The fall and rise of the plankton

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Hidden deep within rocks of central Australia is a microfossil record that may revolutionise our interpretation of the evolution of plants and animals, thanks to an asteroid that slammed into South Australia 580 million years ago.

The geological timescale is very long. It takes even the most experienced geologist a long 'time' to come to terms with it. Here is an analogy that may help with perspective. Stretch out your arm and imagine its full length, from your nose to your fingertips, to be the entirety of geological time. Let your nose represent the time of Earth formation, 4.6 billion years ago, and the present day your fingertips. What may surprise you is that animals first appeared in the geological record half way along your palm, about 600 million years ago. If you accept the evidence of Earth's oldest fossils in Australia's geological record, which are 3.5 billion years old, microscopic organisms ruled Earth for nearly 3 billion years.

Animals evolved rapidly, so that by the end of the Cambrian Explosion (about 515 million years ago), a period of about 15 million years, most extant phyla had evolved [1]. The rapidity of animal genesis contrasts with the conservative rates of evolution prior to this and is a major problem in the history of life. This is not to say that there weren't some significant evolutionary events in the first 3 billion years of life, such as the evolution of eukaryotes and multi-cellularity. However, there are more questions than answers in the debate on what triggered the evolution of animals.

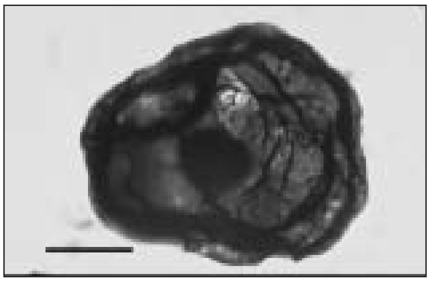

Figure 1. A simple, smooth-walled acritarch. Scale bar is 10µm.

Now a new theory has emerged that challenges all that has gone before.

About 600 million years ago the Earth was in crisis. Earth's most intense glaciation was at its peak, with glaciers extending to near the equator. Life stagnated for about 10 million years, then conditions improved dramatically. The small percentage of life forms that made it through this evolutionary bottleneck should have flourished and diversified markedly in the ensuing greenhouse Earth, re-populating niches opened-up by species that could not adapt to these freezing conditions. This is the 'Snowball Earth' theory [2] and it has been put forth as the trigger of the rapid evolution of plants and animals leading up to the Cambrian Explosion.

But this is not the story we are being told by Australia's microfossil record. The hypothesis is that the Acraman asteroid, which slammed into South Australia 580 million years ago, played a pivotal role in the evolutionary jump to more complex life forms [3].

The Acraman impact structure, Australia's largest known asteroid impact site, and one of the ten largest in the world, is located about 350kms northwest of Adelaide. The collapse crater is 85-90kms in diameter, which is about half the size of the 65 million year old Chicxulub crater at the Cretaceous-Tertiary geological boundary (when the dinosaurs were wiped out).

The estimated impact energy of Acraman exceeds the threshold for global catastrophe. Material thrown-out by the impact is spread over a radius of more than 500kms and provides a synchronous stratigraphic horizon against which to test the hypothesis that the impact was responsible for an unprecedented radiation and diversification of acritarchs – spheroidal microfossils of eukaryotic origin and planktonic habit – about 580 million years ago. It is about this time that we first see animals in the geological record. It could be the Proterozoic equivalent of the extinction of the dinosaurs.

Acritarchs are conventionally interpreted as metabolically inert resting stages of planktonic algae, their symmetric ornamentation reflecting morphological self-organisation during cyst-wall synthesis. They are comparable to modern cyst-forming planktonic algae (e.g. dinoflagellates). Before the Acraman impact event most acritarchs were simple and smooth-walled, with a diameter no more than 100µm, or 0.1mm (Figure 1). After the Acraman impact event most

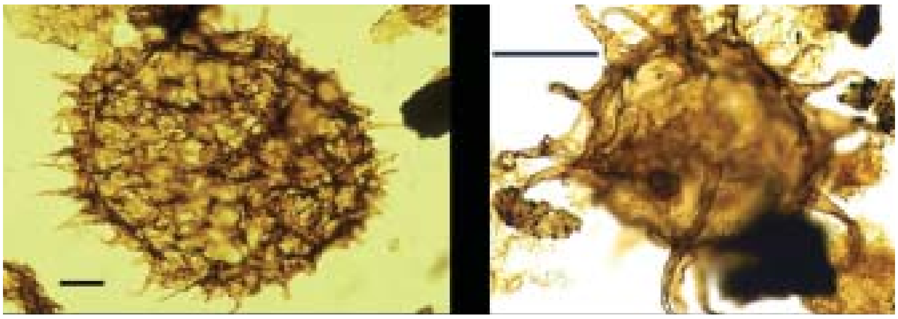

Figure 2. Complex, 'spiny' acritarchs. Scale bars: (A) 10µm; (B) 100µm.

acritarchs were complex and 'spiny', and up to 500µm in diameter (Figure 2) – ten times larger than younger planktonic algae.

The stratigraphic distribution of these fossil plankton from ten drill holes across Australia, as predicted by the Snowball Earth theory, indicates that bacterial mats and a few simple spherical species of plankton were the only organisms that managed to survive the intense ice age (Figure 3). As the sea level rose at the end of the ice age, these spherical forms increased in number, but there is no sign of a new species emerging to support ideas of the rapid diversification of life at this time. It wasn't until about 20 million years later that more than 50 new and highly complex species suddenly replaced the small number of simple species in the fossil record, immediately above the Acraman impact ejecta layer. The pattern of appearance of these first species is similar to those at other mass-extinction and recovery events in younger rocks.

It is also possible to use chemical fossils to discern patterns of extinction and radiation, or periods of low and high biological productivity. The stable isotopic ratio of carbon (carbon-12: carbon-13) in fossil organic matter is diagnostic of changes in productivity. In the modern oceans, plankton are the main primary producers. When they photosynthesise, they consume vast quantities of carbon dioxide, but they prefer to use carbon-12 because it is thermodynamically easier to incorporate. If productivity remains high over long periods, large amounts of carbon-12 are sequestered into ocean sediments, leaving the remaining carbon dioxide in the ocean relatively carbon-13 enriched. The result is a record of a positive carbon isotope shift in the geological record. Consequently, if there is a collapse in ocean productivity, there would be a negative isotope shift.

This is what appears to have happened after the Acraman impact event. There is a negative carbon isotope shift coinciding with the ejecta layer, probably as a result of a collapse in primary productivity. The Acraman impact theory[2] suggests that the impact-generated dust cloud was large enough to be globally distributed and severely restricted the amount of sunlight, thus dramatically reducing oceanic primary production through photosynthesis. Most of the algal species that did survive – the complex, spiny acritarchs – were highly resilient, and had the ability to remain dormant through the cosmic winter that followed. When the dust settled and the light conditions improved, these species had an advantage over their competitors and were able to proliferate and diversify. There is a steep positive carbon isotope shift which complements a renewed production and the appearance of the 50+ new species. These biotic and chemical changes were probably rapid and consistent with an impact-generated catastrophe of regional to global scale that affected the tempo of evolution.

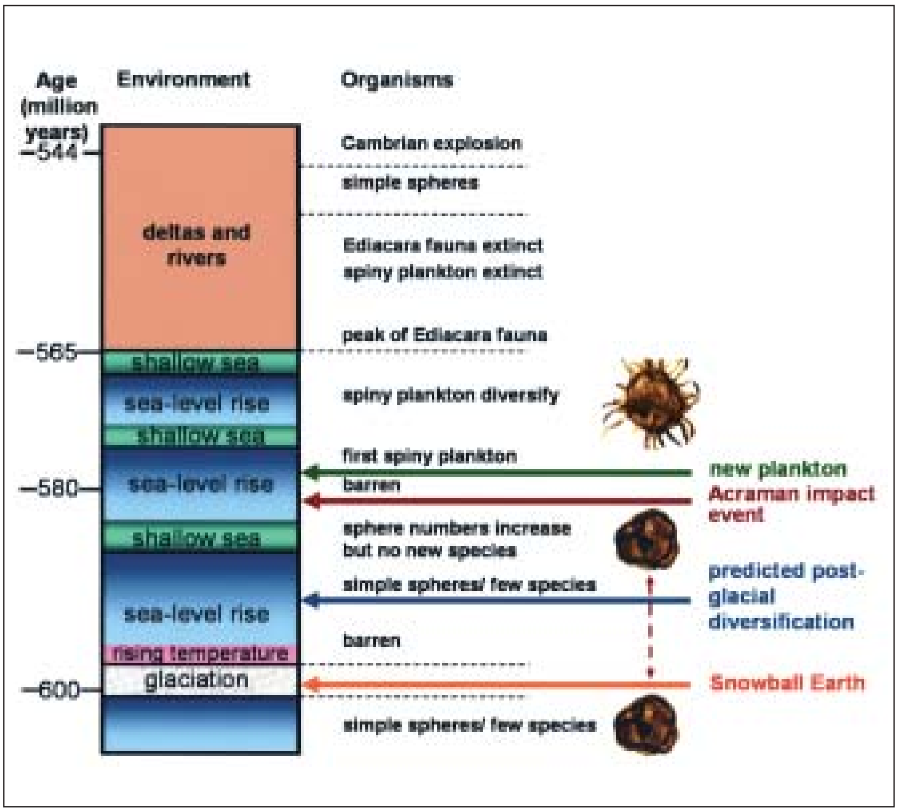

Figure 3. Stratigraphic distributions of organisms before and after the Acraman impact event.

Is it possible that the plankton diversification played a vital role in the subsequent development of the animals dependent on plankton as a food source? Or did the rise of the plankton play an indirect role?

It has long been postulated that atmospheric oxygen had to reach a critical concentration (about 10% of the present-day atmospheric level, or higher) for macroscopic animals to evolve and diversify rapidly. A way to increase the 'oxidising potential' of the atmosphere is to bury large amounts of organic carbon, which would mostly be of biological origin, in the oceans. There is a global positive carbon isotope excursion that continues after the Acraman event right up to the Cambrian boundary, a time span of about 20 million years.

In most situations, organic carbon is re-oxidised to carbon dioxide as it sinks through the water column. However, at the time of the Acraman impact event, and right up to the Cambrian boundary, the Earth's continents were breaking apart. Ocean basins were being formed, but they had an unusual feature – they were elongated and stagnant. This means they were able to bury and preserve unprecedented amounts of organic carbon, thereby releasing vast amounts of oxygen to the oceans and atmosphere. Did the Acraman impact event trigger a 20 million-year algal bloom that buried enough organic carbon to increase oxygen concentrations sufficiently for animals to evolve?

Research continues at the Australian Centre for Astrobiology to resolve the precision and timing of chemical and biotic changes at the Acraman impact ejecta layer, and to assess its greater impact on biological evolution. There are now collaborators in Sweden and the USA which attest to the international significance of the Acraman impact event. Preliminary microfossil results from rocks in China and Siberia show that there are some species in common with the spiny post-Acraman acritarchs from Australia, which will enable a global test of the Acraman impact theory in the near future. Watch this space.

References

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