

Contributions of Professor Martin Brasier to the study of early life, stratigraphy and biogeochemistry

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Abstract: Understanding early life has been one of the hottest topics in palaeobiology for many years, attracting some of the finest palaeontological minds. Three of the most fundamental innovations in the history of life were the appearance of the first cells, the evolution of multi-cellularity and the evolution of animals. The MOFAOTYOF principle (my oldest fossils are older than your oldest fossils) commonly clouds discussions around the oldest fossil evidence, requiring a rigorous and critical approach to determining which fossils are reliable and should form the basis of our understanding of early life. In addition, evidence for early fossils must be considered within their spatial context; we need to understand the conditions under which they were preserved and how they were preserved. This book summarizes recent progress in the fields of: (1) the cellular preservation of early microbial life; and (2) the early evolution of macroscopic animal life, including the Ediacaran biota. Deciphering the evidence for early life requires some degree of exceptional preservation, employment of state-of-the-art techniques and also an understanding gleaned from Phanerozoic lagerstätte and modern analogues. This integrated approach to understanding fossils, combined with adoption of the null hypothesis that all putative traces of life are abiotic until proved otherwise, characterized the work of Martin Brasier, as is well demonstrated by the papers in this book.

Supplementary material: A chronological listing of all Martin Brasier's publications is available at <https://doi.org/10.6084/m9.figshare.c.3727696>



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The research group that Martin Brasier built over 20 years at the University of Oxford included many research students, postdoctoral researchers and visitors from a wide range of disciplines, most of whom focused on aspects of early cellular life, changes in the geosphere and biosphere during the late Proterozoic to Cambrian, and/or the evolution of early animal life during the so-called Cambrian explosion. Martin moved to Oxford from the University of Hull as part of the controversial University Grants Committee Earth Science Review, which resulted in the closure of the Geology Department at Hull. While at Hull, Martin had helped to set up and run a highly successful micropalaeontology MSc course and was well known for his work on forams and other microfossils (Brasier 2012; Gooday & Gregory 2016). At the same time, Martin had been exploring his interest in the Precambrian and Cambrian, publishing seminal papers on topics including: the pre-trilobite 'small shelly fossils' of

Nuneaton (Brasier *et al.* 1978), India (Brasier & Singh 1987) and Iran (Hamdi *et al.* 1989); the interaction between the Cambrian transgression and palaeobiology (Brasier 1980; Lindsay *et al.* 1996; Peters & Gains 2012); stable isotopic evidence for biosphere–geosphere linkages during the Cambrian explosion (Brasier & McIlroy 1998); and the relationship between palaeo-levels of nutrients and phosphogenesis (Brasier 1990a, b; Shields 2016). All this research surrounded one of the hottest topics of the time: the choice of the Global Stratotype Section and Point (GSSP) for the Precambrian–Cambrian boundary, which was resolved while he was Chairman of the Cambrian Sub-Commission for Stratigraphy (Brasier *et al.* 1994; Brasier 2009; Geyer & Landing 2016). Martin had an exceptional memory and always seemed to be able to juggle the local stratigraphic names from key sections worldwide and to keep the inferred correlations in mind when discussing issues relating to the GSSP.

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These were topics that Martin had not given up on in retirement – for example, in the first years of his retirement he was preparing to defend the choice of trace fossils as the basis for defining the boundary level in the Chapel Island Formation of southeastern Newfoundland (cf. Babcock & Peng 2007; Landing *et al.* 2013; Geyer & Landing 2016; McIlroy & Brasier 2016).

From about 1992, Martin's research became increasingly student-focused, with two major palaeontological themes emerging during that time: (1) the palaeobiology of the Ediacaran–Cambrian; and (2) early life on Earth and its implications for astrobiology. Martin was quick to realize the potential impact of new methods, analytical tools and technology for palaeontological research, although the use of the humble thin section and good old-fashioned field mapping remained staples of his research (Brasier *et al.* 2011a; Battison & Brasier 2012).

Deciphering the evidence for earliest life

In the mid- to late 1990s, Martin was conducting fieldwork with the late John Lindsay in the Proterozoic of Western Australia. It was on one of these trips that they first visited the Archean Apex Chert at Chinaman Creek in the Pilbara region. This locality was regarded at the time to host the Earth's oldest 3.46 Ga carbonaceous microfossils, which could be found in many palaeontology textbooks as the earliest fossil evidence for life on Earth (e.g. Schopf 2001). Martin borrowed the type material, which is in thin sections, from the Natural History Museum in London as he intended to illustrate the specimens in a new edition of his classic textbook on microfossils. His initial petrographic investigations revealed that all was not as it first seemed with these purported microfossils. Critical re-analysis of the Apex microtextures by Martin and colleagues (Fig. 1) followed three main strands: (1) investigation of the geological context of the Apex Chert, particularly the relation of the black organic dyke cherts that hosted the 'microfossils' with the stratiform seafloor cherts (Brasier *et al.* 2011a); (2) detailed petrographic mapping and investigation of the chert fabrics that hosted the 'microfossils', involving the development of automontage imaging techniques (Brasier *et al.* 2005); and (3) study of the crystallinity and distribution of the organic matter using laser Raman spectroscopy and, subsequently, other analytical techniques such as focused ion beam transmission electron microscopy and laser confocal scanning microscopy (Brasier *et al.* 2015; Wacey *et al.* 2016a). This work culminated in the publication of the paper 'Questioning the evidence for Earth's oldest fossils' (Brasier *et al.* 2002), which was a landmark paper that stimulated much

controversy surrounding the oldest reliable fossil evidence for life on Earth (Schopf *et al.* 2002; Schopf & Kudryavtsev 2013). A public debate between the main protagonists (Schopf and Brasier) was held at a NASA Astrobiology Institute meeting in 2003 and was vividly described by Robert Hazen (McLoughlin *et al.* 2015).

Martin's Apex Chert work motivated him to develop a critical framework for investigating the earliest traces of life, which he published and refined in a series of papers (e.g. Brasier *et al.* 2005, 2006, 2015). This involves a set of criteria and tests that span a range of scales from the outcrop and thin section scales to the sub-cellular level to establish the biogenicity of a candidate trace of life. As reviewed by Antcliffe *et al.* (2016), this required the adoption of a philosophical position, which Martin termed the null hypothesis, 'that all ancient candidate fossil structures should not be accepted as biological in origin until all possibility of their non-biological origin has been tested and falsified'. This cautious standpoint from which to evaluate candidate traces of life in the early rock record can be regarded as one of the most provoking and broad-reaching contributions of Martin's work to the field of early life research.

During this period Martin developed a strong interest in complexity theory and morphospace analysis of biotic v. abiotic forms. This approach was first outlined in Brasier *et al.* (2006), in which he applied morphometrics to test the biogenicity of a range of microfossils and microfossil-like structures from several Precambrian deposits. Morphometrics was a tool that he would also develop in other areas of his research, such as the investigation of Ediacaran fossil growth and forms (Antcliffe & Brasier 2007) and stromatolite morphology (Brasier *et al.* 2006).

Martin and his students were inspired to investigate several other Archean sites in Western Australia and alternative traces of early microbial life. For example, their work led to the discovery of sulphur-metabolizing microfossils from the 3.4 Ga Strelley Pool Chert (Wacey *et al.* 2011); the description of putative microbial mat fabrics in seafloor cherts of the 3.46 Ga Apex Chert described in this book (Hickman-Lewis *et al.* 2016) and the hypothesis of Archean volcanic pumice as a possible prebiotic substrate for life (Brasier *et al.* 2011b). Much of this early Archean research had implications for the emerging field of astrobiology, a discipline that excited Martin and inspired several of his students – leading, for example, to work discussing the protocols for testing for signs of life in Martian samples (Brasier *et al.* 2004; Brasier & Wacey 2012) and to developing biogenicity criteria tailored for samples from both the early Earth and extraterrestrial materials (McLoughlin *et al.* 2007).

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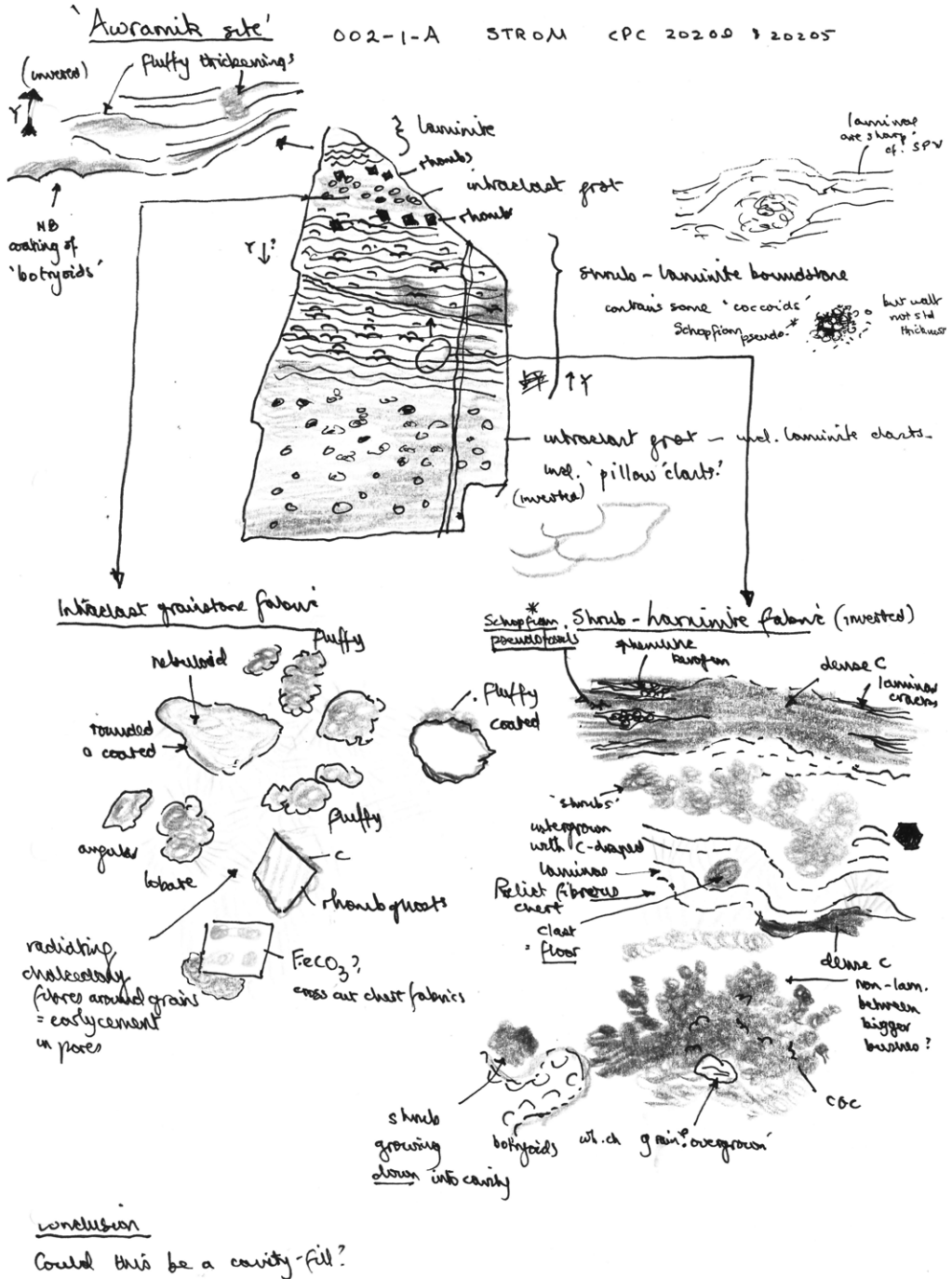


Fig. 1. Page from Martin Brasier's notebook relating to his investigations of thin sections from the c. 3.5 Ga Dresser Formation in the North Pole Dome, Pilbara Craton, collected from the 'Awramik' site. This locality in the Warrawoona group of the Pilbara, Western Australia was purported to host early microfossils described in Awramik *et al.* (1983). The page shows how Martin worked in the laboratory, the kind of detailed notes that he took and his fabric analysis of microtextures found in early Archean carbonaceous cherts, similar to those described in Brasier *et al.* (2005).

Martin's work in the Archean was among some of his most high profile, not least because of the notoriety that surrounds the MOFAOTYOF (my oldest fossils are older than your oldest fossils) principle. In his work, Martin was not just aiming to debunk some of the claims for earliest life on Earth, as he was sometimes misrepresented as doing. Rather, he wished to advocate a more critical approach to evaluating the oldest evidence for life on Earth. Martin and colleagues were inspired to re-examine other benchmark microfossils from the Precambrian, such as the Gunflint Chert, the Bitter Springs Formation and selected Phanerozoic horizons, including the Rhynie Chert, producing new insights into microfossil origins and preservation (e.g. Wacey *et al.* 2011; Qu *et al.* 2015). In short, one of Martin's most significant contributions was to emphasize a more rigorous and sceptical approach to testing and documenting the earliest evidence for life on Earth and to explore new windows onto early life beyond cherts, which had traditionally been the favoured exploration target. This inspired the development of new petrological techniques, highlighted the importance of mapping and geochronological constraints, and led to the use of morphological analysis to question the biogenicity of titanite microtextures. The latter had previously been suggested to be the oldest traces of sub-seafloor life in 3.5 Ga pillow lavas from the Barberton Greenstone Belt of South Africa (Grosch & McLoughlin 2014). In this book, **Grosch *et al.* (2016)** report the application of high-resolution *in situ* thermodynamic mapping and iron speciation spectroscopy to show that these disputed titanite microtextures are metamorphic mineral artefacts and present a new critical approach to seeking traces of early life in Archean and extraterrestrial metabasalts (Grosch *et al.* 2014). Through his highly critical assessment of, and objective approach to, the search for early life, Martin leaves a rich legacy of critical thinking relating to the fossil record of the emerging microbial biosphere, both in his own published work and through those that he inspired.

Preservation, origins and interactions of early multicellular organisms

The NW Highlands of Scotland and their Precambrian to Lower Palaeozoic strata were a favourite location for Martin. Family 'holidays' (field trips) were taken to Islay, Jura and Lochinver. He completed important work on the Neoproterozoic Dalradian rocks of Islay, which are related to the Snowball Earth (Brasier & McIlroy 1998; Brasier & Shields 2000). In recent years, Martin focused on the Neoproterozoic Torridonian Supergroup rocks to the north and south of Lochinver, which

had long been known to contain carbonaceous microfossils (Teall 1907). The predominantly red Stoer Group sediments have been interpreted as deposited in an interior-draining, sulphate-rich lacustrine environment under semi-arid conditions around 1 billion years ago (e.g. Stewart 2002; **A.T. Brasier *et al.* 2016**). By contrast, the Diabaig lake systems contain phosphate and are considered to have formed in a more open-draining lacustrine system under a cooler and more humid climatic regime (Stewart 2002; **A.T. Brasier *et al.* 2016**). **Muirhead *et al.* (2016)**, through the use of Raman spectroscopy of organic carbon, have demonstrated a significant time gap between the Stoer and Diabaig lakes.

Martin, along with several cohorts of students and former students, took a new look at the Torridonian Supergroup microfossils within their palaeoenvironmental context in the early 2000s. Martin's DPhil student Rich Callow built on the work of his colleague Tony Prave (Prave 2002) by exploring microbially induced sedimentary structures (MISS) preserved on the siltstone and sandstone bedding surfaces. Using modern microscopy techniques, Martin and his team studied the carbonaceous microfossils, uncovering preserved cellular features consistent with multicellularity (Strother *et al.* 2011; Battison & Brasier 2012; Strother & Wellman 2016). This implied that the key steps towards the evolution of complex cellular processes may have taken place in terrestrial settings. While he was working on Torridonian-related challenges, Martin hosted at Oxford his friend Lynn Margulis (previously Sagan), who was the first to propose the endosymbiosis hypothesis for the evolution of cells (Sagan 1967). This period of intense discussion and collaboration was undoubtedly a catalyst for some of his work on the origins of multicellularity (e.g. Brasier 2012).

Beyond the analysis of microfossils themselves, Martin followed a mantra, 'context is king', driving him to try to truly understand the palaeoenvironment in which these ancient organisms lived and were preserved. Martin and his student Leila Battison surprisingly found that it was the phosphate nodules and phosphorites of the Diabaig Formation that provide some of the highest fidelity preservation known in rocks of that age. This led to a number of questions. How were the phosphates formed? And why in the Diabaig Group, but not the older Stoer Group? Some of Martin's previously unpublished thoughts on the biogeochemistry of the Stoer and Diabaig lakes are included in **A.T. Brasier *et al.* (2016)**. Some of Martin's last work was a collaboration with David Wacey on cellular preservation, making use of the best available nano- to microscale petrographic and geochemical techniques (Wacey *et al.* 2013, 2014a, b; Brasier *et al.*

2015). This approach is now yielding results and **Wacey *et al.* (2016b)** present geochemical data contextualized using modern high-resolution petrography to show how the Torridonian microfossils were preserved in phosphatic materials. There is clearly much still to understand about these ancient lacustrine systems and the extremely high fidelity of preservation found within them.

Progress on understanding the evolution of animal life

With the establishment of his research group at Oxford in 1992, Martin became progressively more involved in the palaeontology of the Precambrian to Cambrian transition. From his first dalliances with archeocyathans and stromatolitic bioherms (Brasier 1976) – which can now be traced back into the Ediacaran (**Wood 2016**) – Martin became increasingly fascinated with the evolution of animal life and the Precambrian–Cambrian boundary. His first DPhil student, Duncan McIlroy, was directed towards many of his projects in progress, but with free rein to go and explore. A note in one of Martin's older field notebooks from the 1970s states that 'the rock is the father of the fossil', which is something that he instilled in all his students. You cannot in good faith interpret fossils without paying attention to the rock in which they are hosted. Making thin sections and mapping – at whatever scale was appropriate – was expected. Many of these earlier papers had echoes of Martin's interest in protists (McIlroy *et al.* 1994, 2001), a group that he was coming back to study in the Ediacaran (Antcliffe *et al.* 2013). With the decision on the GSSP (Brasier *et al.* 1994) there was an obvious renewed interest in the ichnology of Avalonia, which encouraged him to link his recent studies on stable carbon isotopes (Brasier *et al.* 1992, 1996) to changes in the carbon cycle associated with the evolution of bioturbation (Brasier & McIlroy 1998; McIlroy & Logan 1999). A natural extension of this is recent work that assesses the potential of different trace fossil types to be ecosystem engineers that have altered the seafloor and its biogeochemistry ever since their evolution around the Ediacaran–Cambrian boundary (**Herringshaw *et al.* 2017**).

As Martin himself eloquently describes in one of his books relating the controversies surrounding the GSSP decision (Brasier 2009), he always had a soft spot for Newfoundland and its people. His first expedition to Newfoundland was with Mike Anderson to look at GSSP candidate sections. Back then, Martin was largely focused on the potential of the pre-trilobite small shelly fauna and stable isotopes for defining the boundary level. Newfoundland

was a place that he returned to every year during the last 10 years of his career, accompanied by many research students, working closely with the first of his Ediacaran–Cambrian *protégés* (his phraseology), Duncan McIlroy, in the Department of Earth Sciences at the Memorial University of Newfoundland (MUN). Martin was soon appointed as an adjunct professor at MUN, a title and responsibility that he was very proud of. One of his favourite places in the world was the remote rugged coastline around Mistaken Point that he helped to promote as a candidate UNESCO World Heritage Site, a bid that was successful, but, unfortunately, not announced until shortly after his passing. His work in promoting Mistaken Point and the first geoconservation-related research at the site (**Matthews *et al.* 2017** and work in progress) will constitute a significant part of his legacy.

Martin always encouraged his students to undertake local UK-based fieldwork and was himself a very skilled field geologist with a sharp eye; he was quick to spot potential. A good example of this is Martin's first study of the Ediacaran of Charnwood Forest (Fig. 2), where detailed field mapping and careful petrography allowed constraints to be put on the age of the Ediacaran fossils in the UK (McIlroy *et al.* 1998). At the same time, claims for very ancient trace fossils in the Vindhyan (1100 Ma) (Seilacher *et al.* 1998) were met with careful stratigraphic, geochronological and palaeontological/biological arguments, which demonstrated that the rocks were deposited at about the base of the Cambrian and that the burrows were likely to have been produced by triploblastic, probably worm-like, Cambrian organisms (Brasier 1998). This burgeoning interest in the Ediacaran, which was to become one of his greatest contributions to palaeontology, stemmed from this desire to determine whether the Ediacaran fauna were unusual ancient animals that recorded a long history of animal life prior to the Precambrian–Cambrian boundary (cf. **Dufour & McIlroy 2016**), or whether it was a different experiment at life as had been proposed by others (Seilacher 1992).

Martin and his students spent much of the last decade documenting, describing and analysing Ediacaran fossils (Fig. 3), many of which came from the ancient microcontinent of Avalonia. Crucial to that work was determining how the Ediacaran organisms grew and, in the process, demonstrating that they did not grow like morphologically similar modern taxa (Brasier & Antcliffe 2004, 2008; Antcliffe & Brasier 2007, 2008). Demonstrating what fossils 'are not' is only the beginning of the process, however. One of the greatest problems in progressing our understanding of the palaeobiology of the Ediacaran fauna is communication of the complex morphology associated with the Rangoomorpha in Avalonia.

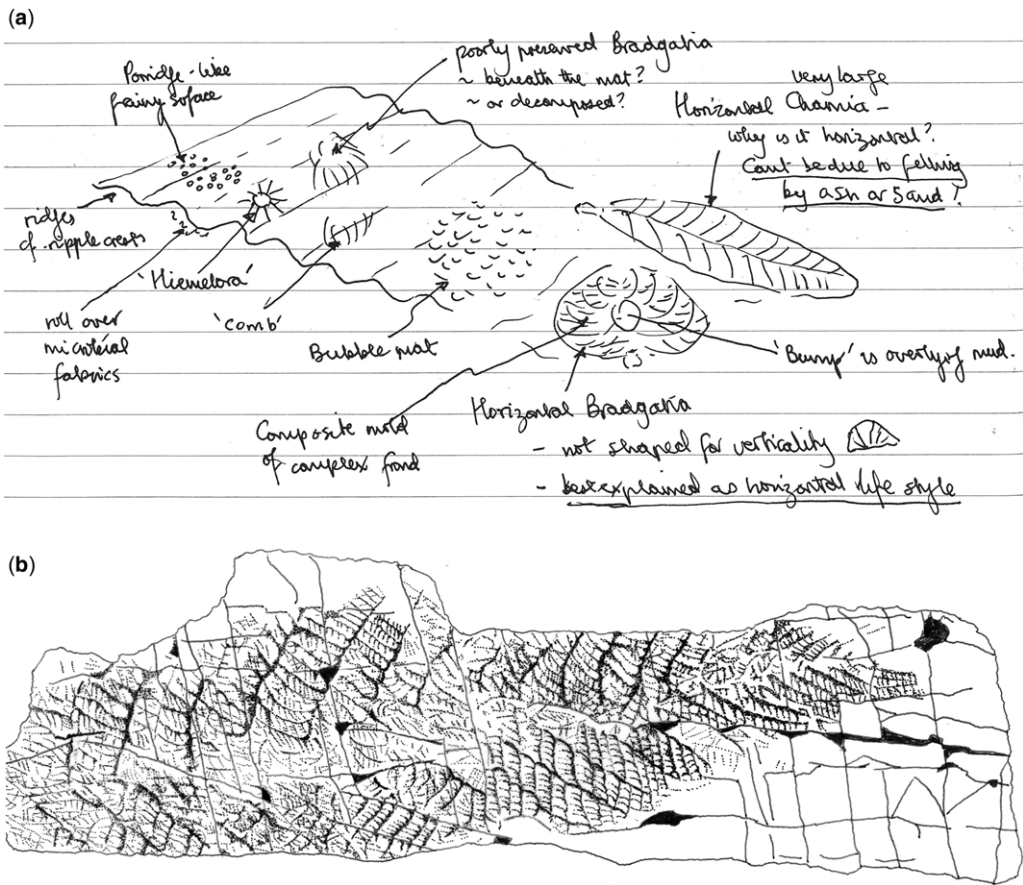


Fig. 2. Charnwood Forest was a site dear to Martin, which he worked on over many years. (a) A page from a field notebook with the kind of musings that could be saved and re-examined at future dates, either by himself or his students, who had free access to his notebooks. (b) Detailed sketch of the large *Charinia* from Bradgate Park in Charnwood, which is a composite image produced by illuminating a cast from several directions and sketching multiple times to reveal structures only visible with particular lighting.

Through the careful drawing of new material (Fig. 4), including juvenile forms (Liu *et al.* 2012), various taphomorphs (Liu *et al.* 2010a) and several new rangeomorph/frondose taxa – including *Beothukis* and *Vinlandia* (Brasier & Antcliffe 2009; Brasier *et al.* 2012) – several repeating morphological elements were determined that could form the basis for a formal taxonomy (Brasier *et al.* 2012; Liu *et al.* 2016b), with the allowance that there may be some element of ecophenotypism (Liu *et al.* 2016a), although the latter is questioned by multivariate statistical analyses using the Brasier descriptive scheme as its basis (Kenchington & Wilby 2017). Through all this careful descriptive work, the group remained open-minded to the possibility that the Ediacarans might not have been animals (Antcliffe *et al.* 2016).

In recent years, however, the group has uncovered increasing evidence for animal-like trace fossils and cnidarians among the Ediacaran. Trace fossils from 560 Ma demonstrate that, unlike the rangeomorph taxa, there were rare motile organisms within the fauna that were probably cnidarians (Liu *et al.* 2010b, 2014b; Menon *et al.* 2013, 2014). This inference was clinched by the discovery of one of the most exquisitely preserved Ediacaran fossils anywhere in the world, *Haootia quadriformis* (Fig. 5; Liu *et al.* 2014a, 2015), which is now widely accepted among the biological community as a staurozoan cnidarian (Miranda *et al.* 2015). This paradigm shift towards an acceptance of the existence of animals within the earlier Ediacaran (i.e. a long fuse to the Cambrian explosion) is supported by the interpretation of *Fractofusus*

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Fig. 3. Martin Brasier in the field in southeastern Newfoundland, Canada on one of his many summer field seasons to the region. Martin would commonly spend hours sketching and note-taking, producing very clear, easily accessible notes including ideas and hypotheses.

and other rangeomorphs as chemosymbiotic pre-placozoan diploblastic organisms (**Dufour & McIlroy 2016**), *Yorgia* and *Dickinsonia* as placozoans (e.g. Sperlina & Vinther 2010; although see McIlroy *et al.* 2009) and *Kimberella* as a mollusc (Fedonkin & Waggoner 1997) – notwithstanding Martin’s critique of the poriferan fossil record (Antcliffe *et al.* 2014).

It is clear that a new understanding of the Ediacaran biota is underway, but, as part of this process, there needs to be careful critique of both new and old material. One of the most commonly misinterpreted Ediacaran structures is the discoidal forms that dominate the matground-rich facies of the latest Cambrian in Avalonia, Baltica and Siberia, which was previously thought to reflect a biotic event known as the Kotlin Crisis (Brasier 1995), although many such taxa have been reinterpreted as MISS in stressed Ediacaran environments (Menon *et al.* 2016a, b). Matground facies were the norm in Proterozoic sedimentary successions in both marine and non-marine basins (**A.T. Brasier *et al.* 2016**). From the later Ediacaran – and through much of the lower Palaeozoic – microbial matgrounds are common components of normal marine assemblages. From the latest Ediacaran onwards,

matgrounds are increasingly rare, showing abundant evidence for metazoan grazing and bioturbation (McIlroy & Logan 1999; Buatois *et al.* 2014; **McIlroy & Brasier 2016**). Positive feedback loops have been uncovered between the productivity of sedimentary microbiota and the increase in size and depth of trace fossils (McIlroy & Logan 1999; **Heringshaw *et al.* 2017**). There is also a suggestion of phagocytotic or chemosymbiotic feeding on matground microbial communities by the earliest Ediacaran animals (**Dufour & McIlroy 2016**). One of the most common features of Ediacaran and early Palaeozoic marine successions and many lacustrine basins throughout the Phanerozoic is the superabundance of subaqueous cracks, some of which are associated with microbial matgrounds (Harazim *et al.* 2013; **McMahon *et al.* 2016**).

The dramatic changes in the linked geosphere–biosphere system that characterize the Ediacaran–Cambrian boundary are generally considered to reflect the diversification of complex triploblastic organisms, such as annelids and arthropods, which are simultaneously the basis of the stratigraphic definition of the most important boundary in the rock record (the Proterozoic–Phanerozoic boundary; **Geyer & Landing 2016**) and provide



Fig. 4. Like many of the best palaeontologists, Martin loved drawing fossils. The quality of his penmanship speaks for itself, but there is something about the act of making such a detailed drawing that focuses the mind on morphology and growth. This sketch is of the Ediacaran fossil *Dickinsonia* from the collection of Martin's friend and mentor, the late Roland Goldring.

evidence for the Cambrian explosion (McIlroy & Brasier 2016). Much has been written about both topics, but Martin encouraged work that creates a sound stratigraphic framework based on geochronology and stable isotope geochemistry (e.g. He *et al.* 2016) to calibrate the biostratigraphy and provide evidence for the Cambrian explosion. Martin constantly encouraged his students to bear in mind the limitations of the fossil record, including the shortcomings of first appearance datums and the dangers of MOFAOTYOF (Brasier 2009), emphasizing that the onus is on the researcher to unequivocally demonstrate any claim for anomalously old fossils. This principle is particularly pertinent to claims for fossil distributions around the Ediacaran–Cambrian boundary (Landing *et al.* 2013; Geyer & Landing 2016). Attempts to use first occurrence datums for stratigraphy at the level of the Ediacaran–Cambrian boundary are likely to be complicated by the potential for the diachroneity of the Cambrian explosion of complex animal life (McIlroy & Brasier 2016), and provincialism of these earliest biotas (McKerrow *et al.* 1992; Waggoner 2003).

Adventures in exceptional preservation

Anyone who had the pleasure of being in the field with Martin will know that he was amazingly good at finding interesting, well-preserved things of scientific importance. In the early 1960s, when Martin was in his mid-teens, he and his brother Clive excavated a Romano-British refuse pit they discovered in their back garden in Colchester (ancient Camulodunum), which was full of Claudian domestic artefacts. Martin's attention was drawn to a distinctive burnt layer in the upper profile that he considered to possibly have been a consequence of Boudicca's revolt against the Roman occupation. Martin wrote up the excavations and submitted them to *Transactions of the Essex Archaeological Society* in the mid-1960s. For a long time, the paper was lost or misfiled, but was rediscovered and finally published without his knowledge (Brasier 1986). While this was not the first paper he published, it was the first that he wrote. The excitement of the dig and the cataloguing of the material, especially the nail and pot-herd profiles, started Martin's fascination with stratigraphy, classification and a lifelong passion for Roman coins.

Always a naturally curious scientist with his eyes open, Martin relished exploring scientific and palaeobiological challenges far beyond the Precambrian–Cambrian boundary. With his doctoral student Louise Purton, Martin went on to pioneer oxygen and carbon isotope studies of Eocene mollusc shells (Purton & Brasier 1997). Some remarkable discoveries came from Martin's visits to his elderly parents in Bexhill, Sussex in the first decade of the twenty-first century. Martin would walk along the beach looking for dinosaur bones and geological curiosities. Here he came across Jamie Hiscocks, a collector who had found early Cretaceous amber in the local rocks. Martin eagerly examined several Bexhill amber specimens with his microscopes, discovering entombed within them the 'world's oldest fossil spider's web' (Brasier *et al.* 2009). A Fourier transform infrared spectroscopy analysis of the Bexhill ambers, and those of others from around the world, is reported in this book (Cotton *et al.* 2017), resulting from the Master's thesis of the first author. An aim of that work was determining potential age- or location-related similarities between different amber deposits from around the world. Also found in the Bexhill amber-yielding rocks of the Wealden Group were millimetre- to centimetre-sized, amber-coloured fossils that Martin had tentatively identified as amber-coated insect cocoons. A.T. Brasier *et al.* (2017) undertook further high-resolution stereomicroscopic imaging and computed tomography scanning of these fragile fossils. Their morphological findings include fibrous structures and wall-penetrating pores that are

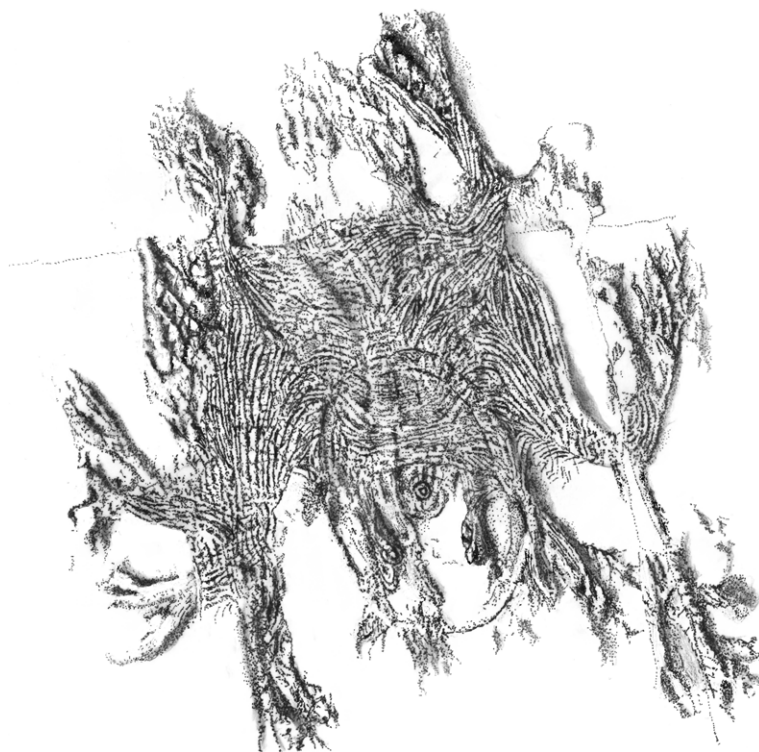


Fig. 5. *Haootia quadriformis* sketched here is one of the most important Ediacaran fossils known because it provides strong evidence that cnidarian animals, relatives of the jellyfish, lived alongside the Ediacaran biota. The fossils are considered to be stalked cnidarians known as stauromedusans. By sketching, Martin was better able to understand the distribution of the different components of the fossil, which are draped over one another.

compatible with their interpretation as early Cretaceous insect cocoons. The authors provocatively speculate that some early Cretaceous insects deliberately coated their cocoon fibres in toxic plant resins as a defence against contemporaneous predators.

Another important fossil from Bexhill was a small brown pebble, also found by Jamie Hiscocks, that Martin recognized as being the mineralized brain of a dinosaur. He, and several of his students, began a series of analytical studies over several years that enabled them to demonstrate fossilized dinosaur brain tissue for the first time (M.D. Brasier *et al.* 2016).

Martin had a family holiday cottage in the hamlet of Llanteg, on the border of Pembrokeshire and Carmarthen in South Wales, UK. This location was carefully chosen for its proximity to interesting Palaeozoic rocks that Martin had already started work on (Fig. 6). Indeed, among them, Martin discovered a site of exceptional fossil preservation: the Middle Ordovician Llanfallteg lagerstätte (Hearing *et al.* 2016). This site exhibits Ordovician communities with types more usually associated

with Cambrian lagerstätten, including pyritized carbonaceous compressions displaying a similar form of preservation to the early Cambrian Burgess Shale. This was part of his plan for a long, active retirement that was sadly not to be.

Conclusions

Martin's time at Oxford spanned 26 years and included many DPhil and, in later years, MEarthSci student projects focused on aspects of early microbial and animal life. Martin had the knack of inspiring undergraduate students through his teaching and designing of projects that were meshed with those of more senior research students. Martin leaves a rich scholarly record in the academic literature. We have attempted to summarize the highlights of this here, but a full bibliography of Martin's work also accompanies the supplementary material to this book. In more recent years, Martin wrote two books for a popular scientific audience *Darwin's Lost World: the Hidden History of Animal Life*

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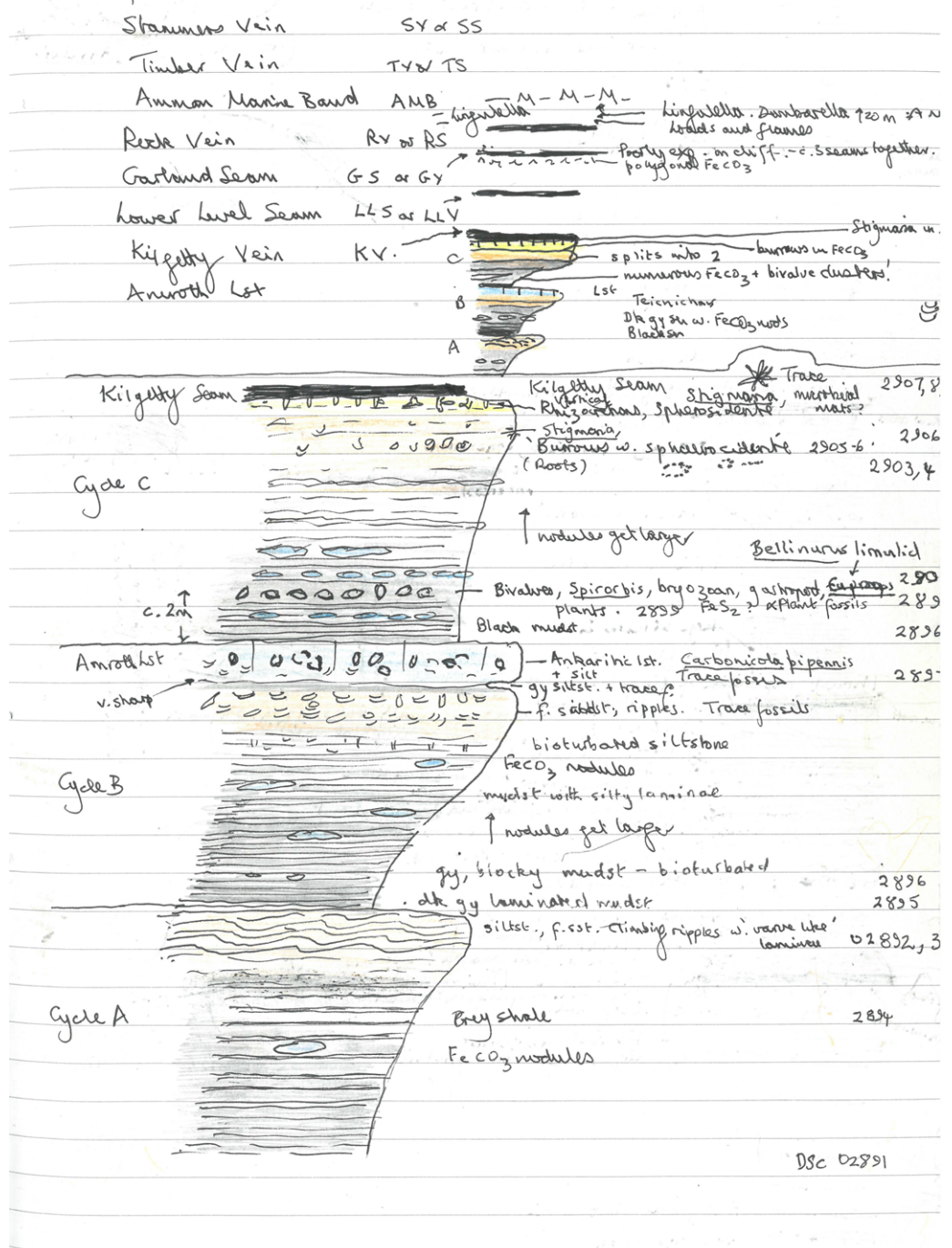


Fig. 6. Continued.

(Brasier 2009) and *Secret Chambers: the Inside Story of Cells and Complex Life* (Brasier 2012). There was to be a third book focusing on the origins of life and the earliest fossils, but sadly this was never written. Martin's collection of rocks and fossils is to be curated by the Natural History Museum in Oxford and will be accessible by academic request. Martin also kept many private notebooks, which are a rich treasure trove of ideas, sketches and jottings that spanned his academic career and through which he formulated his scientific ideas, often accompanied by amusing anecdotes.

Martin considered that his responsibilities towards his former students did not stop at the time of graduation. He took a lot of time and great care in writing letters of reference for his *protégés*; we all remained, literally, under his protection for as long as we needed him. As many readers will know, academia is not always a straightforward path and Martin could always be counted upon as a source of advice when needed. In Martin's last years, several of his students moved on to become faculty members and postdoctoral students, taking with them his ideas and research expertise to share with the next generation of students. This can be uncomfortable for academics, especially if their students

continue to work closely with them in the same field. Although this source of potential conflicting interests was something he initially wrestled with, Martin soon came to realize that he was not so much losing his best students to other universities as letting his academic family spread its wings, and that in doing so his own influence and legacy was spreading. This concept of the Brasier Academic Family is something that he embraced wholeheartedly in his last years, especially around his retirement event at Oxford in 2014, when many of his academic family and friends came together to celebrate his achievements and set a path for the future (Fig. 7). At that gathering of the Brasier Academic Family, we talked about compiling a book of academic work by his extended research family as he started to tie up some of his loose ends of projects. Sadly, Martin did not live to see that realized, but in the spring of 2015 his students and some of his family gathered again in Oxford to come together to celebrate his life, to help to resolve some of the loose ends that were left by his untimely passing, and to support the junior researchers who had lost their mentor. This book is the product of that meeting; many of the papers in this book are the work of the Brasier Academic Family, including hitherto



Fig. 7. Photograph of the Brasier Academic Family and friends who attended Martin's retirement celebration at the University of Oxford. The event consisted of a day of talks followed by a meal and an entertaining evening of speeches and entertainment at St Edmund Hall, at which Martin, to the delight of all, played jazz piano.

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unpublished work from his many Master's students, augmented with papers by some of Martin's close colleagues. The book is unashamedly broad, but it needed to be to encompass the breadth of experience, expertise and interests of a truly fascinating naturalist/geologist, whose contributions and insights across a wide range of disciplines will benefit generations of scientists to come.

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