in sediment samples collected from the Benguela upwelling system off the coast of Namibia. In the presence of sulphide-oxidizing bacteria, up to 11% of the phosphorus radiotracer spike was converted into apatite. In the absence of these bacteria, most of the radioactive phosphorus remained in the abiogenic phosphorus pool, and none was found in apatite. The findings therefore provide direct evidence for the involvement of bacteria in apatite formation (Fig. 1). Most importantly, they were able to show that the radioactive tracer added to their incubations was incorporated into newly formed apatite on the relatively short, 48-hour timescale of their experiments.

Surprisingly, apatite formation was greatest under anoxic, rather than oxic, conditions. This finding contradicts studies in both modern and ancient sediments, which suggest that phosphorus-burial efficiencies decrease in sediments overlain by anoxic waters, leading to an enhanced flux of phosphorus from sediments to the water column under anoxic conditions. Enhanced phosphorus burial under anoxic conditions could have significant oceanographic and atmospheric implications, given the importance of phosphorus levels for oceanic productivity and the stability of atmospheric oxygen levels over geologic timescales.

The unexpected findings of Goldhammer and colleagues may be specific to nutrient-rich upwelling systems such as Benguela. Nevertheless, long-term models of ocean circulation — most of which project an expansion of present-day oxygen-minimum zones — should consider the possibility that phosphorus burial increases under anoxic conditions, similar to those in the Benguela upwelling system.

Goldhammer and colleagues present unique evidence for a bacterially mediated mechanism of apatite formation in a nutrient-rich upwelling system. The next step is to determine whether bacterially mediated processes govern the production of dispersed micrometre-sized apatite grains that occur in more typical marine sediments worldwide.

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EARLY EARTH

Microbes and the rise of oxygen

Reconstructions of atmospheric chemistry and microbial life early in the Earth’s history have been contentious. Observations increasingly point to the evolution of complex and variable environments earlier in time.

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Unravelling the history of life on Earth in the eons before the Cambrian explosion about 542 million years ago is as fascinating as it is challenging. Direct evidence for life in the Precambrian was first convincingly identified from the 1.9-billion-year-old Gunflint Iron Formation in the 1960s. The biologic origin of these microfossils is undisputed, and it is now commonly — though not universally — accepted that life existed as early as 3.5 billion years ago, based on not only morphological evidence, but also detailed geochemical and palaeoecological studies. Further evidence of ancient life is provided by geochemical and biological constraints on metabolic diversity. The study of ancient life and how it made its living requires pulling together data from numerous lines of enquiry to understand these ancient organisms and the palaeoenvironments in which they existed (Fig. 1). A series of presentations at the Goldschmidt 2010 conference held in June in Knoxville, Tennessee, and in particular those of a session titled ‘Life before the rise of oxygen’, attempted to do just that.

Essentially the full gamut of metabolic pathways in operation today is thought to have arisen early in the Precambrian. Perhaps most important to life as we know it today, it has been suggested that organisms that produced or consumed free oxygen had evolved by 2.67 billion years ago. However, it is unclear whether oxygen production resulted in a significant flux to the atmosphere and oceans or remained a local phenomenon at this time. According to the present majority view, oxygen levels in the atmosphere of the early Earth remained below 10⁻³ times the present atmospheric level until sometime between 2.4 and 2.2 billion years ago, and then rose to between 10⁻¹ and 10⁻² times present-day levels in the Great Oxidation Event. However, evidence is emerging that the transition from anoxic to oxic was far from simple.

Despite the title of the session at Goldschmidt, many of the early signs of life seem to have been accompanied by ‘whiffs of oxygen’, long before the Great Oxidation Event. The earliest putative microfossils of possible cyanobacteria occur in the 3.5-billion-year-old Apex Chert of Western Australia, at essentially the same time as the first — controversial — evidence for oxygen in the Archaean oceans. The purported oxygenated oceans are recorded in the 3.46-billion-year-old Marble Bar Chert, also of Western Australia. Isotopic, mineralogical and elemental evidence from these rocks are all consistent with the presence of microbes that are capable of producing oxygen.

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manganese and, so far, there is no known mechanism for the oxidation of manganese that does not require free oxygen. At this stage, it is impossible to tell whether this oxidation would reflect a local oxygen oasis, or more global oxygen pulses, but it is certainly suggestive of a flux of oxygen from the surface to the deeper ocean.

However, apparently the oxygen was not entirely widespread at this point because approximately 200 million years later even shallow surface waters still showed signs of anoxia (C. Thomazo, Universität Münster). Iron-speciation data (which were corrected for the effects of thermal alteration) show that sediments of the 2.73-billion-year-old shallow-water Tumbiana Formation of Western Australia were deposited under predominantly anoxic, iron-rich conditions, with suggestions of only the occasional pulse of oxygen seeping in.

So although the physiological capabilities of fossil microbes remain contentious, evidence for at least some oxygenation of the oceans before the Great Oxidation Event seems to be mounting. Furthermore, the oxygen was perhaps not restricted to the surface. It may be that it is impossible to consider ‘Life before the rise of oxygen’\(^2\), at least in the strictest sense.

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2. Goldschmidt 2010 (Geochemical Society and European Association of Geochemistry, USA, 2010); www.goldschmidt2010.org/index

University; H. Ohmoto, Pennsylvania State University), but the physiological capabilities of the original microfossils are far from certain.

Microchemical techniques applied to samples collected from the same Apex Chert locality as the original microfossils\(^1\) suggest that the microstructures were composed of hematite, rather than the organic matter that would be expected if they were biological in origin (J. Emry, University of Kansas). Similar analyses of the original samples, however, demonstrate that they are indeed organic structures\(^13\)–\(^15\). Thus, although these hematitic microstructures largely resemble the originals, they do not rule out a biological origin for the original microfossils. Looking 500 million years later, however, more evidence for microscopic life is emerging.

Microstructures from 3-billion-year-old rocks, again in Australia, are tantalizing: the submicrometre-scale distribution of biologically important elements is not inconsistent with biological remains (D. Oehler, NASA Johnson Space Center). Of course, some of the structures seemed to be solid assemblages of organic matter with no known modern morphological analogues, making any definitive assignment challenging.

Evidence of oxygen around this time is equally indirect, but new elemental-speciation and carbon-isotope data may provide a clue. Manganese-reducing bacteria could be the source of manganese-rich carbonate deposits from 2.92- to 2.96-billion-year-old rocks in South Africa (A. Smith, University of Johannesburg). The key is that manganese-reducing bacteria require a source of oxidized

Figure 1 | Cyanobacteria at work. Modern cyanobacteria are relatively easy to identify. However, their ancient counterparts are much harder to recognize. Evidence for the earliest pulses of oxygen in the oceans, and the putative fossil remains of organisms that might have produced it, was presented at the Goldschmidt 2010 conference.\(^5\)