debris flows to deposit diamictites (a purely descriptive term for sediments containing a wide variety of clast sizes). The most spectacular diamictite in the Dalradian Supergroup, and perhaps anywhere, is the Great Breccia of the Garvellachs. Recent work suggests strongly that it is not glaciogenic, but the product of such a debris flow (Arnaud, E. & Eyles, C.H. 2002. [Catastrophic mass failure of a Neoproterozoic glacially influenced continental margin, the Great Breccia, Port Askaig Formation, Scotland](#). *Sedimentary Geology*, v. **151**, p. 313-333; doi: 10.1016/S0037-0738(01)00283-4). The supposedly clinching evidence for diamictites' origin from iceberg armadas is the way in which some clasts ("dropstones") puncture underlying stratification. All that is required is a means of puncturing, and sediment compaction around large, resistant clasts in a water saturated matrix is quite capable of doing that. Even the long-held belief that glaciation is uniquely signified by polished and striated surfaces beneath diamictites containing similarly scratched clasts is coming into question. Sites of large impacts, such as the Ries crater in Germany, include exactly similar features caused by ejecta blasted from the crater, cited by Vern Oberbeck, formerly of NASA, in a little-cited paper that proposed an impact origin for diamictites (Oberbeck, V.R. *et al.* 1993. [Impacts, tillites and the breakup of Gondwanaland](#). *Journal of Geology*, v. **101**, p. 1-19).

### **Post-apocalypse weathering in the Early Triassic (November 2002)**

Environmental crises do not come bigger than that at the end of the Permian, when marine ecosystems virtually collapsed, and similar extinctions of terrestrial flora and fauna are becoming clear. Whereas the Siberian Traps may indeed have been a triggering mechanism, there are carbon-isotope indicators that vast amounts of methane entered the atmosphere shortly afterwards, rapidly being oxidised to CO<sub>2</sub>. The density of respiratory openings (stomata) in fossil leaves from the lowest Triassic is unusually low, indicating an abundance of CO<sub>2</sub> in the atmosphere and probably enhanced "greenhouse" conditions. Hot and humid conditions encourage weathering of the continental surface, and there are many Early Triassic palaeosols, some which mimic those in the tropics being found at unusually high palaeolatitudes. Such soils harbour crucial evidence for surface conditions, and the high-latitude ones present a surprise (Sheldon, N.D. & Retallack, G.J. 2002. [Low oxygen levels in earliest Triassic soils](#). *Geology*, v. **30**, p. 919-922; doi: [10.1130/0091-7613\(2002\)030<0919:LOLIET>2.0.CO;2](#)). Unlike tropical laterites, which are rich in kaolinite, high-latitude soils are dominated by illitic clays that signify incomplete breakdown of silicates. The surprise comes in the form of an unusual mineral, berthierine; a green, serpentine-like mineral that is easily confused with chlorites in hand specimen. It can form by reaction between clays and ferric oxy-hydroxides, but only under highly reducing conditions. Because most soils since about 2000 Ma ago have formed in contact with an increasingly oxygen-rich atmosphere, achieving suitably reducing conditions demands input of a reductant to the soil "atmosphere". The most likely candidate is methane, whose oxidation would consume oxygen. However, methane's residence time in the air is around 10 years, because it is quickly oxidised to CO<sub>2</sub>, so methane release following the P-Tr boundary event seems as if it was sufficiently prolonged to influence considerably longer term soil formation.

## Hair trigger for gas hydrates (*December 2002*)

The curious mix of water ice and methane, known as gas hydrate or clathrate, which is stable at ocean depths greater than 300 m, is one of the largest potential components of the active carbon cycle ( $\sim 10^{13}$  t). Its methane content stems from bacterial breakdown of organic matter buried in anaerobic sea-floor sediments. As well as being pressure sensitive, gas hydrate also has a narrow stability “window” as regards temperature. Geothermal heat therefore limits the depth of gas-hydrate accumulations to a few tens to hundreds of metres below the seabed. Its vast methane content is clearly something on which energy transnationals have an eye. However, methane is almost four times more powerful as a “greenhouse gas” than CO<sub>2</sub> emissions. Carbon-isotope studies from sedimentary rocks show signs that several times in the distant past methane was released catastrophically to the atmosphere, the timing coinciding with signs of rapid global warming. The last major event of this kind was around 55 Ma ago, when the end of the Palaeocene Epoch witnessed an 8°C global temperature rise in a matter of a few thousand years (Thomas, D. *et al.* 2002. [Warming the fuel for the fire: Evidence for the thermal dissociation of methane hydrate during the Paleocene-Eocene thermal maximum](#). *Geology*, v. **30**, p.1067-1070; doi: 10.1130/0091-7613(2002)030<1067:WTFETF>2.0.CO;2). The warming “spike” eases because methane is quickly oxidised to water and CO<sub>2</sub> in the atmosphere, but that still allows abnormally warm conditions to linger.

Sonar surveys of the seabed, including that of the North Sea, reveal pits and funnels that probably mark sites of past methane releases from destabilised gas hydrates. In theory, two general processes lead to their instability: falling global sea level that reduces the pressure on gas hydrates formed at shallow water depths; a rise in the temperature of ocean-bottom water. The second could produce more widespread methane release than the first. Refining these crude prognoses needs detail about the structure of gas-hydrate zones beneath the seabed. Conventional seismic surveys conducted at the sea surface show the clathrate-rich zones just beneath the sea floor, but no detail. Towing sources and receivers just above the seabed reveals intricate structures (Wood, W.T. *et al.* 2002. Decreased stability of methane hydrates in marine sediments owing to phase-boundary roughness. *Nature*, v. **420**, p. 656-660; DOI: 10.1038/nature01263).

Wood and co-workers from the US Naval Research Laboratory, the University of Victoria and the Pacific Geoscience Centre in British Columbia, Canada surveyed the Pacific floor off Vancouver Island. Their most striking observation is of many vertical, chimney-like structures that puncture the gas-hydrate zone in the upper sediment layer. They reckon that these structures are where methane and warm fluids find their way to the seabed; they are probably the expression in cross section of the surface pitting formed by past degassing. They also may supply gas to the zone where it becomes locked in metastable water ice. The sheer number of the “chimneys” indicates that the surface area of gas-hydrate stability is many times larger than previously supposed, as a result of their “roughening” effect. Since the base of the gas-hydrate stability zone is most prone to the effect of warming of sea-bottom water, which shifts the geotherm slightly, an increase in its surface area, together with its closer approach to the seabed around the “chimneys”, could further increase its sensitivity to small changes. Up to now, many specialists have suggested that major methane releases resulted from sudden collapses of sea-floor sediments in tectonically unstable areas, such as the Storegga Slide off western Norway. They may instead have been due to more widespread instability resulting from environmental change. Since the largest

pressure decreases due to sea-level falls accompanied glacial epochs, some clues to whether the “chimney” effect has had an influence may come from a fresh look at methane contents of trapped air bubbles in Antarctic and Greenlandic ice cores. The extent to which methane releases might effect climate depends on how much is oxidised to CO<sub>2</sub> in sea water, before it can enter the atmosphere to enhance the “greenhouse” effect. Little is know about such processes.

**See also:** Pecher, I.A. 2002. Gas hydrates on the brink. *Nature*, v. **420**, p, 622-623; DOI: 10.1038/420622a