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- **NATURE**

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On the origin of high-temperature ferromagnetism in the low-temperature-processed Mn–Zn–O system 709–714
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Photosynthetic microbial mats in the 3,416-Myr-old ocean 549
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Recent re-evaluations of the geological record of the earliest life on Earth have led to the suggestion that some of the oldest putative microfossils and carbonaceous matter were formed through abiotic hydrothermal processes. Similarly, many early Archaean (more than 3,400-Myr-old) cherts have been reinterpreted as hydrothermal deposits rather than products of normal marine sedimentary processes. Here we present the results of a field, petrographic and geochemical study testing these hypotheses for the 3,416-Myr-old Buck Reef Chert, South Africa. From sedimentary structures and distributions of sand and mud, we infer that deposition occurred in normal open shallow to deep marine environments. The siderite enrichment that we observe in deep-water sediments is consistent with a stratified early ocean. We show that most carbonaceous matter was formed by photosynthetic mats within the euphotic zone and distributed as detrital matter by waves and currents to surrounding environments. We find no evidence that hydrothermal processes had any direct role in the deposition of either the carbonaceous matter or the enclosing sediments. Instead, we conclude that photosynthetic organisms had evolved and were living in a stratified ocean supersaturated in dissolved silica 3,416 Myr ago.

Excitation of Earth's continuous free oscillations by atmosphere-ocean-seafloor coupling 552
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The Earth undergoes continuous oscillations, and free oscillation peaks have been consistently identified in seismic records in the frequency range 2–7 mHz (refs 1, 2), on days without significant earthquakes. The level of daily excitation of this 'hum' is equivalent to that of magnitude 5.75 to 6.0 earthquakes, which cannot be explained by

summing the contributions of small earthquakes. As slow or silent earthquakes have been ruled out as a source for the hum (except in a few isolated cases), turbulent motions in the atmosphere or processes in the oceans have been invoked as the excitation mechanism. We have developed an array-based method to detect and locate sources of the excitation of the hum. Our results demonstrate that the Earth's hum originates mainly in the northern Pacific Ocean during Northern Hemisphere winter, and in the Southern oceans during Southern Hemisphere winter. We conclude that the Earth's hum is generated by the interaction between atmosphere, ocean and sea floor, probably through the conversion of storm energy to oceanic infragravity waves that interact with seafloor topography.

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- **EARTH PAGES**

Anthropology and geoarchaeology

Your ancestor was a cannibal

The world was shocked when Armin Meiwes of Rotenburg, Germany admitted eating his pen pal, the more so when he convinced his trial jury that his friend was a willing menu item. However, so bizarre was their mutual obsession that ordinary folk could rest easy that human cannibalism was an aberration or born of necessity; no need for nervous glances at your neighbourly gourmand. Every time earlier human remains that show signs of cut marks or having been boiled in the proverbial pot emerge the "necessity" card or that of burial practices are played in the storm of controversy surrounding possibly unwholesome aspects of older cultures. That is not so easy when forensic pathology is applied to cooking utensils and fossilised dung, spanning several hundred years, and finds traces of protein that can only have come from deep muscle tissue (myoglobin), as occurred in archaeological investigations in pre-Columbian Colorado. But there is worse, as recounted by Richard Hollingham (Natural born cannibals. *New Scientist* 10 July 2004, p. 31-33). Hollingham reviews recent research that has cannibalistic themes. The truly grim findings were made by a group at University College, London, who have studied a brain disease related to the variant CJD induced in humans who ate BSE-infected beef (Mead, S. *et al*. 2003. Balancing selection at the prion protein gene centre consistent with prehistoric Kuru-like epidemics. *Science*, v. **300**, p. 640-643). Kuru affected the Fore people of highland Papua New Guinea, who ritually ate dead relatives' brains, before the authorities banned the practice, and is caused by rogue proteins known as prions. In that respect it is similar to vCJD, BSE and a number of other mammalian brain disorders. The UCL group studied the genetic effects of Kuru on the Fore, to see if any immune resistance to prion infections had developed. There are two genes linked with prions, and people who possess both have greater resistance to vCJD, whereas people having only one are susceptible. In the Fore study, a surprising 75% of women (usually the main consumers of human brain tissue) had both, which the team put down to evolutionary pressure that had resulted from thousands of years of the practice. Turning to genetic data from different ethnic groups world-wide, they found such heterozygotes were widespread, although with different proportions in different groups. Even though these global populations do not generally eat other people now, there is a distinct possibility that their distant ancestors did, for a very long time. That is welcome news that counters the fears of massive vCJD epidemics from eating animals unnaturally fed on animal protein. What is wholly disturbing is that for much of human evolutionary history cannibalism was unnecessary for survival, and Miewes, in his initial police statement, claimed that there are around 800 cannibals in Germany alone…..

Climate change and palaeoclimatology

Antarctic climate back to 740 ka: cause for optimism?

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, sometimes of the order of 50 years. 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. The Greenland ice goes back only to cover the last glaciation and part of the interglacial period the 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 give hints of a global harmonisation of events though. 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 on climate that may be about to change anyway within this millennium, 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 from 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). 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.

The first focus, naturally enough, 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 ny saying, "…our results may imply that *without human intervention*, a climate similar to the present one would extend well into the future" [my italics]. 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 process that really call the tune.

Smoking gun for end-Palaeocene global warming: an igneous connection

The sudden warming of the Earth at the start of the Eocene 55 Ma ago has been a topic touched on several times in *EPN*. 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 gives 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. Release of methane from a volcanic basin as a mechanism for initial Eocene global warming. *Nature*, v. **429**, p. 542-545). 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. 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

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, slowly increasing in its energy output 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. 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 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 soils 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. 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 in a recent article (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.

Economic and applied geology

Putting off the evil day

The US oil economist M.K. Hubbert issued a chilling warning in the late 1960s that foretold the eventual decline of the single most important physical resource of the global economy. His simple approach was to consider petroleum, and by implication a great many other commodities, as having a fixed abundance that was not added to naturally at a rate that could keep pace with its exploitation. Oil and natural gas are non-renewable, as far as human society is concerned; they are "wasting" resources built slowly and episodically over tens of million years. Hubbert matched the exponential rate at which petroleum is extracted with various notions of how much is in the ground and how the easiest to find and pump out inevitably will give way to more tenacious reserves. His model for the future of the petroleum economy centred on a theoretical bell-shaped curve relating production to time, and we are now entering his predicted period of increasing difficulties. Estimates of reserves have increased considerably in the last 35 years, and so has the efficiency of getting out the fluids. Recent news leaking from the Shell oil giant that there has been a certain fiddling of the books about how much remains in its licence areas (a 20% overestimate) is perhaps a sign of just how difficult it is to keep pace with growing demand. Oil companies hope for the best as regards how quickly new discoveries add to their assets, yet they can never voice their fears of the worst for the sake of investor confidence and the volatility of the oil futures market. The history of petroleum discovery is indeed a bell-shaped curve, and it has been on the slippery downward slope for about 30 years, with a few cheering but brief upswings. On average, annual discovery has decreased from about 50 to 10 billion barrels each year, noting that the size of the discoveries is always an estimate of what might eventually be extracted to be tempered by the fact that it rarely if ever is. A great deal of the petroleum products now being used emerge from massive discoveries in the late 30s and 40s and the mid 1960s. Nothing like the huge Arabian and Iraqi fields has been found since then. Many commentators, as usual, consider the present upsurge in oil prices to stem from political issues, but there are deeper economic and technical issues that suggest that it is an irreversible trend while ever demand is insatiable and supply more difficult to achieve. Standing above the generally quoted reserves that can reasonably be expected to flow using current methods, are several categories of petroleum in the ground that require new extraction methods and a higher price to implement them. They are considerably larger, though much more fuzzily defined, and range from the dregs that are not easily pumped, through viscous oils, tars sands to oil shales, the primary source rocks for conventional petroleum fields when geological processes free their organic content to move. So the future is likely to depend increasingly on new extraction technologies, that Jim Giles of *Nature* recently reviewed (Giles, J. 2004. Every last drop. *Nature*, v. **429**, p. 694-695). There are several problems to solve in boosting production: decreasing the viscosity of oil, freeing oil that remains in sediment pore spaces, and driving the oil out under pressure. One interesting possibility is setting fire to oil in the reservoir rock, by pumping air into it. That would create gas pressure as well as lower viscosity, and has been tried before after Russian engineers accidentally set fire to a deposit by trying pressurised air to drive oil out. Following their surprise (and no doubt a ticking off by top political management), oil did flow more freely from nearby wells, but later experiments have had mixed success. Bacteria that metabolise oil are increasingly used to clean up spills. Since they break it down to lighter and less viscous molecules, and generate various gases, they have a role to play underground. However, all kinds of secondary recovery methods that are deployed today do not add a great deal to production – about 3 to 4% - and are unlikely to stave off eventual decline without further massive increases in price.

Structural control over hydrothermal gold mineralisation

One of the world's richest gold provinces is centred on the town of Kalgoorlie in Western Australia, site of the "Golden Mile" whose production and reserves exceed 2500 tonnes of gold. The geological control is a 200 km long shear zone trending SSE that cuts Archaean greenstone associations of mafic-ultramafic and felsic lavas, and volcanoclastic rocks of the 2700 Ma Yilgarn Province. Exploration along the trend has revealed a number of other world-class gold deposits, and the Boulder-Lefroy Shear Zone has come to typify syn-tectonic hydrothermal mineralisation. Detailed work has long demonstrated that smaller shear zones slightly oblique to the main trend focus the mineralisation. That is because the main line of movement was probably in compression, having a strike-slip sense of motion. Depending on the local orientation of lesser shear zones, some have trends likely to have encouraged dilatation in transtensional environments. Fluids are more likely to favour such opening zones, thereby concentrating their flow and deposition of minerals from them. Much of the research in the area has focussed on detail, in an attempt to discover a means of predicting new deposits, and exploration is dominated by systematic drilling in what is not a particularly well-exposed terrain, and one where standard methods of stream sediment analysis are thwarted by low rainfall. Robert Weinberg of Monash University, Paul Hodkiewicz and David Groves of the University of Western Australia have taken a broader view of the structural setting (Weinberg, R.F. *et al*. 2004. What controls gold distribution in Archean terranes? *Geology*, v. **32**, p. 545-548). So intensively explored is the gold province that it is unlikely that any large deposits remain to be discovered, but very similar shear zones affect most of the world's Archaean granite-greenstone terranes, where exploration is at an earlier stage of progress. A model of regional controls over gold is therefore pretty valuable. Weinberg *et al*. divide the Boulder-Lefroy Shear Zone into boxes along its length, each centred on 8 gold "camps". They plotted the deviation in trend of local segments of the shear zone in each box from its overall trend against the box's known gold "endowment". What emerged was a clear confirmation of the regional association of mineralisation with likely zones of regional transtension, trend deviation matching closely the estimated gold endowment. The abundance of structural data also enabled the authors to analyse the fractal dimension of all shears and fractures, thereby assessing the variation in overall geological complexity of the province. The results are odd. The least well-endowed parts of the gold province are more complex than those containing the most gold. The Golden Mile itself occurs where complexity changes from low to high. The ideas await testing on less mature shear zones cutting Archaean greenstones elsewhere in the world, such as in South India and East Africa.

Environmental geology and geohazards

Arsenic tragedy in Bangladesh

Almost 35 million people in Bangladesh are probably drinking well water that contains arsenic well over the accepted safe limit. Why that is so is one of the greatest tragic ironies of our age. In an attempt to reduce the incidence of gastrointestinal disease from drinking polluted surface water, the government, with assistance from international agencies, sank millions of tube wells from the 1970s onward. The wells tapped abundant and seemingly clean groundwater from the alluvium beneath the Brahmaputra and Ganges plains. Health problems dropped dramatically, especially among children. But by 1983 a Calcutta dermatologist reported skin lesions on patients from neighbouring West Bengal in India that are a sure sign of arsenic poisoning. Even though the British Geological Survey conducted a pilot survey of water chemistry in some Bangladeshi well waters in 1991, the danger from arsenic remained unknown; BGS did not test for the element, despite routinely analysing it in British groundwater. Shortly after the report was published, typical symptoms of arsenic poisoning appeared from a wide tract of low-lying Bangladesh. Dermatological symptoms generally only start to appear about 10 years after individuals are exposed to low, but dangerous levels of arsenic in water. They are followed by a variety of cancers (of the skin, bladder, liver and kidneys) at around 20 years from the start of exposure. A number of affected Bangladeshi people have taken legal action against BGS for negligence (see *British Geological Survey sued over arsenic* in *EPN* of October 2002). However, on appeal against a legal decision to put their case to trial, Britain's Natural Environment Research Council, of which BGS is a part, were judged to be too distant from the villagers to have had a duty of care. The issue will not go away, and informing as many people as possible about the arsenic tragedy, its causes and possible remedies is vital. This has been taken a step forward by a clear review article by a Bangladeshi health scientist, Mushtaque Chowdhury who co-chairs the UN

Millennium Project's task force on child and maternal health (Chowdhury, A.M.R. 2004. Arsenic crisis in Bangladesh. *Scientific American*, August 2004, p. 70-75).

Geobiology, palaeontology, and evolution

Carbon-isotope resonance of the end-Permian extinction

As with several major extinction events, the Permian-Triassic boundary is characterised by a major excursion in carbon isotopes of marine towards negative d^{13}C. This is often taken to indicate a reduction in the burial of dead organic matter, perhaps because of low global biomass. US, Chinese and Canadian geoscientists have added great detail to the P-Tr carbon-isotope record from analysis of three continuous sections through carbonate-dominated sequences in an Early Triassic reef system in southern China (Payne, J.L. *et al*. 2004. Large perturbations of the carbon cycle during recovery from the end-Permian extinction. *Science*, v. **305**, p. 506-509). This is no ordinary reef, for it was built by carbonate secretions by micro-organisms, either algae or bacteria. The tabulate coral reef builders of the Palaeozoic became extinct at the end of the Permian (251 Ma), and their successors, scleractinian corals, do not appear until about 10 Ma later. The Early Triassic was undoubtedly characterised by low animal diversity, before adaptive radiation could "re-stock" a devastated biosphere. The authors found a remarkable series of ups and downs in d^{13}C within the reef carbonates, some of the negative excursions being even more severe than that just after the mass extinction. Some of the positive peaks go far beyond the d^{13}C levels in preceding and following times, and could be due to periods of extremely high burial of organic matter. But the fossil record shows that such burial probably involved a restricted number of taxa, so perhaps there were huge "blooms" among a few groups that filled vacant ecological niches only to collapse. As suddenly as this see-sawing of the carbon cycle had begun, at about 246 Ma it settled to a more or less constant level, just after the start of the Middle Triassic. There are two reasonable explanations for the fluctuations. One is that biotic recovery from the mass extinction was set back three of four times by further environmental upheavals, thereby dashing diversification. The other is that the fluctuations reflect instability in the simple ecosystems of the Early Triassic and their control on carbon burial.

Calcium in the ocean and the Cambrian Explosion

If ever there was a geoscientific topic that would "run and run", it would be explaining why creatures with hard parts just popped into being 542 Ma ago. Physiologically, members at the phylum level of the Cambrian fauna have little in common apart from hard parts made from calcium compounds, either carbonate or phosphate. Calcium carbonate was secreted as stromatolites by blue-green bacteria as far back as the Archaean, but not in an organised form linked to their function. In the very latest Precambrian, the Ediacaran, there are tiny shell-like bits and pieces in its very uppermost strata (the "small shelly fauna") but they suggest no obvious function and no association with any of the various soft-bodied metazoans that define that Period. The Cambrian Explosion has no rudimentary precursor. Because calcium is an element with a very narrow tolerance in cells, from the level needed for viable function (it has a "messenger" function) to that at which it is fatally toxic, and it is a common element in all environments, adoption of calciferous hard parts seems very likely to have a risen as a means of avoiding toxicity, without any other role. Once established in large animals, hard parts provide a means of and a defence against predation, so losing the ability to secrete hard parts would be an evolutionary risky strategy; once established it cannot be lost except when substituted by other effective defences or mealtime tackle. There were times in the Precambrian record when calcium compounds exceeded their solubility, and they are marked by inorganically precipitated crystalline forms in sediments. The early Archaean was one such period, but if levels of Fe-2 are high in water those solubilities are enhanced. Therein lies a link between Archaean and Palaeoproterozoic stromatolites, banded iron formations and the oxidation potential of seawater. In fact precipitation of BIFs seems to link nicely with the abundance of stromatolites, because the production of oxygen by blue-green bacteria would locally have consumed electrons to oxidise soluble Fe-2 to Fe-3 that has insoluble oxides and hydroxides. This connection returned several times in the Neoproterozoic, oddly at the times of so-called “Snowball Earth” episodes, first noted by Preston Cloud. Could the last of these have triggered adoption of calcium secretion by the early metazoan animals? That is hard to judge, because it preceded the Cambrian by several tens of million years. Geochemists from the US Geological Survey, the State University of New York and the US Oak Ridge National Laboratory have taken a cunning route to shedding some light on the biggest of all palaeontological mysteries (Brennan, S.T. *et al*. 2004. Seawater chemistry and the advent of biocalcification. *Geology*, v. **32**, p. 473-476). They sought crystals of evaporitic halite that spanned the Precambrian-Cambrian boundary, and which usually contain fluid inclusion containing samples of the brine from which they formed, hopefully seawater. So far, they have two sets of suitable halites that can be assigned to a marine environment, from Siberia and the Oman, and their measurements of calcium concentrations are very precise. The first is dated around 515 Ma the other set from 544 Ma. Two sample points are not enough to prove a role for elevated calcium levels in the ocean, but the results are encouraging. Calcium concentrations (with suitable corrections for changes during evaporation of restricted seas) jumped by a factor of 3 from the very end of Precambrian to Cambrian times. Over the same period, it is thought that global sea-floor spreading rates were much higher than at present, and there is also strontium-isotope evidence for an increase in ocean-floor hydrothermal activity that adds elements derived from oceanic basalts to seawater. That, however post-dates the start of the Cambrian by about 15 Ma. With a CO_2-rich atmosphere and elevated continental weathering calcium is likely to have been supplied from the continents. Whatever, the results fit with models based on variation of continental and oceanic additions to seawater with changing spreading rates (Hardie, L.A. 2003. Secular variations in Precambrian seawater chemistry and the timing of Precambrian aragonite seas and calcite seas. *Geology*, v. **31**, p. 785-788). Hardie suggested that calcium in seawater fell to very low levels during the Neoproterozoic from an unprecedented high at its outset at 1000 Ma. That is a time when metazoans were probably not around, while the period when they appear in the later Neoproterozoic record was one of calcium-poor conditions. Large animals may have evolved when there was little danger of calcium shock, only to face it once they were well established. Then would have had to rid their cells of it very efficiently. Studies of fluid inclusions from marine precipitates seem likely to grow following Brennan *et al*.’s important discovery, though suitable samples are likely to be few and far between. One important role they need to play is verifying Hardie’s model for secular variation in seawater chemistry, which depends on difficult interpretations of rates of sea-floor spreading and continental erosion.

Ancestral animal?

The significant feature of the first appearance of widespread, large fossils during the Cambrian Explosion about 542 Ma ago was really the adoption of hard parts by most of the existing (and some now extinct) phylla of animals. The preceding Neoproterozoic Ediacaran Period witnessed lots of large life forms, but preserved them only as imprints; they were soft bodied. Superficially, the outset of the Cambrian appears to marked the simultaneous emergences of the rough blueprints of all subsequent animals. In reality, this was probably not a faunal explosion, but one of biochemical processes, wherein many phylla turned the fundamental cell process of excreting excess calcium as carbonate and phosphate to generating functional parts of their bodies. Why that happened explosively is still a mystery. Looking for the origin of animals requires going further back in geological time, and an element of luck as regards exceptional preservation of soft tissue. The other way is using a molecular clock approach to the genetic differences among modern phylla, but that is fraught with uncertainties and gives a very large time range (possibly 1500 to 600 Ma) in which to find tangible evidence. The maximum limit is around 2200 Ma, when oxygen became significant in the atmosphere and the upper ocean – the prime condition for eukaryote life. A rather dull carbonaceous fossil, with a spiral form and thought to be the first known multicelled eukaryote (*Grypania*) appears in the record about 1500 Ma ago, but what it was is unclear. The best place to look for ancestral animals is in known repositories of well preserved organisms.

One such *lagerstät* is the Doushanto Formation in SW China. This goes back to the last "Snowball Earth" event at 600 Ma, and has been heavily mined for primitive life forms. Chinese palaeontologists, teamed up with others from the USA have indeed found something intriguing (Chan, J-Y. *et al*. 2004. Small Bilaterian Fossils from 40 to 55 Million Years Before the Cambrian. *Science*, v. **305**, p. 218-222). Only about 0.2 mm across, 10 specimens seems to show microscopic signs of all the basic elements of many members of the Animal Kingdom: bilateral symmetry, a mouth and gut, skin tissue and possible sensory organs. The layers from which they were extracted are between 580 to 600 Ma, well before the Cambrian Explosion. However, micropalaeontologists in general subscribe to the "once bitten, twice shy" outlook, especially following controversies over even earlier evidence for small organisms and those purported to occur in Martian meteorites, which are as likely to be results of inorganic mineralisation as fossils. Various mineral crusts and films, formed inorganically, can mimic organic structures. The one feature that persuades Chen and colleagues is that the same features show up in all the specimens, and they are all the same size. That is highly unlikely from some inorganic process.
Source: Stokstad, E. 2004. Controversial fossil could shed light on early animals' blueprint. *Science*, v. **304**, p. 1425.

The case of the stranded, tiny mammoths

It does seem likely that our ancestors ate all the mammoths (*Mammuthus primigenius*), a species that had wandered over the northern tundras bordering the Northern Hemisphere ice sheets through several glacial-interglacial periods. But some of them did escape to survive into the Holocene. They were stranded on high-latitude islands off NE Siberia and Alaska as sea levels rose. The last of them died on Wrangel island about 4 thousand years ago. A common tendency in small populations of large mammals that are restricted to islands is that they become smaller and smaller with each generation. This happened to the stranded mammoths of the Bering Straits islands, remains of which are often dwarfs. (Guthrie, R.D. 2004. Radiocarbon evidence of mid-Holocene mammoths stranded on an Alaskan Bering Sea island. *Nature*, v. **429**, p. 746-749). St Paul Island is now only 91 km^2 in area, too small to support even tiny, woolly elephants, but it was probably much larger when sea-level rise first isolated it from the vast Bering steppe across which mammoths roamed. It was that isolation about 13 thousand years ago that probably helped the stranded mammoth population avoid the hunters who colonised the Americas, until 7 900 when the last mammoth there died. The even later population on much larger Wrangel Island fell to human colonisation, but there are no signs of human intervention on St Paul. The earlier extinction there was probably a result of shrinking browse as sea level steadily rose., when St Paul would have been 5 to 10 times larger than it is now.

Geochemistry, mineralogy, petrology and volcanology

Seismic detection of zones of crustal melting

The Himalaya and Tibet are known for their huge granite batholiths that show geochemical signs of having formed by partial melting of the continental crust. They also show signs of ductile zones in the deep crust. Whether or not this ductility is associated with incipient melting cannot be judged easily, as there are no examples of active felsic volcanism. However, it is possible to predict theoretically where crustal temperatures exceed the solidus of the crust, whose paths in pressure-temperature space for various amounts of water content is well known. The problem is knowing the way in which temperature increases with depth. That is usually estimated from the surface heat flow and modelling the likely thermal conductivity of different crustal layers, but it isn't suitably precise. German, US and Chinese geophysicists have tried a clever means of estimating crustal temperature using seismic data (Mechie, J. *et al*. 2004. Precise temperature estimation in the Tibetan crust from seismic detection of the a-b quartz transition. *Geology*, v. **32**, p. 601-604). Experiments show that quartz in its low-temperature a form transforms to b quartz above 575ºC at atmospheric pressure, and at higher temperatures with increasing pressure. The P-T change in the transition is well known, so if b quartz can somehow be detected in the deep crust, its depth gives the crustal temperature. As luck would have it, the transition results in a significant change in the elastic properties of quartz that should effect the speed at which seismic waves travel through rocks rich in b quartz. More precisely, the P-wave speed should increase abruptly by a detectable amount. Mechie and colleagues have indeed found the depth of this transition below a seismic profile running across part of the Tibetan Plateau NNW of Lhasa. Its depth varies between about 20 to 15 km coinciding with the upper-middle crustal boundary. At its shallowest levels, the transition is directly above a large zone of high electrical conductivity, discovered by magnetotelluric surveys, which has been suggested to be due either to a high content of aqueous fluids or crustal melts. The geotherm (about 40ºC km^{-1}) associated with the shallow a-b quartz transition crosses the wet granite solidus about 5 km beneath it, so the lower crust itself is likely to be generating granitic magmas. Although the deepest levels of the a-b quartz transition also predict likely conditions for wet melting in the lower and middle crust, below those zones there is no evidence that it is happening. One possibility is that water content varies considerably in the sub-Tibetan crust. Where melts or fluids are moving in the crust, heat transfer is not purely by conduction, and steep geothermal gradients can stem from heat being transported upwards with moving fluids.

Geomorphology

Climate and mountain relief

The greater the rainfall, the more effective streams become as agents of erosion. So, "common sense" suggests that very wet mountain areas should be eroded more quickly and develop a more profound relief than those that are drier. With the advent of detailed digital elevation models that cover the world, it is very easy to calculate slope angles and relief over huge areas, and match them with rainfall records. Geomorphologists from the Universities of Montana and California have done this for the wettest and most rugged area in the world, the Annapurna area of the Himalaya (Gabet, E.J. *et al*. 2004. Climatic controls on hillslope angle and relief in the Himalayas. *Geology*, v. **32**, p. 629-632). The main agent of erosion there as streams cut downwards is by landslides. The region also shows a profound gradient in annual rainfall from about 1000 mm in the High Himalaya to 4500 at the front of the range, where the monsoon rains hit hardest. "Common sense" is wrong, for the slopes decrease from an average of 35º to 25º as rainfall increases. The authors believe this is due to the influence of deeper weathering in more humid parts that reduces the strength of slope materials so that they must stabilise at lower angles than those in dry areas. Their other finding is that relief (elevation difference in small segments of an area) and slope angle have a strong positive correlation, so that relief itself is inversely related to rainfall. They are able to comment interestingly on various ideas about mountain evolution. Their main conclusion is that in any particular area, a transition from dry to wet conditions lowers mountain ridges faster than valley incision can shift the debris, whereas during drying, ridges are barely lowered, while streams cut unhindered into bedrock, thereby sharpening up the landscape.

Formation of gorges in tectonically quiet areas

The flanks of the North Atlantic probably became tectonically inactive in Mesozoic times, yet rivers large and small have cut large gorges, often through highly resistant bedrock. But they also have developed broad valleys over millions of years, and it is into them that the gorges are incised. Slow upward flexing caused by sediment loading on the continental shelves, a general lowering of sea level since Antarctica first formed a permanent ice cap, and isostatic response to gradual denudation help explain the full extent and shape of the rivers drainage basins. The gorges are young, and must have developed rapidly. Old ideas focussed on W.M. Davis' theories of landscape evolution, particularly rejuvenation associated with changing base levels of erosion, but with no quantitative backing. The development of means of dating eroded surfaces using the decay of short-lived radioactive isotopes that cosmic-ray bombardment creates now offers an opportunity to test hypotheses rigorously and come up with others. Quite a few published works on cosmogenic dating applied to landform development seem to add little to geomorphological knowledge, so it is a relief to find one that does (Reusser, L.J.

et al. 2004. Rapid late Pleistocene incision of Atlantic passive-margin river gorges. *Science*, v. **305**, p. 499-502). The authors, from the Universities of Vermont and Maryland, the USGS and the Lawrence Livermore National Laboratory, focus on impressive gorges in the lower reaches of the Susquehanna and Potomac Rivers as they drain the eastern US into the Atlantic, and a series of higher surfaces which they cut into to leave as rocky straths. The oldest ages occur on the highest of these straths, as expected, and age decreases on successively lower ones to the rocky flood plain of the modern rivers just above their current channels. The highest levels are between 85 and 97 ka, the most prominent strath formed between 30 and 33 ka, succeeded by one at 19 ka and the lowest level seems to have formed between 13 and 14 ka. Interpreting the periods of intense erosion that cut each level must involve late Pleistocene climate change, sea-level shifts, and the bulging effect due to the North American ice sheet which reached its maximum extent in the northernmost part of the Susquehanna basin. It seems that during the early part of the last glacial episode, incision was slow, although probably faster than during the Holocene. But around 30 to 33 ka ago it accelerated rapidly to half a metre every thousand years, some 1 to 2 orders of magnitude greater than at present. This was at a time when ice loading was only half that at the glacial maximum around 20 ka, so it seems likely to have been initiated more by increased storminess and torrents, and indeed correlates with an abrupt increase in sea-salt content in the Greenland ice cap brought in by winds at that time. Lasting through the glacial maximum, increased frequency of flooding combined with more rapid sea-level fall, also beginning at around 32 ka, were probably the main driving forces for gorge incision. This still leaves a puzzle. Both drainage basins had been in existence since well before the cycles of glacial and interglacial periods began on the flanks of the North Atlantic around 2.5 Ma ago. Similar periods of accelerated incision must have been repeated, at least during the last 6 or 7 glaciations which were the most extensive. Did earlier topographic features exert any control over later ones, and do any relics of them remain?

Planetary, extraterrestrial geology, and meteoritics

Sudbury impact turned the crust inside out

The 1800 Ma old Sudbury complex in eastern Canada is one of the largest repositories of nickel ores and contains commercial platinum deposits. It has also been ascribed to a major impact that produced a crater over 200 km across. The evidence is the common presence of shocked minerals and a sheet of very homogeneous, once molten rock, whose andesitic major-element composition suggests that it represents melting of the local upper crust. However, the trace elements, including platinum group metals, have all the hallmarks of the lower crust (Mungall, J.E. *et al*. 2004. Geochemical evidence from the Sudbury structure for crustal redistribution by large bolide impacts. *Nature*, v. **429**, p. 546-548.). The melt sheet is mixed with upper crustal rocks, including sediments that formed in a shallow marine basin into which the meteorite plunged. This suggests that impact not only affected the whole crust, but excavated it as well, so that a 30 km deep crater formed at the instant of collision. The bulk of the homogenised crustal melt remained molten for long enough for complex fractional crystallisation to take place, thereby forming the classic layered Sudbury Igneous complex, in which the nickel ore bodies are located. They may well represent relics of the impactor itself, that mixed with molten crust.

Tectonics

Plastic deformation beneath Tibet

Plate tectonics' basic tenet is that discrete segments of the lithosphere behave as rigid bodies, whose motion is accommodated by extensional, overriding and strike-slip faulting at equally discrete boundaries. That is true to a first approximation for the parts of plates made up from oceanic lithosphere, which is rheologically strong because of its mineralogical composition. Continental lithosphere is weakened by its quartz-rich crust, which tends to behave plastically at high temperatures deep within it. So it is no surprise that opposed motions of plates induce large-scale shortening and thickening of continental lithosphere that they carry, but there are no orogens in the ocean basins. The largest site of active continental shortening and thickening is, of course, the Alpine-Carpathian-Himalayan orogen. The Tibetan Plateau is underpinned by continental crust that is in the process of being thickened as India drives north-eastwards into Asia, at about 4 to 5 cm per year. Consequently it the largest area of high-elevations on the planet. In the 1973 John Dewey and Kevin Burke speculated that forces involved in continent-continent collisions with irregular margins might expel thickened continental lithosphere sideways, at right angles to the opposed plate motions. Peter Molnar of the University of Colorado in Boulder and Paul Tapponnier of the Institute of Global Physics in Paris applied this on a grand scale to the neotectonics of the Tibetan Plateau and East Asia in 1975. They considered that south-eastward expulsion was channelled by the many enormous strike-slip faults in the region. In a sense, this notion considers the continental tectonics to be akin to the rigid-body behaviour of oceanic parts of plates. If the overall motions involving Tibet and continental lithosphere to the east was dominated by plastic deformation in the deep crust and mantle, the motion would be taken up by a host of smaller faults in the brittle upper crust. Geodetic measurements using GPS over the last 17 years do conflict with the movement of discrete blocks of East Asian crust (see *Quantifying motions inside continents*, March 2004 *EPN*). Two papers published in July 2004 also lean towards plastic behaviour of the bulk continental lithosphere. One uses data from surface seismic waves to show about 30% ductile thinning in the middle and lower crust beneath Tibet (Shapiro, N.M. *et al*. 2004. Thinning and flow of Tibetan crust constrained by seismic anisotropy. *Science*, v. **305**, p. 233-236). The other is based on interferometric analysis of radar data from satellites, which involves measuring signal differences between radar data captured on different dates, in this case between 1992 and 1999 (Wright, T.J. *et al*. 2004. InSAR observations of low slip rates on the major faults of western Tibet. *Science*, v. **305**, p. 236-239). The technique has mainly been used to look for vertical displacements associated with earthquakes and volcanoes. By eliminating the effects on signals by terrain, using an accurate digital elevation model, InSAR results can estimate the motion of the surface along and opposite to the illumination direction of the radar pulses, thereby detecting horizontal ground movements over a period of several years with sub-centimetre precision. Rather than revealing large movements in the two opposed directions that are expected on either side of large strike-slip faults, such as the Karakorum and Altyn Tagh Faults, there was none. In a zone crossing western Tibet from NNE to SSW, much of the orogen appears to be moving slowly eastwards, irrespective of the large faults. Tapponnier still maintains the importance of the big faults, and perhaps the InSAR survey coincided with a period of tectonic quiescence.

Early Earth's Nemesis

William Hartmann's proposal that, shortly after it formed, the Earth suffered impact by a planet about as big as Mars has become a central feature on ideas about our planet's evolution and the origin of the Moon. The problem with the theory is a conundrum that lies in quite esoteric geochemistry. Studies of meteorites show that the oxygen isotopes in them vary considerably, and that almost certainly resulted from their forming at varying distances from the Sun where fractionation among oxygen's stable isotopes had different effects on their proportions. So it is possible to judge the original orbits in the solar system of meteorites' parent bodies. Martian meteorites are identified on this basis. The difficulty with Hartmann's idea is that rocks from the Earth and Moon have nearly identical oxygen isotope proportions. There seems no way that an errant planet that crashed into the Earth could not have left its mark in oxygen isotopes, particularly in those of the Moon, for debris flung off from the Earth would have mixed with that from the colliding body. It turns out that there is a possible explanation (Chown, M. 2004. The planet that stalked the Earth. *New Scientist*, 14 August 2004, p. 26-30). The Earth's orbit could have involved the accretion of more than one planet from interstellar dust. This can happen once a planet has grown until it has sufficient gravitational potential to interact with solar gravity. The result is a series of points in the orbit (Lagrange points) where the two gravitational fields exactly balance. Matter that drifts into Lagrange points accumulates there rather than being swept up by the growing, larger planet. So considerable mass can build up, even enough to make a small companion planet. While all the main planets were growing, gravitational fields were continually changing, so the Lagrange points would not remain as stable as they are today. A small planet formed at one of them would begin to move erratically within the Earth's orbit. Eventually it would be caught up by mutual attraction between the two, and then would collide with the Earth, but not at immense speed. So far, the hypothesis based on complex modelling of Lagrange accretion seems plausible. Geochemists will be pleased because it resolves their fundamental conundrum about the similar chemistries of the Earth and its Moon.

Uranium in the core?

The constant, but complex circulation in the Earth's liquid outer core almost certainly results in the self-exciting dynamo believed to be responsible for the geomagnetic field and its periodic reversals in polarity. If an electrical conductor moves in a magnetic field a current is generated in it, which in turn creates a magnetic field, hence self-excitation. The outer core's convective motion requires a heat supply of some kind. There are three general possibilities: the heat is left over from the Earth's energy of accretion; it is generated from latent heat released as the solid inner core grows slowly by crystallization of iron-nickel alloy; or there is significant radioactive decay in the core. Compared with estimates for the Earth's overall radioactive heat production, based on the composition of the primitive meteorites (ordinary chondrites) from which it is thought to have formed, there is excess heat flowing through the surface. This is believed to emanate from the core. Separating the three possible heat sources is not yet possible, but it is possible to rule the generation of enough to account for excess heat flow by one of the possible mechanisms. If the inner core has been crystallising out since the core formed around 4500 Ma ago, the latent heat being released is too small. Much attention has focussed on a possible radioactive source, for which the unstable natural isotope of potassium (^{40}K) is a plausible candidate. The sulphide phases of metal and chondritic meteorites do contain potassium, so the element has affinities for sulphur as well as its dominant tendency to enter silicate melts and minerals. The core almost certainly contains a sizeable proportion of Fe-Ni sulphides. One geoscientist, Marvin Herndon based in San Diego, California, reckons there is another possibility (Battersby, S. 2004. Fire down below. *New Scientist*, 7 August 2004 issue, p. 26-29); uranium. To most geochemists, the idea is implausible, because uranium has such a strong affinity for silicates that it ought never to have entered the metallic and sulphide liquids that sank through the early Earth to form the core. Herndon bases his idea on an alternative type of meteorite from which the Earth could have formed by accretion, enstatite chondrites. They have lower oxygen contents than ordinary chondrites, and would have created strongly reducing conditions in the undifferentiated early Earth. Such planetary chemistry, claims Herndon, would induce uranium to enter dense sulphide liquids and the core. This view has not found much support, but experiments in detection of neutrinos and antineutrinos, when they are more efficient than at present, may resolve the issue of radioactivity in the core, because decay of unstable isotopes produces antineutrinos.

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