# Early Life on Earth
## A Practical Guide

Geological Context ?

Microfossils

Stromatolites

Pseudofossils

Biological Morphology ?

Isotopes

Trace Fossils

Biominerals

Biological Processing ?

By

David Wacey

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Early Life on Earth

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*Cover illustration:*
**Main Image Caption**
Illustration of the DNA double helix containing key words associated with the search for early life on
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Small Figure 1 – Biological stromatolites or physical sedimentary artefacts? Intriguing structures within
the ~3,400 Ma Strelley Pool chert of Western Australia.

Small Figure 2 – Microfossil or abiogenic artefact? One of the intensely debated microstructures from
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been found in ~3,400 Ma sandstone and chert units.

# Acknowledgement

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# Setting the Scene: Milestones in the Search for Early Life on Earth

**M. D. Brasier**

Some 150 years ago, Charles Darwin was greatly puzzled by a seeming absence of fossils in rocks older than the Cambrian period (Darwin, 1859). He drew attention to a veritable Lost World that we now know to have spanned more than 80% of Earth History. To put our modern evidence and thinking about Precambrian life into perspective, this introduction will reflect upon the development of three key ideas in this field: the Victorian *Eozoon* controversy, the ongoing stromatolite debate, and the recent Apex microfossil debate.

"How on Earth did life begin?" This is one of the noblest questions we can ask in science. But it took well over a century from 1859 to gain an understanding of life in the Precambrian – the world before the Cambrian explosion of animals. Why did an understanding take so long? Arguably it was because it was, and still remains, a very big and very difficult problem. Its study now involves the whole of the natural sciences. Progress has been a matter of slow attrition. For most of this time, for example, there has been no concept of the vast duration of Precambrian time, nor any evidence for a distinct biota.

As explored below, each generation has come up with its own favourite solution to this question – *whence cometh life*? – only to watch each one fall as the next generation of science and scientists has arrived on the scene. As such, this story provides us with a salutary tale of 'paradigm shifts' that have taken place about every 50 years or so. And, as I shall explore below, this process is ongoing and continuous. It is no surprise then, to find that the majority of uniformitarian interpretations for Precambrian fossil assemblages established over the last 50 years now appear highly questionable. That is, of course, exactly how it should be.

Palaeontologists and biologists had struggled to answer questions about the emergence of animal life long before Charles Darwin was to unveil his theory of evolution in 1859. Erasmus Darwin, his illustrious grandfather, wrote about the origins of life in his treatise 'Zoonomia' (Darwin, 1794). In so doing, he almost anticipated a modern definition of life: material that responds to stimuli, grows, reproduces inaccurately, and evolves by the transmission of these changes.

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By 1837, radical science was leading towards a concept of "progressive development". This referred to geological evidence then unfolding about the great history of life, from a lack of fossils in the 'Primary' rocks, to marine invertebrates in the Silurian, towards land vertebrates by the Jurassic, and ultimately to modern man, the whole chain arising from some ultimate cause. The great Oxford geologist Charles Lyell explained away this troubling phenomenon as the result of incompleteness in the early fossil record (Lyell, 1837). His strict adherence to the Principle of Uniformity was arguably a necessary step: an unwillingness to accept negative evidence; or determinism; and the need for a null hypothesis against which to test the claims of progressive development. Until we have evidence to the contrary, Lyell was saying, then we should assume that everything in the past worked in exactly the same way as we see now.

A wide but controversial airing in polite society was, however, given to the idea of evolution when Robert Chambers published his anonymous musings about progressive development and evolution (Chambers, 1844). But strong establishment reactions against his account, together with the barely known fossil record, still spoke against the suggestion that all of life shared a common ancestor. Anticipating other legitimate, or establishment, criticisms against his theory, Darwin was therefore obliged to speak cautiously about the absence of ancestors or obvious intermediates between the known animal groups: "*There is another difficulty which is much graver. I allude to the manner in which numbers of species of the same group, suddenly appear in the lowest known fossiliferous rocks. … I cannot doubt that all Silurian trilobites have descended from some one (form), which must have lived long before the Silurian age. … If my theory be true, it is indisputable that before the lowest Silurian stratum was deposited, long periods elapsed, as long, or probably far longer than, the whole interval from the Silurian age to the present day; and that during these vast, yet quite unknown, periods of time, the world swarmed with living creatures … the case at present must remain inexplicable; and may be truly urged as a valid argument against my views here entertained*" (Darwin, 1859).

Darwin's evolutionary theory of 1859 gave, of course, a revolutionary and coherent significance to the search for 'increasing organism complexity' through the rock record, as both Huxley's collected essays (see Huxley, 1894) and Haeckel's embryology (Haeckel, 1872) over the next decade show. But as we shall see, progress in the last half of the nineteenth century was mired in the famous *Eozoon* debate. A brief look at this debate is therefore rather instructive.

# 1   The *Eozoon* Debate and the 'Foraminosphere'

While Charles Darwin was polishing off the Origin of Species in 1859, Sir William Logan in Canada was contemplating what he took to be the world's oldest fossil. This consisted of thin layers of green serpentine alternating with calcite (Fig. 1a). It had been found on the banks of the River Ottawa to the west of Montreal, within a bed of marble some 500 m thick, intermixed with thick layers of banded gneiss and micaceous schist, now known to be some 1,100 million years old. Sir Charles

Lyell provides us with a description of the fossil as it seemed to him in 1865: "*It appears to have grown one layer over another, and to have formed reefs of limestone as do the living coral-building polyp animals. Parts of the original skeleton, consisting of carbonate of lime, are still preserved; while certain interspaces in the calcareous fossil have been filled up with serpentine and white augite*" (Lyell, 1865).

In 1864, this strange rock had been shown to Dr J.W. Dawson of Montreal – a one-time pupil of Lyell – who named it the 'Dawn Animal of Canada'. It is worth observing that Dawson was equally intrigued by the abundance of carbon – in the form of graphite – to be found in rocks with *Eozoon*. Not unreasonably for the time, he inferred that this pointed to some kind of vegetation long ago, though quite what kind of vegetation he could not say (Dawson, 1888). *Eozoon* was duly taken on world tour by Sir William Logan, to be displayed before the Geological Society in London. There, the eminent microscopist William B. Carpenter was struck by a seeming resemblance between ancient *Eozoon* (Fig. 1a) and some living foraminifera, such as *Discospirina* (Fig. 1b, which he called '*Orbitolites*') as well as some rock-forming types such as *Homotrema*. The white layers of marble were therefore regarded, by both Dawson and Carpenter, as the remains of skeletons that had grown, layer by layer, to contribute towards great reefs of limestone. These layers were then infilled by serpentine by some uncertain process.

Decoding of such 'metamorphic' rocks was to remain enigmatic – indeed it was largely guesswork – until about 1880. It was only then that the real advances came, following hard upon the heels of the petrographic microscope, the polariser, the analyser, the rotating stage and the diamond wheel for rock cutting. Thus it was, for nigh on 20 years after publication of 'the Origin of Species', that decoding the oldest crystalline rocks – and hence of *Eozoon* – was a difficult endeavour.

But with both Dawson and Carpenter enthralled by the resemblance between *Eozoon* and foraminiferids, both Lyell and Darwin were caught in a trap. Darwin was therefore moved to write, in the later editions of the Origin of Species: "*and the existence of the Eozoon in the Laurentian Formation of Canada is generally admitted. There are three great series of strata beneath the Silurian system in Canada, in the lowest of which Eozoon is found, Sir W. Logan states that their "united thickness may possibly far surpass that of all the succeeding rocks from the base of the Palaeozoic series to the present time. We are thus carried back to a period so remote, that the appearance of the so-called Primordial fauna (of Barrande) may by some be considered as a comparatively modern event." The Eozoon belongs to the most lowly organized of all classes of animals, but is highly organized for its class; it existed in countless numbers and, as Dr. Dawson has remarked, certainly preyed on other minute organic beings, which must have lived in great numbers. Thus the words which I wrote in 1859 about the existence of living beings long before the Cambrian period, and which are almost the same with those since used by Sir W. Logan, have proved true.*" (Darwin, 1871).

This concept of finding large and complex deep sea foraminifera in the oldest rocks needs to be placed in its proper historical context. In the 1840s, the deep sea world had not yet been explored. The geologist Edward Forbes had speculated that progressively more primitive forms would be found alive as deeper and deeper waters were sampled.

**a**



**b**
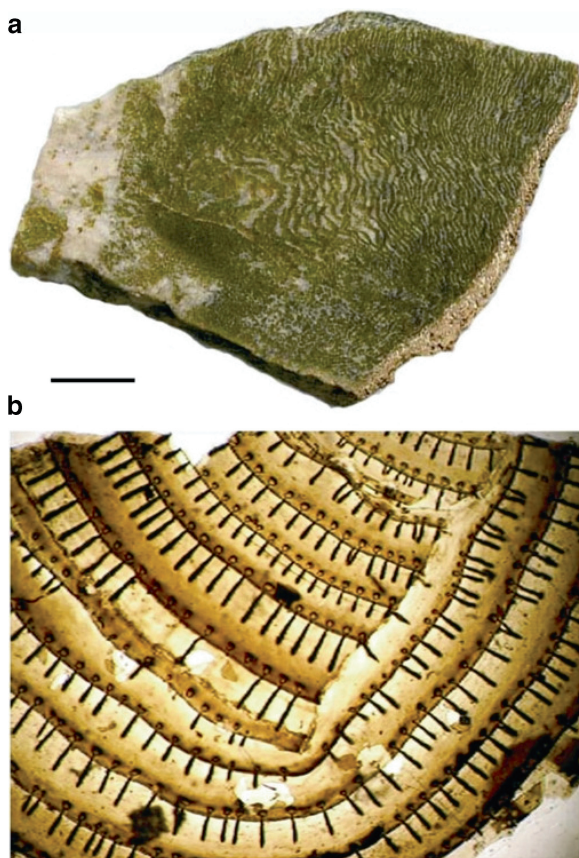


**Fig. 1** The Protozoan quest – foraminifera as the search image for the earliest life. (**a**) Hand specimen of *Eozoon canadense* (Carpenter, 1864), collected from the ~1,100 million year old ophicalcite of Cote-St-Pierre, Quebec, Canada. This was thought by Darwin, Dawson and Carpenter to provide the earliest evidence for life, and interpreted as a foraminiferid like the specimen below. (**b**) Transmitted light micrograph of the empty test of living foraminiferid *Discospirina*, imaged from the W.B. Carpenter collection held at Exeter University. Scale bar: 1 cm for (**a**); 100 μm for (**b**)

If so, deepest oceans would probably prove completely barren of life. That being so, the water column was thought to be a mirror of the history of life, with a Precambrian world in the deepest parts and a modern world in the shallows. But Forbes great idea was to receive a knock on the head in 1856, when British and American naval ships began to survey the deep Atlantic in readiness for the laying down of cables for the new electric telegraph. They found, of course, those vast carpets of tiny foraminiferal tests that we now call *Globigerina* Ooze. At the time, these globigerine tests were argued by Thomas Huxley – 'Darwin's Bulldog' – to have lived on the seafloor and not in the water column as we now understand (Huxley, 1893–94). One of the earliest students of this chalky deposit was also one W.B. Carpenter.

As we can now appreciate, Carpenter and Dawson were to combine two distinct strands in their thinking about the early ancestors of life on Earth: that they will have been like those being found in the deep sea today – much as Forbes had suggested. And that that they will be like benthic foraminifera – much as Huxley believed. That is arguably why *Eozoon* fitted the search image – it was thought to be a pre-Cambrian benthic foraminiferid that hailed from the dawn of life itself.

But problems were soon to emerge. The first was the inferred but mistaken similarity between ancient *Eozoon* and complex living foraminifera such as *Discospirina*. This had led both Carpenter and Dawson to conclude that foraminifera had barely evolved since the 'Laurentian' (Proterozoic) period (see Darwin, 1871). But then a second set of observations sorted all this out – *Eozoon* was not a *fossil* at all. That was first shown by Irish geologists William Kind and Thomas Rowney in 1866, and later by the German microscopist Karl Mobius, in 1879. By the time of Darwin's death in 1882, the scientific community had condemned *Eozoon* to death as little more than a mineral growth, formed at great depth and high temperature. In Scotland, it was found next to major faults and intrusions. And in Italy it was seen coming out of a vent in Vesuvius (see Hofmann, 1971). The game was up and hard lessons had to be learned.

What strikes us first was how strange this scientific paradigm of the mid nineteenth century sounds to us now. The prediction at that time was that early life would somehow resemble those things now found living in the deep sea, namely benthic foraminifera. Not only that, but very complex foraminifera like those we can find today, such as *Homotrema*. But we now know that foraminifera such as *Homotrema* are highly adapted to a world fit for metazoans because they use sponge spicules to trap their prey; capture tiny zooplankton in the water column; and have calcium carbonate shells to stop them being eaten alive by fish. None of this was known back in 1866. This lack of understanding caused both Dawson and Carpenter to lead the world up the garden path. They believed that seemingly simple organisms like foraminifera had barely evolved at all – a view we can now see to be greatly in error.

An important lesson to be learned from *Eozoon* is this one: that we must not expect to find modern kinds of creature in the rock record before the Cambrian. The Earth before animals was like an alien planet.

## 2   The Cyanosphere, Phase 1

The place of *Eozoon* was quickly taken by that of the structures we now like to call 'stromatolites'.

Among the first to notice and wonder about the strange forms of stromatolitic growth was Charles Darwin, back in the 1830s, who included a figure (Fig. 2a) in his published 'Journal of Researches' and made the first ever pertinent observations on splash-zone stromatolites during the voyage of HMS Beagle: "*The rocks of St Paul appear from a distance of a brilliantly white colour. This is partly owing to a*
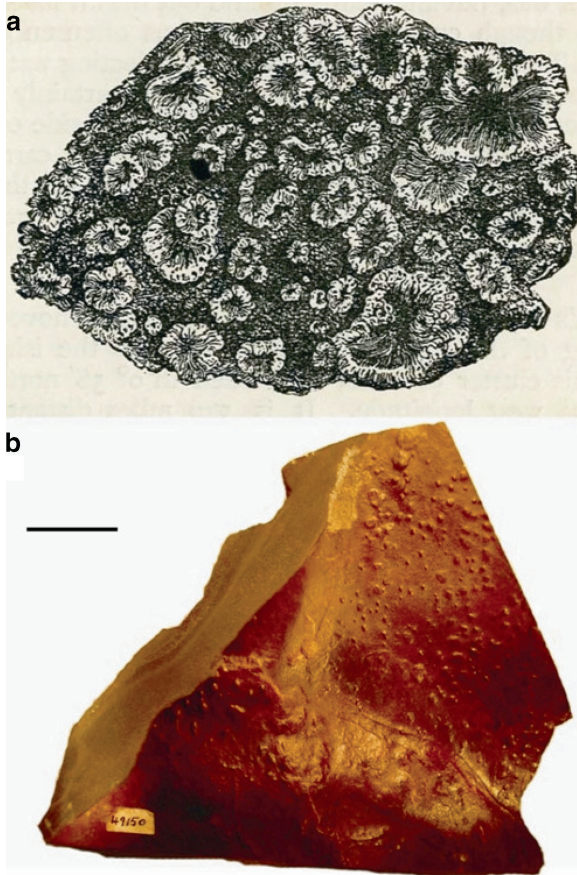
**Fig. 2** The Cyanobacterial quest – the discovery of self-organized sedimentary structures. (**a**) A woodcut used by Charles Darwin to illustrate vegetable-like growths of calcium phosphate found growing in the splash zones of oceanic islands; no scale was given. (**b**) One of several specimens of '*Arenicolites sparsus*' collected by J.W. Salter in 1856 from the Ediacaran Longmynd beds of England and illustrated by him the following year (Salter, 1857, pl. 5, Fig. 3). It is arguably among the first Precambrian fossils ever to be figured, named and described. This specimen is now regarded as a microbially-induced sedimentary structure. Scale bar is 5 cm

*coating of a hard glossy substance with a pearly lustre, which is intimately united to the surface of the rocks. This, when examined with a lens, is found to consist of numerous exceedingly thin layers, its total thickness being about the tenth of an inch. It contains much animal matter, and its origin, no doubt, is due to the action of rain or spray on the birds' dung. … When we remember that lime, either as phosphate or carbonate, enters into the composition of hard parts, such as bones and shells, of all living animals, it is an interesting physiological fact to find substances harder than the enamel of teeth, and coloured surfaces as well polished as those of a fresh shells reformed through inorganic means from dead organic matter – mocking,*

*also, in shape some of the lower vegetable productions.*" (Darwin, 1839). We can only guess that he was thinking about comparisons with fungi and lichens.

The earliest microbially-mediated sediment to be figured from the Precambrian was discovered as early as 1855, by the great palaeontologist John Salter (see Fig. 2b) in the Ediacaran sediments of the Longmynd in England (Salter, 1856, 1857). This material was originally regarded by him as the markings of worm burrows of Cambrian age, but its Precambrian and microbial origin has now become well known. Interestingly, the specimen in Fig. 2b was indirectly referred to by Darwin (1859) while writing about the Origin of Species, as follows: "*Traces of life have been detected in the Longmynd beds beneath Barrande's so-called primordial [Cambrian] zone*" (Darwin, 1859).

From at least 1851, we also find discussions taking place about stromatolitic structures in the ~2,000 million year old Banded Iron Formations from the Great Lakes region of North America (Gunflint chert, see Fig. 3a). Such ancient rocks were then placed in the Azoic period because of their "*entire absence of organic*
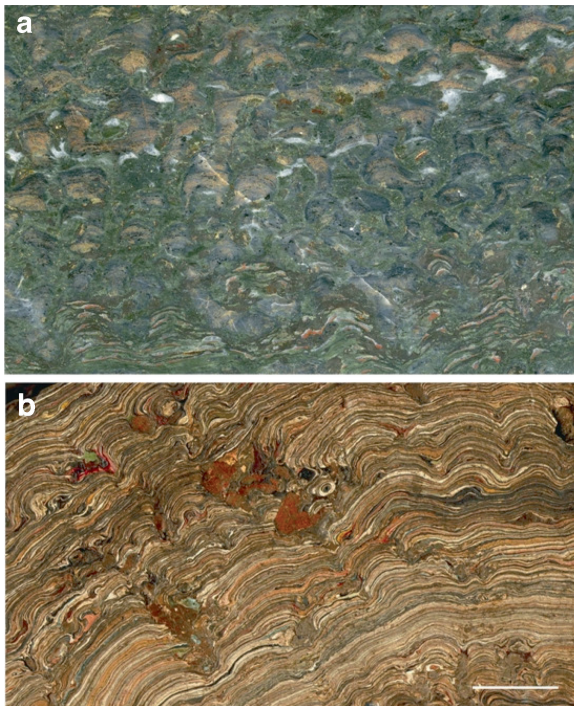
**Fig. 3** The Cyanobacterial quest – the discovery and decoding of self-organized sedimentary structures. (**a**) Hand specimen of a stromatolite from the ~2,000 million year old banded ironstones of the Gunflint chert, Minnesota. Similar structures were interpreted as igneous features by Foster and Whitney (1851) and as paradoxical sedimentary structures by Irving (1883). (**b**) Hand specimen once in the collection of Sir George Taylor, Director of the Royal Botanic Gardens at Kew. The specimen is made from layers of lead-based paint and was likely generated in a spray booth without any participation from biology. Note its similarity to 'a', including the non-isopachous laminae and the inter-columnar spaces filled with matrix. Scale bar is 2 cm for both images

*remains*" (e.g., Foster and Whitney, 1851). At that early time in geological thinking, the Gunflint chert was thought to have been laid down under the great residual heat left over from the fiery origins of the primordial Earth: "*The Azoic period having been one of long continued and violent mechanical action* (ibid., p. 67)." The concern, therefore, was whether the "*beautiful series of intricate convolutions of alternate bands of bright-red and steel-grey*" were really the result of sedimentary processes. "*The flexures are exceedingly intricate and bear no marks of having been the result of original stratification. There is no actual line of separation between the lighter and darker bands*" (ibid., p. 68). Their final suggestion was that they were crumpled by igneous phenomena and had "*risen up, in a plastic state from below*" to pour out onto the deep sea floor.

But the geological surveyor Roland Irving was to return to this question in his early monograph on the Archean of the north-western United States. By 1883, it was becoming clearer that the banded iron formations were some kind of paradoxical sedimentary deposit: "*the cherty and jaspery portions, frequently strongly charged with magnetite and other oxides of iron, present often peculiar irregularities and contortions in subordinate bedding, and also often a confused concretionary appearance, and even a brecciated appearance. All of these irregularities are very plainly subordinate to a simple bedding, corresponding entirely to that of the rest of the Animikie series. … I anticipate that when we shall have completed our microscopic studies of them we shall get from them some light as to the origin of these confused and much discussed rocks. I may now merely say that … all of these cherts and jasper schists are original, and not the result of a metamorphism upon ordinary sedimentary deposits, though manifestly they are not of eruptive origin, as has been maintained by some*" (Irving, 1883).

It was also at about this time that curious case of *Cryptozoon* began to emerge from the fossil record. This cabbage-like structure had been found spread across bedding planes in the upper Cambrian carbonates of New York State. First reported by James Hall in 1883, it was originally interpreted as some kind of calcareous algal growth, a view that was later developed by Charles Walcott and then by V.H.E. Kalkowsky (1908), who first introduced the concept of 'stromatolite' as follows: "*organogenic, laminated calcareous rock structures, the origins of which is clearly related to microscopic life, which itself must not be fossilized*" (translation in Krumbein, 1983). Stromatolites are so named from the Greek for 'flat stones'. But as can be seen, the definition of Kalkowsky was a genetic one, though direct observation of microbes was seemingly precluded by him. From this strange mismatch there has arisen much misunderstanding, not only about stromatolites but about the word 'stromatolite' itself (see Fig. 3b and McLoughlin et al., 2008).

The role of biology in stromatolite growth was widely ignored until Cambridge sedimentologist Maurice Black canoed across the tidal flats of Andros Island in the Bahamas (Black, 1933). He noticed that dense growths of cyanobacteria were forming an 'algal mat' that seemed to survive episodes of sediment deposition by growing upwards through the sediment.

Black's work went largely un-noticed for several decades. By 1954, the search for cyanobacteria-like microfossils in the Gunflint chert stromatolites was starting to bear some fruit in the form of fossilized cells, coccoidal colonies and filaments (Tyler and Barghoon, 1954; Barghoorn and Tyler, 1965). There followed an increasing number of descriptions of stromatolites, and of microfossils from stromatolitic cherts, in the succeeding decades (e.g., Walter, 1976; Krumbein, 1983). During this phase, it was widely assumed that stromatolites were largely formed by the trapping and binding activities of microbes such as living cyanobacteria. Such work was helping to promote and establish the paradigm that cyanobacteria are a search image for the earliest life, and that stromatolites are their constructions (see Schopf and Klein, 1992; Schopf, 1999).

This cyanobacterial vision of the early biosphere was to reach its zenith – or maybe its nadir – in the Viking Missions to Mars in 1976. During those expeditions, the chemical tests for early life were clearly designed to sniff out the evidence for cyanobacteria-like photosynthesis. Those early astrobiologists were looking for kinds of metabolisms that involved the uptake of carbon dioxide and the release of gaseous oxygen by means of photoautotrophic enzymes like chlorophyll. As is now well known, they found nothing to their liking.

The strangeness of distant planets and of early worlds really dates from this moment of realization back in 1976. But it has taken 3 more decades for the cyanobacterial paradigm – the cyanosphere – to crumble. The first nail in the coffin came with the discovery of stromatolite-like growth around the chimneys of deep sea 'black smokers'. Clearly, these ecosystems and the stromatolites they contain, cannot be photoautotrophic, let alone oxygenic. A major step forward was then taken by the MIT group of John Grotzinger and Dan Rothman (1996) who showed by experiment that stromatolitic growth, leading to branching and columnar forms, is the predictable outcome from some kinds of non-biological crystal growth, much like the growth of calcareous flowstone (cf. Fig. 4a). They suggested that such potentially non-biological stromatolites had isopachous laminae (Fig. 4b) whereas biologically mediated stromatolites tended to have non-isopachous laminae (Fig. 4c).

These conclusions were to have serious implications for the interpretation of stromatolites from the c. 3,400 million year old Strelley Pool Formation of Western Australia. First regarded as biological (Lowe, 1980), they were later rejected by him (Lowe, 1994), but further examples and arguments were resurrected by Hofmann et al. (1999) and then more recently by Allwood et al. (2006). My own studies (e.g., McLoughlin et al., 2008; Wacey et al., 2008), however, reveal that these structures typically show isopachous laminae, and form part of a spectrum that ranges from ripple-like corrugations of linear, through sinuous to linguoid and lunate forms, culminating in asymmetrically conical morphologies (Fig. 5). As such, they may be explained as accretionary flow-stone like bed forms formed under supersaturated conditions on the seafloor. As yet, there is no evidence in these stromatolites for the preservation of microbial fossils in the form of sheaths, filaments or cells.
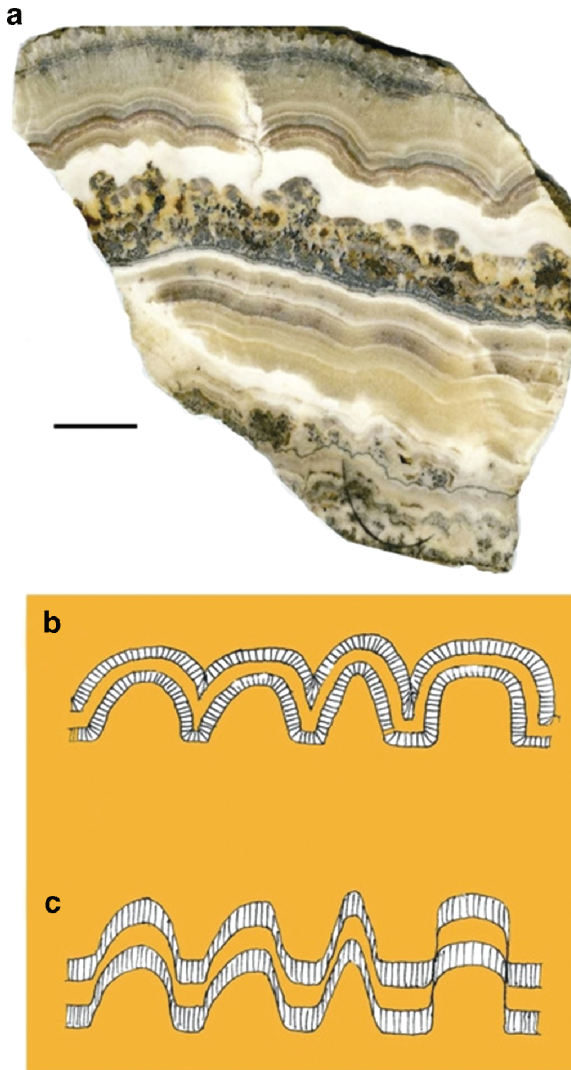
**Fig. 4** The Cyanobacterial quest – the decoding of self-organized sedimentary structures. (**a**) Hand specimen of banded agate showing stromatolite-like domes and bush-like dendrites, from an un-named deposit in Wyoming. Note the isopachous nature of the laminae, regarded by Groztinger and Rothman (1996) as potentially non-biological. Scale bar is 2 cm. (**b**) Sketch to show the nature of isopachous growth, typically found in agates, malachites and other hydrothermal mineral deposits. (**c**) Sketch to show the nature of non-isopachous laminae supposedly typical of stromatolites with a biological component

A further challenge to the paradigm of stromatolites as cyanobacterial markers – and even as biosedimentary structures – is now coming from experimental work at Oxford University, undertaken by Nicola McLoughlin and colleagues. They have managed
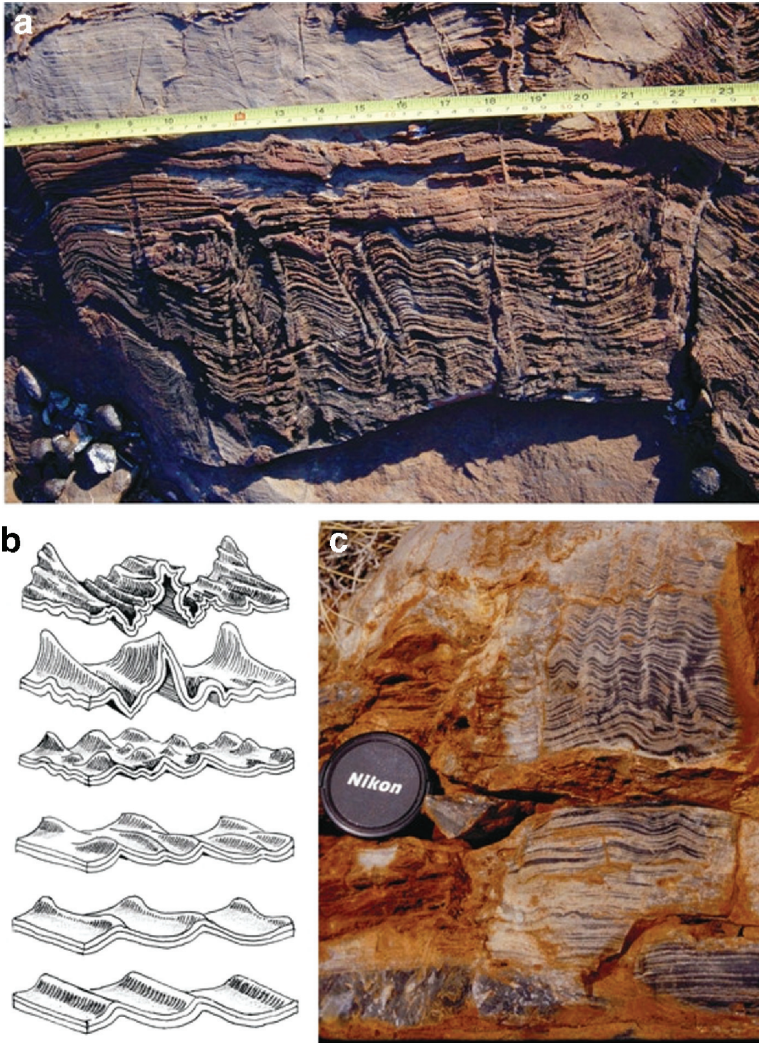
**Fig. 5** The Cyanobacterial quest – the decoding of self-organized sedimentary structures from the ~3,400 Ma Strelley Pool Formation. (**a**, **c**) Field photographs showing stacked pseudocolumns of linear, ripple-like features, commonly regarded as 'stromatolites'. (**b**) Reconstructions of the geometry of the so-called stromatolites from the Strelley Pool Formation, showing the continuous spectrum from linear ripples to oversteepened lunate ripples and pseudoconical structures. Scale is variable to fit observed morphologies

to grow complex digitate and inclined stromatolites with non-isopachous laminae (cf. Fig. 3b) under conditions that are relevant to the accretion of stromatolites (e.g., on the early land surface), and to the accretion of calcareous tufas and siliceous sinters (e.g., in the early oceans). These laboratory simulated stromatolites show some remarkable similarities with the famous Gunflint stromatolites (Fig. 3a).

From this and other studies, it emerges that stromatolite morphologies tend to accumulate along the edges of a deposition system where the supply of material is starting to fail – in what can be called the zone of complexity. At best, they may tell us something indirect about viscosity and the presence of extracellular mucilage. But clearly, they can also grow completely without the participation of biology. A plethora of studies have now shown that stromatolitic morphology should henceforth be regarded as a branch of physical sedimentology. That is to say, whereas ripples are the products of low viscosity accretion, stromatolites may be seen as the products of accretion under more viscous conditions. Clearly, this viscosity may take the form of either non-biologically- or biologically-induced crystal precipitates and gels. Both systems can produce self-organized structures of domes and columns under non-equilibrium conditions.

## 3　The Cyanosphere, Phase 2

The search for well-preserved *cells* in ancient rocks has a surprisingly long history. In the seventeenth century, Oxford microscopist Robert Hooke first observed the structures we call cells in the bark of the cork tree and the study of spores and pollen followed not long after. During the voyage on the Beagle in South America during the 1830s, Charles Darwin was moved to write about cherts from Chile: "*how surprising it is that every atom of the woody matter … should have been removed and replaced by silex so perfectly, that each vessel and pore is preserved!*" (Darwin, 1839).

The earliest *bona fide* report of cellular preservation in Precambrian rocks seems to have been that made by Jephro Teall in the ~1,000 million year old Torridonian sedimentary phosphates, first reported in 1899 and soon after described and illustrated (see Peach et al., 1907). It was to be nearly another 50 years before comparable reports were to arrive from the ~2,000 million year old Gunflint chert (Tyler and Barghoon, 1954; Barghoorn and Tyler, 1965) and there were many followers to this work (see Schopf, 1999; Knoll, 2003).

This phase of research culminated, most famously, in the claim for a diverse suite of microfossils from the ~3,460 million year old Apex chert of Western Australia (Schopf, 1992, 1993, 1999). That work carried with it the implication that the origin of life likely took place about 4,000 million years ago on Earth. Life was then thought to have diversified rapidly by about 3,500 million years ago, culminating in the evolution of oxygen-releasing photosynthesis by cyanobacteria by that time (Schopf, 1993, 1999).

This concept of a Cyanosphere on the early Earth and Mars is now undergoing a critical scientific rethink. Brasier et al. (2002) began their challenge to this 'early Eden paradigm' by questioning the Earth's oldest supposed 'microfossil' assemblage, from the Apex chert. Schopf (1999) had inferred that eleven separate types of micro-organism were preserved in Apex cherts from Chinaman Creek, near Marble Bar in Western Australia. Of these, a number were compared with fossil and living cyanobacteria, with the major implication that oxygen was already being

released into the atmosphere. The dubious nature of the Apex chert 'microfossil' assemblage came to light when the rock slices were examined in detail by Brasier and his co-workers for the first time since they were deposited, in the early 1990s, at the Natural History Museum in London. These 'microfossils', which include some of the smallest fossils ever named (*Archaeotrichion* is as small as 1/3,000th of a millimetre) were seen to grade into non-biological structures resulting from recrystallization of the rock fabric (see Fig. 6). Another structure, called *Eoleptonema apex*, seems to have grown down a post-depositional crack (Dr. A. Steele, 2008 personal communication). Such 'morphing' goes against one of the cardinal rules previously set up for the recognition of potentially biological structures (see pp. 44–50).

Given these concerns, Brasier et al. (2002) subjected the Schopf site and microstructures to new, high-resolution techniques, of the kind hitherto thought more appropriate for the study of Mars and potential Martian microfossils. Mapping was undertaken at a range of scales from kilometres to microns, and integrated with newly applied techniques for geochemistry and microfossil morphology. Together, these built up a completely new picture for the Apex chert 'microfossil' site, comprising hydrothermal fissure fillings rising towards the ocean floor through cracks in submarine basaltic lavas. These hot springs were being fed by a deep igneous heat source. The organic matter is very abundant in these dyke systems. Re-assessment of the Apex chert and its context revolves around eight major arguments (Brasier et al., 2002, 2005, 2006), summarized below.

1. The context for the 'microfossil' samples is not (as previously thought) a conglomerate formed on a beach or near the mouth of a river, but part of the feeder dyke/vein for a seafloor hydrothermal spring. This can be demonstrated by mapping, by fabrics and by geochemistry.
2. The putative 'microfossils' are not restricted to a distinctive class of clasts, often rounded (as was claimed). The structures actually occur in three successive generations of brecciated hydrothermal fissure fillings and glassy cements, while comparable structures occur in associated volcanic glass where temperatures must have reached 500°C, well above those viable for life. It could no longer be claimed, therefore, that all the fossils have simply fallen down the dyke from surface environments.
3. Associated structures that were once regarded as 'stromatolite-like clasts' were found to have fabrics that intergrade with laminated fissure fillings and are arguably laminites of non-biological origin.
4. The spatial arrangements of the 'microfossils' did not compare with that seen in the next oldest, diverse microfossil assemblage: that of the ~2,000 million year old Gunflint chert. There, filaments are wrapped around each other and clustered into layers that show clear behavioural orientation parallel to the laminae, whereas the 'microfossils' in the Apex chert show no coherent arrangement (e.g., Fig. 6) that might be thought consistent with biology.
5. The filaments are not all simple and unbranched (as previously thought). At least four of the holotypes have side branches, and all of them intergrade with adjacent branched structures. They form part of a morphological continuum that appears to
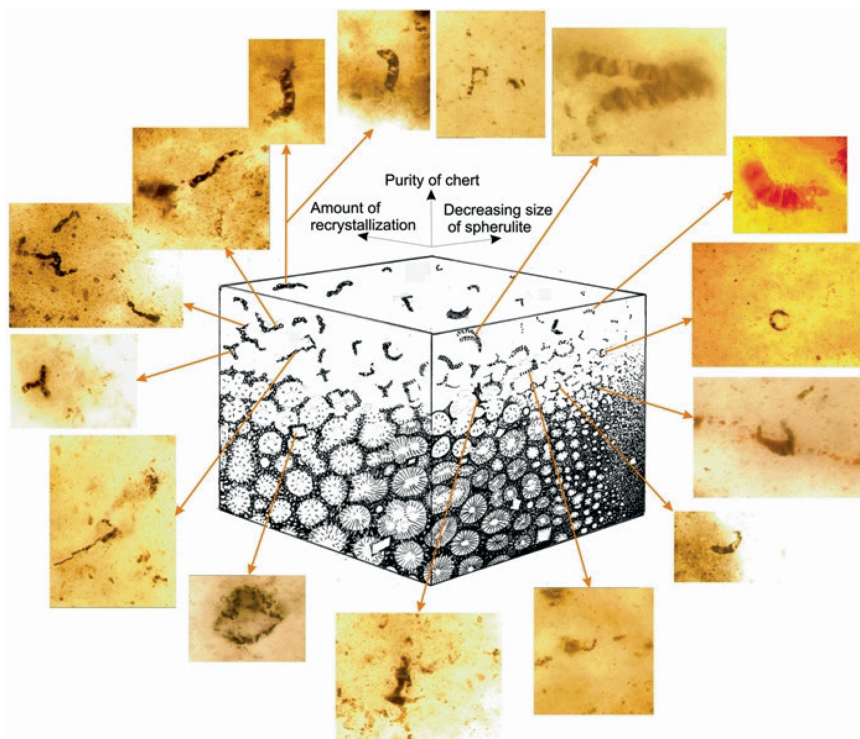
**Fig. 6** The Cyanobacterial quest – the decoding of self-organized hydrothermal structures from the ~3,460 Ma Apex chert. This three dimensional morphospace model (*centre block*) shows how this spectrum of microfossil-like structures (*outer images*) was most likely created entirely by physicochemical controls during recrystallization of the chert and the redistribution of carbonaceous material around spherulite and crystal margins. The key controls here were the relative purity of the chert (*vertical axis*), the degree of recrystallization of the fibrous chalcedony to equigranular microcrystalline chert (*left horizontal axis*), and the decreasing size of the spherulites (*right horizontal axis*). Arrows link theoretical with observed and reported microfossil-like artefacts having similar morphologies (see also pages 155–159). The scale is somewhat variable; the microfossil-like artefacts are between 10 and 100 μm in length

be due to the recrystallization of hydrothermal silica glass (see Fig. 6). As the silica recrystallized, it pushed carbonaceous impurities ahead of the radiating crystal fans because they could not be incorporated in the lattice. Such a process results in rounded sheets of carbon where the impurities are abundant, to branched, dendritic or simple arcuate filaments where the impurities become scarce.

6. The appearance of 'septa' (cell walls) and of 'bifurcated cells' (in the process of cell division), is also seen in the associated non-biological structures (of spherulitic and dendritic filaments). Both are reinterpreted as products of recrystallization, leading to interleaved quartz and carbonaceous matter.

7. The structures are indeed made of carbonaceous matter. But this carbon is no different from that seen in the associated non-biological artefacts with which they intergrade, nor does it differ significantly from that seen in disordered graphite or in carbonaceous meteorites. It is misleading, therefore, to infer a biological origin for this carbonaceous matter.

8. The ratio of the light stable isotope of carbon ($^{12}$C) to the heavier stable isotope ($^{13}$C) has been used as an indication of biological fractionation where this ratio (standardised against the Pee Dee Belemnite) is found to fall between c. $-20$ and $-40$ parts per thousand. But while carbon isotopes in this range are consistent with a biological origin for this carbon (possibly from hyper-thermophilic bacteria), it is important to note that a similar range of values can be produced by non-biological Fischer Tropsch-type synthesis (e.g., Holm and Charlou, 2001), also suspected in Archean dyke systems.

# 4   Implications

Several major conclusions can be drawn from these case histories. Clearly there is a need for a geological understanding of the context for early life on Earth or Mars, not merely a biological understanding. This means the acquirement of a thorough training in metamorphic, igneous and sedimentary petrology, and the study of context at a range of scales, including the premier disciplines of geological mapping and fabric mapping. Only in that way can scientists yet hope to form an opinion as to whether the context and burial history of the host rock is consistent with claims made for early life. The second conclusion is equally serious. It concerns facing up to a non-biological rather than biological origin for candidate morphological (or biogeochemical) signals from the early Earth or Mars. As we have seen with *Eozoon*, *Cryptozoon* and *Eoleptonema*, we can no longer afford to ignore the ways in which abiology can simulate earthly biology, let alone unearthly biology. The main problem here is that morphological complexity has for long been taken to be a keystone characteristic for the earliest fossils (e.g., Buick et al., 1981; Schopf, 1999). A basic understanding of self-organizing structures (SOS) and complexity is therefore an essential step if the early fossil record is to be correctly decoded. Unfortunately, complex structures do not require complex causes, as shown nearly a century ago by d'Arcy Thompson (1917). As we have seen with stromatolites, they can arise naturally in physico-chemical systems within the realms of 'chaotic' behaviour (Grotzinger and Rothman, 1996).

In Fig. 7, attention is therefore drawn to a range of physico-chemical gradients that can lead to the formation of macroscopic stromatolites (a) and ripples (b) as well as to microfossil-like structures generated by the growth of dendrites (e), 'coffee-ring' effects (f), polygonal crystal rims (g) and spherulites (h). In each of the systems shown, a move to the right of the diagram results in a loss of symmetry but a gain in morphological or temporal complexity towards the 'chaotic domain' (see Stewart and Golubitsky, 1992). This leads to a 'symmetry-breaking cascade',
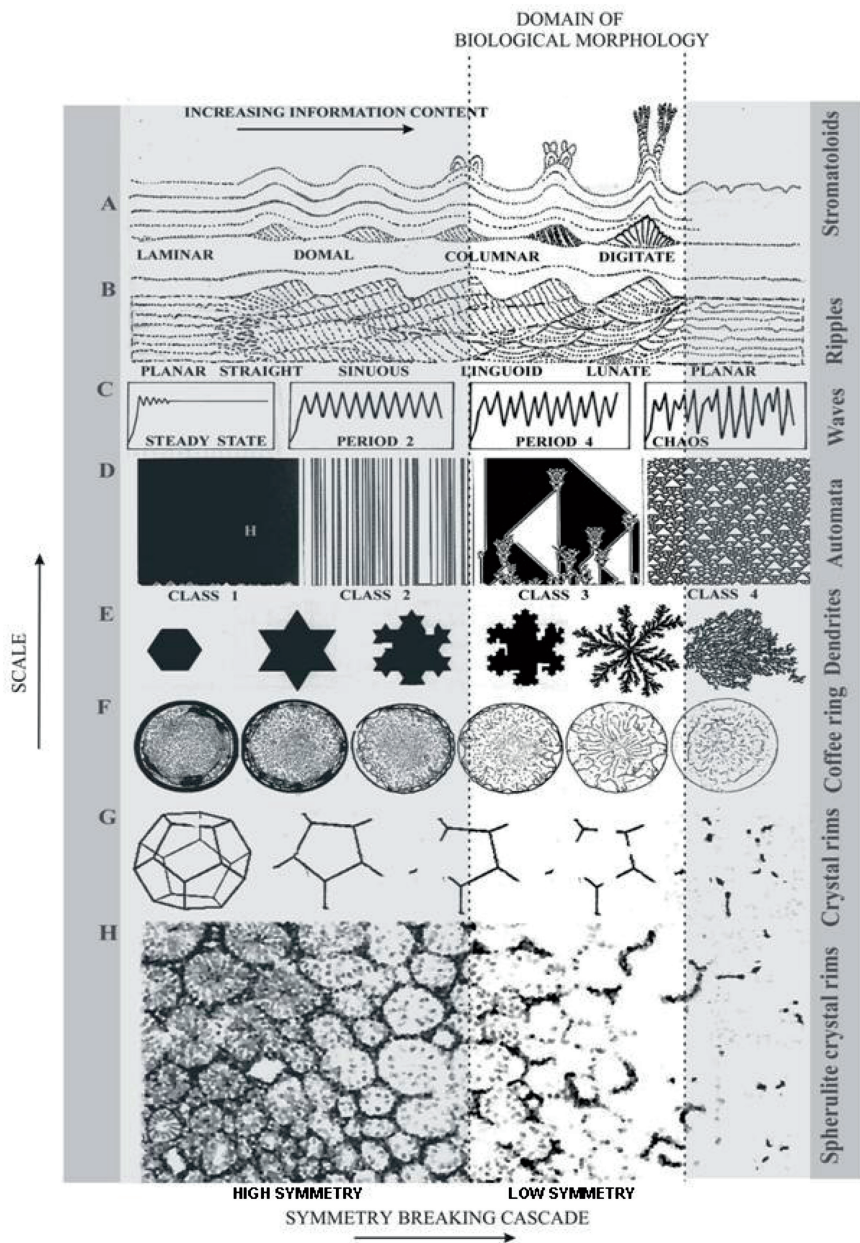
**Fig. 7** The range of self-organising structures (SOS) that can arise naturally in physico-chemical systems within the realms of chaotic behaviour. Symmetry is lost as one moves to the right but morphological complexity increases. In well preserved microfossil assemblages morphological variation of the fossil assemblages is usually less than co-occurring non-biological structures and so should occupy a more restricted domain ('domain of biological morphology') within the morphospace (From Brasier et al., 2006)

wherein the 'symmetry group' falls and the level of information rises. Symmetry-breaking is a particularly conspicuous phenomenon during the growth and recrystallization of spherulites, leading to natural assemblages of structures that can range from spheroidal (broadly rotational symmetry), to dendritic (reflectional to slide symmetry), to arcuate (no clear symmetry; Fig. 7h). Such symmetry-breaking cascades appear to arise when localised changes in the ionic concentrations of the constituent chemicals (e.g., iron oxide, carbon) fall below a critical threshold, so that the higher levels of symmetry became unstable. In this way, the margins of crystal growth can provide a rich harvest of pseudofossil structures, ranging from polygonal to dendritic to filamentous (e.g., snowflakes, moss agate, pyrolusite 'moss'; Fig. 7e–h) and from spherulitic/ botryoidal to dendritic to filamentous (e.g., hydrothermal cherts and jaspers; Fig. 7h). Such complex systems have also been simulated by computational experiments and digital automata (Fig. 7c–d), replicating the self-organization seen within stromatolites and dendrites (Grotzinger and Rothman, 1996; Wolfram, 2002). Brasier et al. (2006) have reviewed the problems of spheroids, filoids, septate filoids, stromatoloids, wisps and fluffs and the challenges that they present for decoding the earliest fossil record. Given such a challenge, it therefore seems wise to remain cautious and regard many Archean microfossils, stromatolites and carbon isotopic values (older than, say, c. 3,000 million years) as open to question until their origin by likely alternative, non-biological, processes has been falsified (the 'null hypothesis').

*The main aim of this book is therefore to draw attention to the remarkable number of highly interesting candidate structures that now await critical scrutiny by the next generation of explorers, in the quest to decode the earliest evidence for life on Earth.*

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