Fungal clue to fate of North American megafauna (January 2010)

More than 30 large mammal species, including elephants and giant sloths, that had roamed North America during the Pleistocene met their end between 13 and 11.5 ka. Whether or not predation by newly arrived humans caused these extinctions remains unresolved, as are the triggers for coinciding changes in plant communities and evidence for increased burning of biomass. While the ages of fossil bones are direct evidence for species being present, they are not found everywhere that a megafauna likely lived and occurrences are patchy in time. There is however a proxy for the presence or absence of large herbivores: spores of fungus that thrived on their dung (Gill, J.L. et al. 2009. Pleistocene megafaunal collapse, novel plant communities, and enhanced fire regimes in North America. Science, v. 326, p. 1100-1103; DOI: 10.1126/science.1179504). Sporormiella can only complete its life cycle after herbivores have digested plant matter. So its spores in sediment cores form an impressive link to the local presence of herds. In a lake core from New York State such fungal spores, having been much more abundant beforehand, fell to less than 2% of all spores and pollen about 13.7 thousand years ago. This suggests that large herbivores vanished from this area at that time. Interestingly, the timing is during a warm period (the Bølling-Allerød) rather than the stress of the Younger Dryas glacial re-advance. Moreover, the local disappearance predates the first signs of Clovis people, although there is evidence for earlier human colonisers back to 15 ka. It is possible that it was the disappearance of large herbivores that allowed the development of extensive mixed coniferous-deciduous woodland, broad-leaved trees having perhaps been browsed severely by earlier herbivores.

Evolution of first land vertebrates in disarray (March 2010)

The finding of Tiktaalik, a supposed ‘missing link’ between bony fishes and amphibians (see A fish-quadruped missing link May 2006) seemed nicely to resolve the descent of tetrapods. As is common, if inconvenient, nature has thrown a spanner in the works through a remarkable find in Polish rocks much older than those containing Tiktaalik and more evolved tetrapods (Niedźwiedziński, G. et al. 2010. Tetrapod trackways from the early Middle Devonian period of Poland. Nature, v. 463, p. 43-48; DOI: 10.1038/nature08623). Quarrymen unearthed extensive tracks appeared during excavation of intertidal limestones of the Middle Devonian Eifelian Stage (392-398 Ma). The bedding surface also shows raindrop pits and desiccation cracks, so the tracks were made by creatures able to survive out of water. The prints (up to 26 cm wide) are three times bigger than the paws of later amphibians that left fossil remains, but like them they show signs of more than 5 toes. The maker of one trackway was a good walker, having left no trace of dragging its belly through the mud, and it either had no tail or carried it aloft since there is no trail left by a tail either. Another, smaller animal left a separate trackway showing a very different gait. There seems little doubt that these animals were well advanced towards completely terrestrial lifestyles. Tiktaalik from 380 Ma sediments in Arctic Canada obviously cannot have been ancestral to them, and nor are there any fossils from the Middle Devonian that look like candidates. The
hunt is on for fossilised remains of whatever walked the walk, and may emerge in the not-too-distant future from subtidal sediments of the same formation.

Mid-Devonian tetrapod prints and stride pattern. (Credit: Niedźwiedski et al. 2010; Fig. 2)


‘Roger, I think that triffid just moved’ (March 2010)

The nasty surprise awaiting the bulk of the human population blinded by radiation from a meteor shower in John Wyndham’s Day of the Triffids was that the genetically engineered, oil-yielding triffid plants could not only deal out deadly stings but they walked and ate dead meat. So it is that palaeontologists have found with the flabby, quilted bag-like organisms of the late Neoproterozoic Ediacaran fauna. They were animals of some kind, but hitherto considered to be completely sessile, except in larval form. They seem not to have been able to bite or gnaw, but probably absorbed nutrients through their skins. Imagine the shock when palaeontologists from Oxford and Memorial University of Newfoundland found trackways in the famous biome of Mistaken Point in Newfoundland (Liu, A.G. et al. 2010. First evidence for locomotion in the Ediacaran biota from the 565 Ma Mistaken Point Formation, Newfoundland. Geology, v. 38, p. 123-126; DOI: 10.1130/G30368.1).

This throws an entirely new light on the very first sizeable animals: some of them were muscular. But not very adventurous, for the trails are only up to 17.2 cm long. Several of the traces show curved ridges, much like though far smaller than those left in wet sand by a buttock-shuffling baby, but ascribed by the authors to use of an ‘inflatable pedal disk’ in the manner of some cnidarians today. The things must have had a purpose in moving, and chasing down prey springs easily to mind, only to be swiftly rejected. Alarmingly, at least for their totally torpid companions, some of the trackways clearly end in a depression: did they lie in wait? Yet not a one shows the telltale three-fold pedestal symmetry of triffids...
Believable Archaean fossils (March 2010)

Some years back a major spat broke out over the reality of microscopic features purported to be evidence for bacterial life in 3.5 Ga rocks from Western Australia (See Doubt cast on earliest bacterial fossils April 2002), which has rumbled on ever since among groups of palaeontologists. Those who refuted those finds as merely mineralogical structures that just seem to look biogenic have more work pending. Much more convincing evidence has been found in 3.2 Ga cherty rocks from South Africa (Javaux, E.J. et al. 2010. Organic-walled microfossils in 3.2-billion-year-old shallow marine siliciclastic deposits. Nature, v. 463, p. 934-938; DOI: 10.1038/nature08793). By microfossil standards they are big, 3-dimensional structures up to a third of a millimetre across, and clearly resemble cells. Some have even been separated from their matrices by dissolving away silica with hydrofluoric acid, so are not merely figments of the authors’ imagination. They are carbonaceous with very negative δ\(^{13}\)C values typical of organically processed carbon and show abundant evidence of intricate structures found in living cells. Raman infrared spectroscopy also shows that they have been metamorphosed at the same grade as the rock that host them, so they cannot be later contaminants. In all these respects the little spherules are a cut above previously described structures reckoned to have been early Archaean life forms, convincingly taking concrete evidence for the existence of living things back a remarkable billion years: the previous oldest true fossils are about 2.2 billion years old.

In one respect the find may be truly breathtaking. Spherules this size cannot be from the life-domain Archaea, and at the very least they are particularly large cells of Bacteria. Yet, bacterial cells contain little that could produce such robust little objects, which resemble single-celled eukaryotes known as acritarchs. The earliest definite acritarchs data back to 1.8 Ga. Geochemical evidence for eukaryotes was not sought in the spherules, but there has been speculation that some Archaean rocks have yielded chemical biomarkers that point to the presence of the ancestors of multicelled life at an astonishingly early date in Earth’s history. Clearly Javaux and colleagues work is a precursor of a lot more, now that we have hard-to-refute evidence for 3.2 Ga life.

A vicious ginger dinosaur (March 2010)

The Early Cretaceous of SE China is a regular supply of superbly preserved small dinosaurs and early birds believed to have had a dinosaurian ancestry in the Jurassic. We have become accustomed to seeing computer generated graphics of brightly coloured dinosaurs since the BBC series Walking with Dinosaurs, first broadcast in 1999, but they owe more to imaginative assumptions based on strongly patterned living lizards than to fossil evidence. That is set to change, with the discovery of actual colouring agents in a Chinese find (Zhang et al. 2010. Fossilized melanosomes and the colour of Cretaceous dinosaurs and birds. Nature, v. 463, p. 1075-1078; DOI: 10.1038/nature08740). The melanosomes are in exquisitely preserved feathers that adorned and probably warmed small dinosaurs as well as the famous bird fossils from the same sedimentary rocks. One specimen of Sinornithosaurus may have sported a coat patterned in black and russet, while Sinosauropteryx seems to have had a tail and back crest striped in shades of red-brown. Could this be for camouflage, display or some aspect of regulating heat? The big leap follows some 6 months on from the discovery of melanosomes in bird feathers from Eocene oil shales in Germany, that may have given them a starling- or hummingbird-like iridescent
sheen (Vinther, J. et al. 2009. Structural coloration in a fossil feather. Biology Letters, v. 6, p. 128-131; DOI: 10.1098/rsbl.2009.0524). The huge diversity of modern coloration among birds, from feathers and in the skins of lizards is widely believed to function primarily as a species-dependent means of display, with some influence from camouflage and thermal properties. Whichever, it must have been an integral aspect of speciation for a very long time indeed, yet even the best fossils cannot yield full ornament information, and reconstructions will rely on artistic licence, but now with a little more confidence that creatures didn’t just come in one colour, like Model-T Fords.

To spice up the stereotypical view that ginger = bad-tempered it seems that as well as being mottled with that hue Sinornithosaurus may have been venomous (Gong, E. et al. 2010. The birdlike raptor Sinornithosaurus was venomous. Proceedings of the National Academy of Science, v. 107 p. 766-768; DOI: 10.1073/pnas.0912360107). Its skull shows grooved teeth, the grooves leading to a pocket at the base of the teeth. It may also have evolved to feed on birds...

End-Cretaceous mass extinction moving towards ‘closure’? (May 2010)

Apart from the change in name from the K-T (Cretaceous-Tertiary) to the K-Pg (Cretaceous-Palaeogene) Event, following the abolition by the International Commission on Stratigraphy of the name Tertiary – given by Giovanni Arduino to the penultimate geological Era, in favour of Cenozoic (Palaeogene + Neogene + Quaternary) the eponymous mass extinction has steadily become a less regular news item. Views had settled in to three camps: driven by an impact; by Deccan volcanism or by the two conspiring together. Yet a host of geoscientists, from institutions whose addresses take up 8 column inches in Science, have been beavering away to settle the issue one way or another (Schulte, P. and 40 others 2010. The Chicxulub asteroid impact and mass extinction at the Cretaceous-Paleogene boundary. Science, v. 327, p. 1214-1218; DOI: 10.1126/science.1177265). The main biotic changes and geochemical signatures of the K-Pg Event all coincide at 65.5 Ma with the world-wide Chicxulub ejecta layer, after two thirds of the Deccan Traps had been erupted. In an extensive and readable summary of all the evidence the authors conclude that the Chicxulub impact did trigger the massive die-off. Despite global change associated with volcanism, life went on ‘down to the wire’. The authors rule out the Deccan volcanism as a causative factor on account of little more than a 2° C warming effect while it lasted, set against the likely near-instantaneous release of at least 100-500 billion tons of SO2 by an impact into sulfate-rich sediments around the Chicxulub site (the release by Deccan volcanism has been estimated at 0.05 to 0.5 Gt per year throughout its million-year duration). Such a release along with dust and water vapour flung into the atmosphere are modelled to have reduced global temperatures by up to 10° C – a reduction greater than that reached by the last glacial maximum. The re-entry of such a mass in rainfall within a few years would have acidified large areas of surface ocean water: a 3-4 orders of magnitude larger effect than that of slow release by volcanism. The authors conclude that the most important remaining work is to delve deeper into the impact site itself to quantify likely chemical emissions, and then to develop models of the actual deadly processes that ensued.
The earliest multicelled life (July 2010)

Being multicellular does not necessarily qualify a fossilised organism as a member of the eukaryote domain: such a classification is assured when there is strong evidence for many cells constituting a functional whole with specialised parts. That eukaryotes also have cells with nuclei and a variety of organelles is a prerequisite for living members, though such evidence is extremely rare and disputed for fossils. The earliest convincing examples are from 1700 Ma sedimentary rocks. Using a molecular clock approach to the differences in genetic make-up between modern eukaryotes might seem one means of estimating when the last common ancestor of all of them lived, but the Catch-22 is having incontrovertible examples from the distant past as means of calibrating that approach. A fourth possible ‘fingerprint’ is the presence of biomarker chemicals in sedimentary rocks that are exclusive to living Eucarya, steranes derived from sterols being an example.

Since the 1970s the oldest candidate for eukaryote status has been a coiled form a few centimetres across made from a strap-like carbon film, known as *Grypania* that some regard as a primitive alga. Yet it could equally be a colonial bacterium. *Grypania* are known as far back as those found in the 1900 Ma ironstones of Michigan, USA. Thin black shales from a mixed marine and terrestrial sequence of 2100 Ma siltstones and sandstone in Gabon, West Africa now provide something far more spectacular (El Albani, A. and 21 others 2010. *Large colonial organisms with coordinated growth in oxygenated environments 2.1 Gyr ago*. *Nature*, v. 466, p. 100-104; DOI: 10.1038/nature09166). They are complex and look a little like an irregular discus 1-2 cm across. Being replaced by fine grained iron sulfide they preserve odd internal structures discernible using X-ray tomography – folds of their central node – signs of flexibility in the original material – and scalloped flanges with radial slits. To the authors this suggests coordinated growth rather than the amorphous characteristics of bacterial biofilms such as stromatolites. They are completely unlike any living colonial bacteria. Their host rocks have yielded steranes characteristic of eukaryote biochemistry, but contamination from groundwater cannot yet be ruled out.

2.1 Ga old fossil from Gabon and reconstructions – scale 5 mm. (Credit: El Albani et al; Fig. 4)

Only the one and a half billion year younger Ediacara fauna comes close in terms of complexity of form to the Gabon fossils. Yet whether they are the earliest-known eukaryotes or bacterial colonies whose growth was coordinated between the cells of which they were composed by some unknown exchange of information cannot be pinned down. However, their age is appropriate for the rise of the oxygen-demanding Eucarya, a few hundred million years after the start of planetary oxygenation. Perhaps more important, the surprising find will give palaeobiologists the impetus and confidence that large body fossils can indeed be found in the Palaeoproterozoic Era.
Ordovician lagerstätte in Morocco (July 2010)

It was during the Ordovician Period that multicelled life really took off (see The Great Ordovician Diversification September 2008), but the fossil record seems to suggest that the wonderfully diverse soft-bodies fauna of the Cambrian, exemplified by that from the Burgess Shale, didn’t survive to take part. It turns out that this may be an artefact of imperfect preservation, for a Lower Ordovician equivalent of the Burgess Shale has been unearthed in Morocco (Van Roy, P. et al. 2010. Ordovician faunas of Burgess Shale type. Nature, v. 465, p 215-218; DOI: 10.1038/nature09038). It is just as rich and even shows more organic detail, highlighted in reds, oranges and yellows because iron sulfide that mineralised soft parts has since been gently oxidised. A fascinating link with the Burgess Shale is that the fossil taxa from the Moroccan lagerstätte are related to those in that most famous Middle Cambrian rock unit.

Ordovician arthropod from Morocco. (Credit: Van Roy et al. 2010; Fig. 1)

On the subject of exceptionally preserved fossil material, one of the Burgess Shale oddities, new specimens of Nectocaris pteryx allow a detailed reconstruction. What a stunning beast! This 5 cm stem-group cephalopod had two tentacles, enormous stalked eyes and a funnel shaped device that may have been for squid-like jet propulsion. Reconstruction of its back-end suggests a cuttlefish-like means of propulsion by a flap of tissue around the main body, but with no sign of any stiffening ‘bone’

Possible abiotic mechanisms for DNA splitting and cell membranes (July 2010)

The central feature of the DNA double helix is its ability to ‘unzip’ and recombine as part of the replication that is essential for all known living things. In doing this, DNA copies itself. It is one thing to deduce this from DNA’s structure and the meiotic aspect of reproduction, but
quite another to figure out how it might have arisen. An experiment that mimics conditions in porous sea-floor lava – a temperature gradient and small-scale convection inside a capillary tube – shows that this lengthways splitting does occur on the hot side of the gradient. On the cool arm of the convection the halved ribbons of DNA reassemble (Mast, C.B. & Braun, D. 2010. Thermal trap for DNA replication. Physical Review Letters, v. 104, p. 188102-188105; DOI: 10.1103/PhysRevLett.104.188102). This is a long way from life’s origin and even that of DNA as an isolated entity without a cell, but perhaps one step towards a better understanding of both. It seems pretty certain from a range of evidence – e.g. heavy metal centred proteins and heat-shock proteins – that life sprang from physical and chemical processes around hot vents on the ocean floor. What’s next on the experimental agenda: membranes to bag-up genetic material such as DNA as a precursor to the cell? It’s been done (Budin, I. et al. 2009. Formation of protocell-like vesicles in a thermal diffusion column) using fatty acids that are relatively easy to generate abiotically. Some can transform into flexible membranes that curve in on themselves – amphiphiles – and vesicles of these formed in Budin et al.’s capillary tubes.


**Correction to marine biodiversity record and mass extinctions (November 2010)**

The mainstay of geobiologists’ efforts to chart the timing and pace of mass extinctions and diversification since 1997 has been the monumental collation of information in fossil collections undertaken by the late Jack Sepkoski from the 1980s until shortly before his death in 1999. It was his plotting of marine fossil genera numbers against their time ranges that first quantified the ‘Big Five’ and lesser mass extinctions, and the course of re-diversification that followed in their wake. One problem that Sepkoski was unable to account for was the inherent biases in collections: under-representation of earlier genera than younger ones; different representation from different areas partly because developed-world collections are larger than those from the majority world and partly because modern diversity changes with latitude; and varying preservation of less-substantial organisms. Well aware of the shortcomings of his initial compilations, Sepkoski with others set up the Palaeobiology Database (PBDB) that now encompasses almost 100 thousand collections. Sadly, Sepkoski did not live to analyse this record with statistical methods that lessen the influence of bias, but one of his successors has done just that (Alroy, J. The shifting balance of diversity among major marine animal groups. Science, v. 329, p. 1191-1194; DOI: 10.1126/science.1189910).

Alroy’s approach sets out to represent the rare with a fair weighting relative to common groups of organisms, using a complex multivariate method called ‘shareholder’ sampling, which corrects some of the artefacts in Sepkoski’s work and earlier manipulation of the PBDB. One important feature is that Alroy’s method does not assume that all groups follow the same ‘rules’ of diversification and adaptive radiation, particularly after mass extinctions. The upshot is a history with ups and downs, but not such a prominent growth in diversity in the late-Mesozoic and Cenozoic Eras as that in Sepkoski’s original compilation, although life did become richer. For someone, like me, who has not followed the developments since Sepkoski’s original work, there is another significant difference. There are 7 or 8 significant falls in diversity rather than 5. The Triassic-Jurassic boundary no longer shows a mass
extinction, but the opposite. Major extinctions show up for the mid-Carboniferous, mid- and end-Jurassic and the Oligocene, where none were especially noticeable in the original plots by Sepkoski. Finally diversity peaks in the Siluro-Devonian and the Permian figure as prominently as that of the late-Cretaceous. Clearly, rules are few and one that was almost an assumption, that diversification of marine life after mass extinctions was exponential, is no longer borne out. Whether or not this new approach will bear fruit in refining or redefining the ecological dynamics that shaped and continue to shape life on Earth remains to be seen. It is tempting to be a bit cynical: is it all punctuated chaos (Bennett, K. 2010. The chaos theory of evolution. New Scientist, v. 208 (16 October 2010), p. 28-31)?
Comet impacts’ candidature for origin of life (November 2010)

Most researchers concerned with the origin of life acknowledge that some preparatory organic chemicals would have been required, whose origin Darwin ascribed to a ‘warm, little pool’, and Haldane and Oparin to electrical discharges in the early atmosphere; both lines having been followed-up in practice by more recent scholars. A variety of biologically useful chemical ‘building blocks’ have also been recognised in comets, some meteorites – carbonaceous chondrites – and even in interstellar dust clouds. So one school looks to their supply from outside the Earth system. One possibility has had more scanty attention – the effects of impacts, as the power involved seems overwhelming for the survival of delicate organic molecules. Nir Goldman and his colleagues at the Lawrence Livermore National Laboratory in California have had a second look at this unlikely scenario (Goldman, N. et al. 2010. *Synthesis of glycine-containing complexes in impacts of comets on early Earth*. *Nature Chemistry*, v. 2, p. 949–954; DOI: 10.1038/nchem.827). Their approach has been to examine the implications of impact shock at likely collision speeds followed by post-shock expansion on mixtures of water, ammonia, carbon monoxide and dioxide, and methanol that are almost guaranteed in the make-up of most cometary ices. Their modelling suggests that carbon-nitrogen bonds form under shock conditions in long chain compounds. In the aftermath of huge collision shock the impact products undergo rapid expansion and cooling during which the chains can break down to simpler molecules, including some akin to amino acids such as glycine. The bombardment of Earth in the Hadean Eon (4.5-3.8 Ga) involved huge masses of material, almost certainly some delivered by icy comets that would have greatly increased the amount of water and the number of CHON compounds in the early Earth’s outer parts.

Phosphorus, Snowball Earth and origin of metazoans (November 2010)

As any gardener knows, the element phosphorus is an essential plant nutrient or fertiliser, along with potassium and nitrogen plus a host of minor elements that are rarely mentioned because sufficient amounts are generally available in soils. The same necessities for life apply to oceans too, in which amounts vary a great deal from place to place and whose relative proportions have changed through geological time. For the oceans the main source of phosphorus is the continental crust, where the element resides mainly in the mineral apatite (Ca$_5$(PO$_4$)$_3$(F,Cl,OH)). This is not an easily dissolved mineral, which is why for agricultural fertiliser it is generally made available in the soluble form of calcium superphosphate (Ca(H$_2$PO$_4$)$_2$) that is produced by reaction between apatite and sulfuric acid. Since the land surface was colonised by plants about 450 Ma ago, biological processes made phosphorus more readily available to solution in river water by their break-down of apatite; supply by rivers to the ocean nowadays is of the order of 10$^9$ kg y$^{-1}$. Ups and downs of P dissolved in ocean water though geological time would be expected to have influenced its overall biological productivity, controlled by photosynthetic phytoplankton and prokaryotes. Variations of carbon isotopes ($\delta^{13}$C) in organic and carbonate sediments are known to have occurred episodically since Archaean times, suggesting wide fluctuations in both bioproductivity and burial of dead organic matter. However, it has been hard to judge any geochemical reasons underpinning such variations. Since it is now clear that the common iron mineral goethite (FeOOH) ‘mops up’ many chemical species including phosphate ions
by adsorption on its grain surfaces, measuring the P/Fe ratios in marine ironstones containing these minerals is a potential guide to the changing phosphorus concentration in the oceans (Planavsky, N.J. et al. 2010. The evolution of the marine phosphate reservoir. *Nature*, v. 467, p. 1088-1090; DOI: 10.1038/nature09485).

The US-French-Canadian researchers charted P/Fe ratios in banded iron formations and ironstones precipitated around ocean-floor hydrothermal vents since the Archaean. What emerged were four episodes: from 2900 to 1700 Ma with generally low ratios; the Neoproterozoic from 750 to 635 Ma with much higher ratios; the Phanerozoic from Cambrian to Jurassic with low ratios and post-Cretaceous high ratios. There are several significant gaps in the record of ocean phosphate levels, notable one a billion years long from 750 to 1700 Ma. One factor that probably affected the variation is the way that dissolved silica (SiO₂) drives down the proportion of phosphate adsorbing onto goethite. The rapid evolution and expansion since the Cretaceous of diatoms that secrete silica probably reduced SiO₂ concentration in ocean water as their remains rained down to be buried on the ocean floor; that explains the high P/Fe ratios since about 100 Ma. Earlier Phanerozoic oceans are estimated to have had as much as seven times the present concentration of dissolved SiO₂, thereby explaining the low values of P/Fe in ironstones deposited in the 100-540 Ma range. From 1700 to 3000 Ma the low P/Fe suggests oceanic phosphorus levels equivalent to those from the Jurassic to Cambrian (but perhaps up to 4 times that, depending on the poorly constrained SiO₂ concentrations).

The Neoproterozoic phosphorus ‘spike’, at a time when dissolved SiO₂ would have been no different from that in earlier times, suggests a massive influx of phosphate to the oceans at that time. It coincides with the two greatest glacial epochs the Earth has experienced: ‘Snowball’ Earth when glacial ice existed at tropic latitudes. In themselves the massive glaciations offer an explanation for high phosphorus delivery from the continents through glacial erosion and massive run-off during melting. More exciting is that the P/Fe ‘spike’ occurred at a time of massive perturbations in stable carbon isotopes ascribed to huge explosions of phytoplankton and organic carbon burial, which would have been permitted by high dissolved phosphate in the oceans. A large increase in primary biological productivity, i.e. photosynthesis, would have boosted oxygen levels; a necessity for the emergence of metazoan life forms soon after the end of ‘Snowball’ Earth conditions. But that begs the question of how glacially ground-up apatite, abundant as it would have been together with vast amounts of other rock debris, came to be dissolved. In today’s oceans crystalline apatite is barely soluble. It seems that apatite’s solubility decreases as temperature rises, and increases with pH – in alkaline conditions. As well as being cold, Neoproterozoic ocean water around the time of the ‘Snowball’ Earths was saturated with carbonate ions that helped thick, almost pure limestones to form globally after each glaciation. That spells alkaline conditions favouring phosphate solution. The authors speculate that global geochemical conditions during the Cryogenian Period (850-635 Ma) may have fostered the origin of the metazoans. Maybe, but their data have a billion-year gap immediately before that Period, and genomic molecular clocks suggest that the root metazoans emerged as much as half a billion years earlier.