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Martin Brasier (1947–2014): astrobiologist

Sean McMahon[1] and Charles Cockell[2]

[1] *Department of Geology & Geophysics, Yale University, New Haven, CT 06520, USA e-mail:* sean.mcmahon@yale.edu
[2] *UK Centre for Astrobiology, Edinburgh, UK*

Abstract: How did life on Earth begin? What does the search for life in the distant past tell us about the search for life on distant planets? How should the most ancient and ambiguous putative biosignatures be critically evaluated? How did the Earth–life system evolve through the dramatic upheavals of the Precambrian–Cambrian boundary? When and why did eukaryotes begin to produce mineralized skeletons? These are among the astrobiological questions to which palaeobiologist Martin Brasier made profound contributions in a career spanning nearly half a century and tragically cut short late last year. Here, we summarize and celebrate Martin's contributions to astrobiology.

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Introduction

Martin David Brasier was born in Wimbledon, England in April, 1947 and died in a car accident on 16 December 2014, just a few months after retiring from the Professorship of Palaeobiology at Oxford. Over the previous five decades, his work on a wide range of topics from modern seagrass communities (Brasier 1975) to spider-webs in Cretaceous amber (Brasier *et al.* 2009) had established his reputation as one of the world's leading palaeobiologists. In the astrobiology community, Martin was respected for the analytical sophistication and critical rigour he applied to ambitious 'big picture' questions about fossils and evolution in deep time. Martin was proud to be an astrobiologist; he taught a wide-ranging astrobiology course at Oxford and appeared at many of the notable astrobiology meetings of the last 20 years, including the 2002 Astrobiology Science Conference at NASA Ames where he famously debated J. W. ('Bill') Schopf (see below), the São Paulo Advanced School of Astrobiology in 2011, and in 2012 the 50th Anniversary symposium for NASA's Astrobiology Program. In Martin Brasier, our community has lost a highly creative colleague, an incisive but constructive critic, and a stalwart friend and ally. Much has been written elsewhere to commemorate Martin the palaeobiologist (e.g. Green 2015; McLoughlin *et al.* 2015; Wacey 2015). In this paper, we pay special tribute to the work of Martin the astrobiologist.

Scientific biography

Even in early boyhood, Martin's curiosity was piqued by the absence of the whole Precambrian Eon from a BBC radio programme about evolutionary history. Nonetheless, his earliest scientific predilections were for botany and archaeology. In the 1960s, he and his brother Clive discovered and excavated Roman and Pre-Roman artefacts in the garden of their family home in Colchester (Essex, England). Their findings included a burnt layer possibly connected with Celtic Queen Boudica's famous revolt, and were eventually published (Brasier 1986). Later developing an interest in volcanic rocks, Martin went on to obtain a first-class degree in Geology from Chelsea College, London (subsequently subsumed by King's College) and in 1969 began graduate studies at University College London under the supervision of Tom Barnard. Martin's doctoral research on the ecology of microbes, plants and animals in modern carbonate reefs called, happily, for many months of fieldwork in the Caribbean, which he carried out as Ship's Scientist on the hydrographic survey ship *HMS Fawn* (this was a successor to the famous *Beagle* aboard which Darwin once sailed in an analogous role).

After obtaining his PhD, Martin worked briefly for the British Geological Survey before lecturing for 1 year at Reading University and then another 14 years at Hull. While at Reading, Martin acquired an interest in the archaeocyathids, enigmatic calcareous colonial organisms that thrived for only 10 or 20 million years during the Cambrian period. He concluded from their patterns of growth that they were animals, and most probably early sponges (Brasier 1976). In the 1970s and 1980s, Martin also studied the evolution, ecology and architecture of foraminifera ('forams'), a phylum of amoeboid protozoa with beautiful mineralized shells (forams are of course well known to geologists as important markers of the age and depositional environment of sedimentary rocks). Among the notable studies from this early period was a novel mathematical analysis of foraminiferal geometry and its evolution (Brasier 1982). In 1980, Martin published *Microfossils* (Blackwells), now the standard undergraduate textbook on the subject (in its second edition, co-authored with Howard Armstrong, 2004).

In 1988, Martin was transferred to Oxford as a Lecturer in Geology and Tutorial Fellow of St Edmund Hall. He became Reader in Earth Sciences in 1996 and full Professor in 2002, the year of his famous debate with Bill Schopf (see below). As he would later remark upon receiving the Lyell Medal, Martin worked on 'ever older and more puzzling rocks' as he himself 'grew more ancient and more puzzled'. Accordingly, much of his work during the 1990s aimed to illuminate the great convulsion of the Earth–life system across the Precambrian–Cambrian boundary. He also helped to pinpoint the boundary itself as chair of the Subcommission on Cambrian Stratigraphy and leader of a related project for UNESCO (The United Nations Educational, Scientific and Cultural Organization). After extensive investigations of candidate sites in China and Siberia, this work concluded in 1993 with the decision to situate the Precambrian–Cambrian boundary type section at Fortune Head in Newfoundland (Brasier *et al.* 1994).

For several years in the early 2000s, Martin conducted fieldwork in Oman with his Oxford colleague Philip Allen. The Neoproterozoic successions they explored included pebble beds deposited by the Sturtian and Marinoan 'Snowball Earth' glaciations. Rippled sandstones interlayering the glacial beds indicated that ice cover had been intermittent, with frequent long-lasting intervals of open-water sedimentation, counterevidence to the more extreme snowball models. The several papers resulting from this work advanced the debate about the extent and severity of the Neoproterozoic glaciations, itself an issue with clear astrobiological implications. It was also during the 2000s that Martin began to study the Ediacara biota in Newfoundland and elsewhere, and he accepted an Adjunct Professorship at Memorial University, Newfoundland in 2005.

Oxford University Press published Martin's first popular science book, *Darwin's Lost World*, in 2009, and his second, *Secret Chambers: The Inside Story of Cells and Complex Life*, in 2012. In 2014, Martin received the prestigious Lyell Medal of the Geological Society of London, awarded annually since 1876 to geologists of notable merit. Martin's citation emphasized in particular his contribution to the understanding of the Cambrian Explosion and to 'tackling fundamental questions about how and when life arose on Earth'. It is sad to reflect that, although Martin ostensibly retired in 2014, he had every expectation of continuing his work on these fundamental questions in the years to come.

Astrobiological contributions

Three of astrobiology's central concerns recurred in Martin's work. Firstly, and for the greater part of his career, he explored the *history of life on Earth* – in particular the major evolutionary transformations that led from molecules to protocells to prokaryotes to eukaryotes to multicellular organisms to animals and to biomineralizing, skeletal animals. Secondly, Martin showed how the lessons of terrestrial palaeobiology could inform the *search for life on Mars and beyond*. Thirdly, late in his career, Martin brought new geological insights to bear on the very old problem of *life's origin*. In the remainder of this review, we summarize Martin's various approaches to these astrobiological problems. Our summary is far from exhaustive, but we hope to convey both the grand scope and the analytical rigour of Martin's work to readers of all scientific backgrounds.

The oldest fossils

Martin is perhaps best known among astrobiologists for his role in the critical reappraisal of microscopic threads, purportedly composed of kerogen, in the 3.46-Ga Apex Cherts of Western Australia. At the time these were widely thought to be Earth's oldest cellular fossils. This hypothesis was advanced by J. W. Schopf of University of California, Los Angeles (UCLA), who described the structures as cyanobacterial filaments (Schopf & Packer 1987; Schopf 1993). Martin and his co-authors showed in *Nature* (2002) that these structures occurred in a wide, continuous range of shapes and sizes, many of which were straggly, irregular and wholly unlike bacterial cells. A montage of photomicrographs captured at different positions along the *z*-axis confirmed that some of the putative individual filaments illustrated by Schopf (1993) were in fact small sections of longer, amorphous blobs that had not previously been illustrated. Moreover, the geological setting is highly complex. The carbonaceous microstructures occur in multiple generations of fissure-fill within and between clasts buried in a hydrothermal vein, hinting at a subsurface origin for the carbon. Martin and his colleagues concluded that the thread-like structures originated from the reorganization of carbon during the development of a spherulitic fabric in the chert (Brasier *et al.* 2005).

The formal Brasier–Schopf debate at the 2002 Astrobiology Science Conference at the NASA Ames Research Center (Moffett Field, CA) has become the stuff of legend; good accounts of it are available elsewhere (Dalton 2002; Hazen 2005). The biogenicity of the Apex Chert microstructures remains controversial partly because of the complex geological history of their host rock, the presence of non-indigenous microfossil-like structures in the chert (Pinti *et al.* 2009) and the possibility that the Raman spectra of the carbon indicate multiple origins (e.g. Marshall *et al.* 2012). Schopf *et al.* have recently argued that their kerogenous composition (as confirmed by Raman spectroscopy), three-dimensional structure and balance of carbon isotopes continue to favour a biotic origin (e.g. Schopf & Kudryavtsev 2012). However, Martin's final, posthumously published paper on the subject takes issue with each of these claims, arguing that the structures are largely hydrothermally altered clay minerals, the kerogenous carbon is patchy and extends around and beyond the putative cells, and the isotopic composition of this carbon is somewhat moot because even biogenic carbon might be abiotically reorganized into pseudofossils (Brasier *et al.* 2015). Whatever the truth about the Apex structures may be, it is safe to say that Martin's work raised the standards of evidence and argument expected in the study of extraordinary putative microfossils. In particular, the Apex debate encouraged the development of important new techniques for analysing carbonaceous microstructures, including laser confocal Raman analysis and imaging (e.g. Marshall & Marshall 2013), Scanning Transmission X-Ray Microscopy (STXM) (de Gregorio *et al.* 2009) and Focused Ion Beam Scanning Electron Microscopy (FIB-SEM) serial sectioning (Brasier *et al.* 2015).

In his book *Darwin's Lost World* (2009), Martin wrote that ambiguous shapes in ancient rocks are like Rorschach's inkblots: their interpretation often hangs mostly on the interpreter. He gently mocked the tendency among geobiologists – including himself – to claim self-interestedly that 'my oldest fossils are older than your oldest fossils'. Since the 19th century, a series of sensational 'world's oldest fossils' have turned out not to be fossils at all. It is because of this embarrassing record, and because our judgment is easily compromised by the exciting prospect of such a major discovery that claims for the oldest fossils must be vigilantly scrutinized. Martin's own preferred candidates for the oldest known cellular fossils were the spheroidal, ellipsoidal and tubular microstructures in the Strelley Pool Chert in Western Australia (as it happens, outcropping only 20 miles away from the Apex Chert – but 65 million years younger and hailing from a very different depositional setting). With David Wacey and others, Martin highlighted multiple arguments supporting the biogenicity of these structures, including geological evidence of a habitable environment, an enrichment in nitrogen, isotopically very light carbon and a close association with isotopically fractionated pyrite consistent with a sulphur-based metabolism (Wacey *et al.* 2011). Martin and his colleagues were also the first to recognize the oldest known non-marine eukaryotes in the fossil record, in the exquisitely preserved organic microfossils of the 1-billion-year-old lacustrine Torridonian Group in Northwest Scotland (Strother *et al.* 2011; Battison & Brasier 2012).

Extraterrestrial applications of palaeobiology

Martin recognized that concepts and methods for the critical assessment of putative Precambrian microfossils found a second application in the search for microfossils on Mars, in martian meteorites, and in other extraterrestrial materials (e.g. Brasier *et al.* 2004; Rose *et al.* 2006; McLoughlin *et al.* 2007). In 2012, he and David Wacey summarized this line of thought in the present journal (Brasier & Wacey 2012). Drawing on selected examples from the fossil record, their paper set out a four-part 'protocol' for evaluating claims for both extraterrestrial and early terrestrial microbial fossils. Firstly, the putative fossils should be clearly assignable to an originally habitable environment by mapping of petrography and geochemistry at the µm–nm scale and of geological facies at the metre and kilometre scale. Secondly, the range of sizes and shapes of the 'fossils' should resemble that of biological populations. Thirdly, the 'fossils' should associate with each other and with certain preferred substrates, forming biofilm- or mat-like textures and structures. Fourthly, cell-like walls and their surroundings should retain chemical biosignatures revealing metabolic cycles, tiers and zones. Only when these criteria are met can we discard the null hypothesis that putative fossils in remarkably early or extraterrestrial rocks are abiogenic objects resulting from mineral growth or other natural processes.

Life in the late Precambrian and early Cambrian

Earth's biosphere changed dramatically across the Precambrian–Cambrian boundary (around 540 million years ago). In a span of only a few tens of millions of years, most of the familiar modern animal phyla appeared in the fossil record, an evolutionary event of striking astrobiological significance (e.g. Ward & Brownlee 2000). There is no widely accepted explanation for why this happened, and some have argued that the 'Cambrian Explosion' was an explosion only of fossils, not of animals (e.g. Towe 1981). Martin worked extensively throughout his career on the palaeobiology, stratigraphy and geochemistry of the Precambrian–Cambrian boundary and concluded that the Cambrian Explosion was essentially a genuinely rapid biological radiation, accompanied in fact by a *lowering* of the potential for fossils to form owing to both chemical changes and the increased disturbance of seafloor sediments by animals (e.g. Brasier *et al.* 2011a).

Nevertheless, a number of diverse, complex soft-bodied macro-organisms do appear in the fossil record prior to the Cambrian. Exceptionally well-preserved assemblages of the so-called 'Ediacara Biota' occur in rocks of Ediacaran age (635–540 Ma) at localities around the world, commonly in association with microbial mats. Their affinities are controversial; they include grazers probably belonging to the phylum Mollusca, irregular circular patches known as 'pizza discs', and sessile branching frond-like organisms often compared with sea pens. Martin and his co-workers at Oxford made a series of important studies of these enigmatic fossils, especially the Charnwood Forest assemblage in Leicestershire in the UK and the thousand-odd exquisite specimens exposed on shale surfaces at the Mistaken Point locality in Newfoundland. The 'pizza discs' were shown to be degraded frond-holdfasts, and the fronds themselves were shown by careful anatomical comparison to have grown in a manner inconsistent with a close affinity to sea pens (Antcliffe & Brasier 2008; Liu *et al.* 2011). This finding weakly supports the astrobiologically interesting contention that these creatures were not animals but a separate 'failed experiment' in the construction of large, complex organisms somewhat convergent with animals (Seilacher 1984). Nevertheless, evidence suggestive of animal life was also uncovered at Mistaken Point by Martin's team in the form of possible locomotion tracks and muscle tissue (Liu *et al.* 2010, 2014).

The origin of life

In 2011, having travelled backwards through evolutionary history for most of his career, Martin reached at last the problem of life's beginning. Marshalling a range of geological arguments, he and his co-workers postulated that floating rafts of frothy, vesicular volcanic rock (pumice or scoria) may have participated in the origin of life on Earth (Brasier *et al.* 2011b). These rocks combine a high internal surface area, catalytic mineral constituents and the unique ability to float. At the present day, such rafts achieve enormous bulk, travel thousands of miles after an eruption and become heavily loaded with microbial contaminants before sinking. As fresh pumice cools, floats and finally sinks, it traverses a range of different physico-chemical environments, each with their own potential contribution to prebiotic chemical reactions. Geological evidence adduced in favour of the hypothesis included

Archaean pumice from Western Australia permeated by C, O, N, P and S in mutual association, with catalytic vesicle linings (Brasier *et al.* 2013a). The possibility that the origin of life requires materials and processes occurring exclusively at the surface of Earth-like planets implies that many habitats on other planets, such as those occurring in deep aquifers or subglacial oceans, are perpetually uninhabited (Cockell 2014).

Conclusion

Martin's work was characterized by a high standard of argument and evidence, respect for the complexity of real geological and biological systems, and a willingness to engage robustly in debate when necessary. He emphasized that ambiguous putative signals of ancient (or extraterrestrial) life must always be evaluated against the null hypothesis that they are non-biological. And he stressed that this evaluation requires such signals – and, crucially, the rocks in which they appear – to be subjected to the most careful analytical scrutiny, including detailed mapping from sub-µm to km scales. This critical attitude to biogenicity was applied not only to the Apex Chert microstructures but also to putative endolithic microborings (McLoughlin *et al.* 2007), claimed traces of Ediacaran bioturbation (Brasier *et al.* 2013b) and stromatolites (McLoughlin *et al.* 2008). It is the same approach, Martin argued, that should guide our search for life on other planets (e.g. Brasier & Wacey 2012). Martin Brasier combined the imaginative, technically advanced exploration of deep questions with bracing critical rigour, and should therefore be remembered as an exemplary astrobiologist.

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