Palaeontology, palaeobiology and evolution

Broody dinosaurs (*January 2009*)

The most likely ancestors of birds evolved in the Jurassic from a group of nimble and mainly carnivorous theropod dinosaurs known as Deinonychosaurs, which included the now famed *Velociraptor*. One of the oddest fossils ever found was the skeleton of one of these preserved together with eggs of what were originally thought to have been laid by *Protoceratops*. This Mongolian animal, seemingly caught in the act, was given the name *Oviraptor* or 'egg seizer'. Specimens of *Oviraptor* and closely related dinosaurs found subsequently show them sitting on eggs; clear evidence of bird-like brooding. If this wasn't a sufficient surprise, the clutches were enormous: 20 to 30 eggs. Detailed study of the skeletons shows that they are all males (Varricchio, D.J. *et al*. 2008. Avian parental care had dinosaur origin. *Science*, v. **322**, p. 1826-1828). About 90% of all living bird species involve males in care of chicks, including sharing of incubation (5% of mammals share parental care). However, only among ratites (ostriches and the like) and tinamous do males brood eggs clutches continuously. This behaviour is generally associated with polygamy and large clutches. So the misnamed *Oviraptor* and its kin were not only progenitors of birds but may well have passed on the peculiarities of avian parenting.

Molecular evidence for the environment of the universal ancestor (*January 2009*)

If ever there were a 'holy grail' for palaeobiologists, it would be the nature and ecology of the original beings from which all life on Earth subsequently evolved. That is, the primitive organism – among perhaps many that were extinguished 'intestate' – whose genetic 'footprint' alone survived to be common to all three domains of modern life: Archaea, Bacteria and Eucarya. For some time, attention has focused on extant heat-tolerant Archaea and Bacteria species (hyperthermophiles) found in hot springs (≥ 80ºC), whose genetics seem primitive. This, together with other features such as the adaptation of heat-shock proteins to other functions and the abundance of metals at the cores of other widespread proteins, has led to notions that life originated under high-temperature conditions such as those around sea-floor hydrothermal vents. The ongoing explosion in nucleic acid analysis and software to sift through vast amounts of molecular data from many sources potentially may provide the key to more concrete ideas of the origin of Earth's life. A recent comparative study of both ribosomal RNA and protein sequences among representatives of all three of life's domains gives a clue to surprises ahead for palaeobiologists (Boussau, B. *et al*. 2008. Parallel adaptations to high temperatures in the Archaean eon. *Nature*, v. **456**, p. 942-945; DOI: 10.1038/nature07393). 'Exobiologists', who nurture great, but perhaps folorn, hopes of being alive and sentient when extraterrestrial life forms are 'bagged' may also find themselves perplexed; such is the fate of hubris without substance.

The team of francophone biochemists claims that their analyses show signs of a two-fold adaptation to changing environments during the earliest period of surviving life. Rather than having emerged from high-temperature conditions, the last common universal ancestor, or LUCA, probably adapted to more temperate conditions (≤ 50ºC), the hyperthermophile Bacteria, Archaea and Eucarya evolving from it. Heat tolerance then declined as the later mass of life forms developed. Sadly, the authors do not address the issue of deep ocean-floor origins in their discussion, preferring to speculate about Archaean climate change and rather odd notions about adaptation to high-temperature meteoritic ejection from extraterrestrial sources. It may be that they too are in for surprises when more mature investigations hit the press.

When bacteria became more sturdy (*January 2009*)

It's easy for geologists to forget that most of the genetic diversity on Earth is and always has been in organisms that rarely if ever fossilise; those with only a single cell, among the Archaea, Bacteria and Eucarya. All that is known is from those still alive, and they occupy a vast range of environments, most of which are not 'friendly' to multi-celled eukaryotes. Unsurprisingly, they don't look very different from one another; just tiny bags full of water and a tiny amount of complicated biochemistry. They become distinct from their molecular make-up and also from what they do and where they live, some tending to reproduce best within the bodies of eukaryotes, such as ourselves sometimes with no noticeable effect, sometimes beneficially, but most spectacularly when they make us ill. Bacteria and Archaea have long histories, so their genetic material and proteins are easily distinguishable from group to group. This makes them amenable to the use of a 'molecular clock' approach in seeking out when and how they evolved. Analysis of these differences among more than 250 species of bacteria in the context of their living in water or under terrestrial conditions has thrown up some surprises (Battistuzzi, F.U. & Hedges, S.B. 2008. A major clade of prokaryotes with ancient adaptations to life on land. *Molecular Biology and Evolution*, doi:10.1093/molbev/msn247). Two thirds seem to stem from a common ancestor that had colonised the land around 3.2 Ga ago, 800 Ma before preservation of the first undisputed fossils. To live on the continental surface, all have to have evolved or inherited resistance to environmental hazards such as drying out, UV radiation and high salinity. Many pathogenic bacteria belong to the Gram-positive group, whose cell walls are distinctly adapted to terrestrial life. Despite having to live in eukaryote-free world for a billion years or more, their ancestors were especially well-suited to infesting multi-celled life when it emerged, and to being notoriously adaptable when they are threatened with toxicity themselves.

Did a comet slay large mammals of the Americas? (*March 2009*)

Shortly before the start of the Younger Dryas cold period, around 12.9 ka, the Palaeoindian Clovis culture of North America seems to have come to an abrupt halt. The North American mammoths on which the Clovis people preyed also disappear from the fossil record. Some folk reckon that early immigrants from NE Asia devoured the last of the mammoths, as they ate their way through two continents en route to Tierra del Fuego. Equally imaginative scientists have been suggesting since 2007 that an extraterrestrial cataclysm was responsible for climate change and the demise of both mammoths and the Clovis people (see *Whizz-bang view of Younger Dryas* July 2007, and *Impact cause for Younger Dryas draws flak* May 2008). Evidence found just beneath a sediment layer that marks the outset of the Younger Dryas included: excess iridium; tiny spherules; fullerenes containing extraterrestrial helium; nanodiamonds and evidence for huge wildfires. Neither crater nor shocked mineral grains have been found, and the proponents of this controversial idea have opted for a cometary airburst as culprit – an impact would have produced shocked debris.

The authors have had a 'bad press', but remain undeterred and have published photomicrographs of diamonds in minute spherules made of amorphous carbon (Kennett, D.J. and 8 others 2009. Nanodiamonds in the Younger Dryas boundary sediment layer. *Science*, v. **323**, p. 94; DOI: 10.1126/science.1162819). There is a problem or two with the hypothesis: mammoths, albeit little ones, lived on Wrangel Island in the Arctic Ocean until 1650 BC; had some kind of cosmic encounter in North America set global cooling in motion at 12.9 ka, then the best place to look for evidence would be in the Greenland ice cores, in which diamonds have yet to be found. No-one doubts that diamonds do occur in the sediments formed just before the Younger Dryas, but experts don't accept them as irrefutable evidence for impacts (Kerr, R.A. 2009. Did the mammoth slayer leave a diamond calling card? *Science*, v. **323**, p. 26; DOI: 10.1126/science.323.5910.26). But the plot thickens. A Belgian and German team has discovered that forest topsoils, grasslands and swamps, no more than a few thousand years old, from 70 sites across Europe also contain nanodiamonds. Although one member of that team reportedly has no idea where they came from, a website hints that a very young (2500 years) impact site in Bavaria may be the source. While the end-Clovis diamonds may not have triggered global cooling and killed off mammoths, they could well set off a research line aimed at documenting hazardous extraterrestrial events of the recent past and puzzling occurrences in the archaeological record.

See also: Herd, C.D.K *et al*. 2009. Anatomy of a young impact event in central Alberta, Canada: Prospects for the missing Holocene impact record. *Geology*, v. **36**, p. 955-958; DOI: 10.1130/G25236A.1.

Nitrogen isotopes and a change in the Archaean biosphere (*March 2009*)

All life forms require nitrogen fixation; pretty obviously, since they are largely made of C, H, O, N and P. It happens through two main processes in the nitrogen cycle: anaerobic reduction of dinitrogen (N_2) to ammonium ions (NH_4^+) and the degradation of that by oxidation to nitrite (NO_2^-) or nitrate (NO_3^-) ions (nitrification). Both kinds of process allow nitrogen to enter cells today, but before the Earth's biota evolved oxygen production through photosynthesis only the first, anaerobic process was possible. As with many elements that have several stable isotopes – nitrogen has two: ^{14}N and ^{15}N – such chemical processes favour one isotope over the others leading to fractionation in the overall environment. A measure of the relative proportions of nitrogen isotopes is $\delta^{15}N$, and its mean value in modern seawater is +5‰ due mainly to the reduction of nitrite and nitrate ions by denitrification. In an oxygen-free ocean $\delta^{15}N$ would be significantly lower. Nitrogen-isotope studies of the organic matter in ancient sediments should therefore be a test for the presence of free oxygen in the environment.

In lightly metamorphosed Archaean shales $\delta^{15}N$ is generally low, as expected. However, there have been hints of higher values from the youngest Archaean strata that do indicate oxygen. The Hamersley Group of Western Australia, famous for its vast reserves of banded iron formations (BIFs), includes a 50 m thick carbonaceous shale deposited at the very end of the Archaean around 2.5 Ga (Garvin, J. *et al*. 2009. Isotopic evidence for an aerobic nitrogen cycle in the latest Archaean. *Science*, v. **323**, p. 1045-1048; DOI: 10.1126/science.1165675). Detailed geochemical analyses through the shales and enveloping BIFs, including nitrogen isotopes, show considerable variations ascribed to environmental changes. Aerobic denitrification is marked by a shift from 1 to 7.5‰ in $\delta^{15}N$ within the shales, which correlates with shifts in molybdenum and the proportions of sulfur isotope. The real significance of the paper is not that the study detected evidence of free oxygen in the Archaean – the BIFs formed by combination of iron-2 ions with oxygen. It shows that before 2.5 Ga prokaryote organisms had already to perform aerobic nitrification as well as denitrification, of which there are only three groups nowadays, two of Bacteria the other of Archaea.

The Palaeocene Death Snake and torrid times (*March 2009*)

As a reader of anything connected with exploration of the Amazon as a kid, I developed a perfectly rational fear of snakes, especially anacondas that ate humans. To my horror I awoke one a snowy February morning to an item on the BBC Radio 4 *Today* programme about the biggest snake that ever lived (Head, J.J. and 7 others 2009. Giant boid snake from the Palaeocene neotropics reveals hotter past equatorial temperatures. *Nature*, v. **457**, p. 715-717; DOI: 10.1038/nature07671). At 13 m long and weighing in at over a ton, *Titanoboa* could have eaten an entire family at one sitting, and gone next door for seconds: and it would probably get in the house with the booid's celebrated stealth. Becoming calmer, I saw how interesting this gigantic people crusher must have seemed to its discoverers. Seemingly the maximum size of snakes is governed by ambient temperature. The anaconda that gave me bad dreams gets to a maximum length of around seven metres in present equatorial South America (mean annual temperature in the upper 20s). Modelling based on a range of snakes now living at different latitudes suggests that *Titanoboa* grew Topsy-like at hotter Palaeocene tropical latitudes (a mean around 33ºC at least). We can all be thankful that such tropical temperatures would require atmospheric CO_2 levels around 2000 parts per million, but this century's possible global warming will probably mean bigger anacondas and boas for the Amazonian explorer to grapple with.

Snowball Earth and the major division among animals (*March 2009*)

There are two basic kind of animals: those whose embryos show bilateral symmetry – bilaterians like ourselves, sea urchins and lobsters, for instance – and those that don't, such as corals and sponges. Evidence from genetic differences among living animals suggests that the evolutionary separation of the two fundamental groups was probably during the Proterozoic Eon. Calibrating molecular clocks based on DNA sequences of living organisms is possible to some extent for animal groups and the ancestral kinds preserved as fossils, for instance humans and domesticated chickens share a common ancestor that lived during the Carboniferous Period. (A propos of very little, mammals have uvulas dangling in their throats that have no other function than to make one throw up if they are tickled, and we share the uvula with birds that still use them to sing: food for the imagination there.) However, the separation of bilaterians from the others, and a great many living phyla, must have taken place in Precambrian times among ancestors with no hard parts and therefore no palpable trace of their existence. Thus, any evidence of when one or another was around is highly useful in phylogenic studies. Most such evidence is likely to come from resistant kerogen and bitumen hydrocarbons found in reduced facies sediments that occur as far back as the Archaean.

Biomarkers include organic molecules that can sometimes be linked to specific phyla, and distinctive ones are associated with either side of the bilaterian-'others' split (Love, G.D. and 12 others 2009. Fossil steroids record the appearance of Demospongiae during the Cryogenian period. *Nature*, v. **457**, p. 718-721; DOI: 10.1038/nature07673). The US-UK-Australia team sampled kerogen and bitumen from reduced carbonate sediments in the now famous Omani sequence that almost continuously spans times from the Cryogenian Period of Snowball Earth episodes, through the trace-fossil rich Ediacaran and across the Cambrian boundary. Incidentally, strata like these are source rocks for petroleum reserves in many parts of the Arabian Peninsula. Among the various kinds of molecule identified by chromatography are 24-isopropylcholestanes, degraded remnants of steroids based on 30 carbon atoms per molecule. These are characteristic of one group of sponges, i.e. non-bilaterians, and occur in the oldest samples (around 700 Ma). This shows clearly that the big evolutionary divergence predated that time and may have happened during the climatically dramatic Cryogenian.

Possible effects of mid-Ordovician bombardment (*March 2009*)

Limestones dated at around 470 Ma in Sweden contain highly altered chondritic meteorites, ranging in mass up to 3.4 kg and up to 20 cm across, along with chromite grains and high iridium. There are so many that investigators have estimated a flux of extraterrestrial debris that was a hundred times greater than at present. The remarkable repository is matched in age by sediments rich in chromites in central China. The Darriwilian Stage (460-470 Ma) of the Ordovician is also notable for evidence of powerful downslope sediment movement in many continental margin sequences. John Parnell of Aberdeen University reviews the many megabreccias or olistostromes of this geologically short time span (Parnell, J. 2009. Global mass wasting at continental margins during Ordovician high meteorite influx. *Nature Geoscience*, v. **2**, p. 57-61; DOI: 10.1038/ngeo386). Most seem to be associated with continental margins of the mid-Ordovician Southern Hemisphere. While some occur at what were probably seismically unstable volcanic arcs, most are associated with stable carbonate platforms. Together with the link in time to evidence for enhanced meteorite flux, this association suggests slope failure associated with large impacts. However, the megabreccias are so widespread that they are unlikely to have been formed by a single tsunami resulting from one giant impact. Indeed there is no evidence for a catastrophic event, either as a large crater or evidence for mass extinction: the mid Ordovician was a time of rising faunal diversity (see *The Great Ordovician Diversification* September 2008). Parnell calculates that there may have been as many as 10 Chicxulub-sized impactors per million years during the Darriwilian, but the lack of catastrophic consequences suggests that the megabreccias may have resulted from a great many smaller events, probably of bodies less than 300 m across. That would also explain the lack of global evidence traditional sought to identify impacts, such as iridium, glass spherules and shocked mineral grains. If he is correct, then other olistostromes of different ages in aseismic settings could point to extraterrestrial causes.

Experiments on formation of organic compounds by impacts (*March 2009*)

Many mechanisms have been speculatively proposed for the origin of complex organic chemicals from which life may have originated on Earth. The best known of these is the 1929 Oparin-Haldane hypothesis that life began with simple organic compounds formed from methane and ammonia in the early atmosphere, followed by more complex compounds formed in the seas through a variety of reactions. This was tested by Miller and Urey in the 1950s, using electrical discharges through a simulation of such a reducing atmosphere, but current views are that the early atmosphere was rich in CO_2 and nitrogen rather than reduced methane and ammonia. Another possibility is synthesis of organic compounds as a result of impact energy; very abundant early in Earth's history. This idea has been tested experimentally using a propellant gun to create high-velocity impacts into a mixture of solid carbon, iron, nickel, water and nitrogen: a highly simplified scenario of ordinary chondrites bombarding atmosphere and ocean (Furukawa,Y. *et al*. 2009. Biomolecule formation by oceanic impacts on early Earth. *Nature Geoscience*, v. **2**, p. 62-66; DOI: 10.1038/ngeo383). The experiments were performed under conditions that excluded possible contamination. Yet they yielded a wealth of organic molecules, including fatty acids, amines and an amino acid (glycene) found in DNA. Scaling up the experimental yields to the mass of meteoritic material accreted to the Earth during the Hadean Eon (of the order of 10^{24} g), the authors estimate that at least 10^{17} g of organic material would have been present in the surface environment by the time life eventually emerged. Furukawa *et al*. rule out the delivery of ready-made organics by carbonaceous chondrites, in which a great variety has been found. As well as their decomposition by the heat of entry, the lack of metallic iron in carbonaceous chondrites would promote oxidation rather than reduction of organic compounds preformed in early evolution of the Solar System.

The ancestral animal (*May 2009*)

The Cambrian Explosion of shell-bearing animals and the preceding, diverse and very odd Ediacaran fauna that left imprints and moulds in the Late Neoproterozoic both posed two puzzles for early palaeontologists. What organisms evolved so that unmistakable traces of animal life were able to leave fossils after about 600 Ma, and what pace did evolution take to present us with virtually all the animal phyla, including some not around nowadays, 'fully separated'? Molecular genetic studies of living animals are beginning to throw up some answers (Holmes, R. 2009. Spongebob the ancestor: The evolution of animals. *New Scientist*, v. **202** (2706), p. 38-41; DOI: 10.1016/S0262-4079(09)61203-3). It is a complex and growing field, so Bob Holmes' review of current ideas on the last common ancestor of the animals is welcome for non-specialists. It does look as though the radiation was long before the Ediacaran, but may well have been very rapid. The genetically closest single-celled organism to metazoan animals are the rare choanoflagellates; filter feeders with a collar-like structure and a tail. They bear some resemblance to the feeding cells of sponges, but sponges in their current form seem highly unlikely as the Ur-creature, totally lacking any organs and really just a coexistence of clone-like cells. Gene sequencing from 42 animal groups puts sponges at the bottom of a relatedness tree, yet at the bottom of two of the main branches. So the sponges do indeed seem to have it as our ultimate ancestors. Yet the flurry of ever-more detailed sequencing, for more and more groups using increasingly sophisticated statistical analysis has fired up controversy. Jellyfish-like ctenophores now have a look-in too, as do mysterious placozoans, according to one or other researcher. This field is throwing up an object lesson for hubristic scientists used to counting their chickens… No, the votes are never all in, and surprises always lie ahead for both the unwary and the patient.

Luckily, Holmes closes by looking at a careful proposal for the 'How'. Claus Nielson of the University of Copenhagen, a major 'player' in this field, has suggested how starting with a slab-like choanoflagellate, with all its function cells on the outside, might have evolved be curling to enclose a tube of inward facing cells; a precursor of a gut. One next step from there could be specialisation of some cells as nerves, then the development of a 'mouth' and 'anus' – the basis for the bilateral symmetry of all higher animals including ourselves. As for the 'When', there are sufficient leads from a molecular clock approach to settle on the oddest climatic events of the last 1.5 Ga of the Proterozoic, the near global glaciations or 'Snowball Earth' events that began around 750 Ma ago.

Photosynthesis from way back when: the hunt for RuBisCO (*May 2009*)

Charles Darwin had an abiding fascination with plants, though one that was essentially practical through observation and breeding. That is sufficient excuse in his bicentenary for reviews, but a good way to honour his legacy is again to push essays to the leading edge of present understanding (Leslie, M. 2009. On the origin of photosynthesis. *Science*, v. **323**, p. 1286-1287; DOI: 10.1126/science.323.5919.1286). Being able to convert sunlight, water and carbon dioxide to the basis of their own life and that of the rest of the planet, plants and other photosynthesising organisms are the fundamental essence of the living world. Land plants are recent developments, emerging in the Silurian around 425 Ma ago with presumed terrestrial spores some 50 Ma earlier. Their forbears were almost certainly marine algae. Yet they are highly evolved, and it is not to separate precursors that palaeobotanists can look for origins, but to the internal chloroplasts that look remarkable like cells in their own right with separate DNA and RNA. They perform the astonishing trick of breaking the extremely strong OH-H bonds that form the water molecule otherwise achieved either by extremely high temperatures or by electrolysis. The trick is for an organism to grab an electron thereby releasing the bond and both hydrogen and oxygen. The hydrogen links to carbon and oxygen from CO_2, and the other oxygen is freed. Similar to a magician's trick with smoke and mirrors, photosynthesis uses pigments. Colour in any object or material results from photons of one wavelength range in sunlight being absorbed so that those reflected make up the colour. The most familiar is chlorophyll which absorbs two wavelength ranges: the red and the blue regions to leave green to be reflected for us to see. It is actually a bit of quantum mechanics, as the absorbed photons carry the energy needed to stoke up that of electrons so that they can break free of the OH-H bond in water and split the molecule. The chain of organic chemistry which follows this trick is hugely complex, and it seems to have taken several forms reflected in specific genes in a growing array of photosynthesising bacteria of various genetic antiquities. There are green ones, blue ones, the reds, yellows and oranges.

Luckily the chemical remnants of photosynthesising bacteria are pretty robust, and also distinctive. The central one for most photosynthesising organisms is an enzyme that is complicated, called Ribulose-1,5-bisphosphate carboxylase/oxygenase, or RuBisCO for short. Euan Nisbet of Royal Holloway, University of London has been hunting RuBisCO for most of the latter part of his career as a Precambrian geologist. He and colleagues found relics of it in 2.7 Ga Archaean sediments from Zimbabwe and Canada (Nisbet, E.G. *et al*. 2007. The age of Rubisco: the evolution of oxygenic photosynthesis. *Geobiology*, v. **5**, p. 311-335; DOI: 10.1111/j.1472-4669.2007.00127.x) and claim there are far older signs. Needless to say.

A fluffy grazing dinosaur (*May 2009*)

Reconstruction of *Tianyulong confuciusi* (Credit: Wikipedia)

The Cretaceous of NE China is becoming a favoured destination for palaeobiologists interested in well-preserved vertebrates; little dinosaurs especially. An increasing number turned up by fossil hunters have skin relics covered in feathers, although they are rarely if at all equipped for flight, are. Recently, something even more bizarre was unearthed (Zheng, X.-T. *et al*. 2009. An Early Cretaceous heterodontosaurid dinosaur with filamentous integumentary structures. *Nature*, v. **458**, p. 333-336; DOI: 10.1038/nature07856). In plain-speak, *Tianyulong confuciusi* was fluffy as evidenced by red-coloured filaments on parts of the specimen. The heterodontosaurs were largely Jurassic herbivorous creatures, 70 Ma older than *T. confuciusi*; a good example of a 'living fossil' in its own time. They evolved to large Cretaceous herbivores, such as the famous duck-billed hadrosaurs, *Triceratops* and *Stegosaurus*, members of the Ornithischia as opposed to the more commonly carnivorous Saurischia. It was the latter that were widely believed to have been evolutionary branch from which birds sprang. There is a complex argument surrounding T. *Confucius,* based on which is a proposal that the ancestral dinosaurs were themselves fluffy. First, thoughts of brightly coloured 'monsters' and now the possibility that some may even have *looked* cuddly.

See also: Witmer, L.M. 2009. Fuzzy origins for feathers. *Nature*, v. **458**, p. 293-295; DOI: 10.1038/458293a.

Mantle link with biosphere (*July 2009*)

It is fairly clear that events in the deep Earth, which give rise to surface changes such as topographic uplift and increases or decreases in the pace of continental drift, feed into changes in the biosphere. A convincing example of that is the manner in which uplift of the flanks of the East African Rift System led to climate change that favoured bipedal apes. But is there a more direct link involving chemical influences?

The earliest autotrophic organisms may have performed a variety of chemical tricks in order to create energy and chemical conditions that moved matter back and forth through their cell walls. As well as photoautotrophs of different kinds, including those that release oxygen as waste, there would have been chemautotrophs, such as sulfate-sulfide reducers, methanogens and considerably more. Apparently, oxygenic photosynthesis was functioning almost 3500 Ma ago, long before the Great Oxidation Event, yet it was slow to make any impact on the atmosphere. In the Archaean oceans free oxygen would have been consumed by oxidation of soluble iron-II, probably creating banded iron formations. But photosynthesis has to take place in shallow sunlit water, so it might seem that it would have been easy for oxygen to enter the atmosphere. Since carbon dioxide in the atmosphere is unable to react with oxygen, oxygen build up in the air might be expected to have built far faster than it did. That is, unless there was a reducing gas present in sufficient amounts to consume oxidation. The most likely buffering agent holding back an oxygen-bearing atmosphere is methane produced by methanogen autotrophs, and it has been suggested that falling methane levels towards the end of the Archaean and start of the Proterozoic Aeons eventually permitted atmospheric oxygen to remain unreacted. Since very little methane is produced by inorganic processes, that hypothesis has a corollary; that there was a decline in methanogen Bacteria and Archaea. So, how might that be tested?

A cunning piece of lateral thinking presents a test, and suggests a mechanism linked to processes in the Late Archaean – Palaeoproterozoic mantle (Konhauser, K.O. and eight others 2009. Oceanic nickel depletion and a methanogen famine before the Great Oxidation Event. *Nature*, v. **458**, p. 750-753: DOI: 10.1038/nature07858). The first cunning bit comes from the biochemistry of modern methanogens: Methyl-coenzyme M reductase (MCR) catalyses the formation of methane from methyl-coenzyme M and coenzyme B in methanogenic Archaea. This enzyme contains the nickel-centred porphinoid F430 tightly bound in its structure. Needless to say, the olivine-rich mantle contains abundant nickel, so the greater the percentage of mantle partial melting, the more nickel enters the surface environment. Archaean stratigraphy, especially its earlier parts, contains abundant ultramafic lavas known as komatiites, associated with some of the world's big nickel mines. From the Late Archaean onwards, komatiites are rare rocks. The second master stroke by the authors is to find a means of charting the varying abundance in Archaean and Proterozoic seawater: they analysed the Ni content relative to that of Fe in banded iron formations. To as late as 2700 Ma the Ni/Fe ratio remains high in BIFs, but thereafter it falls sharply. That seems to support the hypothesis that a decline in the mass of methanogens did allow oxygen to build up in the atmosphere, and that decline reflected a fall in the supply of mantle nickel to the oceans. The next step would be to exploit the recently demonstrated ability of methanogen Archaea to fractionate nickel isotopes during their metabolism of dead organic matter. That would ideally be done using Ni-rich BIFs, as in this study.

Hadean not so hellish for life (*July 2009*)

Although the Earth's history before 4 Ga is not the mystery that it was, following the discovery of 4.3 Ga-old metasedimentary rocks in NE Canada (see At last, 4.0 Ga barrier broken in Planetary Science 2008), the early history of the Moon suggests that it was hectic and plagued by very large asteroid and comet impacts. The mightiest events occurred around 3.9 Ga, forming the huge mare basins on the Moon. Scaling up for the Earth's greater gravitational pull even larger catastrophes would have pounded our planet, although its turbulent tectonics has removed all tangible traces of them. From detailed studies of rocks and impact melts from the Moon – much of the lunar regolith comprises glass spherules produced by cratering over its entire history – the late heavy bombardment (LHB) was not prolonged in geological terms, lasting 20 to 200 Ma. Yet it involved the most extreme delivery of kinetic energy since the giant Moon-forming event around 2.45 Ga, which generated stupendous power – the rate of energy delivery by impactors moving at a minimum of 15 km s^{-1} is about a second. This has encouraged speculation that the Earth was effectively sterilised for a second time in its history. The 500-600 Ma of Hadean history may have witnessed emerging life forms of the most basic kind, only to see them wiped out, perhaps more than once. It has been assumed, therefore, that the earliest living things which left descendants, including us, had a universal ancestor that appeared only after 3.9 Ga. Now it seems a serious rethink is needed (Abramov, O. & Mojzis, S.J. 2009. Microbial habitability of the Hadean Earth during the late heavy bombardment. *Nature*, v. **459**, p. 419-422; DOI: 10.1038/nature08015).

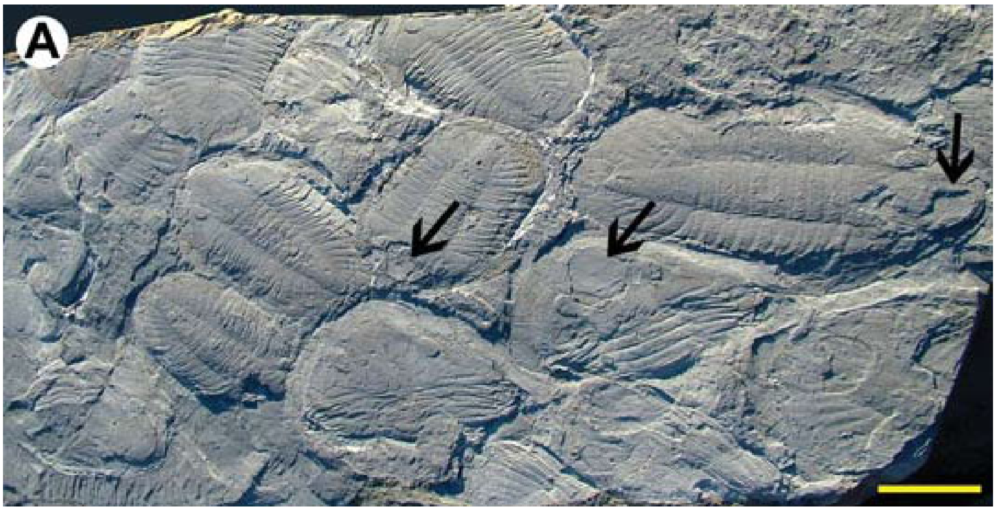
Feeding the impact data from the Moon and terrestrial planets into new modelling software run on a super-fast computer, Oleg Abramov and Stephen Mojzis of the University of Colorado have been able to assess the degree of thermal metamorphism that the Earth's crust may have undergone during the LHB. Interestingly, they reveal that less than 10% of the surface would have been heated above 500°C, and only 37% would have been sterilised, even if all the huge impacts predicted for Earth landed at the same time. Assuming that any basic life forms that had arisen in the Hadean were randomly distributed at the surface and in the subsurface – a variety of extremophile bacteria still live at depths down to 4 km – populations would survive to leave descendants. If they could survive temperatures up to 110ºC, which modern hyperthermophiles do, then so much the better for life as a whole.

Although based on modelling, the work by Abramov and Mozjis, gives palaeobiologists another half billion years in which inorganic processes could have assembled the immensely complex molecules the living processes demand. The earliest possible signs of life, based on carbon isotopes locked in stable minerals of a Greenland metasediment, date to 3.8 Ga. Previous assumptions about life's slate being wiped clean by the LHB therefore left only a few tens of million years for that assembly by some kind of thermodynamic miracle. The new vista will please Mike Russell of the University of Strathclyde in Glasgow. Russell is an economic geochemist turned palaeo-biochemist set on testing the Oparin-Haldane hypothesis of the origin of life using apparatus and approaches that are much more sophisticated than those used by Miller and Urey who created amino acids in vitro during the early 50s. The 21 May 2009 issue of *Nature* includes an account of Russell's plans and the views of those with a more cautious outlook (Whitfield, J. 2009. Nascence man. *Nature*, v. **459**, p. 316-319; DOI: 10.1038/459316a).

See also: Rothschild, L.J. 2009. Life battered but unbowed. *Nature*, v. **459**, p. 335-336; DOI: 10.1038/459335a.

Social behaviour among giant trilobites (*July 2009*)

There's something about a trilobite that causes outbreaks of hyperbole: as far as I know they are the only class of animals to warrant an exclamation in serious literature (Fortey, R. 2001. *Trilobite!* Flamingo). The title conjures a vision of a three-lobed, segmented alien hurtling for one's nether regions, hideous malice in its compound eye. Well, most trilobites were little, albeit with anorak-rending diversity in form and habit: they ranged from burrowing bottom feeders to inhabitants of the ocean meniscus – rather like early water boatmen. If you want to use an exclamation mark for an invertebrate, then it might be better to reserve it for the fearsome Eurypterids or sea scorpions. At up to 2 m, with mighty pincers and capable of galloping across a beach, they certainly would have best been avoided in the Ordovician to Permian. Yet, from time to time big trilobites do turn up, such as *Paradoxides, Ogyginus* and *Hunioides* that break the metre barrier.



Possible moult assembly of *Ogyginus forteyi* (Credit: Gutiérrez-Marco, J.C. *et al*; Fig. 3a)

Rather a lot of them have been found in a Portuguese lagerstätte of Middle Ordovician age (Gutiérrez-Marco, J.C. *et al*. 2009. Giant trilobites and trilobite clusters from the Ordovician of Portugal. *Geology*, v. **37**, p. 443-446; DOI: 10.1130/G25513A.1). They were up to something, as the locality described by Gutiérrez-Marco *et al*. contains huge numbers that were apparently having been overwhelmed by a sudden turbidity flow once they had gathered together. Some of them are in single file… It could be some sexual frenzy; fearfulness when moulting synchronously or something at which we cannot even guess. Whatever, it seems likely that the gigantism in the deposit is something to do with these being high-latitude animals.

What's green and lies above sea level? (*September 2009*)

Most geologists would answer, 'The continents after the start of the Silurian Period', but from now on they could be wrong. Evidence for an earlier 'greening' of the land comes from a detailed analysis of thousands of oxygen- and carbon-isotope measurements in Neoproterozoic carbonate rocks (Knauth, L.P. & Kennedy, M.J. 2009. The Neoproterozoic greening of the Earth. *Nature*, v. **460**, p. 728-732; DOI: 0.1038/nature0821). An important consideration in understanding the geochemistry of limestones is that however they originally formed as wet sediments at some later stage their constituents were largely transformed into crystalline aggregates by lithification through the intermediary of pore fluids. During lithification chemistry is equilibrated between crystals and the pore fluids, so if pore fluids are chemically (in this case isotopically) different from the sediment the resulting rock will have been changed isotopically. Studies of Cenozoic carbonates strongly suggest that the place where carbonate sediments are lithified most quickly is in coastal areas where terrestrial groundwater mixes with marine formation water in sediments. Since colonisation of the land by photosynthesising organisms groundwater C- and O-isotopes evolves in equilibrium with those organisms. The terrestrial biomass fixes ^{12}C preferentially thereby depleting their proportion of ^{13}C by up to 20‰. Groundwater, having originated as water vapour evaporated from the oceans that acts preferentially on ^{12}O is also depleted in ^{18}O. Consequently, low $\delta^{13}C$ and $\delta^{18}O$ signatures are passed on to groundwater and thence to carbonate rocks when groundwater participates in lithification.

Neoproterozoic carbonates plot in the same $\delta^{13}C$ vs $\delta^{18}O$ fields as those from the Phanerozoic. Earlier Precambrian carbonate data plotted in the same way show depletion in $\delta^{18}O$ but not in $\delta^{13}C$, which signifies no terrestrial life, but normal preferential evaporation of ^{16}O from the ocean surface to form rain and then groundwater. Knauth and Kennedy's results suggest a strong likelihood that carbonates of the late Precambrian were lithified by groundwater from a land surface where photosynthetic organisms were well-established and abundant. There is likely to be a sceptical backlash to this remarkable conclusion, largely because it seems that the terrestrial biomass in the Neoproterozoic would have needed to be of the same order as that in later times. Yet molecular evidence from modern fungi, lichens, liverworts and mosses suggests that they evolved in the Neoproterozoic and Chinese scientists have found traces of what look remarkably like lichens in the 600 Ma Doushantuo lagerstätte – fungus-like hyphae and cells that resemble those of cyanobacteria (see The earliest lichens May 2005). In an earlier paper, Martin Kennedy had noted that around 700 Ma, the record of marine limestones show increasing $^{87}Sr/^{86}Sr$ ratios, suggesting an increase in the chemical weathering of ancient continental rocks. That may have coincided with biological agencies helping break down bare rock chemically to swelling clays that show a surge in Neoproterozoic sedimentary sequences (see Clays and the rise of an oxygenated atmosphere in Sedimentology and stratigraphy 2006). The same paper pointed out that such clays increase the chances of preservation of buried organic matter, thereby boosting build-up of atmospheric and dissolved oxygen, as would terrestrial photosynthesisers. The feedback of increased oxygen to other eukaryotes that had evolved as heterotrophic animals would have enabled them to increase in size. Interestingly the earliest fossil animals occur in the same Chinese lagerstätte as the putative terrestrial photosynthesisers.

See also: Arthur, M.A. 2009. Carbonate rocks deconstructed. *Nature*, v. **460**, p.698-699; DOI: 10.1038/460698a. Hand, E. 2009. When Earth greened over. *Nature*, v. **460**, p.161; 10.1038/460161a.

Life originated as an oddity (*November 2009*)

Coming up with a theory for the origin of something so complex and ancient as life on Earth might seem to be at the pinnacle of hubris, yet such ideas are not uncommon. A novel slant on the 'Big Question' centres on how cells get their energy, rather than on trying to put together all manner of chemical prerequisites. Nick Lane summarises the ideas of Mike Russell – see *Hadean not so hellish for life* above (Lane, N. 2009. The cradle of life. *New Scientist* v. **204** (17 October 2009) p. 38-42). Mike Russell began his career as a geochemist looking at hydrothermal mineral deposits and the intricacies of their formation, while at the University of Strathclyde, Scotland. He now works at NASA-JPL in Pasadena, California inspired by the views of a self-funded eccentric Cornish farmer, Peter Mitchell. Cell energetics, according to Mitchell, are about pumping protons through cell membranes to effect the oxidation and reduction fundamentals of metabolism; in short electrochemical gradients. That is now recognised by every cell biologist, though once it was considered absurd. Russell's take on that novel truism is that the environment of life's origin must have involved similar processes taking place in the absence of living cells, which inherited proton pumping. His choice is mineralised pinnacles full of foam-like voids that can act as minute chemical factories: not the famous sulfidic black smokers of ocean ridge systems, but cooler features formed of carbonates precipitated from alkaline sea-floor hydrothermal vents. The carbonate foam in ancient examples, well-known to Russell from their mineralisation, contains bubbles lined with iron sulfides. Sulfides are known to have catalytic properties; proteins in living cells that convert CO_2 to sugars have Fe-S bonds at the core of their structure; alkaline hydrothermal vents emit hydrogen released by alteration of olivine in ocean-floor basalt to serpentine minerals; bubbles in carbonate foam look very like potential precursors to cells. To produce the first living cells, these features together in one enclosed space need 10 steps of quite simple chemistry. Except, that is, for nucleic acid production…

End-Permian crisis not so bad for ammonites (*November 2009*)

The greatest known mass extinction at the end of the Permian Period snuffed out 85% of marine species. It is widely understood to have taken at least five million years for ecosystems to begin recovering during the Early Triassic. Indeed, some animal groups remained depressed for longer still, especially those living at or near the sea floor. Yet one group of cephalopods, the ceratidid ammonites, almost immediately began to thrive, despite the ammonoid sub-Class having been among the hardest hit groups (Brayard, A. *et al*. 2009. Good genes and good luck: ammonoid diversity and the end-Permian mass extinction. *Science*, v. **325**, p. 1118-1121; DOI: 10.1126/science.1174638).

Triassic ammonite *Ceratites* (Credit: Fossilera.com)

Only three genera of ceratidids survived the cataclysm, but within 1-2 Ma there were almost 100 representatives. A similar swift recovery is shown by the completely unrelated conodont animals (now-extinct eel-like vertebrates whose teeth are generally the only parts to be fossilised). For such a success story to emerge by pure chance seems intuitively unlikely: for cephalopod equivalents of Lazarus to go forth and multiply so nicely requires genes well-suited to the conditions that followed the mass extinction.