Climate change and palaeoclimatology

Collapse of the continental margin and methane release (*January 2004*)

The vast reserves of methane-water ice deposits (gas hydrate or clathrate) in sea-floor sediments are the most likely source of methane releases that could generate sudden warming events, such as that at the end of the Palaeocene, and left traces in polar ice cores during the last few glacial-interglacial episodes. Methane probably leaks from the sea floor all the time, but is soon oxidised to the lesser "greenhouse" gas CO_2 in the atmosphere, so muting its potential effects to a low background level. For methane to have a sizeable effect on global warming, lots of it has to blurt out suddenly.

Possibly the only mechanism that can trigger such explosive releases are failures of sea-floor sediments, either by those beneath a steep surface slope collapsing under gravity, or as a result of seismicity. Geoscientists from University College London and the British Geological Survey have tried to correlate known peaks in atmospheric methane from the recent past (shown by ice cores) with episodes of mass flow on the seabed (Maslin, M. *et al*. 2004. Linking continental-slope failures and climate change: Testing the clathrate gun hypothesis. *Geology*, v. **32**, p. 53-56; DOI: 10.1130/G20114.1). They found that the periods of greatest disturbance of continental-slope sediments over the last 45 ka took place at the tail-end of the last glaciation, between 13 and 15 ka and 8 to 11 ka. Each correlates with methane highs in the Greenlandic ice cores and with bouts of rapidly rising sea level (the Bølling-Ållerød and Preboreal warming periods). So they conclude that there is support for a "clathrate gun" model for sudden warming associated with glacial to interglacial transitions. However, seafloor collapses also correlate with Heinrich events (ice-sheet surges that launched iceberg "armadas" to low latitudes) that punctuated glacial times. These marked brief periods, repeating every 1000 years or so, which mark cooling when sea-levels were low. None are associated with upsurges in atmospheric methane., although the following interstadial warmings are. This lack of correlation rules out a "clathrate gun" influence on millennial-scale climate fluctuations during glaciations.

Super-eruptions and climate (*January 2004*)

The biggest known, young volcanic crater is that of Toba on Sumatra, which is a caldera complex measuring 30 x 100 km. Around 74 ka Toba emitted an eruption that dwarfed any in more recent times, and spread a dust cloud around the world – it is present in ice cores from Greenland, and has been linked with a cooling step during the onset of the last glaciation. It happened around the time that anatomically modern humans had begun to spread across Asia after migrating from NE Africa – an Acheulean hand-axe has been found in the Toba Tuff – and may have deeply affected those pioneering bands. There are older ash levels that can also be attributed to Toba eruptions, one found 2500 km away in the sediments of the South China Sea (Lee, M-Y. *et al*. 2004. First Toba supereruption revival. *Geology*, v. **32**, p. 61-64; DOI: 10.1130/G19903.1) and at other sites up to 3000 km from Toba. This gives an age around 800 ka. Lee and colleagues from Academica Sinica (Taiwan), the National Taiwan University and the University of Rhode Island estimate that almost 1000 km^3 of ash was expelled by the eruption. Unlike the 74 ka ash, this layer falls in the transition from a glaciation to an interglacial period; instead of a possible cooling influence through dust blocking solar heating, there is a warming trend. Although not quite as big as the 74 ka eruption of Toba, that of 800 ka is still vastly bigger than any other explosive volcanism during the Pleistocene. So, it suggests that super-eruptions are not significant climate triggers after all.

Satellite view of the Toba caldera. The image is 80 km across

Influence of continental weathering on climate boosted (*February 2004*)

Since the resurrection of Chamberlin's idea that the rate of chemical weathering of continental crust helps regulate atmospheric CO_2 by Maureen Raymo, the hypothesis has not yet been supported by convincing geochemical evidence. There is such a lag between changes in ocean chemistry and evidence for global climate change, that correlations are flimsy. The need is for a proxy for weathering of the land surface that resides in seawater for a geologically very short period. Such an element is osmium (Os), which passes from river water through the oceans to sea-floor sediments in about 25 thousand years, so changes in its abundance in sediments ought to match the pace of any climatic shifts. In principle, there are two main sources for elements in seawater, from sea-floor hydrothermal alteration of oceanic crust, and from continental weathering. The first can be considered to be more or less constant, except on time scales of tens of million years. Continental weathering is a response to climate change, and keeps pace with it.

Researchers at the UK Open University and the University of Köln in Germany analysed samples for osmium and carbon isotopes through a sequence of Jurassic mudstones on the NE coast of England (Cohen, A.S. *et al*. 2004. Osmium isotope evidence for the regulation of atmospheric CO_2 by continental weathering. *Geology*, v. **32**, p. 157-160; DOI: 10.1130/G20158.1). The carbon isotopes show a sudden drop in $\delta^{13}C$ within a very hydrocarbon-rich unit famous for it contribution of jet (oil-rich lignite) to Victorian funereal jewellery. This negative excursion is recognisable world-wide at around 180 Ma. The most likely explanation is a monstrous blurt of methane from destabilised gas hydrate on the Jurassic sea floor (see *Methane hydrate - more evidence for the 'greenhouse' time bomb*, August 2000). The Jet Rock of the Whitby coast therefore preserves a nice example of sudden climatic change, and by the end of its deposition carbon isotopes returned to Jurassic background values. Methane, a powerful "greenhouse" gas, is rapidly oxidised to CO_2 in the atmosphere, so reducing its initial warming effect, but climate would have been hotter for some time afterwards until the excess CO_2 was drawn down somehow. Interestingly, the Jet Rock also shows a sudden leap in the abundance of ^{187}Os, reflected in the $^{187}Os/^{186}Os$ ratio of the samples, and an upward step in the value of the $^{87}Sr/^{86}Sr$ ratio – one of the fastest rises known. The latter is generally assigned to an increase in continental weathering, since continental crust contains more radiogenic ^{87}Sr than does oceanic crust. The implication of the osmium-isotopic shift is odd; it requires an increase in the rate of continental weathering by 4 to 8 times that in the preceding period. That is a vast change, even if it only lasted for a short period, but it tallies with what is known about the temperature dependence of the dissolved loads of rivers in more recent times.

If the osmium isotope excursion truly reflects massive continental weathering, then it is possible to calculate the drawdown of the excess CO_2 in the atmosphere from a commensurate flux of calcium and magnesium ions from the continents that would eventually form marine carbonates. The authors estimate a mere 37-123 ka to get rid of it. Yet continent-derived radiogenic ^{87}Sr remained high for much longer, and the authors' arguments become tricky. One interesting aside is that, unlike today, more groundwater found its way to the oceans than surface run-off during the Jurassic; perhaps 6 times more. It is easy to look on weathering as what happens at the interface between rocks and the weather; the land surface. Not so. A great deal of chemistry that releases soluble ions goes on in the subsurface, above and below the water table. It is by no means as simple as reactions between carbonic acid in rainwater and silicate minerals. Weathering is the product of hydrogen ions' (whatever their source) effects on silicates. Bacteria are extremely important actors in modifying pH below the surface, for example the sulphate-sulphide reducers, and the oxidative dissolution of sulphides produces sulphuric acid. Even more interesting for the chemistry of groundwater is the curious role of iron hydroxide. Under oxidising conditions it adsorbs many elements from solution, including platinum-group elements, such as osmium. Should conditions become reducing, dissolution of goethite skins on sedimentary grains releases the accumulated elements. A warming trend almost inevitably results in increased precipitation, and rising water tables. It also should boost biological productivity on land and an increase in the amount of buried organic matter, which create reducing conditions in groundwater.

New take on end-Palaeocene warming (*March 2004*)

In 1998 vast areas of Indonesia caught fire after an unusually dry phase in the El Niño – Southern Oscillation (ENSO). Burning forest and peat deposits swathed a vast area in smoke, but another alarming aspect was the greatest addition of carbon dioxide to the atmosphere in half a century. Such a wildfire on a global scale is thought to have marked the end of the Mesozoic, perhaps triggered by the K-T impact event and encouraged by higher oxygen content in the atmosphere. Present oxygen levels seem to be at a balance that staves off spontaneous combustion of green vegetation, but only a few percent more would render living vegetation much more prone to bursting into flame. The end of the

Palaeocene involved a sudden global warming that coincides with a decrease in the proportion of ^{13}C in marine carbonates. Since photoynthesis, at the base of the trophic pyramid, favours light ^{12}C, such a negative $\delta^{13}C$ "spike" is generally ascribed to an unusually high release of organic carbon to the environment. The end-Palaeocene warming may have resulted from a massive release of methane from gas-hydrate buried in shallow seafloor sediments (See *Methane hydrate - more evidence for the 'greenhouse' time bomb* and *Plankton and the end of the Palaeocene-Eocene global warming* August and October 2000). However, massive burning of living biomass could also produce the carbon-isotope signal. Telling the two mechanisms apart requires information from other organic-related cycles.

One key is comparing the carbon- and sulphur-isotopic records that enables the place in which carbon had been stored geologically. For marine burial, the effect of aerobic bacteria that completely oxidises hydrocarbons back to carbon dioxide and water needs to have been suppressed. Periods of massive marine carbon burial coincide with oceanic anoxia episodes, when anaerobic bacteria beneath the seafloor reduce dissolved sulphate ions to sulphides, thereby depositing lots of iron sulphide (pyrite) in black organic mudrocks. This sequesters sulphur that is depleted in ^{32}S into marine sediments, so that the marine carbon- and sulphur-isotope records fluctuate in a clearly related way. During the Palaeocene this relationship is absent, while overall the carbon isotopes do signify progressive burial of organic carbon. The decoupling of the two cycles points to carbon burial on the continents, forming peat and eventually coal deposits.

Playing games on Snowball Earth (*March 2004*)

For as long as anyone can remember there has been a parade of geoscientific bandwagons in town. Three of the floats today carry banners saying, "Snowball Earth", "Climate models" and "continental erosion and CO_2 drawdown". Of course there is serious science aboard each, but they are getting overcrowded, especially as separate bands try to jump from one to another. When it sometimes seems, as now, that the "next Big Thing" is some way off, we get the unseemly spectacle of some bands trying to straddle two or even several of the wagons. Three is quite a feat, yet the 18 March 2004 issue of *Nature* contains perhaps not a vast human pyramid, but at least a tetrahedron of the genre (Donnadieu, Y. *et al*. 2004. A "snowball Earth" climate triggered by continental break-up through change in runoff. *Nature*, v. **428**, p. 303-306; DOI: 10.1038/nature02408). From about 1100 to 750 Ma ago, the bulk of continental lithosphere was gathered in a supercontinent known as Rodinia (from the Russian for "Mother Earth"). By analogy with modern Eurasia, and the stratigraphic record from the Phanerozoic Pangaea supercontinent, the centre of Rodinia would almost certainly have been dry, being so far from the ocean. Break-up of that continental mass would also probably have allowed moist maritime air to penetrate over a larger proportion of the fragments. The hypothesis that Donnadieu and colleagues try to test using linked geochemical and climate models is that such a tectonic change would increase continental weathering and reduce the "greenhouse" effect. The weak acid formed by solution of carbon dioxide in rain water can provide hydrogen ions to break down silicate minerals. The reactions contribute bicarbonate and soluble metal ions to surface and subsurface water. Ultimately, both reach the oceans and contribute to its chemistry. If conditions are suitable, calcium ions in particular combine with bicarbonate to precipitate calcium carbonate on the ocean floor, either through the action of organisms or inorganically.

The two chemical equilibria involved result in a net burial of one carbon atom out of the two involved in the weathering, thereby drawing down carbon dioxide from the atmosphere. The climate model used in their cyber-experiment resolves the Neoproterozoic Earth into cells that are 10 x 10 degrees (about 100 thousand km^2) and considers Rodinia at 800 Ma and the result of its break-up at 750 Ma, the time of the first good evidence for extensive low-latitude glaciation. The results, after some tinkering, suggest that increased continental weathering could have reduced CO_2 levels to 250 parts per million. Taking account of a 6% less energetic Sun at the time, this would have produced sufficient cooling for ice caps to exist to sea level at the equator. So, taken at face value, the hypothesis seems plausible. However, there are major snags. First, in a mere 50 million years their model sees continental dispersion on a scale that has not yet happened to Pangaea in about 200 Ma of Phanerozoic time. Second, since continental area remains constant, the proportion of rainfall, and therefore weathering and runoff, involving continental crust also stays fixed. Third, continental weathering refers to the crystalline part of its crust, in which there are unstable minerals, such as feldspars, that can do the chemical trick. We have little idea how much of the continents at that time was veneered by sediments that are the products of earlier chemical weathering, and contribute nothing to the process. Exposing such deep crust depends to a large extent on mountain building, which continental extension does not encourage. Fourth, carbon dioxide is not the only source of hydrogen ions that are involved in weathering, especially as much of it goes on in groundwater – bacterial action and oxidation of iron sulphides create much more acid conditions that rainwater. Fifth, and most important, where is the complementary geochemical evidence? Feldspars of the continental crust, on which the hypothesis mainly rests, have high contents of rubidium compared with their oceanic counterparts, and they are old. Much of Rodinia was underpinned by crust formed as far back as 4 billion years ago. Prolonged decay of ^{87}Rb to radiogenic ^{87}Sr makes the strontium isotopes of continental material very different from those of the ocean floor – it has a much higher $^{87}Sr/^{86}Sr$ ratio. Since soluble strontium would be released to runoff by continental weathering, that signature makes its way to the ocean and should pop up in marine carbonates. Although the ocean strontium isotopes in the Neoproterozoic did rise a little, it did not peak until the very end. In fact, the details show that the periods around supposed “snowball” conditions involved downturns in radiogenic strontium supply to the oceans. Whatever the model suggests, all that it amounts to is the equivalent of a table-top train set

Wildfires and oxygen (May 2004)

Ray Bradbury wrote a distopian political novel in the 1950s, called *Fahrenheit 451*. It is about a repressive regime that tries to snuff out dissent by burning books, the title referring to the temperature (233ºC) at which paper spontaneously bursts into flame in the modern atmosphere. With no reference to book burning by some future autocracy, geoscientists have speculated on the possibility of higher atmospheric oxygen contents being able to induce massive conflagration of green vegetation after lightning strikes or meteorite impacts. One often cited case is at the K/T boundary, where the thin layer that signifies the mass extinction event contains a high proportion of sooty particles. Late Cretaceous air probably had significantly higher oxygen content than now, generated by pole-to-pole luxuriant vegetation, and the idea of a global wildfire gained much support when first mooted. During the Carboniferous, there is very good evidence that oxygen levels were as high as 35% compared with 21% today. It was a time of giant flying insects, whose size is limited by the availability of oxygen. Carboniferous and Permian strata contain much charcoal, which suggests that indeed fires then were a great deal fiercer and more capable of spreading. They might have destroyed vegetation, despite evidence that the tree-sized plants of the period had developed fire-resistant structures.

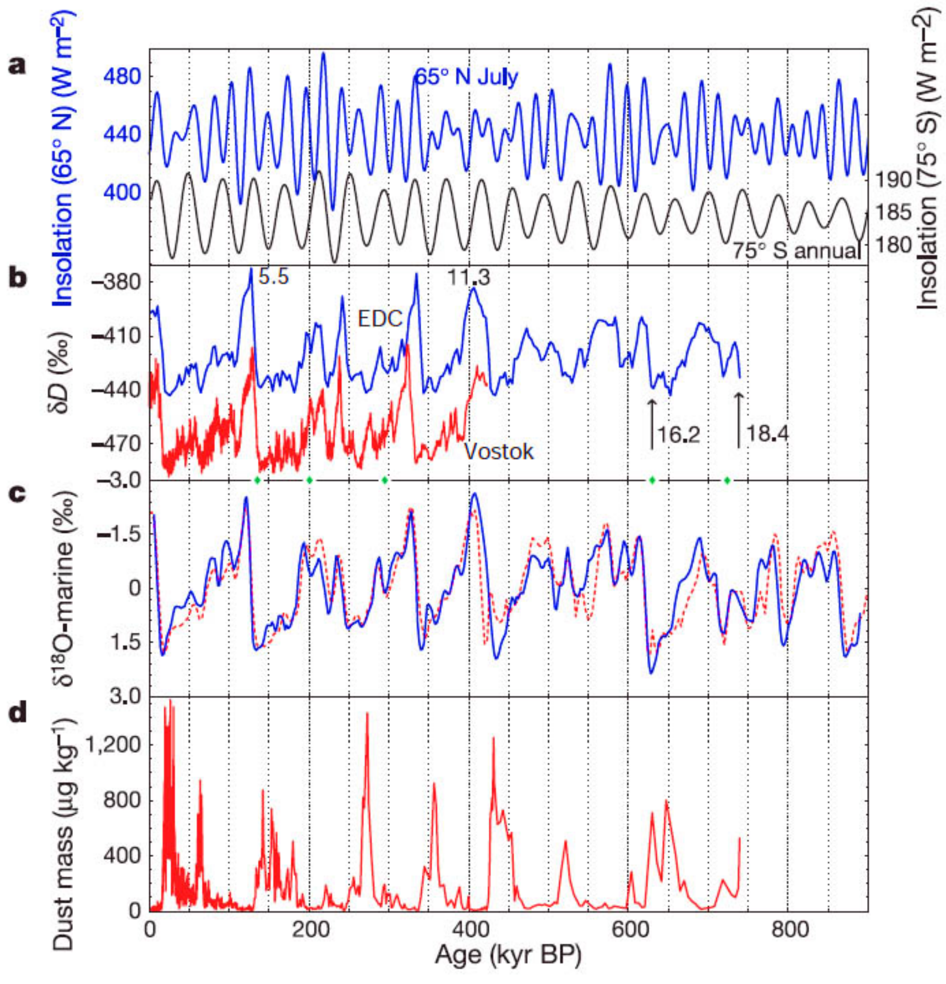
Experiments to simulate the effects up to now have used strips of paper in different oxygen levels, and showed a strong correlation between the minimum energy for ignition and oxygen concentration. US geologists, foresters and engineers have repeated the experiments using a range of natural plant materials as well as paper (Wildman, R.A. *et al*. 2004. Burning of forest materials under late Paleozoic high atmospheric oxygen levels. *Geology*, v. **32**, p. 457-460; DOI: 10.1130/G20255.1). Their results approximately confirm Bradbury's fictional paper-combustion temperature, but monkey-puzzle (*Araucaria*) leaves are more easily set alight. However, the temperature for ignition does not change as oxygen levels increase, although burning is faster. How natural materials burn depends on their relative proportions of cellulose and lignin, the higher the latter, the greater the temperature for complete combustion. They behave very differently from paper. Another finding was that the rate at which burning spreads did not rise as dramatically as expected for Carboniferous conditions. The limiting factor is moisture content, although that for no-burn does increase with oxygen levels. This is particularly important for the firing of dead vegetation lying on the surface, which is essential for catastrophic wildfires. Natural fires are started by lightning, and that occurs during heavy rainfall, when surface debris is thoroughly saturated. Fires in the canopy would have occurred at higher frequencies and with greater intensities, but the authors consider they would not have seriously threatened plant life.

Antarctic climate record back to 740 ka: cause for optimism? (*July/August 2004*)

Ice extracted from ice sheets by core drilling has provided the most detailed historical information on climate variation at high latitudes and about the varying gas and dust content of the atmosphere. It provides the best time-resolution currently available, up to around 50 years and sometimes better. Cores from the Greenland ice sheet revolutionised ideas about the controls over short-term climate shifts in the northern hemisphere – the millennial-scale Heinrich and Dansgaard-Oeschger events. It is from those revelations that fears have arisen about the consequences of deep-ocean circulation shut-downs that might arise from current global warming. But the Greenland ice goes back only to cover the last glaciation and part of the interglacial period that preceded it. Until recently, the Vostok ice core from Antarctica gave the greatest penetration into past climatic events, to around 430 ka that covers the last four glacial epochs. Again, Vostok revolutionised our understanding of past climate change, principally the differences between climate behaviour in interglacials, and those between the records from northern and southern hemispheres.

North and south have not been in exact harmony, at least as far as high latitudes are concerned. Ocean-floor sediment cores and those from mid-latitude glaciers do, however, give hints of a global harmonisation of events. Since we live in an interglacial period, for the last three of which the previous ice-core records suggest a span around 10 ka, it has seemed likely that ours wouldn't have lasted much longer than it already has under purely "natural" conditions.

Modelling the possible effects of anthropogenic warming has left climatologists undecided about the future. That blurring is as much to do with the unknown direction that an unstable climate might take and the limitations of modelling, as with knowledge of past events. So, the more information on past interglacials, the better the chance of getting a "handle" on the climatic frying pan out of which humanity seems to be on the point of jumping. The European Project for Ice Coring in Antarctica (EPICA), which involves 57 scientists from 10 European countries, has dramatically expanded the scope for comparison with the past by a 3 kilometre core through one of the deepest parts of the Antarctic ice (EPICA, 2004. Eight glacial cycles from an Antarctic ice core. *Nature*, v. **429**, p. 623-628; DOI: 10.1038/nature02599). The potential information that eventually will flow from the core will dwarf that from any previous climatic research project. It covers the period when climate settled into a roughly 100 ka rhythm, probably linked with the weakest of the astronomical controls of solar heating, that of orbital eccentricity, and thereby a bit of a mystery, even if it twangs the harmonics of purely terrestrial climatic processes.



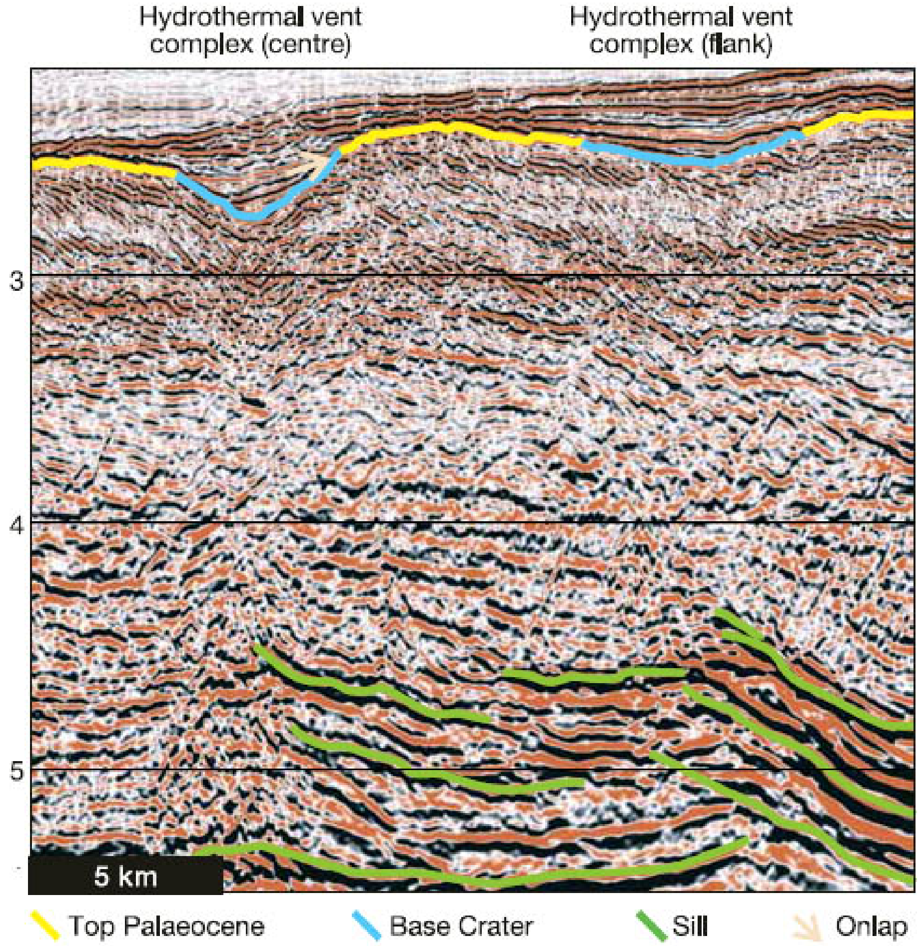
EPICA Dome C record for – from top to bottom – northern and southern hemisphere insolation (from Milankovich modelling); δD that reflects (ice-surface surface temperature); $\delta^{18}O$ from marine sediment cores (ice sheet extents); dust in ice (windiness and aridity). (Credit: EPICA)

The first focus is on the fourth interglacial epoch before the present one, which ended about 400 ka ago. In terms of overall astronomical forcing, that is the time when insolation patterns were most similar to those during the Holocene. Vostok only covered the latter stages, but now its entire span is covered. All the preliminary time-series for it indicate that it was considerably longer than the last three interglacials, around 25 ka rather than 10. Its initiation following the waning of the preceding full glacial period follows a similar patter to the early Holocene; the warming was interrupted by a sudden, one-off cooling, somewhat like the Younger Dryas around 12 ka ago. Although the first EPICA report contains preliminary ideas on several important topics, the one that has caused a stir is that duration of the 5th interglacial. Maybe out own warm times will be naturally prolonged for several more millennia, in which case fears of instability and a plunge to full glaciation soon could be set aside with some relief. However, the abstract to the article, concludes by saying, "…our results may imply that <u>without human intervention</u>, a climate similar to the present one would extend well into the future" [my emphasis]. But we <u>do</u> intervene, and nobody knows the outcome of that on a climatic pace of change that follows the almost infinitesimally small orbital-obliquity forcing of probable oceanic processes that really call the tune.

Smoking gun for end-Palaeocene warming: an igneous connection (*July/August 2004*)

The sudden warming of the Earth at the start of the Eocene 55 Ma ago has been a topic that I have touched on several times. It is widely regarded as a consequence of rapid release of methane from sea-floor gas hydrate, a risk that modern anthropogenic warming presents if deep-water temperatures rise much above their present near-freezing temperatures. However, no evidence has provided a direct connection to the "clathrate gun". The disturbance in carbon isotopes of marine sediments at the P-E boundary is most easily linked to a massive methane release at the time, but precisely where it began has been unknown. Many shallow marine basins, such as the North Sea, have a pockmarked modern floor attributed to minor gas release in much more recent times. The phenomenon can destabilise the sea bed, so more recent releases have been carefully documented where oil-production platforms are situated. A clue to the much larger release at 55 Ma stems from detailed seismic exploration of western Norway that involved over 150 thousand kilometres of profiling (Svenson, H. *et al*. 2004. <u>Release of methane from a volcanic basin as a mechanism for initial Eocene global warming</u>. *Nature*, v. **429**, p. 542-545; DOI: 10.1038/nature02566).

The surveys revealed that beds immediately beneath the base of Eocene sediments are riddled with hydrothermal vents complexes, which take the form of mounds, craters and eye-shaped structures. Some are huge, extending to 5 km across. The profiles also show that beneath the vents are pipes of disrupted strata which extend to the depth of a complex of igneous sills of the North Atlantic large igneous complex, itself emplaced at about 55 Ma. The sills underlie about 80 thousand square kilometres and most of the vents occur within this area. Biostratigraphic dating of the youngest sediments disrupted by the vents gives ages between 55.0 and 55.8 Ma. Intrusion of magma into a deep sedimentary sequence unsurprisingly would set hydrothermal circulation going.



Seismic reflection profile off Norway, showing hydrothermal vent craters beneath the Eocene sediments and strong reflectors that are probably igneous intrusions. The vertical axis is two-way travel-time for the seismic pulses. (Credit: Svenson *et al*. 2004; Fig. 2)

If, as they did, the hot fluids reached the sea bed, they would pass through a zone of gas hydrate, destabilise it and release massive amounts of methane to the atmosphere. In the case of the Norwegian shelf, the intrusions were into deeply buried organic rich rocks, further encouraging methane formation; probably a great deal more than from gas hydrate. An estimate of 10^{12} tonnes of methane generated thermally off Norway is enough to result in a change in carbon isotopes as large as that known from the P-E boundary. In fact, similar sediments throughout the end-Palaeocene North Atlantic large igneous province are likely to have been "over matured" in this way, and no other explanation for the increase in "greenhouse" gases seems necessary. The clear connection with large scale magmatism in thick sedimentary basins may help focus ideas about similar methane-related episodes of global warming, such as the C-isotope excursions at the Permian-Triassic and Triassic-Jurassic boundaries, and within Jurassic and Cretaceous sequences.

Earth's early climate and methane (*July/August 2004*)

At the time the Earth accreted, some 4.6 billion years ago, the Sun was less bright than it is now, so that its warming effect was 30% less. Without some means of retaining in the ancient atmosphere what heat was available, the Earth would have been frigid. This "faint, young Sun" problem would have persisted into the time when the geological record begins, around 4 billion years ago, insolation slowly increasing to its modern level. Even in the oldest rocks, there is abundant evidence for the dominance of liquid water at the surface in the form of oceans and river transport across continents. Unhindered, low solar warming would have made that impossible, and pole-to-pole ice would have made the Earth a highly reflective planet that could never escape glacial condition. That is, unless the atmosphere contained sufficient "greenhouse" gases to retain far more solar energy than now. The favoured gas, until recently, has been the same one that dominates fears of global warming today – carbon dioxide – that volcanoes have probably emitted throughout Earth's history. However, estimates of how much would have been needed to keep the surface free of sea ice and land glaciers, for which there is no evidence until about 2.3 billion years, are extremely high (hundreds of time greater than now). Levels greater than 8 times present levels encourage the precipitation of iron carbonates in soils, yet palaeosols from the late Archaean and Palaeoproterozoic contain none. At those times, CO_2 concentrations less than 8 times present ones would not have prevented runaway "ice-house" conditions, so some other gas had to be involved in atmospheric warming. In a recent article, James Kasting of the University of Michigan, who has been involved in studies of ancient atmosphere and climate for 25 years, summarises the case for methane being the means of keeping Earth free of ice while the sun was fainter (Kasting, J.F. 2004. When methane made climate. *Scientific American*, v. **291**(1)**,** p. 52-59).

Only about 1000 parts per million of atmospheric methane would have been needed to keep the early Earth ice-free, because its "greenhouse" effect is extremely efficient. After oxygen rose to become a major atmospheric gas (since 2.2 billion years), heating induced by methane releases has been tempered by its rapid oxidation to CO_2. At several times in the past, when there were massive methane releases from sea-floor sediments, such as the end of the Palaeocene, that oxidation prevented the opposite problem, a runaway "greenhouse". That is "another story", involving the rise of photosynthesising organisms. Kasting's main theme is the role of methane-generating Archaea (once known as archaebacteria) soon after the origin of life. In the absence of oxygen, rising methane from thriving methanogen communities could itself have produced irreversible heating, were it not for methane's ability to polymerise to heavier hydrocarbons through photochemical reactions. That would have produced a "smog" that not only would have acted as a reflector for solar radiation, but would have added chemical "feedstock" to early life. Kasting gives a fascinating, all-sided summary, but misses what seems to be an obvious point. Without atmospheric methane, any water on Earth would have frozen soon after it appeared, however that happened, perhaps by outgassing, perhaps delivered by comets. Without liquid water, life processes cannot develop. That opens the possibility for a much earlier origin of life, of the methane generating variety, than anyone has dared to speculate on. Many methanogens metabolise hydrogen and CO_2. Volcanoes emit small amounts of hydrogen gas, but an even larger source is from sea-floor hydration of ultramafic lavas, common in early times. Almost certainly the very earliest times would have provided a suitable environment for methanogens to emerge.

How often did it rain? (*September 2004*)

Geoscientists have become used to masses of climate data, in some cases with better than 50 years resolution, from cores through ice sheets and sea-floor sediments. But all of it is from some kind of proxy: oxygen isotopes for air temperature and land-ice volume;

methane for humidity; dust for windiness; and so forth. One aspect of both climate and the British obsession with weather is raininess, for which there is scant evidence. How many rainy days occur in a British summer is interesting, but for studies of past climate evidence for the onset or disappearance of seasonality, and the annual intensity and duration of rainfall would be invaluable, if it could be had. A piece of ingenious research shows that it is possible (Kano, A. *et al*. 2004. High-resolution records of rainfall events from clay bands in tufa. *Geology*, v. **32**, p. 793-796; DOI: 10.1130/G20736.1). Akihiro Kano and Japanese colleagues studied the well-known layering of tufa – carbonate veneers laid down in freshwater that has high dissolved bicarbonate and calcium ions. In "hard-water" areas tufa can be deposited very quickly, at rates above a few millimetres per year, and it tends to be preserved, being quite tough. So tufas have the potential for preserving annual records of various fluctuations. Kano and colleagues saw that colour laminations represented clays deposited in the tufa when the water was turbid after prolonged rainfall. To record the variations they simply measured fluorescent X-rays emitted by silicon when slices of tufa were examined in an electron microprobe – silicon is present in clays and silt, but not in carbonate minerals. Because they used tufa deposited in recent times (1988-2002) they were able to correlate variations in clay content with detailed weather records from the site, thereby calibrating their method. The match was very good and followed rainfall closely at the level of a few days. Of 112 high rainfall days in the abnormally wet year of 1993, 100 showed up in the clay record. So, tufas are potentially more revealing than even the annual growth rings in wood, and some tufa deposits preserve long records.

Details of the last interglacial climate (*September 2004*)

Worries about how anthropogenic warming will affect the course of the Holocene interglacial in which we live might be tempered or exacerbated by knowing what went on during the previous (Eemian) interglacial that ended about 120 ka ago. Data from cores through the Greenland and Antarctic ice sheets have been both ambiguous and plagued by resolution that does not show enough detail, but a core from a new position in Greenland seems to resolve both problems (North Greenland Ice Core Project members 2004. High-resolution record of Northern Hemisphere climate extending into the last interglacial period. *Nature*, v. **431**, p. 147-151; DOI: 10.1038/nature02805). Uniquely, the NGRIP ice still preserves the annual snow layering as far back as 123 ka. This is because the site shows little sign of the deformation at deep levels that characterised previous Greenland cores. That is probably because the site lies above a zone of high heat flow through the underlying crust, so that the base of the ice has melted. Melting helps prevent internal deformation, but that in itself is a surprise because the site was chosen because it is colder and drier at the surface than other sites. The drilling objective was to penetrate older ice than the Eemian to give a fuller record than from earlier cores, yet anticipated poor time resolution. The presence of resolvable annual records from depth was both a surprise and a bonus, although the melting had removed ice from the earliest part of the last interglacial. Despite that, preliminary oxygen-isotope results from the NGRIP core suggest that the Eemian had a remarkably stable climate and one that was warmer than that of the Holocene by about 5ºC; maybe it is an analogue for climate evolution during a future, artificially warmed world. That possibility stems from the observation that around 115 ka, North Atlantic climate suddenly warmed. Thereafter, interglacial conditions did not suddenly change to glacial, as happened several times during the course of the last glacial epoch, but took around five millennia after the sudden warming. The authors make no claims that their preliminary data help resolve current fears of warming collapsing to glacial conditions in a matter of years to decades. That grim scenario has been widely trumpeted both by the media and some climate scientists. There is more to the Eemian than the period after 123 ka, and who knows what the eventual annual resolution will show up? The data presented in the paper are from a coarse sampling of 55 cm that represents about 40 year intervals.

See also: Kuffey, K.M. 2004. Into an ice age. *Nature*, v. **431**, p. 133-134; DOI: 10.1038/431133a.

For and against "Snowball Earth" (*September 2004*)

Reputedly glaciogenic sediments in the Neoproterozoic are reckoned to represent at least three separate cold episodes, the Sturtian (~720 Ma), Marinoan (~600 Ma) and Varangerian (~580 Ma). Sadly, the diamictites that characterise these episodes are not easily dated. Only two have well-defined radiometric ages, the Gubrah Member in the Oman (713 Ma), said to be Sturtian, and the Gaskiers Formation of Newfoundland (580 Ma), a possible example of the Varangerian that is better exposed in northern Norway. The truly whopping Sturtian and Marinoan diamictites of Australia are fitted to a global stratigraphy on the basis of carbon isotope variations, as are those of Namibia on which Paul Hoffman and colleagues stake their claims to "Snowball Earth" events. Another Hoffman, native to Namibia, and geochemists at MIT, have finally given a believable age to one of the Namibian diamictites (Hoffman, K.-H. *et al* 2004. U-Pb zircon dates from the Neoproterozoic Ghaub Formation, Namibia: constraints on Marinoan glaciation. *Geology*, v. **32**, p. 817-820; DOI: 10.1130/G20519.1). Their zircons come from a thin volcanic ash within isolated Neoproterozoic diamictites in central Namibia, and yield an age of 636$\pm$1 Ma. Correlating the studied diamictites with the Namibian sequences elsewhere in the country relies on the presence of a supposed cap carbonate rather than lateral continuity. The authors link them with the younger of the two Namibian diamictites, the Ghaub Formation, rather than the Chuos Formation that lies at depth, despite the fact that both well-studied units are sometimes overlain by carbonate sediments. The conclusion is that the Ghaub is Marinoan, previously thought to be somewhere between 600 and 660 Ma. Interestingly, the new occurrence of diamictites is divided vertically by two thick sequences of volcanic lavas, neither of which have been dated by the authors.

One of the leading experts on what actually constitutes evidence for glacial sedimentation is Nicholas Eyles of the University of Toronto. He has become increasingly disenchanted with notions of Snowball conditions, on the basis of ambiguity in the very evidence said to signify them; diamictites with drop stones. He and Nicole Januszczac have assembled a monumental paper that counsels caution, and perhaps more (Eyles, N. & Januszczac, N. 2004. "Zipper-rift": a tectonic model for Neoproterozoic glaciations during breakup of Rodinia after 750 Ma. *Earth-Science Reviews*, v. **65**, p. 1-73; DOI: 10.1016/S0012-8252(03)00080-1). Part of their argument rests on the very lack of robust ages for Neoproterozoic diamictites that prevents believable correlations from continent to continent. It is the globally synchronous nature assumed for these glaciations that gave rise to the "Snowball Earth" notion. The palaeomagnetic latitudes are often used to support this, but they are error prone both palaeogeographically and geochronologically. Accepting evidence for glaciation at low latitudes is no guarantee of support for even cold extremes, let alone an icebound world. Solar heating in the Neoproterozoic was lower than now, and so, therefore, would be the elevations at which glaciers might form at different latitudes. But the main problem is reconciling the features of many supposed glaciogenic diamictites with modern ideas of what truly constitutes evidence for glacial transport and deposition. Few of the units on which the "Snowball Earth" hypothesis is based stand up to modern scrutiny. Most of the diamictite packages occur in tectonically controlled basins, that were subject to episodic rifting. Each can be considered to form the base of a "tectonostratigraphic" cycle, and many show abundant evidence of having formed as mass flows from a shelf into the basin. They include olistostromes with huge rafts of carbonates likely to represent failure of carbonate platforms and huge submarine landslides, similar to those being discovered off many large islands today. The 750 to 580 Ma period was one of the most dramatic episodes of continental break-up in Earth's history as the Rodinia supercontinent was disassembled. Continental uplift, resulting either from mantle plume activity or rebound of rift shoulders, could have resulted in large areas rising above the ice limit, even at low latitudes in those cooler times. Those diamictites that are undoubtedly glaciogenic could easily have formed haphazardly in time. The carbon isotope record of immense shifts in $\delta^{13}C$ during the Neoproterozoic, linked by some to repeated collapses and resurrections of life, might just as easily have occurred through efficient organic burial in active extensional basins and repeated major volcanism from plumes. Only evidence of timing will tell, and three good dates for "Snowball Earth" events are simply not enough.

Two other papers add weight to the "against" view. One gives an age of 709±5 Ma for tuff immediately beneath a supposed Sturtian diamictite from the western USA (Fanning, C.M & Link, P.K. 2004. U-Pb SHRIMP ages of Neoproterozoic (Sturtian) glaciogenic Pocatello Formation, southeastern Idaho. *Geology*, v. **32**, p. 881-884; DOI: 10.1130/G20609.1), which does not tally with the radiometric age (685 Ma) of similar rocks not far away. The other (Calver, C.R. *et al.* 2004. U-Pb zircon age constraints on late Neoproterozoic glaciation in Tasmania. *Geology*, v. **32**, p. 893-896; DOI: 10.1130/G20713.1), gives a 575±3 Ma age for sills intruding a "Marinoan" diamictite in Tasmana, and 582±4 Ma for a rhyodacite immediately beneath it. This suggests that these antipodean glaciogenic rocks are correlative with those in Newfoundland and Norway, which are supposedly representatives of the Varangerian glacial epoch. Yet the authors are at pains to state that the Marinoan and the Varangerian are one and the same. Read these papers if you are still confused!

Torrid times in the Cretaceous Arctic (*December 2004*)

Despite its latitude (above the Arctic Circle) the sedimentary depocentre of northern Alaska is becoming famous for its Cretaceous terrestrial flora and fauna. Plant remains indicate luxuriant vegetation cover, and high excitement greeted the discovery of 8 species of dinosaurs (4 herbivores and 4 theropod predators (Fiorillo, A.R. 2004. The dinosaurs of Arctic Alaska. *Scientific American*, v. **291**(6), p. 60-67). How dinosaurs were able to survive the darkness of the Arctic winter is a bit of a mystery, unless the migrated as do modern caribou – Fiorillo cites evidence for small juveniles that would have been unlikely to have migrated far, because compared with adults they were much smaller than young caribou. There would have been sufficient winter biomass for survival during the Cretaceous, but seeing and being active as cold-blooded reptiles pose problems. At least one of the species had unusually large eyes, so one of the conditions for dinosaur's remaining year-round seems established.

New data regarding climatic conditions in the far north have turned up after an most unusual and intrepid programme of drilling through a drifting island of pack ice over the Arctic Ocean's Alpha Ridge, not far short of the geographic North Pole. An extraordinary feature of the programme is that it took place between 1963-74, the core having only been examined in detail in the last year (Jenkyns, H.C. *et al*. 2004. High temperatures in the Late Cretaceous Arctic Ocean. *Nature*, v. **432**, p. 888-892; DOI: 10.1038/nature03143). The Late Cretaceous part of the cores is black mud rich in terrestrial vegetation remains and marine diatoms, and totally lacking in evidence for dropstones and other debris from floating ice shelves. Unfortunately, the Arctic sediments lack carbonate-shelled plankton remains, so the now standard method of sea-surface temperature measurement is not possible. However, Jenkyns *et al*. were able to use a method based on the fatty acids that survive in plankton membranes, results from which match oxygen-isotope palaeo-temperature measurements in Cretaceous cores from lower latitudes. Astonishingly, even at polar latitudes, the Cretaceous Arctic Ocean seems to have been as warm as 15°C. Climate modelling based on lower latitude data and estimates of CO_2 concentration in the Late Cretaceous atmosphere falls around 10° short of these levels.

The conventional modelling requires 3 to 6 times more "greenhouse" warming than generally accepted, to account for Arctic sea temperatures in which we could swim in moderate comfort. Possibly the modelling is awry. One of the most important features of Late Cretaceous palaeogeography was a major seaway across North America that connected the Arctic with tropical latitudes. It existed because global sea level was far higher than now, probably due to the oceans' volume having been substantially reduced by huge magmatic outpourings on the floor of the West Pacific basin (the Ontong-Java Plateau), earlier in Cretaceous times, together with higher rates of sea-floor spreading. The seaway would have been shallow, and thereby easily warmed. Had poleward currents been possible in it, their flow would have acted very like the modern Gulf Stream to warm high latitudes. Despite palaeoclimatologists reliance on models of heat circulation, it needs to be remembered that they are based on grossly simplified geographic features. If they get it very wrong indeed for the well-studied Cretaceous, that casts doubts on climate modelling's predictive powers for the course of current climate evolution.

See also: Poulsen, C.J. 2004. A balmy Arctic. *Nature*, v. **432**, p. 814-815; DOI: 10.1038/432814a.