First Life (Inevitable Life?)

Update #5 to *Human Origins: How diet, climate and landscape shaped us*

John S. Compton (www.johnscompton.com)

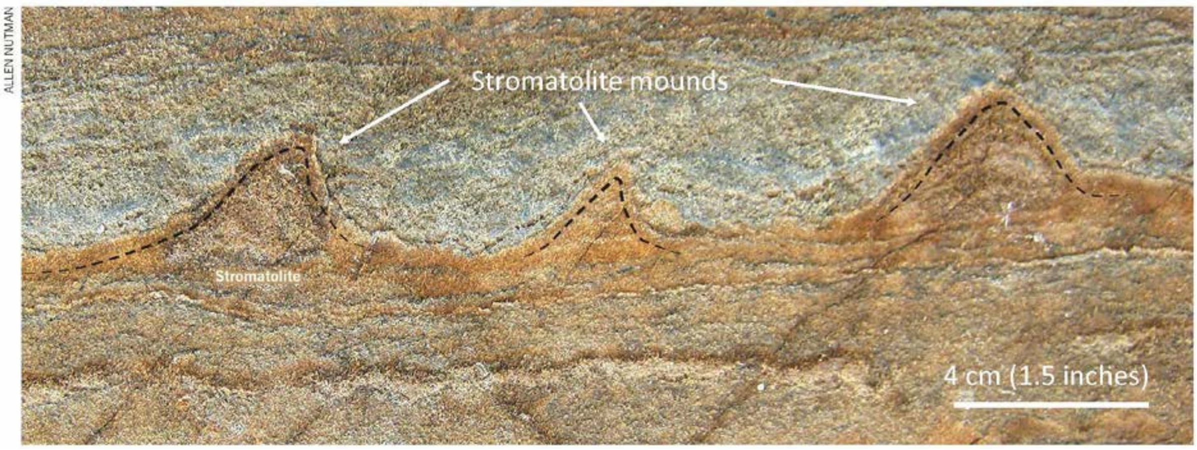
Several recent papers present evidence that life was established early on, soon after Earth's fiery and cataclysmic assembly had ended and its surface had cooled down into a watery world capable of sustaining life. Such an early start implies that life, rather than being unique to Earth may be, if not inevitable, then at least a highly likely outcome here as well as on other Earth-like planets. Give life half a chance and it will rise up and thrive. A result which perhaps shouldn't come as too big a surprise considering the tenacity with which life has persisted and diversified over the many billions of years since it first emerged. One way to ascertain if life on Earth was a highly likely or inevitable outcome is to find it elsewhere. The recent discovery of thousands of distant planets (exoplanets) orbiting within the watery, and hence potentially habitable zone of their stars is a promising sign that we may be closing in on evidence that life does exists out there in the great beyond. Confirming life on just one exoplanet would imply that our universe is home to a multitude of living worlds peppered across its enormous expanse. This is a mind-boggling concept even if our chances of ever directly interfacing with life elsewhere is remote given the distances involved. As our search for life on distant planets continues, we can also look long and hard for evidence of the earliest life here on Earth. Establishing when life first appeared on Earth can provide us with valuable insights into how life might have come about, but finding convincing evidence of life in the ancient rock record is a difficult task.

The first problem is that most life never leaves even a hint of its existence in the rock record. Life is fragile and readily decomposes such that most living things upon death rapidly vanish, recycled back into the world of non-living elements. Hence, fossil remains of life are rarely preserved in rocks of any age, never mind long ago when the abundance and types of life forms were far more limited than today. The other problem is that older rocks become increasingly difficult to find the further back in time you go. This is because Earth is dynamic, with the movement of its crustal plates (plate tectonics) constantly recycling older rocks into younger rocks. The evidence of life can only be found in the rock record and, therefore, the oldest rocks define the limit of how far back we can potentially detect life. And even for those oldest rocks that we are lucky enough to find and that once harboured fossils, most have since been subjected to intense pressures and temperatures over the dynamic history of their long existence. Such abuse is likely to obscure, if not destroy, whatever original fossil evidence the now transformed rocks may have once contained. Despite these problems, what does the rock record reveal about the earliest life on Earth?

The oldest rocks yet found are around 4 billion years old and occur in Canada and Greenland. We know from the age and composition of meteorites that our solar system formed initially 4.56 billion years ago. It was at this time that Earth's assembly began by the collision of the many small rocky and metallic bits circling the Sun in our planet's orbit. Initially gravity pulled in surrounding dust and rock to form small planets (planetissmals) and then these collided gradually to form larger planets. The final, major planetissmal collision that went into the making of Earth occurred 4.44 billion years ago. Our Moon formed from the debris of this collision and the force of the collision transformed Earth into a magma ball, too hot to sustain life. Life could have conceivably been established once the magma ball had cooled and crusted over, and the water vapour had condensed to form the oceans. Conditions on Earth however remained challenging to life as it had to contend with periods of intense bombardment by the sweeping up of the remaining rocky bits. This time of heavy meteorite bombardment is known as the Hadean, named after Hades, god of the underworld. The intense bombardment and the Hadean ended 4 billion years ago to give way to the Archean. To whatever extent life may have started during the Hadean, it was only by the start of the Archean that Earth presented a relatively stable setting for life to persist.

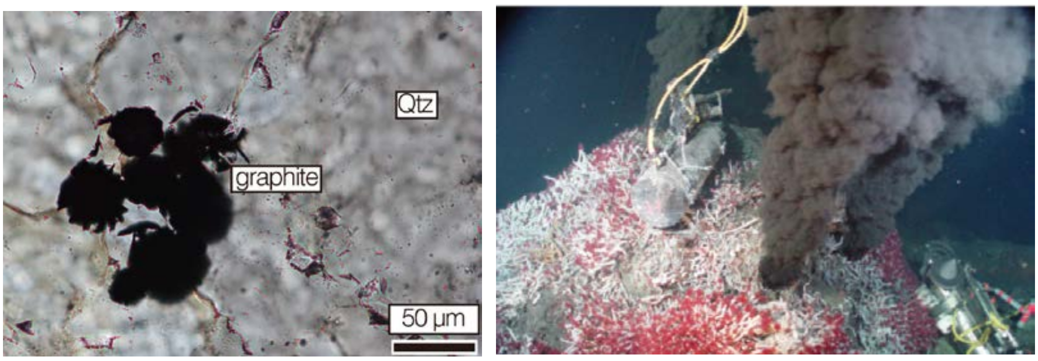
The Hadean (left) was a hellish period of intense meteorite bombardment and vaporised oceans, conditions that were generally not favourable to life, while the Archean world (right) included oceans of water and conditions suitable for the earliest microbial life forms.

The oldest, direct fossil evidence of life is in the form of stromatolites. Stromatolites are mound-shaped structures that form from the activities of microbial mat communities. Stromatolites are common throughout much of the early rock record and some still form today in places like Shark Bay, Western Australia. The minute microorganisms themselves are rarely preserved, but the layered stromatolite structures they build as a result of their activities often are preserved. The distinctive features of stromatolites rule out alternative, non-biological origins for the layered structures, such as the deposition of mineral crusts. The oldest stromatolites were recently discovered in rocks from Greenland 3.7 billion years old (Nutman and others, 2016), significantly older than the previously oldest stromatolites known from Australia dated to 3.48 billion years.



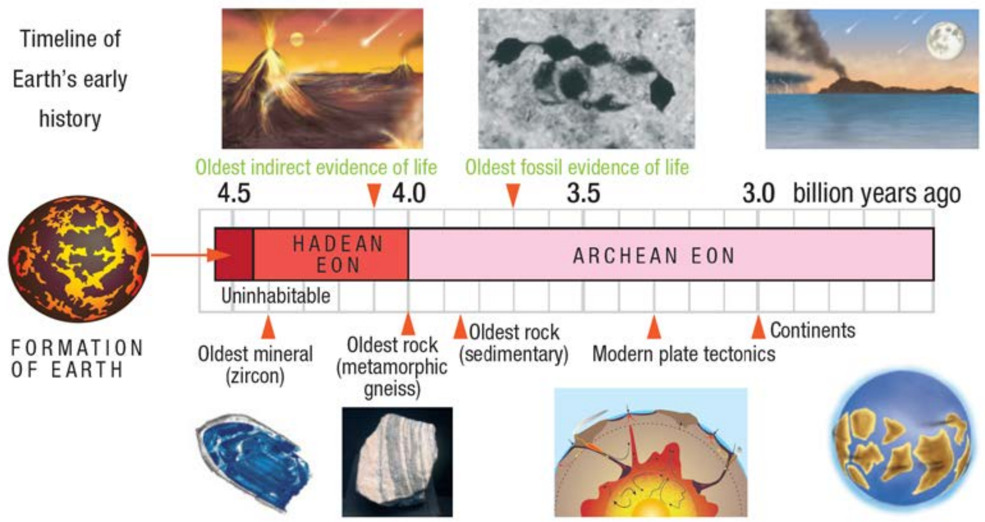
Small conical-shaped mounds (dashed lines) in rocks from Greenland 3.7 billion years old are interpreted to be stromatolites formed by microbial communities (photo by Allen Nutman adapted from Allwood, 2017).

Going back beyond 3.7 billion years, the evidence of life relies on the chemical signature of what is interpreted to be the remains of once living organisms as well as possible fossils. Life on Earth is carbon based and hence most organisms are made up of a significant amount of carbon. For life that grows by taking up carbon directly as CO_2, the lighter carbon isotope (carbon 12) is taken up preferentially to the heavier isotope (carbon 13) (the heaviest isotope (carbon 14) is radioactive and has a short life span). The preferential uptake of the light isotope gives life a distinct, negative carbon isotopic composition. When organisms die and their organic matter decomposes, most of the other elements besides carbon, such as nitrogen, phosphorus, oxygen and hydrogen are lost and eventually all that remains is carbon. When heated up under pressure the remaining organic carbon can form the mineral graphite (a soft, grey mineral that is familiar to us as pencil lead). At extreme pressures graphite can transform to diamond. Some have found organic matter in rocks from Greenland greater than 3.7 billion years old that still contains some oxygen, hydrogen, nitrogen and phosphorus because it was preserved as inclusions within the metamorphic mineral garnet (Hassenkam and others, 2017). But in most cases all that remains is pure carbon in the form of graphite. Graphite from rocks in Labrador Canada greater than 3.95 billion years old have carbon isotope values that suggest the carbon was originally part of living organisms. Some of the graphite takes on globular shapes common to some microorganisms (Tashiro and others, 2017). Structures in rocks at least 3.77 billion year old from Quebec Canada interpreted to represent fossil microorganisms suggest that mid-ocean ridge submarine hydrothermal vents or 'black smokers' are a potential setting in which early life evolved on Earth (Dodd and others, 2017). Unfortunately, the structures interpreted to be fossil bacteria and the carbon isotope values of graphite interpreted to indicate life processes can both be produced by reactions that do not involve living organisms. Therefore, the indications of life earlier than the 3.7-billion-year-old stromatolites are compelling, but remain ambiguous.



Cluster of globular graphite in quartz chert from Canada is suggestive of fossilised microbial organisms (left, from Tashiro and others, 2017). A modern submarine volcanic vent or 'black smoker' is a possible setting where life first emerged on Earth (image from NOAA).

The oldest known rocks are around 4 billion years old, so how can we say anything about earlier periods of Earth history? Some younger rocks contain mineral grains derived from the erosion of older rocks. Zircon is a highly durable mineral that often ends up being eroded out of older rocks but is not destroyed by weathering and ends up being recycled into younger rocks. In fact, the oldest known mineral is zircon dated to as old as 4.38 billion years in rocks from Jack Hills, Western Australia. A small number of these zircon grains have minute inclusions of graphite. The graphite in a zircon grain dated to 4.1 billion years has a carbon isotope signature consistent with a biological origin, but again not unambiguously (Bell and others, 2015). Therefore, the recent evidence pushes back the earliest life on Earth from around 1000 million years to at least 700 million and possibly 300 million years following the final major collisional event 4.44 billion years ago. Assuming it took on the order of 100 million years for Earth to become habitable after the final major collisional event, reduces the time span of life's emergence to between 600 and 200 million years.



Timeline of early Earth history from its formation as a molten, magma ball, through the hellish Hadean and into the Archean. Oldest direct fossil evidence of life is from stromatolites in rocks 3.7 billion year old and indirect chemical evidence of life comes from rocks around 4 billion year old and from graphite inclusions in zircon minerals 4.1 billion years old.

What is the significance of the suggested narrowing of the time it took life to emerge on Earth? The more rapidly life was established, the less difficult or improbable it would appear to be. The origin of life remains a major unknown. We know that early Earth likely had an enormous diversity of chemical compounds to work with including amino acids, which are the building blocks of all life today. But whether life was inevitable or even highly likely to come about is open to debate, because it remains unclear how these compounds became organised into self-replicating, evolving organisms. It could be that the emergence of life is simply too slow a process for us to replicate in the lab. Even the simplest of life forms, bacteria, involve an incredibly complex array of biochemical reactions and processes that would have taken time to evolve from the diverse pool of chemical compounds available. Although less than previously thought, several hundred million years is still a long span of time over which life could have gradually emerged.

It seems unlikely that the rock record will allow us to refine the timing much more or to push it back much further. Thus, the implied ease at which life can emerge on a place like Earth will perhaps have to wait for the discovery of life on another planet. Just what form life will take on other planets is unknown, but if at all like Earth, life is most likely to be dominated by diverse yet small, simple microbial organisms. Perhaps quick to get started, life on Earth appears to have remained fairly simple for a long period of time. It took around a billion years before the more complex eukaryotic cells evolved and another two billion years or so after that before animals evolved. The delay in the evolution of animals has been attributed to the need of an oxygen-rich atmosphere. For the latest ideas on what may have controlled oxygen levels in the atmosphere and how the level became high enough for animals, check out my next blog update #6: First Animals.

Further reading

Allwood, A.C., 2016. Evidence of life in Earth's oldest rocks. *Nature* 537, 500-501 (doi:10.1038/nature19429).

Bell, E.A., and others, 2015. Potentially biogenic carbon preserved in a 4.1 billion-year-old zircon. *PNAS* 112, 14518–14521 (www.pnas.org/cgi/doi/10.1073/pnas.1517557112).

Dodd, M.S., and others 2017. Evidence for early life in Earth's oldest hydrothermal vent precipitates. *Nature* 543, 60-64 (doi:10.1038/nature21377).

Hassenkam, T., and others, 2017. Elements of Eoarchean life trapped in mineral inclusions. *Nature* 548, 78-81 (doi:10.1038/nature23261).

Nutman, A.P., and others, 2016. Rapid emergence of life shown by discovery of 3,700-million-year-old microbial structures. *Nature* 537, 535-538 (doi:10.1038/nature19355).

Tashiro, T., and others, 2017. Early trace of life from 3.95 Ga sedimentary rocks in Labrador, Canada. *Nature* 549, 516-518 (doi:10.1038/nature24019).