Palaeontology, palaeobiology and evolution

Linking oxygen levels to great animal radiations (*January 2011*)

Probably the greatest ecological truism is that without oxygen there would be no life forms on Earth above the level of a restricted number of prokaryotes. Since around 2.4 Ga, when free atmospheric oxygen first appeared, levels have risen to the present 21% – it was probably as high as ~30% in the Carboniferous and Cretaceous Periods. Charting the rise has been difficult and the history of oxygen is written with a very broad brush. If there had been sudden increases in the availability of oxygen in the atmosphere and oceans there ought to have been a bursts of evolutionary radiation and diversity, but often oxygen-related causality for events such as the Cambrian Explosion have been speculative, as have cases for the inverse, declines due to downturns in oxygen levels (see Oxygen depletion before P-T extinction November 2003). Recently a proxy for the redox chemistry of the global ocean, and therefore for relative changes in atmospheric oxygen, has been developed. It is based on the abundance and isotopic composition of the element molybdenum (Mo) in sedimentary rocks: higher ^{98}Mo relative to ^{95}Mo (the $\delta^{98}Mo$ value) signifies higher oxygen levels. Its recent use in relation to evolutionary radiations (Dahl, T.W. *et al*. 2010. Devonian rise in atmospheric oxygen correlated to the radiations of terrestrial plants and large predatory fish. *Proceedings of the National Academy of the US*, v. **107**, p. 17911-17915; DOI: 10.1073/pnas.1011287107) has produced interesting results.

Devonian placoderm fish *Dunkleosteus*, which was up 6 m long (Credit: Wikipedia)

The US-Swedish-Danish-British team analysed the Mo in euxinic (reduced) marine black shales, which concentrate the element from seawater, in the Proterozoic and Phanerozoic Eons. Increases in $\delta^{98}Mo$ occur at the time of the Cambrian Explosion, as expected, and also during the Devonian. The latter correlates with increasing diversification of large fishes and among early terrestrial plants, and may have been the greatest leap in the bioavailability of oxygen in Earth's history, stemming from the 'greening' of the land. So far Mo-isotope data have not been obtained from Carboniferous, Permian or Cretaceous back shales, but the ratio of Mo to organic carbon content in black shales of those ages – a less constrained proxy – does confirm what has been suspected: highs (greater than present levels) in the Carboniferous and Cretaceous and lows during the Permian and Triassic. However, any hopes that the approach can be calibrated to actual oxygen levels seem likely to be optimistic as the controls over dissolved molybdenum supply to the oceans and its transfer to sediments are extremely complex.

Some of the team feature in a related article (Gill, B.C. *et al*. 2011. Geochemical evidence for widespread euxinia in the Later Cambrian ocean. *Nature*, v. **469**, p. 80-83; DOI: 10.1038/nature09700) that ticks all the geochemical boxes for the evolutionary effects of depleted oxygen; i.e. extinctions. They use new measurements of sulfur isotopes in conjunction with published carbon-isotope and other geochemical data from a wide range of Late Cambrian sediment types and environments in six well-known sections of that age. Spikes in the relative abundance of ^{34}S match those in ^{13}C along with a decrease in Mo in one section (see above), suggesting temporary increases in carbon and sulfide burial during periods of oxygen deficiency in the Late Cambrian ocean. Massive sequestration of organic carbon may have led to the extremely cold Late Cambrian climate, as described in *A chilly Late Cambrian* (this issue). Combined with changes in redox conditions associated with ocean anoxia this would have especially stressed animals, even on continental shelves had oxygen depleted water risen from the depths where sulfur and carbon burial were going on.

See also: Shields-Zhou, G. 2011. Toxic Cambrian oceans. *Nature*, v. **469**, p. 42-43; DOI: 10.1038/469042a.

Blood of the dinosaurs (*January 2011*)

Spoof image by Cliff Beckwith

Though it is highly likely that burial of fossils for millions of years destroys any trace of their DNA the massive bones of large creatures can preserve cell material. A near complete 67 Ma old *Tyrannosaurus rex*, fondly known as 'Big Mike' has revealed blood cells in thin sections of its bone (Schweitzer, M.H. 2010. Blood from stone. *Scientific American*, v. **303** (6), p. 38-45; DOI: 10.1038/scientificamerican1210-62). Her article also covers traces of blood vessels, and collagen of similar antiquity. The research involved positive reaction of antibodies against proteins, thereby proving the materials to be organic and not products of biomineralisation formed during the process of fossilisation. Potentially such forensic work can tease out relationships among animal groups whose fossils preserve organic materials, in a similar way to indications of the rise of prokaryote groups by biogeochemical marker molecules in carbonaceous shales. Indeed, sequences of fossil proteins from dinosaurs closely resemble that of modern birds. One of the great surprises of the late 20th century was the growing evidence that the stem-line for birds was dinosaurian, specifically the theropod group. This is nicely summarized by another review article (O'Donoghue, J. 2010. Flight of the living dead. *New Scientist*, v. **208** (2790), p. 36-40) that addresses the certainty of birds' evolution from dinosaurs; which of the fossils is bird, which feathered dinosaur and when did they separate; and why did birds survive the end-Cretaceous mass extinction while dinosaurs famously succumbed – probably a matter of breeding; its pace, that is. The two articles together suggest a fruitful way forward for palaeobiologists.

Further material about biochemical relics in fossils and methods used to detect and analyse them can be found in Hecht, J. 2011. Waking the dead. *New Scientist*, v. **209** (2796), p. 43-45.

Feeding habits of ammonites (*March 2011*)

Emerging in the Upper Palaeozoic and rapidly diversifying through the Mesozoic, thereby surviving over a period of 340 Ma, ammonites proved to be a stratigrapher's dream organism as well as being the most widely collected fossils. As well as their rapid evolution of form, they were able to spread widely though the oceans in larval form, through the jet propulsion they shared with other cephalopods and because they floated when dead and drifted with currents. Much of ammonite taxonomy has centred for almost two centuries on their external form: ribs; keels; knobbles; intricacy of the sutures separating each body chamber and the previous one; and whether or not their growing shell coils hid earlier parts or developed into an open spiral. These characteristics enables such a wealth of easily recognised genera and species that as zone fossils ammonites have been used to finely divide Mesozoic sediments; Jurassic ammonites locally divide the Jurassic (199 – 145 Ma) into time slices each of which represent just a few hundred thousand years.

The uncoiled ammonite Baculites used by Kruta *et al*. 2011. (Credit: Wikmedia)

What is least familiar to non-specialists is the feeding apparatus of ammonites and what they actually ate. Thanks to the use of high energy X-ray images it turns out that, unlike squid, octopuses and the similar looking modern *Nautilus*, some Cretaceous ammonites would not have been able to rip apart large prey (Kruta, I *et al*. 2011. The role of ammonites in the Mesozoic marine food web revealed by jaw preservation. *Science*, v. **331**, p. 70-72; DOI: 10.1126/science.1198793). Instead of a large beak-like process the ammonites studied sported a rasp-like radula, similar to that used on lettuce by the slug. The radula is armed with tiny but quite fearsome looking barbs, suitable for grating but not gnawing. The analysed ammonites may probably have eaten plankton. Indeed, one specimen turned out to have fragments of its last meal lodged in its radula; an isopod and a small gastropod. That diet tallies with the likely habitat of some ammonites; they were probably able to change their buoyancy by manipulating the gas and water content of their abandoned earlier body chambers to move up and down in the upper ocean. However, such was the stratigraphic duration, global spread and diversification of the ammonites, further studies of this kind would be needed to verify general plankton feeding. However, such a diet may well explain the conundrum of the total extinction of ammonites at the end of the Cretaceous while the superficially similar nautiloids survived and live today. The Cretaceous-Palaeocene (K-P formerly K-T) mass extinction devastated plankton, while larger marine organisms lived on to serve as nautiloids' prey.

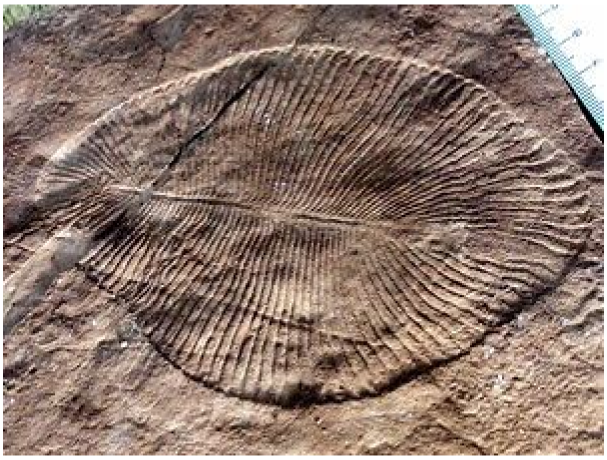
Coal and the end-Permian mass extinction (*March 2011*)

That somehow the massive Siberian Traps – the largest known continental flood basalts – had something to do with the mass extinction that coincides with the Permian/Triassic boundary is hardly contested these days. Yet what actually produced sufficient, planet-wide environmental stress to slaughter up to 90% of all previously living species has not been pinned down. Undoubtedly it was a combination of direct and indirect outcomes of the volcanic outpourings and several have been suggested, such as: acid rain produced by SO_2 emissions; global warming as a result of volcanic CO_2 having accumulated in the atmosphere; a marked fall in the oxygen content of the atmosphere (see *New twist for end-Permian extinctions* May 2005); increased phosphate fertilization of the oceans leading to anoxia and release of hydrogen sulfide gas. Interestingly, the part of Siberia where the basalt floods took place is rich in coal measures and organic-rich shales. Their thermal metamorphism by an overlying pile of lavas could conceivably have added huge amounts of CO_2 and methane to the atmosphere, creating strong greenhouse conditions: gas release from combustion and baking would have been almost instantaneous as each major flow came into contact with carbonaceous sediments. Yet direct evidence of widespread carbon combustion at the P/Tr boundary has not yet been demonstrated, although there are abundant gas-release structures in Siberia of around that age (Svenson, H. *et al*. 2009. Siberian gas venting and the end-Permian environmental crisis. *Earth and Planetary Science Letters*, v. **277**, p. 490-500; DOI: 10.1016/j.epsl.2008.11.015).

From a study of a near-continuous section of deep water marine sediments, whose ages range from Late Carboniferous to Cretaceous, something surprising has emerged. Silica-rich shales that span the P/Tr boundary show a major shift in $\delta^{13}C$ that matches the C-isotopic signature of the boundary elsewhere, and two lesser anomalies before the boundary event. At each C-isotope anomaly the shales also contain fly ash (Grasby, S.E. *et al*. 2011. Catastrophic dispersion of coal fly ash into oceans during the latest Permian extinction. *Nature Geoscience*, v. **4**, p. 104-107; DOI: 10.1038/ngeo1069), which forms today only in the rapid high-temperature combustion of coal in thermal power stations. It does not form from natural fires in underground and exposed coal seams that are caused by spontaneous combustion, usually ignited by rapid oxidation of pyrite in coal. The ash particles are smaller than 50 µm, and like similar sized, but denser, volcanic ash could easily be carried large distances. The Canadian team suggests that the fly ash formed when Siberian Trap basalts burned coals and organic-rich sediments, explosive release or explosive phases of the volcanism injecting them high in the atmosphere. Coal fly ash is not identifiable by normal microscopy, and its absence from the geological record may reflect that fact. Using organic petrography routinely on rocks from occurrences of the P/Tr and other boundary sequences should settle the matter.

Larging the Ediacaran (*March 2011*)

The biota dominated by large, indistinct and generally flabby creatures named together with the eponymous Period (635-542 Ma) from their type occurrence in late Neoproterozoic sediments of the Ediacara Hills of South Australia is made up of imprints of a strange bunch of organisms – bags; discs; donut-shapes and the enigmatic quilted organisms that likely subsisted by osmotically drawing nutrients from ocean water through their skins – together with others that have forms suggestive of extant groups – cnidarians (small predators related to modern jellyfish and coral polyps); bilaterian embryos; mollusc-like and segmented forms. The Avalon fauna of Newfoundland, discovered after those of Charnwood Forest, UK and the Ediacara Hills, added other life forms, including the fractal-like rangeomorphs from earlier (~579 Ma) times in the Ediacaran. Recently, the oldest known (630-551 Ma) members of the Ediacaran biota were presented by scientists from the Chinese Academy of Sciences, Virginia Tech in the U.S., and Northwest University in Xi'an, China (Yuan, X. *et al*. 2011. An early Ediacaran assemblage of macroscopic and morphologically differentiated eukaryotes. *Nature*, v. **470**, p. 390-393; DOI: 10.1038/nature09810).



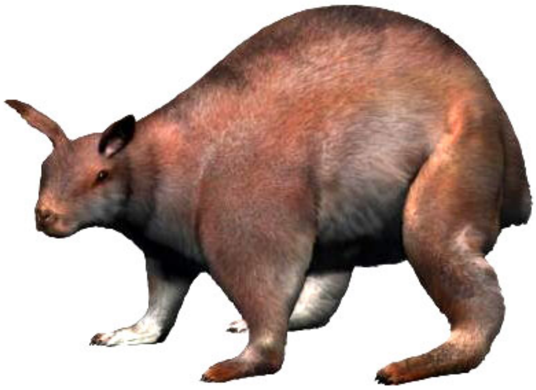
The distinctive Ediacaran fossil *Dickinsonia* (Credit: Wikimedia)

Unlike the better known organisms that were preserved against all odds in quite coarse sand- and siltstones, the host rocks in South China are a more familiar lagerstätten of black shales in which fossils take the form of carbonaceous films. These preserve considerable detail and are unlike the later Ediacaran organisms. There are: filamentous, fan-shapes forms with signs of seabed attachments; kelp-like forms consisting of ribbons; cone shapes; chains of rings and others with consisting of rooted cones and cylinders with finger-like protrusions from their wide ends. Most resemble marine algae (seaweeds), probably in their living positions, and they may represent sunlit shallow seabed habitats (the authors also suggest that some rare forms may be bilaterian worms and cnidarians). Dating of this Lantian assemblage stems from several ash beds and correlation of C-isotope anomalies with other Ediacaran sections.

From their age, the Lantian fossils are of organisms that evolved shortly after the Marinoan (635 Ma) 'Snowball Earth' episode, whereas the faunas of Newfoundland and Australia followed the less prominent Gaskiers glacial epoch (582 Ma). So they represent another evolutionary surge presaged by global ice cover and massive stress for all terrestrial life. If the Lantian organisms were algae, then photosynthesising eukaryotes may have been the first large multicelled organisms. All eukaryotes – autotrophs and heterotrophs – are obliged to live in oxygenated conditions, so at least shallow water after the Marinoan glacial event must have been such, although preservation of the Lantian fossils does indicate anoxic conditions during burial. The association of evolutionary bursts with two 'Snowball Earth' periods ought to point palaeobiologists to the sedimentary sequences that followed the earliest such event, the Sturtian (~720 Ma), which shows similar violent swings in C-isotopes that indicate surges and declines in burial of organic matter. So far only sponge-like fossils have been found from the Cryogenian Period of the Neoproterozoic that encompasses the Sturtian and Marinoan glacial episodes.

Some megafaunas of the recent past

Harvey was an imaginary, 2 m tall rabbit which befriended Elwood P. Dowd in Mary Chase's 1944 comedy of errors named after the said rabbit. Filmed in 1950 *Harvey* starred James Stewart as the affable though deranged Dowd. Though not so tall, a giant fossil rabbit (relative to modern rabbits) weighing it at 12 kg has emerged from the prolific Late Neogene cave deposits of Minorca (Quintana, J. *et* al. 2011. Nuralagus *rex*, gen. et sp. nov., an endemic insular giant rabbit from the Neogene of Minorca (Balearic Islands, Spain. *Journal of Vertebrate Paleontology*, v. **31**, p. 231-240; DOI: 10.1080/02724634.2011.550367). At about 3 times heavier than Barrington my lagomorphophagic (rabbit-eating to the uninitiated) cat, this would have been, to him, a beast best avoided, as the name *N. rex* might suggest. So unexpected was a gigantic rabbit that, interestingly, it was first mistaken for a fossil tortoise, albeit one lacking a carapace.



Reconstructed *Nuralagus rex*, the giant rabbit of Minorca (Credit: Wikimedia)

Island faunas have long been recognized as havens for peculiar trends in evolutionary successions, either towards dwarfism as in the case of the tiny elephants of the Indonesian island of Flores, on which *H. floresiensis* preyed, or gigantism as in this remarkable case. As the authors infer, this was a rabbit which sadly could not hop. Its un-rabbit-like locomotion may well have been a result of it not having *needed* to hop, being so large as to challenge seriously the largest Neogene predators on the island – lizards – and thereby saving energy. For much the same evolutionary logic, neither did *N. rex* have long ears, having less need to detect a stealthy nemesis.

The demise of Late Neogene megafaunas has often been ascribed in general to human intervention. Though *N. rex* became extinct at around 3 Ma and thus avoided human predation, later giants did not fare so well. A case in point is the celebrated wooly mammoth, the last of the steppe mammoths, that first appeared in the fossil record of Siberia around 750 ka ago (Nicholls H. 2011. Mammoth mystery: Why giants no longer rule the north. *New Scientist*, v. **209** (26 March 2011), p. 54-57). DNA evidence from hairs preserved in permafrost suggests that ancestors of the steppe mammoth line diverged with that of Asian elephants from African elephant ancestors around 5 Ma. Interestingly, ancestral steppe mammoths – without shaggy coats but having the archetypical curved tusks – roamed Africa until 3 Ma when they disappear to reappear in Europe and Asia, yet without adaptation to cold until the onset of northern glaciations around 2.5 Ma. At that point the true steppe mammoths evolved increased tooth enamel needed for a diet of mainly silica-rich grasses to resist wear. The family spread to North America when sea-level fell to expose the sea floor of the Bering Straits. The woolly mammoth is the star partly because specimens periodically turn up almost perfectly preserved in permafrost. This has allowed almost half of a full DNA sequence to be restored. Preserved haemoglobin from a woolly mammoth shares with that from modern musk oxen an ability to release oxygen at temperatures well below zero so that they could function even if their extremities became chilled.

Astonishingly, all elephants urinate so copiously that they soak their range lands in DNA, though it only lingers in ultra cold climes. This bizarre fact encouraged a large team of palaeobiologists to comb frozen soils in an alluvium section in Arctic Alaska for mammoth DNA (Haile, J and 17 others, 2009. Ancient DNA reveals late survival of mammoth and horse in interior Alaska. *Proceedings of the National Academy of Sciences of the USA*, v. **106**, p. 22352–22357; DOI: 10.1073/pnas.0912510106). Mammoth DNA turned up in soils as young as 10.5 ka. Moreover mammoth overlapped with human occupation for several millennia, casting doubt on theories that mammoth extinction resulted either from human predation or the introduction of epidemic disease that might have felled mammoths quickly: they declined gradually. Yet the empirical fact that steppe mammoths in general and the woolly mammoth in particular survived through at least 8 major glacial-interglacial transitions only to become extinct at the start of the current Holocene interglacial period at the same time as humans recolonised the frigid desert of Arctic latitudes, where woolly mammoths could survive except at the last glacial maximum surely points to some influence that arose from human activity.

Antarctic analogue for alien life?

The full 'Snowball Earth' model for episodes in the Neoproterozoic that left glaciogenic sediments at near-equatorial palaeolatitudes implies that the oceans were frozen over globally. An objection to that is the likelihood that all photosynthetic activity would have been shut down leading to near catastrophe for all life forms of the time, except those based on chemoautotrophic metabolism, as around hydrothermal vents. Antarctica has around 140 lakes that have been frozen over for at least hundreds of thousands if not millions of years, the best known being Lake Vostok, deep within the continent, that Russian scientists are on the verge of tapping after drilling through more than 3 km of glacial ice. Who knows what they might find? Far less extreme, but also having perennial ice cover, is Lake Untersee close to the coast in East Antarctica. Its summer ice cover is 3 m thick and it is presumed to have remained icebound through previous interglacials, although it is fed by meltwater from a nearby glacier in summer. It is not filled with fresh water, however, having a pH up to 12.1, around that of household bleach. It also has very high oxygen content, in fact supersaturated at 50% more than the solubility expected at 0°C. Lake Untersee would be expected to have little life, being an extremely hostile environment. Nonetheless, it does boast a biome and sufficient light gets through the ice cover to support microbial mats of photosynthesising blue-green bacteria (Andersen, D.T. *et al*. 2011. Discovery of large conical stromatolites in Lake Untersee, Antarctica. *Geobiology*, v. **9**, p. 280–293; DOI: 10.1111/j.1472-4669.2011.00279.x).

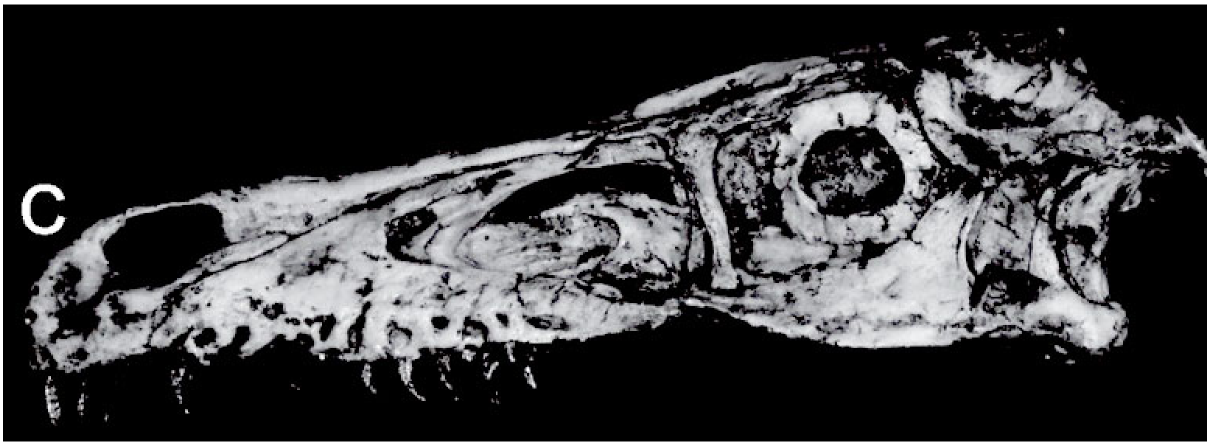
Stromatolitic microbial mats beneath Lake Untersee. (Credit: Andersen *et al*. 2011; Fig. 5)

As well as perhaps helping elevate the oxygen levels in the lake water, these organisms have secreted stromatolite-like cones, pinnacles and mounds, but not ones made of carbonate. Although the water contains plenty of calcium ions, there is insufficient carbon as CO_3 or HCO_3 ions for calcite to be precipitated. The carbon-poor nature of the water seems to confirm its long-term isolation from the atmosphere. Instead, the stromatolites are made of laminated clay, maybe derived by exceedingly slow breakdown of feldspars that would also yield calcium and hydroxyl ions to explain the waters peculiar chemistry. The different shapes of stromatolites are linked to different cyanobacterial communities, which may help explain morphological variations among fossil stromatolites.

The lead author is from the SETI Institute in California, and presumably visited Lake Untersee in the cause of exobiology, as reported in other commentaries on the paper. However, the peculiarities of the lake and its life seem to be just that, with little relevance to frigid sedimentation in the distant past apart from a possible explanation for varying shapes of fossil stromatolites. Nor is the lake sterilised by virtue of perennial ice cover. Being fed by glacial melting it has received rock flour that has broken down to clays, and that implies meltwater carries other materials from the ice cap. Even Antarctica is not isolated from wind-blown dust, so cyanobacteria may have been introduced by sturdy, wind-borne spores being incorporated in the ice cap, eventually to end up in Lake Untersee. It seems that the lead author actually dived in the lake, which puts the fears of contamination by careful drilling into Lake Vostok into perspective. How such an environment links to notions of life elsewhere in the universe is hard to see.

Wide-eyed dinosaurs (*July 2011*)

One of the surprises concerning the dinosaurs was that some species were able to live at near-polar latitudes. The surprise is not about their ability to survive a cold climate, for the Cretaceous world was one characterised by greenhouse conditions and ice-free polar regions swathed in forests. On top of that, evidence is accumulating that some dinosaurs at least were able to regulate their body temperature; they may have been warm-blooded. The oddity is that they were able to survive the winter darkness of latitudes above those of the Arctic and Antarctic Circles. It now seems that some groups of dinosaurs evolved excellent night-time vision (Schmitz, L. & Motani, R. 2011. Nocturnality in dinosaurs inferred from scleral ring and orbit morphology. *Science*, v. **332**, p. 705-708; DOI: 10.1126/science.1200043).



Velociraptor's large scleral ring suggests that it was a night-time predator. Credit: Schmitz& Motani 2011; Fig. 2c)

Not only did some have large eyes, but preservation of the fibrous outer ring of the eye or sclera – the 'whites' in our case – in some large-eyed dinosaurs shows a reduction in width that is characteristic of good scotopic or night vision. Since much of the polar 'night' is more like twilight than perpetually full darkness, enhanced night vision would have allowed high-latitude dinosaurs to survive winter by crepuscular feeding habits. This more or less extinguishes the notional day-night duality of terrestrial vertebrate life during the Mesozoic; dinosaurs by day and early mammals by night that allowed mammalian ancestors to escape the clutches of dinosaur predators. Indeed many Mesozoic mammals show signs of diurnality.

Eukaryote conquest of the continents (*July 2011*)

Geologists often assume that the continents were first colonised by plants, then insects and finally vertebrates, beginning in the Ordovician Period with preservation of spores very like those of the liverworts. Incidentally, those weeds can only be removed from gravel driveways by the use of hydrochloric acid; glyphosate, pycloram and flamethrowers have no lasting effect. The most intractable of all organisms found on the land surface today are prokaryotic (nucleus-free cells) cyanobacteria whose biofilms cement desert varnish (see *Desert varnish*, Remote sensing May 2008). Cyanobacteria are suspected to have been the first life forms to adopt a terrestrial habit, and their cells have been discovered in the now-famous Neoproterozoic lagerstätten in the Doushantuo Formation of China (see *The earliest lichens*, May 2005). The oldest un-metamorphosed sediments in Britain, the Torridonian redbeds that help to form the magnificent scenery of north-western Scotland, now push back the date of the earliest eukaryotic (cells with nuclei) terrestrial life half a billion years before the Doushanto cyanobacteria (Strother, P.K. *et al.* 2011. Earth's earliest non-marine eukaryotes. *Nature*, v. **473**, p. 505-509; DOI: 10.1038/nature09943).

The Torridonian is one of the thickest (~12 km) terrestrial sequences on the planet, and spans a time range of around 200 Ma (1.2 to 1 Ga). It is a repository of almost the entire range of humid continental sedimentary environments: colluvial fan; bajada; alluvial; deltaic and lacustrine build-ups. Grey lake-bed mudstones and phosphate nodules in the Torridonian yield small organic fossils lumped in the sack-term acritarchs. Similar bodies, whose affinities are diverse and generally obscure, have been reported from marine sediments as old as 3.2 Ga. The fascination of those from the Torridonian, other than their terrestrial association, is that some include aggregates of spherical cells with tantalising suggestions of central nuclei and, as a whole assemblage, exhibit a range of morphologies far beyond that of nucleus-free prokaryotes and the signature of cytoskeletal filaments that form a 'scaffold' for eukaryote cells. Worth noting is that one of the authors is Martin Brasier of Oxford University, whose meticulous bio-morphological skills in microscopy has made him one of the foremost critics of speculation on Precambrian microfossils (see *Doubt cast on earliest bacterial fossils* April 2003). The authors opine that the ecological diversity of freshwater and land systems, and the physico-chemical stress associated with repeated wetting and desiccation compared with the marine domain may have been instrumental in origination of the Eucarya, which should give the Torridonian a scientific reputation that extends beyond these shores.

Earliest animals from continental environments (*July 2011*)

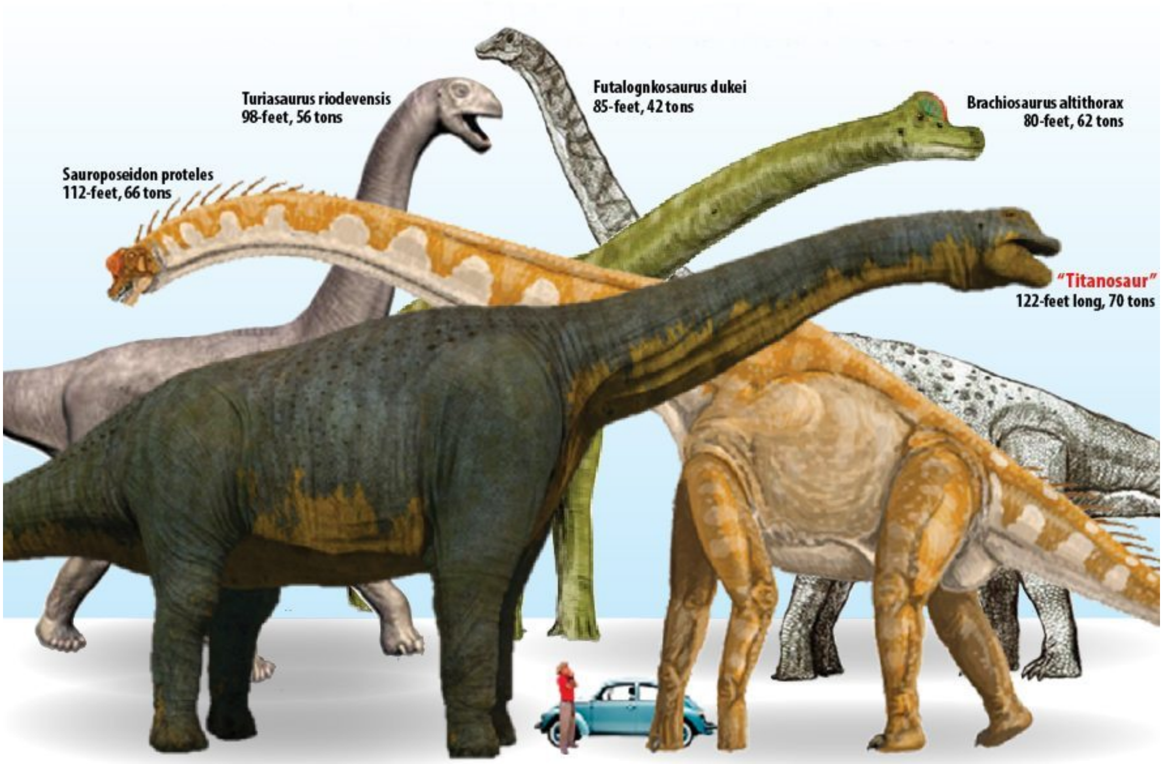
Following closely on discovery in 1 Ga old sediments of the earliest evidence for eukaryote life in continental environments (see *Eukaryote conquest of the continents* above) it seems that metazoan animals colonised non-marine environments earlier than had previously been thought. Up to now most palaeontologists believed that there was a lag of at least 80 Ma between the emergence of marine bilaterian metazoans and their expansion into freshwater, due to a number of physiological hurdles that had to be overcome, such as regulation of trace element chemistry within their cells and bodily fluids. It has been known for more than a century that the first signs of sturdy animals in the marine realm are burrows in tidal sediments that formed more or less at the Cambrian-Precambrian boundary; the earlier sac-like Ediacaran fauna seemed ill-suited to a burrowing or infaunal habitat. A considerable thickness of clastic sediments occur in the Cambrian of eastern California, USA. The earliest are clearly shallow-marine and contain abundant evidence of burrowing. Succeeding them are intensively studied fluviatile sands and silts that have been used a model for sedimentation in the absence of the stabilising influence of land plants. What has been overlooked until recently is evidence for burrowing animals that colonised the river-laid deposits (Kennedy, M.J. & Droser, M.L. 2011. Early Cambrian metazoans in fluvial environments, evidence of the non-marine Cambrian radiation. *Geology*, v. **39**, p. 583-586; DOI: 10.1130/G32737C.1).

Psammichnites from the basal Cambrian of northern Norway (Credit: A. Högström)

The burrows include the vertical U-shaped forms given the name *Arenicolites*, which is the most common trace fossil, simple vertical tubes (*Skolithus*) and horizontal, meandering tubes with furrowed sides (*Psammichnites*). Anyone who has seen the Early Cambrian Pipe Rock of NW Scotland will also have seen these trace fossils, yet the Pipe Rock shows evidence of tidal deposition and is shallow marine. Their non-marine equivalents in California are coeval with the earliest known trilobites in the Cambrian marine sequence. It seems that whatever the burrowing animals were, they easily overcame any physiological or environmental barriers to adopting a life in freshwater, encouraged by the ready sustenance that terrestrially adapted acritarchs and cyanobacteria had provided for half a billion years previously.

From small beginnings (*September 2011*)

The great vegetarian sauropod dinosaurs, such as *Brachiosaurus*, were the biggest animals to walk the Earth, weighing up to 100 tonnes, as long as 60 m from snout to the end of their tails and more than 10 m tall. So big, indeed, that even the largest contemporary predators would have been unable to get sufficient purchase with their jaws to do them much damage. This vast bulk, unlike even bigger modern whales, was unsupported by water and would have posed major problems had the sauropods not evolved very porous, low-density neck and tail bones and kept their heads small relative to the rest of their bodies. Such small heads needed to take in up to a metric ton of vegetation each day to keep the monsters ambling along. Their teeth are not those of a chewer, being peg- or spoon-like and pointed forwards; specialised for raking in leaves and twigs, swallowed unchewed in great gulps. Once that style of eating developed in their precursors, with no need for massive chewing muscles it became possible to evolve necks up to 15 m long with increasingly diminutive heads. Studies of large numbers of some species of sauropod precursors indicate that juveniles grew astonishingly quickly, essential if their initial vulnerability was to be outpaced; newly hatched they would have weighed little more than 10 kg. At the growth rates of modern reptiles, the largest sauropods would only have reached full size in about a century. The estimated growth rates suggest warm bloodedness, research suggesting that they maintained body temperatures up to 12°C higher than do alligators. Clearly, sauropod dinosaurs were highly specialised, and their evolution is now known to have been lengthy.



A selection of titanosaurs with an antique Volkswagen for scale (Credit: Dr Neurosaurus)

A major news feature in *Nature* (Heeren, F. 201. Rise of the titans. *Nature*, v. **475**, p. 159-161; DOI: 10.1038/475159a) traces that evolution through several surprising stages. The earliest likely ancestors, which appear in the Late Triassic (~230 Ma), were about the size of a turkey and had teeth adapted for shredding fibrous plant material; other early dinosaurs show clear signs of a predatory lifestyle. There is a limit to the size of predators bound up with the energy balance between flesh consumption and the energy expended in casing down prey and killing them. The limits on the size of plant eaters are mechanical: how much they can stuff in and the strength of their bodies, especially legs. In a world dominated in numbers by predatory dinosaurs, the selection pressure for herbivores to outgrow them and become too big to bite would have been substantial.

Little Triassic *Panphagia* ('eater of everything') was also bipedal, but the fossil record of sauropod precursors clearly shows their growth to the order of 10 m by the Early Jurassic, but not yet a four-legged gait though they had evolved relatively short but sturdy legs, signs of mass-saving porous neck and tail bones, and jaws with a large gape suited to gulping rather than chewing. By the mid-Jurassic Period sauropods were big, strong and four-legged, and by the Cretaceous they reached unmatched dimensions with the titanosaurs. This evolutionary path was not the only one adopted for dinosaurian herbivory. The famous *Iguanodon* discovered in 1822 by Gideon Mantell in the Early Cretaceous of Sussex was a member of a bipedal group of herbivores, including the duck-billed dinosaurs, that spanned more or less the same time range as sauropods.

Feathers will fly: *Archaeopteryx* relegated (*September 2011)*

This year marks the 150th anniversary of the first *Archaeopteryx* specimen being unearthed from the famous Solnhofen lagerstätte. With its feathered, lizard-like tail; two-clawed, stubby wings; a bill-shaped muzzle with teeth but no keratin coating; feet capable of perching and unlike those of small dinosaurs; a 'wishbone' and lightweight bones, *Archaeopteryx* was just the half-and-half missing link in the fossil record so desperately needed to support Darwin's *Origin of Species*, published two years beforehand. It has remained controversial ever since, even having been claimed to be a forgery by such luminaries as cosmologist Fred Hoyle in 1985, despite its superbly preserved intricacies and the existence at the time of 6 slightly different specimens from the same source some discovered long after Hoyle's supposed master craftsman must have died. Creationists soon after the first discovery claimed it was simply a bird created on a Friday together with fish (*Genesis 1:20*) and must have predated dinosaurs by a day, as they were created on the 6th Day along with all the 'cattle and creeping thing and beast of the earth' (*Genesis 1:24-31*). That scurrilous sect will certainly leap gleefully on the new discovery of a feathered dinosaur from the ever-productive Late Jurassic Tiaojishan Formation in NE China (Xu, X. *et al*. 2011. An *Archaeopteryx* -like theropod from China and the origin of the Avialae. *Nature,* v. **475**, p.

465-470; 10.1038/nature10288) ironically because, by itself, it could be said to be a missing link too.

In fact, *Xiaotingia zhengi* possesses features very like those displayed by *Archaeopteryx* but convincingly close affinities to deinonychosaurian dinosaurs. The close affinities show that neither is a bird (Avialae) and nor are they part of the clade that evolved to birds: they are part of the growing group of feathered dinosaurs that may well have glided or even flown. As Lawrence Witmer of Ohio University has observed (Witmer, L.M. 2011. An icon knocked off its perch. *Nature,* v. **475**, p. 458-459; DOI: 10.1038/475458a), 'This finding is likely to be met with considerable controversy (if not outright horror)...'. However, Witmer still considers *Archaeopteryx* to have iconic status, indeed yet more, for its taxonomy and that of its related feathery dinosaurs provides compelling evidence that the origin and evolution of life was a 'rather messy affair'. Undoubtedly, more feathered creatures hundreds of million years old will be unearthed; it is even possible that further finds will push the beast of Solnhofen back onto its avian perch. Let the celebrations begin!

Life at the cathode (*September 2011*)

Since free oxygen gradually permeated from its initial build up in the atmosphere to the ocean depths, the Earth has been likened to a massive self-charging battery. It has an interior that is dominated by reducing conditions and oxidising surface environments. Electrons flow continually as a consequence of the nature of the linked oxidation-reduction: in terms of electrons, oxidation involves loss while reduction involves gain (the OILRIG mnemonic). Although there are natural electrical currents, most of the electron flow is in the form of reduced compounds rich in electrons that make their way through the flow of fluids from the deep Earth – effectively an anode – towards the surface where the reduced compounds lose electrons to create the equivalent of a cathode. Reduction-oxidation (redox) is therefore a power source. Inorganic reactions, such as the precipitation on the sea floor of sulfides from hydrothermal fluids at 'black smokers' dissipate energy. Yet the power also has considerable potential for organic life.

Black smoker and deep-sea tube worms

Some bacteria oxidise hydrogen sulfide carried by hydrothermal fluids and others do the same to upwelling methane. In 1977 a teeming biome of worms, molluscs and higher animals was discovered in a totally dark environment around ocean-floor vents. It soon became clear that it could only subsist on chemical energy of this kind, rather than any form of photosynthesis. The key to some metazoans' success had to be symbiosis with bacteria that could perform the chemical tricks possible in the cathode region of the Earth's electron flow. There are several candidate compounds: H_2S, CH_4, NH_4, metal ions and even hydrogen gas. As hydrothermal fluids cycle ocean water into the basaltic crust and underlying peridotite mantle, they not only hydrate the olivines and pyroxenes that dominate the oceanic lithosphere but trigger other reactions one of whose products is hydrogen. As well as a reaction being eyed by those keen on a cheap source of clean fuel, hydrogen generates more energy potential for biological metabolism than those which form other common compounds in the returning fluids. Although the nature of hydrogen's organic use has been elusive, it has now come to light in a surprising guise (Petersen, J.M. and 14 others 2011. Hydrogen is an energy source for hydrothermal vent symbioses. *Nature*, v. **476**, p. 176-180; DOI: 10.1038/nature10325).

One highly successful animal in ocean-floor hot spring systems is a mussel called *Bathymodiolus*. Genetic experiments by the German-French-US team revealed that a gene known as *hupL* is present in the mussels' gill tissue. This gene is also found in bacteria that use either carbon monoxide or hydrogen as an electron donor. The *hupL* gene encodes for enzymes known as hydrogenases that are needed to set off the reaction $H_2 = 2H^+ + 2e^-$ that provides electrons needed in bacterial metabolism; a sort of living fuel cell. Hydrogen-using bacteria interact symbiotically with the mussels, which would otherwise be unable to live in the pitch black environment. Genomic sequencing of tube worms and shrimps that occur in the vent communities also contain the bacterial *hupL* gene. Hydrogenase enzymes are proteins with an iron-nickel core, and probably evolved far back in bacterial evolution around metal-rich hot springs. Interesting as the specific detail of hydrogen-based symbiosis is, the general concept of Earth's redox systems' having battery-like behaviour is very useful.

On land groundwater sometimes comes into contact with sulfide ore bodies that are oxidised to yield hydrogen and sulfate ions, while the groundwater is reduced: a battery comes into being with a cathode in the aerated groundwater and electrons flow. Such currents are useful in revealing hidden orebodies using the 'self-potential' or SP method. Indeed the downward change from oxidising to reducing groundwater, caused by the redox reactions involved in weathering and soil formation also result in weak negative and positive 'electrodes' with a sluggish flow of compounds that bacteria can exploit and thereby encourage metazoan life through symbiosis. In doing so, changes in redox conditions affect the inorganic load of the slowly moving groundwater so that reduced metal ions can be precipitated once they rise into the oxidising horizon. The general enrichment of the upper horizons of soils in iron oxides and hydroxides, and metal depletion in lower horizons probably stem from the 'Earth battery' produced by an interplay between inorganic and organic redox reactions. Be on the look-out for more on this topic as the quest for hydrogen fuels becomes more urgent. A former colleague, Gordon Stanger, investigating groundwater in the Semail ophiolite of the Oman for his PhD in the 1970s discovered to his surprise that in outcrops of the mantle sequence there were springs from which hydrogen bubbled freely: fortunately he was not a smoker...