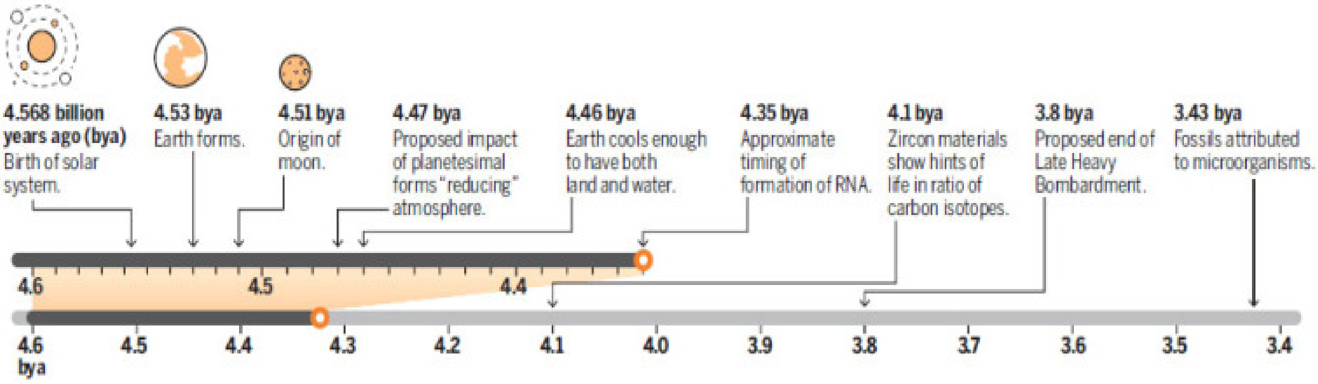
Palaeontology, palaeobiology and evolution

A unifying idea for the origin of life (January 2019)

The nickel in stainless steel, the platinum in catalytic converters and the gold in jewellery, electronic circuits and Fort Knox should all be much harder to find in the Earth's crust. Had the early Earth formed only by accretion and then the massive chemical resetting mechanism of the collision that produced the Moon all three would lie far beyond reach. Both formation events would have led to an extremely hot young Earth; indeed the second is believed to have left the outer Earth and Moon completely molten. All three are siderophile metals and have such a strong affinity for metallic iron that they would mostly have been dragged down to each body's core as it formed in the early few hundred million years of the Earth-Moon system, leaving very much less in the mantle than rock analyses show. This emerged as a central theme at the Origin of Life Conference held in Atlanta GA, USA in October 2018. The idea stemmed from two that reported excessive amounts in basaltic material from both Earth and Moon of a tungsten isotope (^{182}W) that forms when a radioactive isotope of hafnium (^{182}Hf), another strongly siderophile metal, decays. Hafnium too must have been strongly depleted in the outer parts of both bodies when their cores formed. The excesses are explained by substantial accretion of material rich in metallic iron to their outer layers shortly after Moon-formation, some being in large metallic asteroids able to penetrate to hundreds of kilometres. Hot iron is capable of removing oxygen from water vapour and other gases containing oxygen, thereby being oxidised. The counterpart would have been the release of massive amounts of hydrogen, carbon and other elements that form gases when combined with oxygen. The Earth's atmosphere would have become highly reducing.

Had the atmosphere started out as an oxidising environment, as thought for many decades, it would have posed considerable difficulties for the generation at the surface of hydrocarbon compounds that are the *sine qua non* for the origin of life. That is why theories about abiogenesis (life formed from inorganic matter) hitherto have focussed on highly reducing environments such as deep-sea hydrothermal vents where hydrogen is produced by alteration of mantle minerals. The new idea revitalises Darwin's original idea of life having originated in 'a warm little pond'. How it has changed the game as regards the first step in life, the so-called 'RNA World' can be found in a detailed summary of the seemingly almost frenzied Origin of Life Conference (Service, R.F. 2019. Seeing the dawn. *Science*, v. **363**, p. 116-119; DOI:10.1126/science.363.6423.116).

Isotope geochemistry has also entered the mix in other regards, particularly that gleaned from tiny grains of the mineral zircon that survived intact from as little as 70 Ma after the Moon-forming and late-accretion events to end up (3 billion years ago) in the now famous Mount Narryer Quartzite of Western Australia. The oldest of these zircons (4.4 Ga) suggest that granitic rocks had formed the earliest vestiges of continental crust far back in the Hadean Eon: Only silica-rich magmas contain enough zirconium for zircon ($ZrSiO_4$) to crystallise. Oxygen isotope studies of them suggest that at that very early date they had come into contact with liquid water, presumably at the Earth's surface. That suggests that perhaps there were isolated islands of early continental materials; now vanished from the geological record. A 4.1 Ga zircon population revealed something more surprising: graphite flakes with carbon isotopes enriched in ^{12}C that suggests the zircons may have incorporated carbon from living organisms.



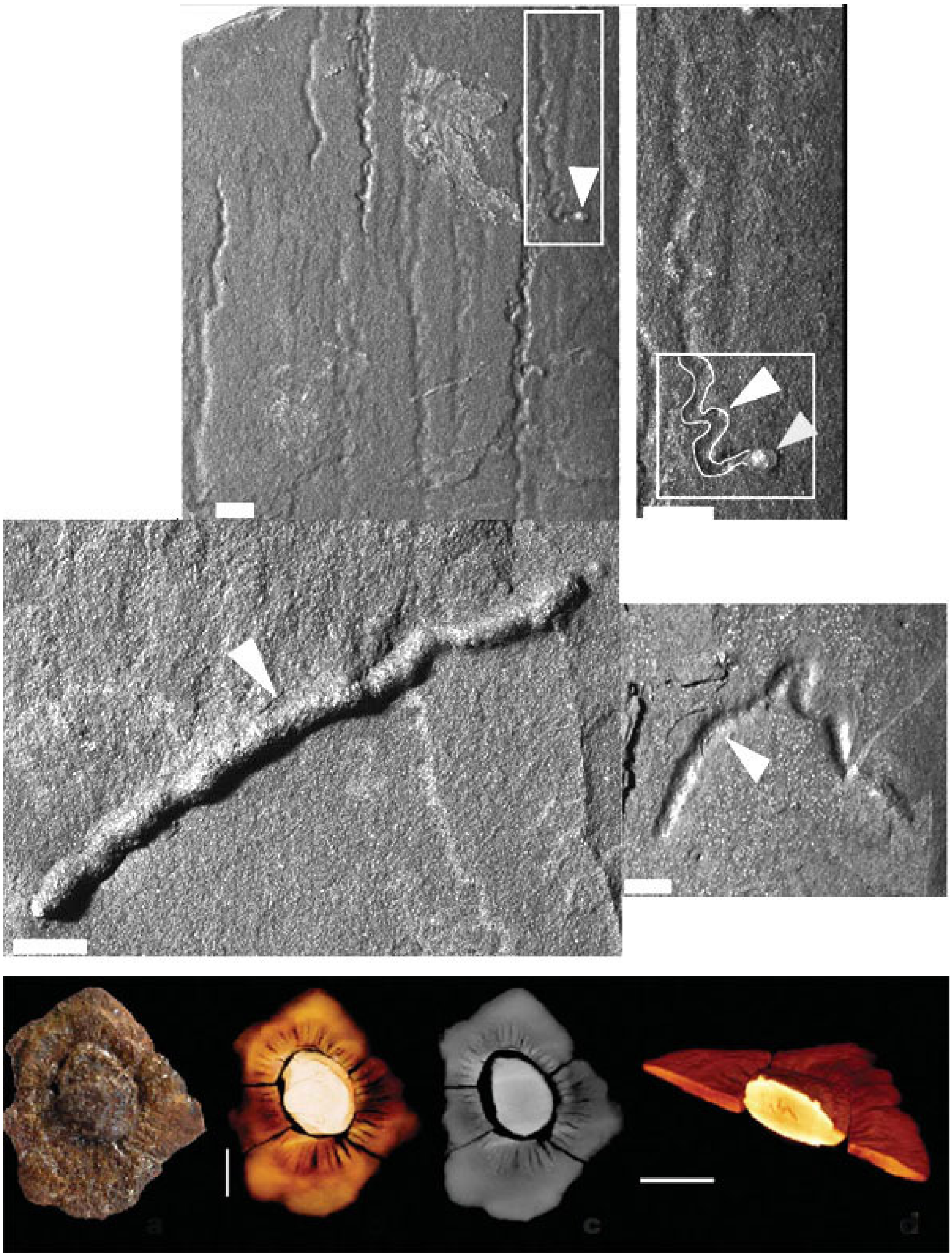
A possible timeline for the origin of life during the Hadean Eon (Credit: Service, R.F. 2019, Science)

Such a suite of evidence has given organic chemists more environmental leeway to suggest a wealth of complex reactions at the Hadean surface that may have generated the early organic compounds needed as building blocks for RNA, such as aldehydes and sugars (specifically ribose that is part of both RNA and DNA), and the amino acids forming the A-C-G-U 'letters' of RNA, some catalysed by the now abundant siderophile metal nickel. One author seems gleefully to have resurrected Darwin's 'warm little pond' by suggesting periodic exposure above sea level of abiogenic precursors to volcanic sulfur dioxide that could hasten some key reactions and create large masses of such precursors which rain would have channelled into 'puddles and lakes'. The upshot is that the RNA World precursor to the self-replication conferred on subsequent life by DNA is speculated to have been around 4.35 Ga, 50 Ma after the Earth had cooled sufficiently to have surface water dotted with specks of continental material.

There are caveats in Robert Service's summary, but the Atlanta conference seems set to form a turning point in experimental palaeobiology studies.

Something large moved 2 billion years ago **(February 2019)**

More than 50 years ago a group of schoolchildren discovered a fronded fossil (*Charnia*) in the Precambrian rocks of Charnwood Forest in the English Midlands. Since then it has been clear that multicellular life originated before the Cambrian Period, when the first tangible life had previously been considered to have emerged. Discovery of the rich Ediacaran fauna of quilted, baglike and disc-like animals in 635 Ma old Neoproterozoic sediments in South Australia, and many other occurrences re-established the start of the 'carnival of animals' in the Ediacaran Period (635 to 541 Ma). It happened to follow the climatic and environmental turmoil of at least two Snowball Earth episodes during the preceding Cryogenian Period (850 to 635 Ma), which has led to a flurry of suggestions for the transition from protozoan to metazoan life. Yet, applying a 'molecular-clock' approach to the genetic differences between living metazoan organisms seems to suggest a considerable earlier evolutionary event that started 'life as we know it'. That may have been confirmed by a discovery in much older sediments in Gabon, West Africa.



Palaeoproterozoic fossils from the Francevillian Series in Gabon. Top: greytone photographs of burrow-like trace fossils (Credit: El Albani et al. 2019; Fig.1). Bottom: colour photograph and 3 CT scans of discoidal fossil (Credit: El Albani et al. 2010; Fig. 4).

A sequence of shallow-marine sediments in the Francevillian Series in Gabon was laid down at a time of fluctuating sea level around 2100 Ma ago, when the upper oceans had become oxygenated. In them are black shales that preserve an abundance of intricate sedimentary features. Among them are curious stringy structures rich in crystalline pyrite (Fe_2S). They are infilled wiggly tubes that lie in the shale bedding. CT scans reveal that the bedding has been flattened around the tubules as it became lithified. So the tubes formed while the sediment was wet and soft (El Albani, A. and 22 others 2019. Organism motility in an oxygenated shallow-marine environment 2.1 billion years ago. *Proceedings of the National Academy of Sciences*, online preprint; DOI:10.1073/pnas.1815721116). They look very like burrows. Up to 5 mm across, they can be considered large by comparison with almost all organisms known from that time. The exception comes from the same stratigraphic Series in Gabon. In 2010, El Albani and colleagues published an account of fossils preserved by pyrite that look like fried eggs, 1 to 2 cm across, with scalloped edges. Internal structures revealed by CT scanning include radial slits in the 'whites' and folding within the central 'yolk'. That paper reported the geochemical presence in the host shales of steranes, which are breakdown products of steroids that are unique to eukaryotes. Could these organisms and the wiggly tube-like trace fossils indicate the presence of the earliest metazoans in the Francevillian Series?

Until the discoveries in Gabon, the oldest organic structure that had been suggested to be a metazoan was the rare Grypania, a spiral, strap-like fossil found in a variety of strata ranging in age from 1870 to 650 Ma. Being made of a structureless ribbon of graphite, Grypania seems most likely to have been made by colonial bacteria. The two Gabon life forms cannot be disposed of quite so easily. The discoids have organised structures rivalling those in Ediacaran animals, while the wiggly tubes clearly seem to indicate something capable of movement. In both cases preservation is by iron sulfide, which suggests the presence at some stage of chemo-autotrophic bacteria that reduce sulfate ions to sulfide. Could these not have formed mats taking up irregular discs and plates? The burrows may have been formed by unicellular eukaryotes, one type of which – the slime moulds – is capable of aggregating together to form multi-celled reproductive structures as well as living freely as single amoeba. Some form slug-like masses that are capable of movement; not metazoans, but perhaps their precursors.

Plants first to succumb to the end-Permian event **(February 2019)**

We have become accustomed to thinking that up to 90% of organisms were snuffed out by the catastrophe at the Permian-Triassic boundary 252 Ma ago. Those are the figures for marine organisms, whose record in sediments is the most complete. It has also been estimated to have lasted a mere 60 ka, and the recovery in the Early Triassic to have taken as long as 10 Ma. There are hints of three separate pulses of extinction related to: initial gas emission from the Siberian Traps; coal fires; and release of methane from sea-floor gas hydrates at the peak of global warming. Various terrestrial sequences record the collapse of dense woodlands, so that the Early Triassic is devoid of coals that are widespread in the preceding Late Permian. A new detailed study of terrestrial sediments in the Sydney Basin of eastern Australia reveals something new (Fielding, C.R. and 10 others 2019. Age and pattern of the southern high-latitude continental end-Permian extinction constrained by multiproxy analysis. *Nature Communications*, v. **10**, online publication: DOI: 10.1038/s41467-018-07934-z).

The distinctive, tongue-like form of Glossopteris leaves that dominate the coal-bearing Permian strata of the southern coninents. Their occurrence in South America, Africa, India, Australia, New Zealand, and Antarctica prompted Alfred Wegener to suggest that these modern continents had been united in Pangaea by Permian times: a key to continental drift. (Credit: Getty Images)

Christopher Fielding or the University of Nebraska-Lincoln and colleagues focused on pollens, geochemistry and detailed dating of the sedimentary succession across the P-Tr boundary exposed on the New South Wales coast. The stratigraphy is intricately documented by a 1 km deep well core that penetrates a more or less unbroken fluviatile and deltaic sequence that contains eleven beds of volcanic ash. The igneous layers are key to calibrating age throughout the sequence (259.10 ± 0.17 to 247.87 ± 0.11 Ma using zircon U-Pb methods). The pollens change abruptly from those of a Permian flora, dominated by tongue-like glossopterid plants, to a different association that includes conifers. The change coincides with a geochemical 'spike' in the abundance of nickel and a brief change in the degree of alteration of detrital feldspars to clay minerals. The first implicates the delivery of massive amounts of nickel to the atmosphere, probably by the eruption of the Siberian Traps , which contain major economic nickel deposits. The second feature suggests a brief period of warmer and more humid climatic conditions. A third geochemical change is the onset of oscillations in the abundance of ^{13}C that are thought to record major changes in plant life across the planet. These features would have been an easily predicted association with the 252 Ma mass extinction were it not for the fact that the radiometric dating places them about 400 thousand years before the well-known changes in global animal life. Detailed dating of the Siberian Traps links the collapse of *Glossopteris* and coal formation to the earliest extrusion of flood basalts, which suggests that the animal extinctions were driven by cumulative effects of the later outpourings

Related article: Chris Fielding comments on the paper at Nature Research/Ecology and Evolution

***Better dating of Deccan Traps, and the K-Pg event* (March 2019)**

Predictably, the dialogue between the supporters of the Deccan Trap flood basalts and the Chicxulub impact as triggers that were responsible for the mass extinction at the end of the Mesozoic Era (the K-Pg event) continues. A recent issue of *Science* contains two new approaches focussing on the timing of flood basalt eruptions in western India relative to the age of the Chicxulub impact. One is based on dating the lavas using zircon U-Pb geochronology (Schoene, B. *et al*. 2019. U-Pb constraints on pulsed eruption of the Deccan Traps across the end-Cretaceous mass extinction. *Science*, v.**363**, p. 862-866; DOI: 10.1126/science.aau2422), the other using $^{40}Ar/^{39}Ar$ dating of plagioclase feldspars (Sprain, C.G. *et al*. 2019. The eruptive tempo of Deccan volcanism in relation to the Cretaceous-Paleogene boundary. *Science*, v. **363**, p. 866-870; DOI: 10.1126/science.aav1446). Both studies were initiated for the same reason: previous dating of the sequence of flows in the Deccan Traps was limited by inadequate sampling of the flow sequence and/or high analytical uncertainties. All that could be said with confidence was that the outpouring of more than a million cubic kilometres of plume-related basaltic magma lasted around a million years (65.5 to 66.5 Ma) that encompassed the sudden extinction event and the possibly implicated Chicxulub impact. The age of the impact, as recorded by its iridium-rich ejecta found in sediments of the Denver Basin in Colorado, has been estimated from zircon U-Pb data at 66.016 ± 0.050 Ma; i.e. with a precision of around 50 thousand years.

The Deccan Traps in the Western Ghats of India (Credit: Wikipedia)

Because basalts rarely contain sufficient zircons to estimate a U-Pb age of their eruption, Blair Schoene and colleagues collected them from palaeosols or boles that commonly occur between flows and sometimes incorporate volcanic ash. Their data cover 23 boles and a single zircon-bearing basalt. Sprain *et al*. obtained $^{40}Ar/^{39}Ar$ ages from 19 flows, which they used to supplement 5 ages obtained by their team in previous studies that used the same analytical methods and 4 palaeosol ages from an earlier paper by Schoene's group.

The zircon U-Pb data from palaeosols, combined with estimates of magma volumes that contributed to the lava sequence between each dated stratigraphic level, provide a record of the varying rates at which lavas accumulated. The results suggest four distinct periods of high-volume eruption separated by long. periods of relative quiescence. The second such pulse precedes the K-Pg event by up to 100 ka, the extinction and impact occurring in a period of quiescence. A few tens of thousand years after the event Deccan magmatism rose to its maximum intensity. Schoene's group consider that this supports the notion that both magmatism and bolide impact drove environmental deterioration that culminated in mass extinction.

The Ar-Ar data derived from the basalt flows themselves, seem to tell a significantly different story. A plot of basalt accumulation, similarly derived from dating and stratigraphy, shows little if any sign of major magmatic pulses and periods of quiescence. Instead, Courtney Sprain's team distinguish an average eruption rate of around 0.4 km^3 per year before the K-Pg event and 0.6 km^3 per year following it. Yet they observe from climate proxy data that there seems to have been only minor climatic change (about 2 to 3 °C warming) during the period around and after the K-Pg event when some 75% of the lavas flooded out. Yet during the pre-extinction period of slower effusion global temperature rose by 4°C then fell back to pre-eruption levels immediately before the K-Pg event. This odd mismatch between magma production and climate, based on their data, prompts Sprain *et al*. to speculate on possible shifts in the emission of climate-changing gases during the period Deccan volcanism: warming by carbon dioxide – either from the magma or older carbon-rich sediments heated by it; cooling induced by stratospheric sulfate aerosols formed by volcanogenic SO_2 emissions. That would imply a complex scenario of changes in the composition of gas emissions of either type. They suggest that one conceivable trigger for the post-extinction climate shift may have been exhaustion of the magma source's sulfur-rich volatile content before the Chicxulub impact added enough energy to the Earth system to generate the massive extrusions that followed it. But their view peters out in a demand for 'better understanding of [the Deccan Traps'] volatile release'.

A curious case of empiricism seeming to resolve the K-Pg conundrum, on the one hand, yet pushing the resolution further off, on the other …

The Cambrian Explosion: a broader view **(March 2019)**

The base of the Cambrian has long been defined as the level where abundant shelly fossils and most phyla first occur in the stratigraphic record. That increase in diversity led to the nickname 'Cambrian Explosion', despite the fact that sheer numbers and diversity of lesser taxa took a long time to rise to 'revolutionary' levels. Yet a great deal of animal evolution was going on during the preceding Proterozoic Era that was revealed once palaeobiological research blossomed in rocks of that age range. Today, the earliest occurrences, or at least hints, of quite a few phyla can be traced to the last 100 Ma of the Precambrian. Clearly, the Cambrian Explosion needs a fresh look now that so many data are in. Any palaeontologist would benefit from reading a Perspective article in the latest issue of *Nature Ecology & Evolution* (Wood, R. and 8 others 2019. Integrated records of environmental change and evolution challenge the Cambrian Explosion. *Nature Ecology & Evolution*, v. **3**, online publication; DOI: 10.1038/s41559-019-0821-6)

Rachel Wood of Edinburgh University and co-authors working elsewhere in Britain, Canada, Japan and Finland sift the growing wealth of fossil and trace-fossil evidence that predate the start of the Cambrian. They also consider the geochemical events that stand out in the Ediacaran Period that succeeds the Snowball Earth events of the Cryogenian. Their account recognises that the geochemical changes – principally a series of carbon-isotope ($\delta^{13}C$) excursions – may have resulted from tectonic changes. The carbon-isotope data mark a series of short-lived penetrations of oxygen-rich conditions deep into the ocean water column and longer periods of oxygen-starved deep water. Such perturbations in oceanic redox conditions 'speed-up' thorough the late-Ediacaran into the Cambrian: a profound and protracted transition from the Neoproterozoic world to that of the Phanerozoic. Over the same time span there is a 'progressive addition of biological novelty' in the form and function of the evolving biota, so that each successive assemblage builds on the earlier advances.

The fossil evidence suggests that the earliest Ediacaran fauna was metazoan but with no sign of bilaterian affinities (i.e. having 'heads' and 'tails'). The rise of bilaterians of which most animal phyla are members occupied the later Ediacaran , with the first evidence of locomotion – and almost by definition animals with 'fore' and 'aft' – being around 560 Ma. Each discrete shift from more to less oxic conditions in the oceans seems to have knocked-back animal life, the reverse being accompanied by diversification of survivors. Oxygenation at the very start of the Cambrian marked the beginnings of a diversification clearly manifested by animals capable of biomineralisation and the secretion of hard parts with clear patterns. Such 'shelly faunas' are present in the latest Ediacaran sediments but with a multiplicity of seemingly arbitrary forms, although trace fossils suggest soft-bodied animals did have definite morphological pattern.

Diorama of the Lower Cambrian Qingjiang fauna (Credit: Fu et al. 2019; Fig 4)

Adding yet more information to early metazoan history is the recently discovered Cambrian Qingjiang lagerstätte of Hubei Province in southern China dated at 518 Ma; similar in its exquisite preservation to the Burgess (508 Ma) and Chengjiang (518 Ma) biotas (Fu, D. and 14 others 2019. [The Qingjiang biota—A Burgess Shale-type fossil Lagerstätte from the early

Cambrian of South China. *Science*, v. **363**, p. 1338-1342; DOI: 10.1126/science.aau8800). The two previously discovered Cambrian lagerstättes are notable for their very diverse arthropod and sponge faunas. That at Qingjiang adds an abundance of cnidarians, jellyfish, sea anemones, corals and comb jellies, rare in the other two biotas, plus kinorhynchs or mud dragons – moulting invertebrates known only from Cambrian and modern sediments. The fossils at Qingjiang include only about 8% of the taxa of the same age found at Chengjiang, suggesting different environments

The idea of a sudden, discrete explosive event in the history of life, which coincided with the start of the Cambrian, now seems difficult to support. This should not damage the status of 541 Ma as the start of the Phanerozoic because stratigraphy basically gives form to the passage of time and has done since its emergence in the 19th century, so keeping the names of the divisions is essential to continuity.

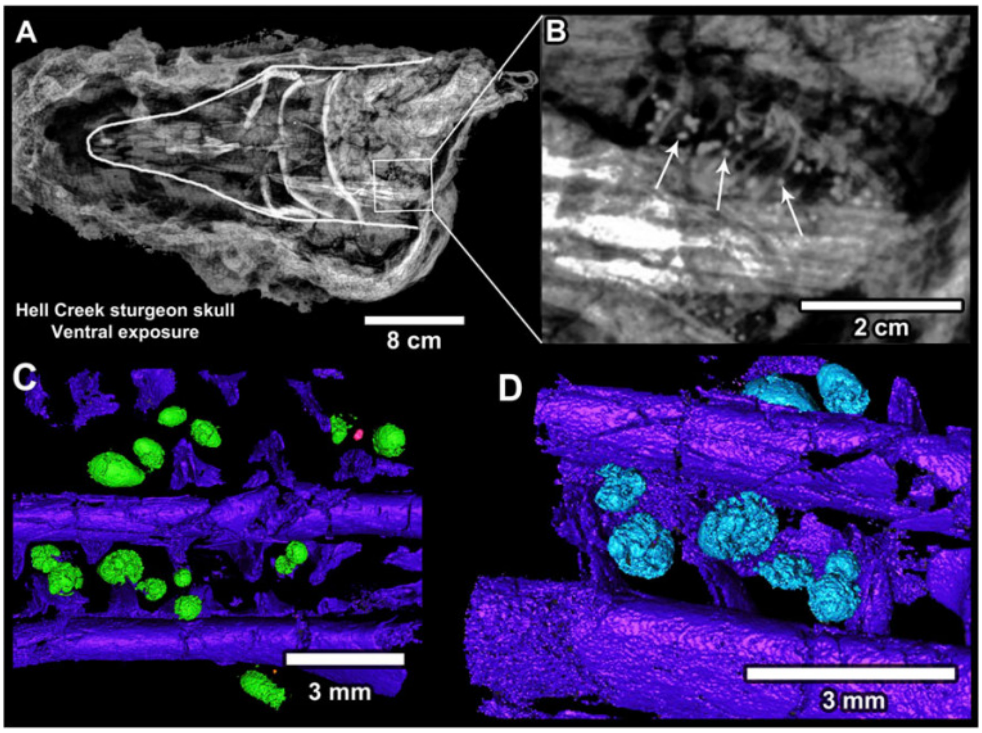
Related articles: Daley, A.C. 2019. A treasure trove of Cambrian fossils. *Science*, v.**363**, p. 1284-1285; DOI: 10.1126/science.aaw8644. Switek, B. 2019. Fossil Treasure Trove of Ancient Animals Unearthed in China (Smithsonian.com)

A bad day at the end of the Cretaceous **(April 2019)**

The New Yorker magazine normally features journalism, commentary, criticism, essays, fiction, satire, cartoons, and poetry. So it is odd that this Condé Nast glossy for the chattering classes snaffled online what may be the geological scoop of the 21st century so far (Preston, D. 2019. The day the dinosaurs died. *The New Yorker* 8 April 2019 issue). The paper that lies at the centre of the story had not been published and nor had the issue of The New Yorker in which Douglas Preston's story was scheduled for publication. The very day (29 March 2019) that Britain was thwarted of its Brexit moment the world's media was frothing with news about the end of another era; the Mesozoic. The paper itself was published online on April Fools' Day with a title that is superficially arcane (DePalma, R.A. and 11 others 2019. A seismically induced onshore surge deposit at the KPg boundary, North Dakota. *Proceedings of the National Academy of Science*, early online publication; DOI: 10.1073/pnas.1817407116). But its contents are the stuff of dreams for any aspiring graduate student of palaeontology: the Indiana Jones opportunity.

An 'onshore surge deposit' occurs at many Western Hemisphere sites where the K-Pg boundary outcrops in terrestrial or shallow-marine sediments. The closer to the Chicxulub crater north of Mexico's Yucatan Peninsula the more obvious they are, for they result from the tsunamis that immediately followed the asteroid impact. Lead author Robert DePalma, now of the University of Kansas, became focussed on the dinosaur-rich, Late Cretaceous Hell Creek Formation of North Dakota as an undergraduate. Accepted for graduate studies he was directed to a project on the fauna of lacustrine sediments close to the K-Pg boundary layer, which is well-known in the area, and that's what he has been engaged with ever since. In 2012 he was guided to a remarkable locality by a rockhound, disappointed because it exposed extremely fossil-rich sediments but was so soft that none could be extracted intact with a hammer and chisel. It turned out to have resulted from a surge along a sinuous river that had washed debris onto a point-bar deposit at the inside of a meander. The debris includes remains of both marine and terrestrial organisms and shows clear signs of having been swept *upriver*, i.e. from the sea and possibly the result of a tsunami. Being capped by a thin, iridium-rich layer of impactite, the 1.5 metre surge deposit is part of the K-Pg boundary layer, and probably represented only a few hours before being blanketed by ejecta.

This Event Deposit comprises two graded, fining-upwards units and thus two distinct surges, with a thin mat of vegetation fragments immediately below the Ir-rich clay cap that also contains sparse shocked quartz grains. The Event Deposit contains altered glass spherules throughout, which gradually become smaller higher in the 1.5 m sequence. Some of the larger spherules produced 'micro-craters' in the sediments. Fossils include marine ammonite fragments (some still nacreous) and freshwater fish (paddlefish and sturgeon). The fish are so complete as to suggest an absence of scavengers. The paper itself contains little of the information that dominated Preston's *New Yorker* article and the global media coverage. This included clear evidence that the fish ingested spherules, found clogging their gills and possible causing their death. There are examples of spherules embedded in amber formed from plant sap, which suggests sub-aerial fall of ejecta, and among the marine faunal samples are teeth of fish and reptiles (see DePalma *et al*'s Supplemental Data). The most startling finds reported by Preston are nowhere to be found in DePalma *et al*'s paper or its supplement. These include possible dinosaur feathers; a fragment of ceratopsian dinosaur skin attached to a hip bone; a burrow containing a mammal jaw that penetrates the K-Pg boundary layer; dinosaur remains, including an egg (complete with embryo) and hatchlings of dinosaurian groups found at deeper levels in the Hell Creek Formation. Previously, palaeontologists had found no dinosaur remains less than 3 m below the K-Pg boundary layer anywhere on Earth, prompting the suggestion that they had become extinct before the near-instantaneous effects of Chicxulub, and were perhaps victims of the general effects of the Deccan Trap volcanism. If verified in later peer-reviewed publications, DePalma *et al.*'s work would help resolve the gradual vs sudden hypotheses for the end-Cretaceous mass extinction.



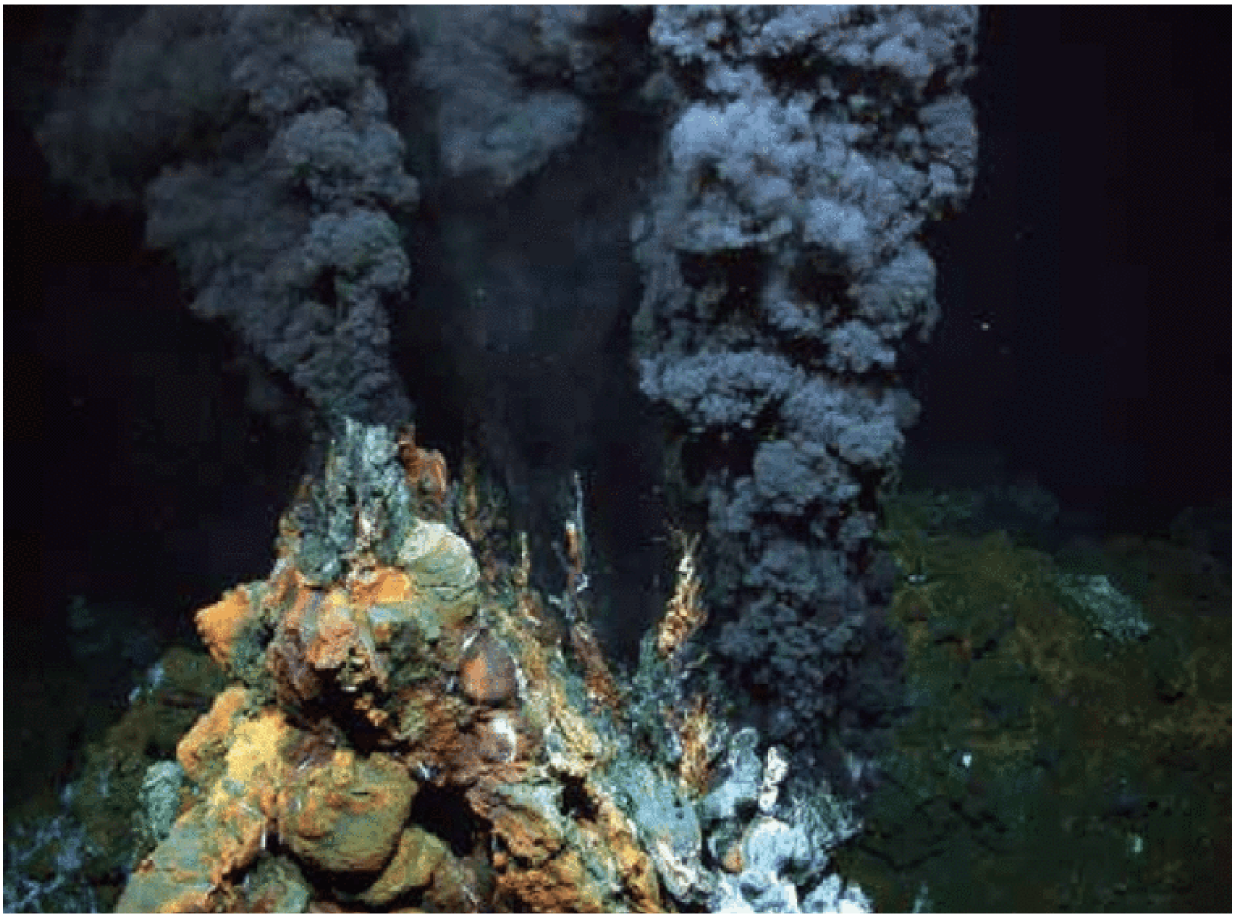
X-ray and CT images of impact spherules in the gills of a fossil sturgeon from the Tanis K-Pg site, North Dakota (credit DePalma et al. 2019; Fig. 6)

Preston reports some academic scepticism about DePalma's work, and emphasises his showmanship at conferences; for instance, he named the site 'Tanis' after the ancient city in Egypt featured in the 1981 film *Raiders of the Lost Ark*. There are geophysical queries too. If the inundation was by the on-shore effects of a tsunami it doesn't tally with the abundance of ejecta fallout of glass spherules: tsunamis propagate in shallow seawater at speeds less than 50 km h^{-1} and more slowly still in channels, whereas impact ejecta travel much faster. This is acknowledged in the paper's supplement, and the paper refers to a seiche wave activated by seismic waves associated with the Chicxulub impact which could have arrived in North Dakota at about the same time as its ejecta blanket. The paper's authorship includes the imprimatur of other authorities in different geoscientific fields, including Walter Alvarez, jointly famed with his father Luis for the discovery of the K-Pg boundary horizon and its impact connections in 1981. So it carries considerable weight. No doubt further comment and further papers on the Tanis site will emerge: DePalma has yet to complete his PhD. It may become the *lagerstätte* of the K-Pg extinction; in DePalma's words, 'It's like finding the Holy Grail clutched in the bony fingers of Jimmy Hoffa, sitting on top of the Lost Ark.' …

A role for iron in the origin of life **(May 2019)**

Experiments aimed at suggesting how RNA and DNA – prerequisites for life, reproduction and evolution – might have formed from a 'primordial soup' have made slow progress. Another approach to the origin of life is investigation of the most basic chemical reactions that it engages in. Whatever the life form, prokaryote or eukaryote, its core processes involve reducing carbon dioxide, or other simple carbon-bearing compounds, and water to synthesise organic molecules that make up cell matter. Organisms also engage in metabolising biological compounds to generate energy. At their root, these two processes mirror each other; a creative network of reactions and another that breaks compounds down, known as the Krebs- and the reverse-Krebs cycles. In living organisms both are facilitated by other organic compounds that, of course, are themselves produced by cells. How such networks arose under inorganic conditions remains unknown, but three biochemists at the University of Strasbourg in France (Muchowska, K.B. *et al*. 2019. Synthesis and breakdown of universal metabolic precursors promoted by iron. *Nature*, v. **569**, p. 104-107; DOI: 10.1038/s41586-019-1151-1) have designed an inorganic experiment. They aimed to investigate how two simple organic compounds, which conceivably could have formed in a lifeless early environment, might have been encouraged to kick-start basic living processes. These are glyoxylate ($HCOCO_2^-$) and pyruvate ($CH_3COCO_2^-$).

The most difficult chemical step in building complex organic compounds is inducing carbon atoms to bond together through C-C bonds; a process that thermodynamics tends to thwart but is accomplished in living cells by adenosine tri-phosphate (ATP). Previous workers focussed on interactions between reactive compounds, such as cyanide and formaldehyde, as candidates for the precursors of life, but such chemistry is totally different from what actually goes on in organisms. Joseph Moran, one of the co-authors of the paper, and his research group recently settled on five fundamental linkages of C, H and O as 'universal hubs' at the core of the Krebs cycle and its reverse. Kamila Muchowska and co-workers found that glyoxylate and pyruvate introduced into a simulated hydrothermal fluid that contains ions of ferrous iron (reduced Fe^{2+}) were able to combine in producing all five ‘universal hubs. Ferrous iron clearly acted as a catalyst, through being a powerful reducing agent or electron donor, to get around the stringencies of classic thermodynamics. Moran’s team had previously shown that pyruvate itself can form inorganically from CO_2 in water laced with iron, cobalt and nickel ions. Formation of glyoxylate in such a manner has yet to be demonstrated. Nevertheless, the two together in a watery soup of transition metal ions seem destined to produce an abundance of exactly the compounds at the root of living processes. In fact the experiment showed that all but two of the eleven components of the Krebs cycle can be synthesised inorganically.



Metal-rich ‘black smoker’ at a hydrothermal vent on the mid-Atlantic ridge(credit: Kate Larkin, Seascape, Belgium)

Until the rise of free oxygen in the Earth system some 2400 Ma ago, the oceans would have been awash with soluble ferrous iron. This would have been especially the case around hydrothermal vents that result from the interaction between water and hot mafic lavas of the oceanic crust, together with less abundant transition-metal ions, such as those of nickel and cobalt. The ocean-vent hypothesis for the origin of life seems set for a surge forward.

See also: Katsnelson, A. 2019. Iron can catalyse metabolic reactions without enzymes.

Geochemical background to the Ediacaran explosion **(June 2019)**

The first clear and abundant signs of multicelled organisms appear in the geological record during the 635 to 541 Ma Ediacaran Period of the Neoproterozoic, named from the Ediacara Hills of South Australia where they were first discovered in the late 19thcentury. But it wasn't until 1956, when schoolchildren fossicking in Charnwood Forest north of Leicester in Britain found similar body impressions in rocks that were clearly Precambrian age that it was realised the organism predated the Cambrian Explosion of life. Subsequently they have turned-up on all continents that preserve rocks of that age (see: Larging the Ediacaran, March 2011). The oldest of them, in the form of small discs, date back to about 610 Ma, while suspected embryos of multicelled eukaryotes are as old as the very start of the Edicaran (see; Precambrian bonanza for palaeoembryologists, August 2006).

Artist's impression of the Ediacaran Fauna (credit: Science)

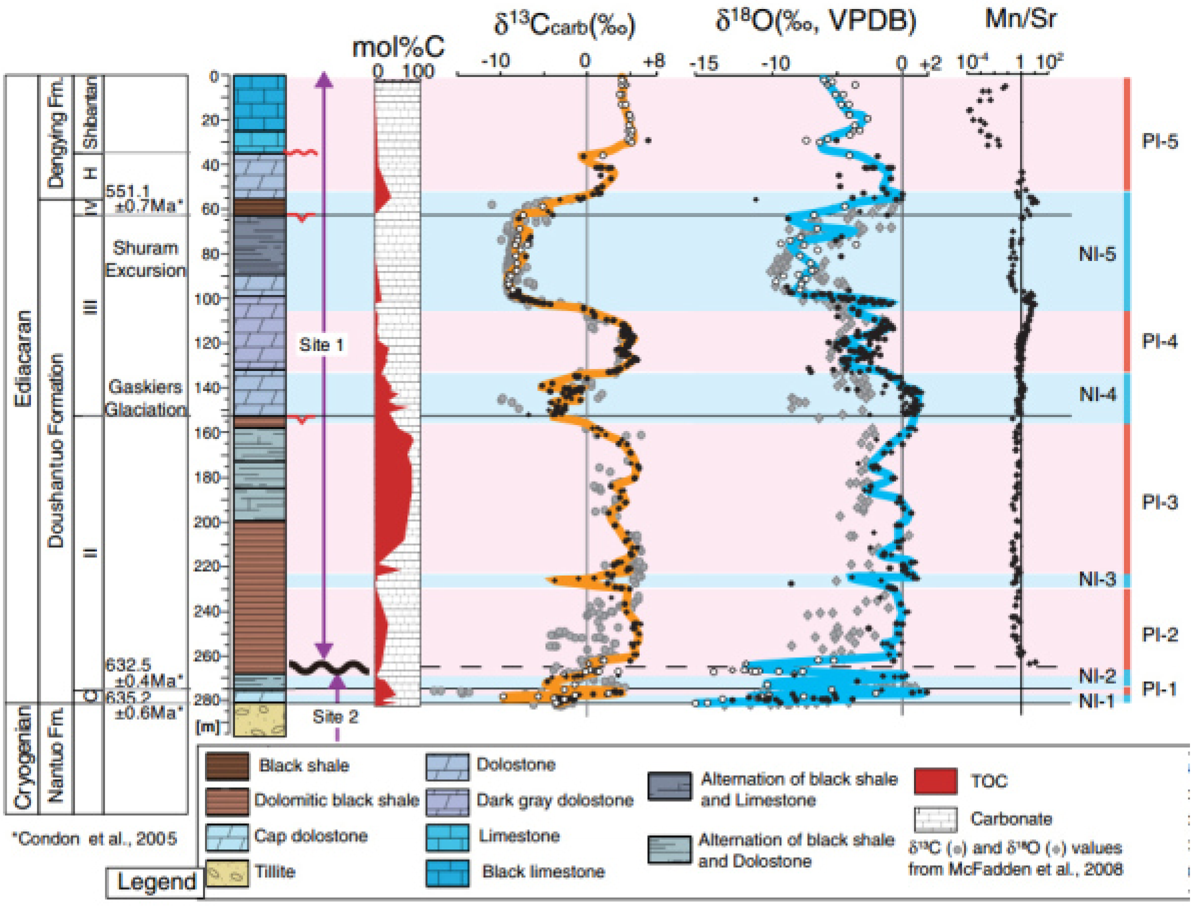
The Ediacaran fauna appeared soon after the Marinoan Snowball Earth glaciogenic sediments that lies at the top of the preceding Cryogenian Period (650-635 Ma), which began with far longer Sturtian glaciation (715-680 Ma). A lesser climatic event – the 580 Ma-old Gaskiers glaciation – just preceded the full blooming of the Ediacaran fauna. Geologists have to go back 400 million years to find an earlier glacial epoch at the outset of the Palaeoproterozoic. Each of those Snowball Earth events was broadly associated with increased availability of molecular oxygen in seawater and the atmosphere. Of course, eukaryote life depends on oxygen. So, is there a connection between prolonged, severe climatic events and leaps in the history of life? It does look that way, but begs the question of how Snowball Earth events were themselves triggered.

There are now large amounts of geochemical data from Neoproterozoic sedimentary rocks that bear on processes in the atmosphere, seawater, continental crust and the biosphere of the time. Some are indicative of the reducing/oxidising (redox) potentials of ocean water in which various sediments were deposited. Carbon isotopes chart organic burial and the abundance of CO_2 in the oceans and atmosphere. Strontium isotopes give details of the rates of continental erosion. The age statistics of zircon grains in sediments are useful; the proportion of zircons close in age to the time of sediment deposition relative to older grains is a proxy for the rate of continental-arc volcanism and thus for subduction rates. Joshua Williams of Britain's University of Exeter and colleagues from the universities of Edinburgh and Leeds have used complex modelling to assess the pace at which oxygen was added to the surface environment through the Ediacaran Period (Williams, J.J. *et al*. 2019. A tectonically driven Ediacaran oxygenation event. *Nature Communications*, v. **10**; DOI: 10.1038/s41467-019-10286-x).

They estimate a 50% increase in atmospheric oxygen during the Ediacaran to about 0.25 % of the present concentration, which would be sufficient to support large, mobile animals. They attribute this primarily to a boost in the supply of CO_2 to the atmosphere as a result of increased volcanic activity. This would have warmed the surface environment so that exposed rock on the continents underwent accelerated chemical weathering. By freeing from continental crust increased amounts of nutrients, such as phosphorus and potassium, the boost to photosynthesis would have increased the oceanic biomass, thereby emitting oxygen. Multicelled animals would have been beneficiaries of such a transformation. The trend continued into the Cambrian, thereby unleashing the explosion of animals and their evolution that continued through the Phanerozoic. Ultimately, the trigger was increased Late-Neoproterozoic tectonic activity that drove the massive Pan-African orogeny and the accretion of the Gondwana supercontinent.

See also: https://www.sciencedaily.com/releases/2019/06/190619130315.htm

Note added, 26 June 2019: Roger Mason has referred me to the carbon-isotope record during the Ediacaran. It shows some of the stratigraphic record's largest negative $\delta^{13}C$ excursions in carbonate rocks (Tahata, M. and 10 others 2013. Carbon and oxygen isotope chemostratigraphies of the Yangtze platform, South China: Decoding temperature and environmental changes through the Ediacaran. *Gondwana Research*, v.**23**, p. 333-353; DOI: 10.1016/j.gr.2012.04.005). Such isotopic excursions went on throughout the Ediacaran, along with sudden fossil appearances and disappearances – so-called 'Strangelove' oceans – plus fluctuations in sediment types and climate. The Ediacaran was a wild time in most respects.



Geochemical changes recorded in the complete Ediacaran sedimentary sequence of the Three Gorges of the Yangtze River, China (credit: Tahata et al. 2013; Fig. 4)

***A dinosaur nesting colony* (July 2019)**

Imagine visiting a colony of nesting seagulls on an exposed sandbar. Their nests are roughly equally spaced, out of pecking range. As well as incubating individuals on their nests the air is full of screaming birds swooping towards you, and even pecking or buffeting your head. But relatively few bird species nest in colonies. Some bury their eggs communally in warm sand or compost abandoning them for solar energy to hatch. That approach is also used by many reptiles, notably turtles and crocodiles, but some crocodiles do behave like gulls, females guarding their buried clutches, so why not dinosaurs? Brooding in colonies has been suspected of dinosaurs, although most fossil eggs seem to have been buried.

Upper Cretaceous sedimentary rocks in Mongolia have yielded more dinosaur eggs than most other places, especially in the northern Gobi Desert's largely unvegetated outcrops. It is from there that exquisitely preserved, firm evidence has emerged of dinosaurs nesting communally (Kanaka, K. and 9 others 2019. Exceptional preservation of a Late Cretaceous dinosaur nesting site from Mongolia reveals colonial nesting behavior in a non-avian theropod. *Geology*, v. **47**, p. 1-5; DOI: 10 .1130 /G46328.1). The site exposes 15 clutches about 1.5 m apart that, together, contain more than 50 spherical eggs 10 to 15 cm in diameter. Modern erosion has dissected the occurrences, and it is estimated that up to 32 clutches may have been laid in an area of ~286 m^2. That the eggs had been laid on the surface, covered – possibly with organic matter – and then incubated is clearly evidenced by all of them resting in pockets on an erosion surface covered by the same thin, continuous layer of bright red sand. About 60% of them seem to have hatched successfully. Each eggshell contains the same doubled-layered infill of fine sediment made of surrounding sediment and broken shell fragments.

Clutch of near-spherical dinosaur eggs from Mongolia: scale bar = 10 cm. (Credit: Kanaka et al. 2019; Fig. 2A)

The detail of the nests suggests that they were created on an exposed surface during a single dry season and after hatching, when their infills formed, they were gently flooded as stream levels rose to deposit the thin, red covering layer. Whether or not the eggs were brooded or merely protected cannot be assessed, despite the excellence of preservation. But the high hatching success suggests that adults fended off predators during incubation. Egg shape and size point to their having been laid by a single species of theropod dinosaur; probably not ancestral to birds, but a group that includes velociraptors and tyrannosaurs. Yet nest-tending has clear parallels among later birds.

***Last day of the dinosaurs* (September 2009)**

As they say, 'everyone knows' that the dinosaurs were snuffed out, except, of course, for those that had evolved to become birds and somehow survived. When it happened is known quite precisely – at the end of the Cretaceous (66.043 ± 0.011 Ma) – and there were two possible causal mechanisms: emissions from the Deccan Trap flood basalts and/or the Chicxulub impact crater. But what was the Cretaceous-Palaeogene (K-Pg) boundary event actually like? Many have speculated, but now there is evidence.

In 2016 a deep-sea drilling rig extracted rock core to a depth of 1.35 km beneath the sea floor off Mexico's Yucatan Peninsula, slightly off the centre of the circular Chicxulub structure (see K-T (K-Pg) boundary impact probed, November 2016). This venture was organised and administered jointly by the International Ocean Discovery Program IODP) and the International Continental Scientific Drilling Program (ICDP) as Mission Specific Platform Expedition no. 364. Results from the analysis of the cored rock sequence have been generating pulses of excitement among palaeontologists, petrologists and planetary scientist on a regular basis. The science has been relatively slow to emerge in peer-reviewed print. Appetites have been whetted and the first substantial paper is about the bottom 130 metres of the core (Gulick, S.P.S. and 29 others 2019. The first day of the Cenozoic. *Proceedings of the National Academy of Sciences*. 9 September 2019; DOI: 10.1073/pnas.1909479116). It might seem as though the publication schedule has been stage managed to begin with, literally, the 'bang' itself.

The deepest 20 m thick layer is mainly silicate glass. It was formed in the seconds after the 12 km-wide impactor arrived to smash through the water and sea-floor sediments of the early Caribbean Sea, at speed of around 20 Km s^{-1}. It vaporised water and rock as well as shoving aside the surrounding sea and blasting debris skyward and outward. In an instant a new hole in the crust was filled with molten rock. The overlying rock is a veritable apple-crumble of shattered debris mixed with and held together by glass, and probably formed as water flowed into the crater to result in explosive reaction with the molten crystalline crust beneath. The fragments lessen in size up the core, probably reflecting ejected material mixed in the displaced seawater. Impact specialists have estimated that this impactite layer formed in little more than ten minutes after collision. The glass-laden breccia is abruptly capped by bedded sediments, considered to have been delivered by the backwash of a huge, initial tsunami. In them are soils and masses of charcoal, from the surrounding land areas, scorched and burnt by the projectile's entry flash, inundated by the tsunami and then dragged out to sea as it receded. These are the products of the hours following the impact as successive tsunamis swashed to and fro across the proto-Caribbean Basin; hence 'The first day of the Cenozoic', of Gulick *et al*.'s title.

Artist's impression of the Chicxulub impact (Credit: Barcroft Productions for the BBC)

Other cores drilled beyond the scope of the Chicxulub crater during offshore oil exploration show a sequence of limestones with thick beds of gypsum ($CaSO_4.2H_2O$). Yet the crater debris itself contains no trace of this mineral. Around 325 Gt of sulfur, almost certainly in the form of SO_2, entered the atmosphere on that first day, adding to the dust. Ending up in the stratosphere as aerosols it would have diffused solar radiation away from the surface, resulting in an estimated 25°C global cooling that lasted 25 years. The sulfur oxides in the lower atmosphere ended up in acid rain that eventually acidified the upper ocean to devastate shallow-marine life.

See also: Amos, J. 2019. The day the dinosaurs' world fell apart. (BBC News 10 September 2019); Rocks at asteroid impact site record first day of dinosaur extinction(Phys.org*)*; Wei-Haas, M. 2019. Last day of the dinosaurs' reign captured in stunning detail. *National Geographic*, 9 September 2019.

***What followed the K-Pg extinction event?* (October 2019)**

A study of boron isotopes in the tests of foraminifera that lived deep in the oceans and near their surface just after the K-Pg boundary event has revealed that ocean water suddenly became more acidic (Henehan, M.J. and 13 others 2019. Rapid ocean acidification and protracted Earth system recovery followed the end-Cretaceous Chicxulub impact. *Proceedings of the National Academy of Sciences*. Online; DOI: 10.1073/pnas.1905989116). Because the data came from marine sediment sequences exposed in Europe and North America and from ocean-floor cores beneath the Atlantic and Pacific Oceans, the acidification was global in scope. The sharp fall in pH, almost certainly due to massive release of sulphuric and carbonic acids from thick anhydrite and limestone beds beneath the Chicxulub impact site was instrumental in the collapse of marine ecosystems. A rebound to higher, more alkaline pH values (overshooting those of the preceding Late Cretaceous) was equally rapid. That is ascribed to the post-extinction dearth of marine organisms that take up calcium in their shells so that dissolved Ca became more abundant. Within less than 100 ka of the Chicxulub impact ocean pH had returned to its pre-impact levels. Since Deccan flood-basalt volcanism was active until long after, Henehan *et al*. consider that its influence on ocean acidification was minimal and that The Chicxulub impact 'was key in driving end-Cretaceous mass extinction'.

Records of marine fossils are both more abundant and continuous than are those of land-based organisms. That animal extinctions on the continents were dramatic has been clear for over a century. Entire classes, notably the dinosaurs (except for birds), as well as orders, families, genera and species disappear from the fossil record. The event more than decimated plant taxa too. How and at what pace the vacated ecological niches were reoccupied during the evolutionary radiation among what became modern fauna and flora remain poorly understood. For the first million years of post-impact time fossils of terrestrial and freshwater organisms are very rare. Well-dated sedimentary sequences are patchily distributed, and fossils preserved in them as rare as proverbial hen's teeth, apart from a few, better endowed strata separated by thick, unproductive sediments. A Lower Palaeocene site near Denver in Colorado, USA extends for 27 km. At first sight it does not impress palaeontologists, but it carries concretions that yield rich hauls of tiny vertebrate fossils. Dating using U-Pb dating of interleaved volcanic ash layers, stratigraphy based on normal and reversed polarity of remanent magnetism, and plant pollen variations. The 250 m thick sedimentary unit can be divided into 150 levels that represent the first million years flowing the Chicxulub impact (Lyson, T.R. and 15 others 2019. Exceptional continental record of biotic recovery after the Cretaceous-Paleogene mass extinction. *Science*, online first release; DOI: 10.1126/science.aay2268.

Reconstruction of the 35 kg early Palaeocene mammal Taeniolabis (credit: Wikipedia)

The levels contain abundant remains of early Cenozoic mammals, particularly skulls that are vitally important in taxonomy and size estimation. During the last few hundred thousand years of the Cretaceous, mammals about the size of a modern racoon (~8 kg) were abundant. The oldest Palaeocene holds nothing bigger than a 600 g rat, and few of them. Then, remarkably, the numbers, diversity and mean body mass of mammals grow; raccoon-size back within 100 ka then, in a series of steps, beasts around 25, 35 and 45 kg emerged successively during the next 600 ka. Clearly, the local food chain had to support this growth in size as well as numbers. Pollen records reveal a terrain first dominated by ferns – not especially nutritious – then after 200 ka by palms and finally legumes (pulses) appear. The diversification of animals and plants changed in lockstep. Studies of fossil-leaf shapes (toothed = cooler; smooth = warmer) indicated a similarly triple-stepwise amelioration in climate from cool, post-impact to hot by 65 Ma ago. This climatic warming may have been connected to successive pulses of Deccan volcanism that drove up atmospheric CO_2 levels. Geologically, that is pretty quick. In the context of a possible, equally rapid mass extinction as a result of anthropogenic factors, such a pace of recovery is hardly reassuring…

Extraterrestrial sugar **(November 2019)**

The coding schemes for Earth's life and evolution (DNA and RNA), its major building blocks and basic metabolic processes have various sugars at their hearts. How they arose boils down to two possibilities: either they were produced right here by the most basic, prebiotic processes or they were supplied from interplanetary or interstellar space. All kinds of simple carbon-based compounds turn up in spectral analysis of regions of star formation, or giant molecular clouds: CN, CO, C_2H, H_2CO up to 10 or more atoms that make up recognisable compounds such as benzonitrile (C_6H_5CN). Even a simple amino acid (glycene – CH_2NH_2COOH) shows up in a few nearby giant molecular clouds. Brought together in close proximity, instead of dispersed through huge volumes of near-vacuum, a riot of abiotic organic chemical reactions could take place. Indeed, complex products of such reactions are abundant in carbonaceous meteorites whose parent asteroids formed within the solar system early in its formation. Some contain a range of amino acids though not, so far, the five bases on which genetics depends: in DNA adenine, cytosine, guanine and thymine (replaced by uracil in RNA). Yet, surprisingly, even simple sugars have remained elusive in both molecular clouds and meteorites.

Artist's impression of the asteroid belt from which most meteorites are thought to originate (Credit: NASA/JPL)

A recent paper has broken through that particular barrier (Furukawa, Y. *et al.* 2019. Extraterrestrial ribose and other sugars in primitive meteorites. *Proceedings of the National Academy of Sciences*. Online; DOI: 10.1073/pnas.1907169116). Yoshihiro Furukawa and colleagues analysed three carbonaceous chondrites and discovered traces of 4 types of sugars. It seems that sugar compounds have remained elusive because those now detected are at concentrations thousands of times lower than those of amino acids. Contamination by terrestrial sugars that may have entered the meteorites when they slammed into soil is ruled out by their carbon isotope ratios, which are very different from those in living organisms. One of the sugars is ribose, a building block of RNA (DNA needs deoxyribose). Though a small discovery, it has great significance as regards the possibility that the components needed for living processes formed in the early Solar System. Moon formation by giant impact shortly after accretion of the proto-Earth would almost certainly have destroyed such organic precursors. So, if the Earth's surface was chemically 'seeded' in this way it is more likely to have occurred at a later time, perhaps during the Late Heavy Bombardment 4.1 to 3.8 billion years ago (see: Did mantle chemistry change after the late heavy bombardment? In *Earth-logs* September 2009)

***When rain kick-started evolution* (December 2019)**

The end of the Palaeozoic Era was marked by the greatest known mass extinction at the Permian-Triassic boundary 252 Ma ago. An estimated 96% of known marine fossil species simply disappeared, as did 70% of vertebrates that lived on land. Many processes seem to have conspired against life on Earth although it seems that one was probably primary: the largest known flood-basalt event, evidence for which lies in the Siberian Traps. It took as long as 50 Ma for ecosystems to return to their former diversity. But, oddly, it was animals at the top of the marine food chain that recovered most quickly, in about 5 million years. There must have been food in the sea, but it was at first somewhat monotonous. The continents were still configured in the Pangaea supercontinent, so much land was far from oceans and thus dry. Oxygen was being drawn down from the atmosphere to combine with iron in Fe_2O_3 to form vast tracts of redbeds for which the Triassic is famous. From a peak of 30% in the Permian, atmospheric oxygen descended to 16% in the early Triassic, so living even at sea level would have been equivalent to surviving today at 2.7 km elevation today. Potential ecological niches were vastly reduced in fertility and in altitude, and Pangaea still had vast mountain ranges inherited from its formative tectonics as well as being arid, apart from in polar regions. Unsurprisingly, recovery of terrestrial diversity, especially among vertebrates, was slow during the early Triassic.

Triassic grey terrestrial sediments on the Somerset coast of SW England (credit: Margaret W.Carruthers; https://www.flickr.com/photos/64167416@N03/albums/72157659852255255)

Then, about halfway through the Triassic Period, it began to rain across Pangaea. Whether that was continual or seasonal is uncertain, although the presence of large mountains and high plateaus would favour monsoon circulation, akin to the present-day Indian monsoon associated with the Himalaya and Tibetan Plateau. How do geologists know that central Pangaea became wetter? The evidence lies in grey sedimentary strata between the otherwise universal redbeds, which occur in the Carnian Age and span one to two million years around 232 Ma (Marshall, M. 2019. Did a million years of rain jump-start dinosaur evolution? *Nature*, v. **576**, p. 26-28; doi: 10.1038/d41586-019-03699-7). A likely driver for this change in colour is a rise in water tables that would exclude oxygen from sediments deposited recently. The red Iron-3 oxides were reduced, so that soluble iron-2 was leached out. Some marine groups, such as crinoids, underwent a sudden flurry of extinctions, as did plants and amphibians on land. But others received a clear boost from this Carnian Pluvial Event. A few dinosaurs first appear in older Triassic sediments, but during the Carnian they began to diversify from diminutive bipedal species into the main groups so familiar to many: ornithischians that lead to *Stegosaurus* and *Triceratops* and the forerunners of the saurischians that included huge long-necked herbivores and the bipedal theropods and birds. Within 4 Ma dinosaurs had truly begun their global hegemony. Offshore in shallow seas, the scleractinian corals, which dominate modern coral reef systems, also exploded during the Carnian from small beginnings in the earlier Triassic. It is even suspected that the Carnian nurtured the predecessor of mammals, although the evidence is only from isolated fossil teeth.

A Carnian shift in carbon isotopes, measured in Triassic limestones of the Italian Dolomites, to lower proportions of the heavier ^{13}C suggests that a huge volume of the lighter ^{12}C had entered the atmosphere. That could have resulted from large-scale volcanism, the 232 Ma old laves of the Wrangell Mountains in Alaska being a likely suspect. Such an input would have had a warming climatic outcome that would have increased tropical evaporation of ocean water and the humidity over continental masses. The once ecologically monotonous core of Pangaea may have greatly diversified into many more niches awaiting occupants, thereby stimulating the terrestrial evolutionary burst. Perhaps ironically, and fortunately, a volcanic near snuffing-out of life on Earth was soon followed by another with the opposite effect. Yet another negative outcome arrived with the flood basalts of the Central Atlantic Magmatic Province at the end of the Triassic (201 Ma), to be followed by further adaptive radiation among those organisms that survived into the Jurassic.

How marine animal life survived (just) Snowball Earth events **(December 2019)**

Glacial conditions during the latter part of the Neoproterozoic Era extended to tropical latitudes, probably as far as the Equator, thereby giving rise to the concept of Snowball Earth events. They left evidence in the form of sedimentary strata known as diamictites, whose large range of particle size from clay to boulders has a range of environmental explanations, the most widely assumed being glacial conditions. Many of those from the Cryogenian Period are littered with dropstones that puncture bedding, which suggest that they were deposited from floating ice similar to that forming present-day Antarctic ice shelves or extensions of onshore glaciers. Oceans on which vast shelves of glacial ice floated would have posed major threats to marine life by cutting off photosynthesis and reducing the oxygen content of seawater. That marine life was severely set back is signalled by a series of perturbations in the carbon-isotope composition of seawater. Its relative proportion of ^{13}C to ^{12}C ($\delta^{13}C$) fell sharply during the two main Snowball events and at other times between 850 to 550 Ma. The Cryogenian was a time of repeated major stress to Precambrian life, which may well have speeded up evolution, sediments of the succeeding Ediacaran Period famously containing the first large, abundant and diverse eukaryote fossils.

A Cryogenian glacial diamictite containing boulders of many different provenances from the Garvellach Islands off the west coast of Scotland. (Credit: Steve Drury)

For eukaryotes to survive each prolonged cryogenic stress required that oxygen was indeed present in the oceans. But evidence for oxygenated marine habitats during Snowball Earth events has been elusive since these global phenomena were discovered. Geoscientists from Australia, Canada, China and the US have applied novel geochemical approaches to occasional iron-rich strata within Cryogenian diamictite sequences from Namibia, Australia and the south-western US in an attempt to resolve the paradox (Lechte, M.A. and 8 others 2019. Subglacial meltwater supported aerobic marine habitats during Snowball Earth. *Proceedings of the National Academy of Sciences*, 2019; 201909165 DOI: 10.1073/pnas.1909165116). Iron isotopes in iron-rich minerals, specifically the proportion of ^{56}Fe relative to that of ^{54}Fe ($\delta^{56}Fe$), help to assess the redox conditions when they formed. This is backed up by cerium geochemistry and the manganese to iron ratio in ironstones.

In the geological settings that the researchers chose to study there are sedimentological features that reveal where ice shelves were in direct contact with the sea bed, i.e. where they were 'grounded'. Grounding is signified by a much greater proportion of large fragments in diamictites, many of which are striated through being dragged over underlying rock. Far beyond the grounding line diamictites tend to be mainly fine grained with only a few dropstones. The redox indicators show clear changes from the grounding lines through nearby environments to those of deep water beneath the ice. Each of them shows evidence of greater oxidation of seawater at the grounding line and a falling off further into deep water. The explanation given by the authors is fresh meltwater flowing through sub-glacial channels at the base of the grounded ice fed by melting at the glacier surface, as occurs today during summer on the Greenland ice cap and close to the edge of Antarctica. Since cold water is able to dissolve gas efficiently the sub-glacial channels were also transporting atmospheric oxygen to enrich the near shore sub-glacial environment of the sea bed. In iron-rich water this may have sustained bacterial chemo-autotrophic life to set up a fringing food chain that, together with oxygen, sustained eukaryotic heterotrophs. In such a case, photosynthesis would have been impossible, yet unnecessary. Moreover, bacteria that use the oxidation of dissolved iron as an energy source would have caused Fe-3 oxides to precipitate, thereby forming the ironstones on which the study centred. Interestingly, the hypothesis resembles the recently discovered ecosystems beneath Antarctic ice shelves.

Small and probably unconnected ecosystems of this kind would have been conducive to accelerated evolution among isolated eukaryote communities. That is a prerequisite for the sudden appearance of the rich Ediacaran faunas that colonised sea floors globally once the Cryogenian ended. Perhaps these ironstone-bearing diamictite occurrences where the biological action seems to have taken place might, one day, reveal evidence of the precursors to the largely bag-like Ediacaran animals