First Animals

Update #6 to *Human Origins: How diet, climate and landscape shaped us*

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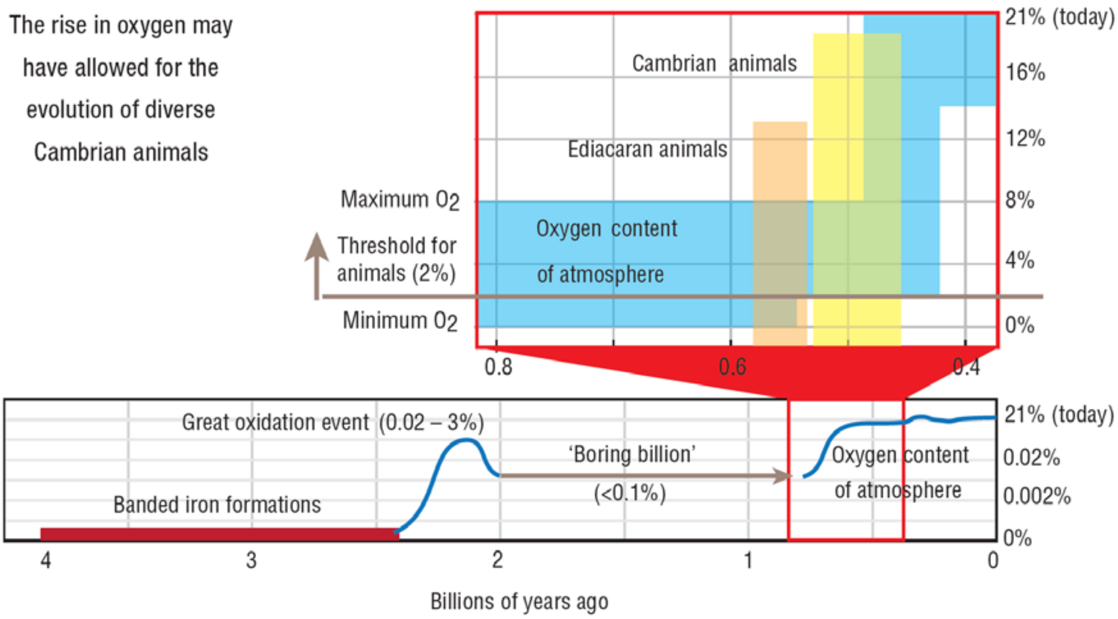
The sudden, but relatively late appearance of animals in the rock record has both fascinated and puzzled scientists for years. Simple bacteria emerged as early as 4000 million years ago, soon after Earth had become habitable (refer to my previous blog: First Life), but complex animals appeared only around 600 million years ago and burst onto the scene from 541 million years ago as part of the 'Cambrian Explosion.' The delay in the evolution of animals is usually attributed to low levels of oxygen gas in Earth's atmosphere, which had to first rise above a threshold value before animals could proliferate. This idea finds support from rock record, which indicates that the arrival of animals coincides broadly with when oxygen levels increase sharply. But why did oxygen levels remain so low for so long, and what was it that led to our oxygen-rich atmosphere and the rapid evolution of diverse animal life?



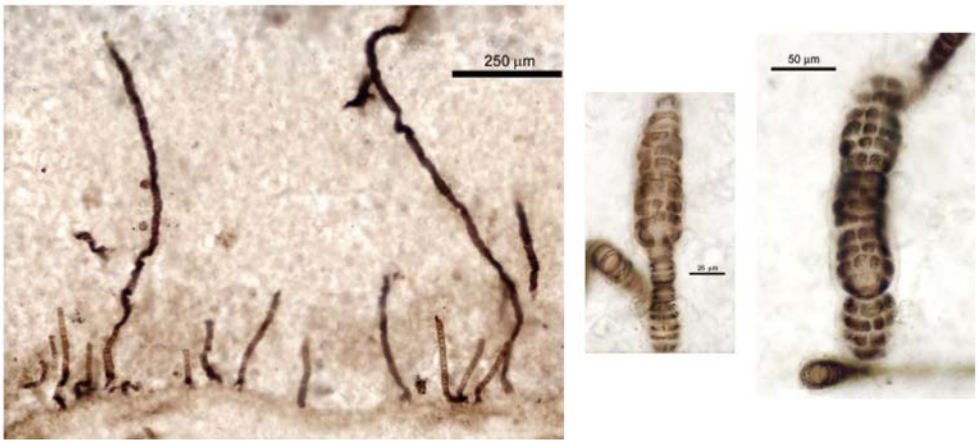
Earth initially had no oxygen gas in its atmosphere, and oxygen remained at low levels (<0.1%) during the 'boring billion' years before it rapidly increased between 600 and 500 million years ago coinciding with the appearance of the earliest animals (adapted from Sperling and others, 2015).

In my book I state that we animals may owe thanks to the algae for our existence. This concept finds support in a recent paper by Brocks and others (2017), in which they show that the transition to an animal world corresponds to when algae suddenly became the dominant primary producers. Primary producers form the base of the food chain by using sunlight to grow by photosynthesis. Oxygen gas is a by-product of photosynthesis, a biological process that is ultimately responsible for our oxygen-rich atmosphere. They propose that greater availability of the nutrient phosphorus in the world's oceans allowed algae to dominate for the first time over bacteria as primary producers.

Algae are significantly larger and more complex than bacteria, and as a result algae are more likely to end up buried in sediment before they react with oxygen and are converted back into carbon dioxide. Hence, the 'rise of algae' resulted in a rise in oxygen levels through enhanced burial of organic matter. The scenario they propose is a good example of how interactions between the living and non-living worlds may have promoted ecological transformations that ultimately led to the emergence of the vast animal kingdom to which we belong. What is the evidence for the rise of algae?

There are a number of ways in which life can leave evidence of its existence in the rock record. Body fossils are the preserved remains of the actual animal and they most commonly consist of hard parts, such as teeth, bone or shell. In rare cases the rapid draping of fine sediment soon after death can preserve soft tissue structures (Lagerstätte). Trace fossils, such as footprints, burrows or tooth marks can also provide evidence, although linking them to a specific animal can be difficult. Molecular fossils are distinct chemical compounds made by organisms referred to as biomarkers. Biomarker molecules, if stable can indicate the existence of an organism or group of similar organisms even in the absence of any other fossil evidence. For example, compounds derived from steroids or sterols (called steranes) have been used to indicate when the first sponges appeared (Love and others, 2009). Sterane biomarkers specific to algae were used by Brocks and others (2017) to document when algae became abundant in the rock record. Importantly, their methods were designed to minimise contamination by petroleum products.

What the biomarker record of Brocks and others (2017) suggests is that, although algae had first appeared by around 1800 million years ago, algae only became dominant much later by 659-645 million years ago. Algae have far more complex, eukaryotic cells compared to bacteria (prokaryotic cells) and by 1600 to 1200 million years ago algae were the earliest multicellular organisms, having specialised cells for attachment, vertical elements and reproduction. These features represent major evolutionary innovations, and yet for all their innovativeness the algae do not appear to have displaced the bacteria as primary producers. Why not? In modern oceans bacteria tend to dominate in nutrient-poor waters, whereas algae take over once nutrients become more abundant. So, one possibility is that the early ocean had few nutrients, such as phosphorus, and that algae struggled to compete with bacteria until the nutrient content of the oceans increased. If this scenario is correct, then what could have increased the nutrient content of the oceans allowing algae to out compete bacteria?



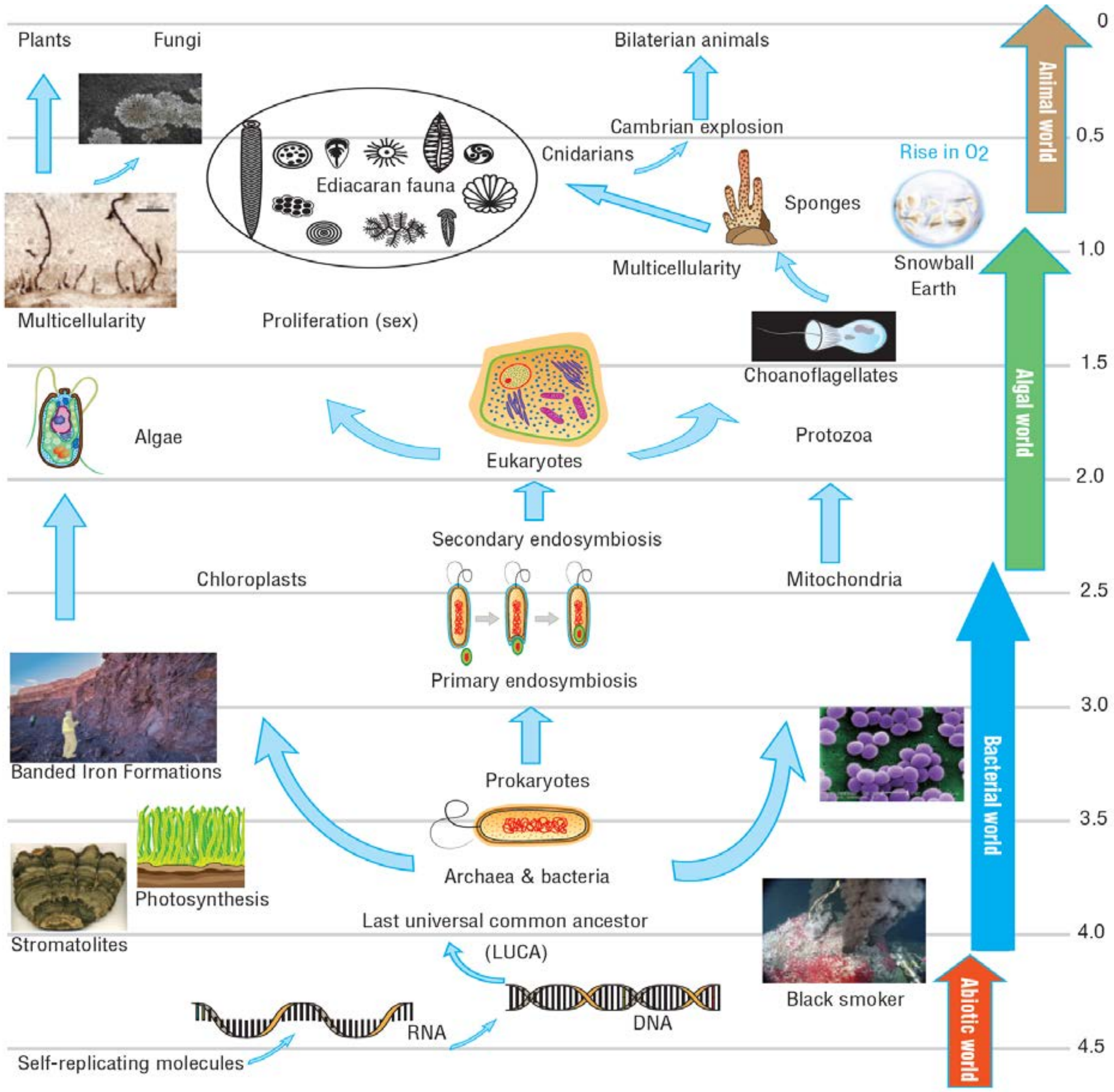
Fossil red algae 1200 million years ago grew in vertical filaments attached to a firm substrate and had reproductive structures (two images on the right) (images courtesy of Nicholas Butterfield).

Snowball Earth is an appropriate name for a most unusual period of Earth history, the Cryogenian, when our planet experienced extreme climate cycles of cold, near complete icing over to hot climates when all the ice rapidly melted. Significant variations in ice and climate are known from the past, but none was nearly as intense as the hot and cold cycles of the Cryogenian. Prior to Snowball Earth oxygen levels were steady and low (<0.1% compared to 21% today) from roughly 1800 to 800 million years ago, a period referred to as the 'boring billion' when Earth was locked into a low-oxygen atmosphere. A low-oxygen atmosphere may partly explain why the nutrient content of the ocean was also kept low for so long. Under low oxygen conditions, the ocean has more iron and iron can keep surface, sunlit surface waters where photosynthesis occurs low in phosphorus by removing it through adsorption to iron oxides. Whatever the reasons for its long stability, the 'boring billion' finally came to an end with the onset of Snowball Earth. The large ice sheets ground large amounts of rock into fine powder that then underwent intense chemical weathering in the ice-free hot climates that ensued. If this weathering released large amounts of phosphorus to the ocean, then it may have spurred on the algae who, having waited patiently in the wings for so long could now take off and displace bacteria as the dominant primary producers.

Snowball Earth is when our planet cycled between cold, ice-covered intervals (centre) and hot, ice-free climates (far left and right). The position of the continents was different then compared to today, with most positioned near the equator where intense weathering may have contributed to initiating Snowball Earth. Input of carbon dioxide, a greenhouse gas, by volcanoes (dark streaks in centre image) eventually warmed Earth and the ice melted.

The dominance of algae as primary producers was a major event and one that has endured ever since, most probably because it established a powerful feedback loop that rapidly led to an oxygen-rich atmosphere. Snowball Earth cycles released more nutrients, more nutrients fuelled more growth of large multicellular algae, some parts of which were more resistant to degradation than others and were more easily buried. Burial of more algal organic matter in turn allowed more oxygen to remain in the atmosphere. Higher oxygen levels resulted in an iron-poor, but nutrient-rich ocean, which promoted the growth and burial of algae and a continued rise in oxygen, rapidly exceeding the threshold level at which animals could thrive. Algae also promoted the evolution of animals by providing a large source of food. Single-celled animals feed on tiny bacteria but large, multicellular animals could fed on algae as well as on other animals consuming the algae. The result was a major global ecological shift to far more complex and intricate food chains cascading up from the algal primary producers.

The timing fits nicely with the rock record. The increase in algal biomarkers occurs between the major icing over episodes of the Cryogenian and coincides with a large, positive carbon isotope shift indicating more efficient organic matter burial just prior to the emergence of the earliest animals. The earliest animals include sponges, jelly fish and odd, pillow-like animals of the Ediacaran fauna that evolved around 600 million years ago and that by 541 million years ago were joined by diverse bilaterian animals, the dominant animals on Earth ever since. Thus, it took a major disruptor in the form of Snowball Earth to knock the biosphere into a new level of complexity driven by a greater flux of nutrients, more organic matter burial, an oxygen-rich atmosphere and more diverse, multicellular animals. If this scenario is correct then we humans, along with all the other animals living today owe thanks to the algae, who waited patiently for the conditions to arrive that allowed them to proliferate and in so doing ushered in the animal world.



Synopsis of the major events in the early evolution of life on Earth up to the emergence of complex animals (time is shown on the far right in billions of years ago).

Further reading

Brocks, J.J., and others, 2017. The rise of algae in Cryogenian oceans and the emergence of animals. *Nature* 548, 578-581 (doi:10.1038/nature23457).

Butterfield, N.J., 2002. *Bangiomorpha pubescens* n. gen., n. sp.: implications for the evolution of sex, multicellularity, and the Mesoproterozoic/Neoproterozoic radiation of eukaryotes. *Paleobiology* 26, 386-404.

Knoll, A.H., 2017. Food for early animal evolution. *Nature* 548, 528-530.

Love, G.D., and others, 2009. Fossil steroids record the appearance of Demospongiae during the Cryogenian period*.* *Nature* 457, 718-721 (doi:10.1038/nature07673).

Sperling, E.A. and others, 2015. Statistical analysis of iron geochemical data suggests limited late Proterozoic oxygenation. *Nature* 523, 451-454-721 (doi:10.1038/nature14589).