Climate change and palaeoclimatology

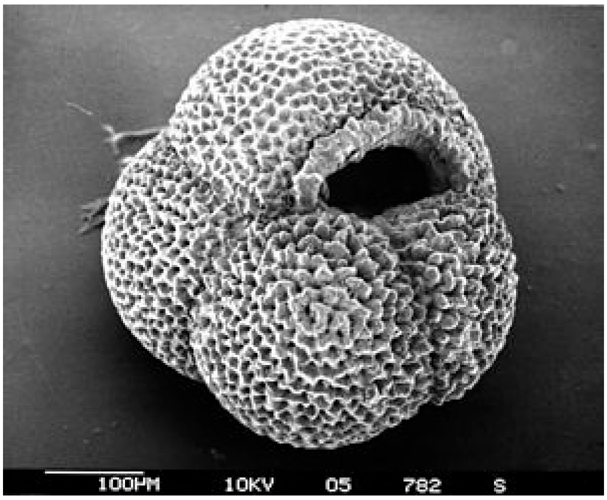
A chilly Late Cambrian? (*January 2011*)

Application of the Uniformitarian Principle by geologists from Minnesota, USA (Runkel, A.C. *et al*. 2010. Tropical shoreline ice in the late Cambrian: implications for Earth's climate between the Cambrian Explosion and the Great Ordovician Biodiversification Event. *GSA Today v.***20** (11), p. 4-10; DOI: 10.1130/GSATG84A.1) may have shown that around the end of the Cambrian period (500 to 488 Ma) global climate was sufficiently cold for sea ice to have formed in the tropics of the time. The evidence comes from curious metre-scale clasts of cemented sands in Late Cambrian beach deposits of the northern USA, some of which show imbrication as if the bodies were shoved together. Others seem to have been extended into boudin-like plates without any sign of tectonic activity, so that isolated clasts occur in offshore deposits. Yet more have been bent to drape over irregularities in the surface beneath them. Somehow individual sand beds must have become cemented quickly so that water action could fracture them in a brittle fashion and then they became softer to experience ductile deformation and even boring by worm-like animals.

Almost exact replicas of such structures form on the shores of the American Great Lakes in winter when water in shoreline sands freezes to cement the grains. Breaking waves and melting explain the peculiar structures in these intraclasts. Examples of ice-cemented sediments abound in glaciogenic deposits, yet the Late Cambrian world is widely considered to have experienced greenhouse conditions and the North American crust was definitely close to the Equator at that time. The intraclasts occur only in one stratigraphic Formation of the Minnesotan Cambrian, because it preserves littoral facies. There are no other reports from elsewhere, but that may well be because few geologists were able to combine the experience of modern frigid shore conditions with that of Cambrian stratigraphy as those from Minnesota surely do.

The Middle to Late Cambrian was a period of faunal hiccups, diversification after the Cambrian Explosion failing to get underway because of repeated minor extinctions spread across the known occurrences of rocks of that age (see Linking oxygen levels to great animal radiations Palaeobiology January 2011) . The Minnesotan evidence could indicate that the global climate was extremely unstable at that time in the manner of Neoproterozoic 'Snowball Earth' conditions, but not so severe. The widespread occurrence of microbial carbonate facies of this age range has long been used as evidence of a warm Earth, but such carbonates form today over a wide range of latitudes: witness the huge coccolithophore blooms so common at high latitudes nowadays. Shoreline sandy sediments of Cambrian age are not uncommon, occurring throughout the English Midlands and in NW Scotland, for instance. So it might be interesting to re-examine easily-reached occurrences such as these to see if similar structures turn-up.

The post-glacial North Atlantic (*February 2011*)



The planktonic foram *Neogloboquadrina pachyderma*. (Credit: Wikipedia)

One of the main controls over Earth's climate is the way that water in the North Atlantic convects. At present it is behaving like a liquid conveyor belt that links the tropics to well to the north of the Arctic Circle. Warm salty water that reaches boreal latitudes cools and also becomes saltier as sea ice freezes out fresh water. It therefore gets denser and sinks to the ocean floor in the Denmark Strait between Iceland and Greenland, and between Iceland and the Faeroe Isles. This downwelling drags surface water polewards from the tropics to replenish the system, thereby creating the Gulf Stream and North Atlantic Drift that warms coastal north-western Europe as far as the northern tip of Scandinavia. It was not always this way; evidence has accumulated to indicate that the North Atlantic 'conveyor' shut down periodically during the run-up to the last glacial period and in the climatic hiccup of the Younger Dryas (12.6-11.5 ka). The best supported hypothesis as to why it may do that is through massive influx of freshwater to lower the density of surface water in the northernmost North Atlantic. The progressive summer retreat of sea-ice in the Arctic Ocean and the likelihood of ice-free summers there in the near future raises fears that such a shut-down may occur once again, because of freshening of surface water by ice meltwater, with devastating climatic results for Europe at least. The circulation also transports carbon dioxide dissolved in cold descending surface water to abyssal depths helping buffer its atmospheric concentration: a shut-down would allow greenhouse gas emitted by society to build up in the air.

One means of investigating the mechanisms that underlie 'on' and 'off' switching in ocean convection is to use sea-floor sediment data from the18 ka long period since the last glacial maximum (Thornalley. D.J.R. *et al*. 2011. The deglacial evolution of North Atlantic convection. *Science*, v. **331**, p. 202-205; DOI: 10.1126/science.1196812). The British-US consortium used oxygen isotope data from the planktonic (near-surface) foraminifera *Neogloboquadrina pachyderma* preserved in sea-floor sediment cores from south of Iceland, close to where surface water descends today, to assess sea-surface temperature variations. Because of the continual exchange of CO_2 between surface water and the atmosphere, the ocean surface contains the same radioactive ^{14}C content in carbon as does the atmosphere, at whose top the isotope is produced. When water descends this connection is cut and the proportion of ^{14}C in it decays so that it is theoretically possible to work out the time at which deep water began to descend – its 'ventilation age'. In practice this is done by measuring the 'age' of carbon preserved in planktonic and benthonic (deep- and bottom-water) foram shells, the planktonic age being the actual age used to assess the age difference between deep and surface waters. In the case of a complete shut-down of the convection the ventilation age should be high and constant; exactly the case during the last glacial maximum (19-22 ka) and most of Heinrich Stadial 1 (16.5-19 ka). When the 'conveyor' is functioning the ventilation age should be low, in fact from about 16-11.5 ka the ventilation age fluctuates to show 3 major and 2 lesser low to high episodes during the Bølling-Allerød and Younger Dryas, suggesting that indeed there was repeated turning-on and turning-off of the conveyor, probably triggered by pulses of fresh water into the northern North Atlantic from glacial melting. The resolution of these data is of the order of 350 years, so there may be finer detail of great interest as regards future climate.

See also: Sarnthein, M. 2011. Northern meltwater pulses, CO_2, and changes in Atlantic convection. *Science*, v. **331**, p. 156-158; DOI: 10.1126/science.1201144.

Snowball Earth melting hypothesis weakens (*July 2011*)

The combination of glaciogenic sediments with palaeomagnetic evidence for their formation at low-latitudes, together with dates that show glacial events were coeval in just two or three Neoproterozoic episodes are the linchpins for the Snowball Earth hypothesis. There is little doubt that the latest Precambrian Era did witness such extraordinary climatic events. Evidence is also accumulating that, in some way, they were instrumental in that stage of biological evolution from which metazoan eukaryotes emerged: the spectacular Ediacaran fossil assemblages follow on the heels of the last such event (see *Bigging-up the Ediacaran* in Palaeobiology March 2011). One of the difficulties with the 'hard' Snowball Earth hypothesis is how the middle-aged planet was able to emerge from a condition of pole-to-pole ice cover; hugely increased reflectivity of that surface should have driven mean global temperature inexorably down. Clearly the Earth did warm up on each occasion, and the leading model for how that was possible is massive release of greenhouse gases from sea-floor sediments or deep-ocean waters to increase the heat-retaining powers of the atmosphere. Sufficiently voluminous release from volcanic action seems less likely as there is little, if any, evidence of upsurges in magmatism coinciding with the events. Almost all glaciogenic units from the Neoproterozoic have an overlying cap of carbonate rocks, indicating that hydrogen carbonate (formerly bicarbonate) ions together with those of calcium and magnesium suddenly exceeded their solubilities in the oceans.

To seek out a possible source for sufficient carbon release in gaseous form geochemists have turned to C-isotopes in the cap carbonates. Early studies revealed large deficits in the heavier stable isotope of carbon (^{13}C) that seemed to suggest that the releases were from large reservoirs of carbon formed by burial of dead organisms: photosynthesis and other kinds of autotrophy at the base of the trophic pyramid selectively take up lighter ^{12}C in forming organic tissues compared with inorganic chemical processes). As in the case of the sharp warming event at the Palaeocene-Eocene boundary around 55.8 Ma ago (see *The gas-hydrate 'gun'* June 2003), these negative $\delta^{13}C$ spikes have been interpreted as due to destabilisation of gas hydrates in sea-floor sediments to release organically formed methane gas. This powerful greenhouse gas would have quickly oxidised to CO_2 thus acidifying the oceans by jacking up hydrogen carbonate ion concentrations.

Grey cap carbonates (716 Ma) resting on brown, glacial diamictites, Yukon Territory. (Credit: Francis Macdonald)

Detailed carbon-, oxygen- and strontium-isotope work in conjunction with petrographic textures in a Chinese cap carbonate (Bristow, T.T. *et al*. 2011. A hydrothermal origin for isotopically anomalous cap dolostone cements from south China. *Nature*, v. **274**, p. 68-71; DOI: 10.1038/nature10096) suggests an alternative mechanism to produce the isotopically light carbon signature at the end of Snowball events. The greatest ^{13}C depletion occurs in carbonate veins that cut through the cap rock and formed at temperatures up to 378°C and even the early-formed fine grained carbonate sediment records anomalously high temperatures. So, it seems as if the cap-rock was thoroughly permeated by hydrothermal fluids, as much as 1.6 Ma after it formed on the sea floor. This triggered oxidation of methane *within* the sediments themselves, with little if any need for an atmospheric origin through massive methane release from destabilised gas hydrates elsewhere.

Dust tied to climate (*September 2011*)

The central areas of the oceans at present are wet deserts; too depleted in nutrients to support the photosynthesising base of a significant foot chain. Oddly, even when commonly known nutrients are brought to the ocean surface far from land by deep-sourced upwellings the effect on near-surface biomass is far from that expected. The key factor that is missing is dissolved divalent iron that acts as a minor nutrient for phytoplankton: even in deep ocean waters any such ferrous iron is quickly oxidised and precipitated as trivalent ferric compounds. One of the suggested means of geoengineering away any future climatic warming is to seed the far-off oceans reaches with soluble iron in the hope of triggering massive planktonic blooms, dead organisms sinking to be buried along with the their carbon content in the ocean-floor oozes. Retrospectively, it has been suggested that the slight lag of atmospheric CO_2 concentration behind climate changes since 0.8 Ma ago may be linked to fluctuating availability of iron dissolved from dust in ocean-surface waters, but so far that hypothesis has not been robustly tested.

It is well known, however, that global cooling is accompanied by drying of continental climates. This causes an increase in the delivery of dust, even to polar ice caps where cores have shown dustiness to fluctuate with temperature. Recently an ocean-floor sediment core from around 42° S has revealed a high-resolution record of the deposition of dust and iron there over the last 4 Ma (Martinez-Garcia, A. *et al*. 2011. Southern Ocean dust-climate coupling over the past 4 million years. *Nature*, v. **476**, p. 312-315; DOI: 10.1038/nature10310). In it one proxy for dust is the amount of organic compounds known as n-alkanes that are a major component of the waxes shed from plant leaves. Others are iron, titanium and thorium concentrations in the ooze. Dust proxies tally with land-ice volumes shown by the fluctuating δ^{18}O measured in bottom-dwelling foraminifera found as fossils in the core to form a convincing link between dust and climate over the Southern Ocean. Those proxies also match nicely the record of dust delivered to Antarctica that emerged from the 0.8 Ma Dome C ice core that was extracted and analysed by the EPICA consortium.

The record shows boosts in iron and dust deposition at 2.7 Ma, when ice first took hold of northern high latitudes, and at 1.25 Ma when larger ice sheets began to develop and climate shifts switched to 100 ka cyclicity. Although the match between marine and glacial dust accumulation in the latter part of this mid-Pleistocene Transition is an important step forward in palaeoclimatology, it is a surprise that the new ocean-floor data is not plotted with the record of atmospheric CO_2 in Antarctic ice bubbles: if there was a clear relationship that would have iced the cake.

Galactic controls (*December 2011*)

Palaeoclimatologists are quite content that an important element in controlling the vagaries of climate derives from gravitational forces that cyclically perturb Earth's orbit, its axial tilt and the way the axis of rotation wobbles in a similar manner to that of a gyroscope. The predictions about this by James Croll in the late 19th century, which were quantified by Milutin Milankovich during his incarceration during World War I, triumphed when the predicted periods of change were found in deep-sea floor sediment records in 1972. Authors of ideas that link Earth system changes to the progress of the Solar system through the Milky Way galaxy haven't had the same accolades. One of the first to suggest a galactic link was Joe Steiner (Steiner, J. 1967. The sequence of geological events and the dynamics of the Milky Way Galaxy. *Journal of the Geological Society of Australia, v.* **14,** p. 99–132; DOI: 10.1080/00167616708728648) but his work is rarely credited.

There has been an upsurge of interest in galactic controls over the last decade or so. In a recent issue of *New* Scientist Stephen Battersby reviews what galactic 'forcings' may have accomplished during the 4.5 billion-year history of our world (Battersby, S. 2011. Earth's wild ride: Our voyage through the Milky Way. *New Scientist*, v. **212** (3 December issue), p. 42-45). Having formed probably much closer to the galactic centre than its current position the Solar System has drifted, perhaps even 'surfed' gravitationally, outwards to reach its present 'suburban' position in one of the spiral arms. There are regularities to the now stabilised orbital movements: once every 200 million years the Solar System completes a full orbit; this orbit wobbles across the hypothetical plane of the galactic disc by as much as 200 light years, moving with and against the Milky Way's cosmic motion. It has proved impossible so far to detect any sign of the orbital 200 Ma periodicity in events on the Earth, and most attention has centred on the wobble.

Artists impression of the Milky Way viewed along its rotational axis.

Steiner suggested that this motion may have crossed different polarities of the galactic magnetic field, perhaps triggering the periodicity of geomagnetic changes in polarity, but this now seems unlikely. However, his suggestion that glacial epochs, such as those in the Palaeo- and Neoproterozoic, at the end of the Palaeozoic Era and at present, may have resulted from the Solar System's passage through dust and gas banding in the Milky Way continues to have its attractions (e.g. Pavlov, A.A. *et al*. 2005. Passing through a giant molecular cloud: "Snowball" glaciations produced by interstellar dust. *Geophysical Research Letters*, v. **32**, p. L03705; DOI: 10.1029/2004GL021890). The direction of motion relative to the Milky Way's cosmic drift governs the exposure to cosmic rays that result from a kind of 'bow-shock' ahead of the galaxy

Stellar motion through the Milky Way is semi-independent so that from time to time the Solar System may have been sufficiently close to regions of dense dust and gas that nurture the formation of super-massive stars. These huge objects quickly evolve to end in supernovae, proximity to which would have exposed life to 'hard' X- and γ-rays and would be trigger for mass extinction, for instance by accompanying cosmic rays in destroying the ozone protection from UV radiation from the Sun.

The dynamism of the Earth and the resulting complexity of its surface processes makes it a poor place to look for physical signs of galactic influences. No so the Moon: for almost 4.5 billion years it has been a passive receptor for virtually anything that the cosmos could fling at it, and so geologically inert that its surface layers may well preserve a complete 'stratigraphic' record of all kinds of process. Should lunar landings with geological capabilities once more prove economically possible, or politically useful, that hidden history could be read.

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