Critical testing of Earth’s oldest putative fossil assemblage from the ∼3.5 Ga Apex chert, Chinaman Creek, Western Australia

Martin D. Brasier*, Owen R. Green†, John F. Lindsay‡, Nicola McLoughlin‡, Andrew Steele‡, Chris Stoakes‡

* Earth Sciences Department, University of Oxford, South Parks Road, Oxford OX1 3PR, UK
† Lunar and Planetary Institute and Johnson Space Center, Houston, TX 77058, USA
‡ Geophysical Laboratory, Carnegie Institution of Washington, 5251 Broad Branch Road NW, Washington, DC 20015-1305, USA

Received 10 December 2004; received in revised form 10 June 2005; accepted 24 June 2005

Abstract

Structures resembling cyanobacterial microfossils from the ca. 3465 Ma old Apex chert of the Warrawoona Group in Western Australia have until recently been accepted as providing the oldest morphological evidence for life on Earth, and have been taken to support an early beginning for oxygen-releasing photosynthesis. Eleven species of filamentous prokaryote, principally distinguished by shape and geometry, have been put forward as meeting the criteria required of authentic Archaean microfossils. They were contrasted with other microfossils that were dismissed as either unreliable or irreproducible. The aim of this paper is to provide a detailed account of research recently reported by us on the type and recollected material, involving optical and electron microscopy, digital image analysis and other techniques. All previously figured holotype materials are illustrated here, and the context for all the published materials is re-evaluated.

The Apex chert ‘microfossils’ occur near the top of a 1.5-km long chert dyke complex associated with major synsedimentary growth faults. Highly localised, glassy felsic tufts erupted explosively from this and other fissures during the early stages of volcanism, and were followed by the deposition of essentially hydrothermal black and white BaSO₄ rich cherts that infiltrated the feeder dykes, underplating and diluting adjacent stratiform cherts before the start of the next volcanic cycle. The Apex chert ‘microfossils’ occur within multiple generations of these metalliferous hydrothermal vein cherts some 100 m down the dyke system. Comparable structures occur in associated volcanic vent glass and in hydrothermal cherts at least 1 km deep. We find no supporting evidence for a primary biological origin. We reinterpret the purported microfossil-like structures as pseudofossils that formed from the recrystallization of carbonaceous matter, mainly during recrystallization from amorphous to spherulitic silica.

Keywords: Apex chert; Archaean fossils; Early life; Warrawoona; Western Australia

© 2005 Elsevier B.V. All rights reserved.

* Corresponding author. Tel.: +44 1865 272074; fax: +44 1865 272072.
E-mail address: martinb@earth.ox.ac.uk (M.D. Brasier).

0012-8252/$ – see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.precamres.2005.06.008

PRECAM-2583; No. of Pages 48
1. Introduction

The extreme rarity of Archaean (3.8–2.5 Ga) microfossils, in comparison with those from the Proterozoic (2.5–0.54 Ga), is surprising given the presence of tufa-like carbonates \( \text{(Grotzinger et al., 1989)} \) and the abundance of sedimentary cherts \( \text{(Irving, 1998)} \). One possible explanation for this paradox is that most Archaean cherts had a lower preservation potential, being formed by hot, acidic, reducing and concentrated hydrothermal fluids, in contrast with the higher preservation potential of relatively cool, neutral and diluted surficial fluids of most Proterozoic cherts \( \text{(Irving, 1988)} \).

But this cannot explain the absence of bacterial molds in tufa-like carbonates of this age. Another possibility, therefore, is that Archaean habitats were largely volcanogenic or hydrothermal and that true cyanobacterial communities did not emerge until near the end of the era \( \text{(Irving et al., 1991)} \). Whatever the reason, morphological evidence for life beyond 3.0 Ga is arguably of such great scientific significance, and now appears to be so rare, that rigorous criteria are needed for acceptance by the scientific community \( \text{(Irving et al., 1991)} \). As others have put it: "extraordinary claims require extraordinary evidence." This cautionary dictum, attributed to the late Carl Sagan, was received wide public notice at the press meeting called by NASA on August 7th 1990 \( \text{(VanCleave, 1990)} \).

On the 7th day of the press conference \( \text{(van Cleave, 1990)} \) noted: "It was here that the biogenecity of the Martian 'microfossils' was first questioned and contrasted with the oldest evidence of life on Earth—microfossils from the 3.46 billion-year-old Apex chert at Chinamian Creek, in the Warrawoona Group, near Marble Bar in Western Australia \( \text{(Golombek et al., 1996; Lindsay et al., 1997, 1998a, b; Catling et al., 2000; Hall, 1998; Summons et al., 2001)} \)."

These world famous Apex 'microfossils' have been described in a series of papers \( \text{(Buick et al., 1984; Hall, 1998; Summons et al., 2001)} \). They have rightly held a key position in Archaean palaeobiology because of their suppositionally good state of preservation and their wide acceptance by the scientific community \( \text{(e.g. Schopf, 1985a, b; Nobel, 1986; Schopf et al., 1991; Schopf et al., 1995; Halasz et al., 1996; Green, 1998; Irwin et al., 1998; Nobel et al., 2000)} \).

This contrasts with preliminary reports of other presumed 'microfossils' from the Warrawoona Group, dismissed as either unreliable or irreproducible \( \text{(Golombek et al., 1996; Lindsay et al., 1997, 1998a, b; catling et al., 2000; Hall, 1998; Summons et al., 2001)} \). In this paper, we begin by re-
evaluating the evidence for these important materials. We then go on to falsify the claims for syngenticity and biogenicity of the filamentous structures from the Warrawoona Group, and question whether the Apex chert dyke provided a potential habitat for early life, developing arguments laid out by us in Brasier et al. (2004a,b). Our abiotic model for the generation of the microfossil-like fabrics involves the recrystallization of carbon-rich chert in a hydrothermal setting. We conclude the paper with detailed petrographic descriptions of rock slices containing the 11 holotypes.

2. Methods

Field mapping of the Apex chert at Chinaman Creek (see Fig. 1) was undertaken by us as part of a wider programme with the Geological Survey of Western Australia, Perth. We implemented in press supplemented by a detailed collaborative programme of mapping and sampling undertaken jointly by Oxford and NASA, Houston across an area of about 12 km². Multiple samples were collected from the microfossil locality around the site between 1999 and 2003, located by means of satellite images and Global Positioning Systems (GPS). Optical petrography and fabric mapping was performed at Oxford on published and re-collected material with the use of 30, 150 and 240 μm thick sections. Polished slices, hydrofluoric acid (HF)-etched rock chips and HF residues were examined in a Zeiss 840A and Philips XL30S field-emission SEM's, fitted with a light-element EDX system operating at 1–15 kV. Rock slices, polished slices, hydrofluoric acid (HF)-etched rock chips and HF residues were also examined at Oxford under epifluorescence, cathodoluminescence, phase contrast and brightfield, polarized transmitted and incident (reflected) light using Nikon Optiphot-2 (biological) and Optiphot-pol (polarizing) and Wild-M8 microscopes. Images were obtained using a single-chip CCD camera, providing live images in full RGB colour, and processed using AcQuis and Auto-Montage image capturing software. AcQuis is a single-frame image capturing, processing and archiving system designed specifically for optical microscopy when using brightfield, fluorescent or polarized illumination. The user can apply a scale-bar and annotation to the processed image, and store this information either engraved onto the original image or as a separate file that can be overlain on the original image. Auto-Montage is a more sophisticated
software package, processing and combining multiple source images, each obtained at a different focal plane within the section. Processing algorithms enable the most sharply focussed areas of each source image to be combined into a single well-focused montaged image. This rendering facility is ideal for obtaining high-resolution images of 3D microscopical artefacts aligned obliquely to the z-axis within a slide. It is similar to the established technique of manual montage, in which images of a microfossil-like structure are collected by optical photomicrography and then manually spliced in the darkroom or laboratory (e.g. Schopf, 1992b, 1993). It differs, however, in that selected focal planes from the montaged image can be displayed on the screen or print. Single-source images can be viewed independently and, when combined, used to scan through the z-plane of the structure or to make a moving image through the structure. The latter allows observers to come to their own opinion about any microfossil-like structure. All images are stored in the Oxford digital database of Archaean microfossil-like structures.

3. Context

3.1. Regional setting

The Pilbara Craton of Western Australia contains some of Earth’s oldest and best-preserved rocks. The craton is part of an Archaean proto-continent, comprising granitoid complexes that were emplaced into and are overlain by the Pilbara Supergroup, now preserved as greenstone belts. The Pilbara Supergroup consists of five unconformity-bound stratigraphic intervals (or groups) that formed as a volcanogenic carapace contemporaneous with the intruding granitoid bodies between ca. 3.51 and

<table>
<thead>
<tr>
<th>GROUP</th>
<th>MEGASEQUENCE</th>
<th>LIFE?</th>
<th>FORMATION</th>
<th>AGE Ma</th>
<th>GRANITES</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>DE GREY GROUP unconformity</td>
<td></td>
<td>Lalla Rook Sandstone</td>
<td>c.2950</td>
<td>3</td>
</tr>
<tr>
<td>M4</td>
<td>GORGE CREEK GROUP unconformity</td>
<td></td>
<td>Pyramid Hill Formation, Honeywater Basalt, Paddy Market Formation, Corboy Formation, Pincunah Hill Formation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M5</td>
<td>SULPHUR SPRINGS GROUP unconformity</td>
<td>(5) Kangaroo Caves Formation, Kununurra Formation, Lesira Formation</td>
<td>3238-3239</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M2</td>
<td>WARRAMOOA GROUP oldest unconformity</td>
<td>(4) Euro Basalt, Streley Pool Chert, Panorama Formation, Apex Basalt, Quater Formation, Assy Formation</td>
<td>3458</td>
<td>H</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(3) Mount Ays Basalt, McPhie Formation</td>
<td>3471-3463</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M1</td>
<td>COONERUNAH GROUP</td>
<td></td>
<td>Double Bar Formation, Coonal Formation, Table Top Formation</td>
<td>3515</td>
<td>H</td>
</tr>
</tbody>
</table>

Fig. 2. Simplified stratigraphy of the Archaean rocks exposed in the Chinaman Creek study area (adapted from Vaik Kranendonk, 1999, 2000 showing confirmed isochron ages and formations that contain putative microfossils and stromatolites. Arrows indicate dated period of activity of the granitoid complexes as distinct from the intrusion of smaller plutons that are shown in cartoon form. Major periods of hydrothermal activity (H) tend to coincide with periods of intrusion. Putative fossils (1) and Packer (1987), (2) and (3) and (4)
2.94 Ga. Components of the granitoid complexes are broadly coeval with the felsic volcanic horizons in the Pilbara Supergroup, with which they can have intrusive or sheared intrusive contacts. The five groups were deposited one above the other and they consistently dip away from the domal granitoids. The dips of the bedding gradually decrease with time, suggesting that they were deposited as thickening wedges adjacent to the growing granitoid domes. Hickman (1975, 1983, 1984; Van Kranendonk, 1999, 2000; Van Kranendonk et al., 2002). This succession is believed to have accumulated in a series of grabens developed in an extensional setting that evolved above the intruding and doming granitoid complexes.

The well-preserved Warrooona Group is 10–15 km thick and accumulated between ca. 3.5 and 3.4 Ga. It consists largely of extrusive volcanic rocks, with less common interstratified chert, barite, sulphide, carbonate and volcaniclastic units (Hickman, 1983). It is these interstratified units that contain the putative microfossils and stromatolites that currently provide the focus for much current research into Earth’s earliest biosphere.

This study focuses on the Apex chert of the Apex Basalt that lies in the middle of the Warrooona Group and is approximately 3.46 Ga old (Van Kranendonk, 2000). The Apex chert is geographically limited to the Panorama Belt of the central Pilbara Craton. The unit consists mainly of tholeiitic basalts and subordinate high-Mg basalts (komatiitic basalts) that show abundant evidence for subaqueous eruption including pillows, chilled margins and hyaloclastic breccias. Doleritic flows and intrusions are also common and doleritic dykes are locally present (Van Kranendonk, 2000). The formation includes several thin (<30 m thick) chert horizons of which the Apex chert, close to Marble Bar in the Chinaman Creek area, is the best known.

4. Results

4.1. Field mapping

Our mapping shows that the Apex Basalts and Apex chert in the Marble Bar area are distributed
This volcaniclastic unit can be seen to overlie vesicular pillow basalts of unit 1. The stratiform Apex chert (unit 4) is underlain by numerous black chert dykes that invade these faults, with the largest dyke cherts marking both the S1 and S4 faults. The stratiform Apex chert is here capped by a pyroclastic breccia bed (unit 5), ca. 3 m thick and thinning northwards, with clasts (<1.0 m across) that also line along the strike northwards. This unit contains large clasts of the underly- ing lithologies, including both stratiform and dyke chert lithologies, and pumice. It is taken to mark the start of the next volcanic cycle (units 5–9). This second volcanic cycle is largely obscured in the South and Central Blocks by an erosional unconformity at the base of the overlying ϵ2700 Ma Fortescue Group.

The Central Block lacks volcaniclastic units 2 and 5 implying uplift and non-deposition or erosion on this block during these phases. The Apex chert is also very thin here and the black chert dykes are correspondingly scarce and small. The North Block is defined along its southern margin by the ca.1500 m long N1 fault and its associated chert dyke system that yields the questionable Apex 'microfossils' (Fig. 5). A wedge of grey-green tuff and ignimbrite with devit- rified glass shards occurs near the top of this dyke (unit 3) here interpreted as an initial volcanic eruption from the fissure now occupied by the dyke chert. Similar felsic tuffaceous mate- rial also occurs within the stratiform chert unit (unit 4) where it has been silicified. This glassy volcaniclastic unit pinches out northwards to dis- appear beneath the stratiform Apex chert. The overlying pyroclastic breccia marker bed (unit 5) that seemingly originates from the S1 fault (see above), reappears in the North Block but continues to attenuate in both thickness and grain size towards the north. A distinctive bed of fine grey tuff (unit 8) thickens towards the N1 fault and also wedges out rapidly towards the north. This unit is not seen in the Central and South Blocks and is inferred to have erupted in the vicinity of the N1 fault system.

Stratiform units within the Apex chert of this area are mainly characterized by planar bedding, with moderate to good local grain sorting and grain orientation. Several volcanic-sedimentary subcycles are present,
Fig. 5. Detailed geological map of S4 dyke in the south block of the Chinaman Creek study area. Note the presence of rounded blocks of stratified chert up to 450 m palaeodepth down the dyke system.

showing rhythms from 1 to 5 m thick that typically begin with grey-green, planar bedded siliceous tuffs plus red-brown jaspilite banded chert (1–4 cm thick layers), passing upwards into grey, black or black-white planar bedded chert (1–10 cm) and thence into black-white banded cherts with localised soft sediment deformation and breccias, indicating zones of liquefaction, cavity formation and collapse. A similar shift, from tuffaceous and jaspilite chert near the base, to black and brecciated chert, can be seen in the stratiform chert as a whole, especially to the north of N4. Earlier reports of cross-bedding from the bed of Chinaman Creek (e.g. Schopf, 1993) are re-interpreted as imbricate slabs of chert that have slumped within a zone of liquefaction (Figs. 4 and 5). Such features are common. Even so, hummocky cross-stratification from the possibly coeval Antarctic Creek cherts of the North Pole area, suggests that water depths were close to storm wave base in parts of the basin (VaNkenr, 2000).

Dyke cherts are abundant in both the South and North Blocks. They are characterised by a cross-cutting geometry; by a lack of grain sorting or grain orientation in the matrix; by multiple generations of fracturing, spalling (with jigsaw puzzle fit of clasts), fissure formation and fissure filling; by fault-rotated geopetal fabrics; by hydrocarbon-impregnated botryoidal and spherulitic chalcedony and chert; by associated megaquartz veining. These dyke cherts tend to fan upwards, and to become both thicker and more multiphase upwards. In the South Block, dyke cherts appear to fan outwards from a depth of about 500 m beneath the palaeosurface. At greater depth are found discontinuous dykes and horizontal sills of grey chert plus sills of vein quartz (Figs. 3–6).

Two black chert dyke systems have been studied by us in detail (see Fig. 3). The S4 dyke complex has a curved outcrop that extends for some 500 m beneath the stratiform cherts, extending along the line of the S4 fault that marks the northern boundary of the South
Block (Figs. 3, 4a, 5a). The grey-green volcanoclastics of unit 2 in the South Block cannot be traced across this fault (Fig. 5a) suggesting they were not deposited or were later removed prior to deposition of the very thin and discontinuous stratiform Apex chert of the Middle Block. By way of contrast, there is a marked thickening of the stratiform Apex chert around the mouth of the S4 dyke on the South Block. This thickening may in part be due to greater accommodation close to the fault, and in part to the dilational effects of black chert sills that intrude southwards from the dyke (Figs. 6a, 7a). Rotated and scattered blocks of black chert are also found around the upper part of S4, presumably displaced by faulting (Fig. 6a). The upper part of the S4 dyke complex comprises black cherts in which float large (<1 m), angular to rounded blocks of stratiform chert (Fig. 6a). These clasts appear to have fallen down the dyke system from the palaeosurface, diminishing in size downwards, being inconspicuous in the bottom 200 m of the black chert dyke. At greater depth are found a few small isolated chert dykes plus a series of north–south trending sills of white vein quartz and brown carbonate-filled veins (see Fig. 6a).

A comparable pattern of relationships is seen along the dyke N1 (Figs. 6b, 6c), which hosts the famous ‘microfossil’ site at Chinaman Creek. The country rock of the North Block here comprises silicified pillow basalts of unit 1. Glassy tufts of unit 3 occupy a triangular outcrop near the top of the dyke (Fig. 6b). There is a slight thickening of the Apex chert immediately to the north of the dyke, due to greater accommodation space plus the effects of dilatation by black chert sills. Distinctive features of the N1 dyke include its great length (over 1600 m), its association with a major offset in the underlying Marble Bar chert (Fig. 6c) and with numerous, upwardly branching and diverging black chert dykes, including the N2 dyke (Fig. 6b).

None of the dyke systems in the area are found to extend to stratigraphic levels above the stratiform cherts of unit 4 except, that is, for minor outcrops clearly associated with major fault displacements (Fig. 6b). Black chert clasts are found within the pyroclastic breccia of unit 5 at the base of the next volcanic cycle. These features are consistent with accu-
Fig. 6. (Continued).

### Table 1

<table>
<thead>
<tr>
<th>Elements</th>
<th>C11</th>
<th>C12</th>
<th>C13</th>
<th>C14</th>
<th>C15</th>
<th>C16</th>
<th>C17</th>
<th>C18</th>
<th>C19</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>71</td>
<td>70</td>
<td>72</td>
<td>78</td>
<td>79</td>
<td>78</td>
<td>80</td>
<td>81</td>
<td>82</td>
</tr>
<tr>
<td>Al</td>
<td>4.8</td>
<td>4.6</td>
<td>4.4</td>
<td>4.0</td>
<td>3.8</td>
<td>4.0</td>
<td>3.8</td>
<td>4.0</td>
<td>4.2</td>
</tr>
<tr>
<td>Ti</td>
<td>1.8</td>
<td>1.6</td>
<td>1.4</td>
<td>1.2</td>
<td>1.0</td>
<td>1.2</td>
<td>1.0</td>
<td>1.2</td>
<td>1.2</td>
</tr>
</tbody>
</table>

(C)  
- In sheets, clasts  
- Around sheets, clasts  
- In matrix  
- In veins  
- Arsenic ochre

CC: 9 locations on figure 6a for samples used for geochemical analysis

Fig. 6. (Continued).
mation of the dilational black cherts along the N1 to N4 fault systems, at a time broadly contemporaneous with the deposition of the stratiform Apex cherts of unit 4 and prior to the extrusion of unit 5.

4.2. Chert microfabrics

Petrographic microfabrics of the kind typically seen in and around the Apex chert dyke systems (S1 to N4) are illustrated in Fig. 7. Stratiform beds of the Apex chert mainly consist of three distinct lithologies: volcanoclastics, including devitrified glassy tuffs (Fig. 7a), jaspillic cherts (Fig. 7b) and c); banded black-and-white cherts (Fig. 7d). Of these, the devitrified glassy tuffs commonly show contorted shards set within a chalcedonic chert matrix. Occasionally, as in unit 3 at Chinaman Creek (Fig. 7c), the shards may have carbonaceous outer margins and voids infilled with carbonaceous chert. Such cherts are assumed to have originated from the explosive eruption of viscous and siliceous magma on the seafloor, with the carbon providing evidence for eruption through carbon-rich rocks at depth. The jaspillic cherts (Fig. 7b and c) typically consist of mm-scale laminations of hematite-rich chert with a ‘micropeloid’ fabric, alternating with hematite-poor chert containing small floating rhomb ghosts infilled with silica after iron carbonate (Fig. 7e). Such cherts are believed to have formed on the seafloor in relation to hydrothermal emanations from submarine vents (cf. Nijman et al., 1998). Many of the banded black-and-white cherts may be secondary in nature (see below) but others are certainly primary because they show clear lamination, with grain orientation, sorting and packing (Fig. 7d). Typically, these grains are of two main types: irregular, jahite-like grains of carbonaceous matter (Fig. 7c); and elongate grains of laminated pale silica and dark carbonaceous matter (Fig. 7e). These are superficially similar to fragments of putative microbial laminae (cf. Lowe, 1999; Fig. 3c), but in this case are laminated-black volcanogenic cherts, best seen immediately to the south of Chinaman Creek near the ‘Microfossil’ Site (Fig. 3a). Near the top of N1 dyke, these laminated fabrics are overprinted by later growths of rhomboidal
grains that now contain exotic sulphates such as barite, alunite and jarosite.

In the areas close to each chert dyke complex, the distinction between black cherts of stratiform, replacive or displacive origin is not easily made (Fig. 3 centre). Figs. 4, 5 and 6 forward a generalised model for fabric evolution in dyke cherts. These typically reveal multiple generations of brecciation, fissure filling and chert veining. For descriptive purposes we identify three main fabric types: A, B and C (see Fig. 8).

Fabric A is a fissure-filling fabric. It comprises pale grey to dark brown or black brecciated clasts that often make up the bulk of the rock in the dyke systems. Some clasts clearly result from the silicification
Fig. 9. The formation of microfossil artefacts by the displacement of amorphous carbon over time in a carbonaceous rich chert. (a) Shows the size and position of ‘microfossil’ like artefacts created around the rims of spherulites (1–4) and replaced carbonate rhombs (R–r), and is controlled by spherulite diameter and silica purity (amorphous material). (b–p) Shows the six shape classes discussed in the text (Section 4.3). Scale bar: (a) 100 μm, (b–p) 40 μm.
and carbon-impregnation of the country rock. At least four successive generations (A1 to A4) can be usually identified in thin sections of such dyke cherts (Figs. A–I).

Fabric B is a microquartz vein fabric. It comprises chalcedonic microquartz that penetrates fabrics of generation A via small fissures, to infill irregularly shaped vugs (Fig. B). Within larger cavities, it forms laminated layers and botryoids of clear chert, including roof pendants (Figs. B–I and b). In most cases, each generation of fabric A was accompanied by veinning of fabric B (Fig. B).

Fabric C is a microquartz vein fabric. It comprises crystals of drusy quartz that infill the central zone of larger veins (e.g. Fig. C) especially after the formation of chalcedonic chert of generation B3. Several phases of fabric C can be present. When studied in greater detail, generation A is seen to comprise brecciated and angular to rounded fragments of microcrystalline quartz containing carbonaceous microclasts, grains of iron oxide, rutile and chrome-magnetite native metals (Fe, Ni, Cu, Zn), pyrite, sericite and rhombic pseudomorphs (Fig. D). The pseudomorphs include relics of barite, plus dark reaction rims of chromeite and rutile (in EDX). The texture of generation A1 tends to intergrade from rather homogeneous and fine-grained (Figs. B–I and b), through cherts with carbon-impregnated cracks (Fig. A–D), and chert-filled vugs (Figs. B–I and b). The texture is more mottled in sections where incipient grains are surrounded by chert-filled cracks (Fig. A–D). These A1 cherts are commonly traversed by small cracks and vugs now of chalcedonic microquartz (generation B1). Both B1 veins and fabric A appear may have been induced by fault-related shearing. More often, however, the chert-filled cracks have an accretion to polygonal pattern (Figs. B–I and b), somewhat resembling the circum-granular cracks of ‘caliche’ and ‘evaporitic palaeosols’ (cf. Bessoua et al., 1994) and suggesting that a comparable, subsurface process of incipient precipitation and lithification has taken place. Generation A1 was clearly brecciated by successive episodes of fracturing in situ, to form fissures, cavities and adjacent clasts with a ‘jigsaw puzzle’ fit (see Fig. A–I and b). Cavities are often lined with epitaxial rims of botryoidal, spherulitic and fan-shaped white chalcedonic microquartz (Fig. A–I), as described below.

Fissure-filling generation A2, which tends to be paler with more distinct lithoclasts, was produced by spalling of A1 and B1, geopetally infilling voids within the breccia (Figs. A–I and b). Generation A2 has quite clearly defined but poorly sorted microclasts of A1 and B1 type, producing a muddy to poorly sorted appearance (see Figs. B–I and b). A comparable set of processes led to generations A3 and B3 (see Figs. B–I and b). Conspicuous lenticular crystals (containing barite in EDX) or voids may float in the outer margins of cross-cutting chalcedonic veins of generation B3 (Fig. A–I). The latter also penetrates the earlier generations A1 and A2 via small fissures and vugs, forming laminated layers and conspicuous botryoids (Fig. A–I and f).

Each of these phases (A1 to B1, A2 to B2 and A3 to B3) appears to have been accompanied by carbonaceous growth or hydrocarbon migration. This carbon has penetrated along microfractures to line or infill small vugs within A1 (Figs. B and I middle), coat and darken lithified clasts of A1 to A3 and B1 to B2 (Fig. A–I, and b and I). and accumulate within laminae and speck-like dendrites within botryoidal-spherulitic fabrics of B2 to B4 (Figs. A–I and I and I and I). The central zone of large chalcedonic veins was later infilled by crystals of drusy quartz (fabric C), especially in conspicuous cross-cutting, linear fractures (Figs. A–I and I and I and I). and these tend to lack carbonaceous matter. Late stage metallic oxides have also infiltrated small cracks and fissures and these may be associated with secondary oxidation and reddening. No carbonate has yet been revealed by geochemistry at this level in the hydrothermal system.

Such fissure-filling black cherts are often seen to both cross-cut and to modify the adjacent stratiform cherts. This phenomenon is especially well displayed in the Marble Bar chert (cf. Krinsley et al., 2001, Plate 2). Where black cherts cross-cut jaspilite cherts (e.g. Figs. A–I), thin sections show progressive removal of the oxidised hematite and its replacement by fluffy black grains of carbonaceous chert (Fig. A–I). This replacement has often resulted in large cavities that were later infilled by carbonaceous black and white cherts showing botryoidal growth of mainly fibrous chaledon around bushes and dendrites of carbonaceous matter that grew either upwards or downwards into the cavities (Figs. A–I and I). Also seen are pillow-shaped botryoids of fibrous chaledony.
containing thin drapes of carbon plus sparse carbonaceous inclusions—these pillows can also grow upwards and downwards into the voids (e.g. BrFr.17).

It is therefore possible to recognise at least three kinds of carbonaceous chert around these systems. Stratiform chert that was originally laid down as bedded sediments (e.g. BrFr.7). Chert that was replacive after stratiform chert, especially ferruginous chert (e.g. BrFr.4); and chert that was displacive, growing by successive episodes of fracturing, spalling, flocculation and lithification (Figs. 2–4 and 2–5).

4.3. Microfossil filaments

All the illustrated ‘microfossils’ from the Apex chert have been re-examined by us, including holotypes and paratypes deposited at the Natural History Museum in London (Schopf and Packer, 1997; Schopf, 1999; W. Schopf). These carbonaceous structures come from three blocks of chert collected from the ‘Microfossil’ site shown in Fig. 2a from a position some 100 m beneath the surface of the N1 dyke system. In Table 1, we summarise the characteristics of all of the figured ‘microfossils’ and list their enclosing fabrics (e.g. fabric generations A1 to A3, B1 to B3 and C outlined in Section 2.2 above). A detailed description of the petrography and the context for each ‘microfossil holotype’ slide is given in the Appendix A.

The majority of the filamentous microfossil-like objects from the ‘Microfossil’ can be assigned to one of six shape classes shown in Appendix A: onephyls (a, 2c, 2d, 3d, 3e), rhomboids (2a, 2b, 3f, 3g, 3h, 4b, 4c and e), sinuous forms (3i, 3j), sub-rhomboids (4d, 4f, 4g, 4h, 4i and k) and arcs (5b, 5c and l). The frequency distribution of these shape classes has been measured along thin section traverses through brecciated shales (previously regarded as ‘microfossiliferous’ clasts), within the dyke chert. The results are as follows: arcs (ca. 50%), dendroids (ca. 30%), spherules (ca. 8%), sinuous forms (ca. 6%), rhomboids and sub-rhomboids (ca. 6%). Hence, the sinuous-shaped filaments imaged in previous studies (Schopf, 1992a, 1992b) are found by us to comprise only a minor component of the morphological population, with the majority of microfossil-like objects being arcuate. In Section 5.3, we combine these results with our fabric observations to propose a model for the formation of the pseudofossils.

The maximum diameter and the maximum length of all microfossil-like objects has been measured by us along traverses across natural populations of structures within each of the previously illustrated ‘microfossiliferous’ classes (Schopf, 1999, 2000). We find no evidence for the bimodal distribution of filament diameters reported by Schopf (1985, Fig. 6). Instead, we find that the structures occupy a morphological continuum in which the filament diameters decrease (exponentially) in frequency as their diameters increase from 1 μm to at least 36 μm.

5. Interpretation

Here, we address questions raised by re-mapping and re-analysis of the Apex ‘microfossil’ materials. These questions are assembled broadly in the order followed by Brasier et al. (1992).

5.1. Context viable for life—neptunian or deep hydrothermal?

Does the context of the Apex chert point to a potentially viable habitat for life? Careful attention to geological context is certainly essential for correctly decoding the signals for early life on Earth. Until recently, it has been accepted that layerd siliceous cherts of the 3.4–3.5 Ga old Warrawoona Group were laid down in settings that were comparable with modern evaporitic and exposed lagoonal environments. Sloss et al. (2003) have shown that the Warrawoona cherts are comparable with the limestone bodies of the Ordovician Siberian platform, which are interpreted to have formed below sea level, although Lowe (in Sloss et al., 2003) has argued that some associated South African dykes are neptunian in origin.

The Apex ‘microfossils’ are now known to have been collected from the ‘Microfossil’ site at Chinaman Creek by Dr. Bonnie Packer, written communication to Brasier, 2002; J.W. Schopf, communication to Brasier, 2002; see Brasier et al., 2005.
Table 1
Characteristics of the previously figured Apex 'microfossils', clasts and fabrics

<table>
<thead>
<tr>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>e</th>
<th>f</th>
<th>g</th>
<th>h</th>
<th>i</th>
<th>j</th>
<th>k</th>
</tr>
</thead>
<tbody>
<tr>
<td>V.63164 [1]</td>
<td>P. conicoterminatum holotype</td>
<td>Schopf (1992b), Fig. 1.5.4C</td>
<td>64C2, Fig. 12a</td>
<td>B</td>
<td>B</td>
<td>A1</td>
<td>sa</td>
<td>5.0</td>
<td>206</td>
<td>–</td>
</tr>
<tr>
<td>V.63164 [2]</td>
<td>P. conicoterminatum paratype</td>
<td>Schopf (1992b), Fig. 1.5.4D</td>
<td>64C PlanM3</td>
<td>B</td>
<td>B</td>
<td>A1</td>
<td>r</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>V.63164 [3]</td>
<td>P. delicatulum paratype</td>
<td>Schopf (1992b), Fig. 1.5.4F</td>
<td>64C PlanM32</td>
<td>B</td>
<td>B</td>
<td>A1</td>
<td>r</td>
<td>0.5</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>V.63164 [4]</td>
<td>P. delticatum paratype</td>
<td>Schopf (1993), Fig. 3K</td>
<td>Not confirmed</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>V.63164 [5]</td>
<td>P. amoenum paratype</td>
<td>Schopf (1992b), Fig. 1.5.5C</td>
<td>64C21, Fig. 12l</td>
<td>B</td>
<td>B</td>
<td>A1</td>
<td>sa</td>
<td>5.0</td>
<td>46</td>
<td>–</td>
</tr>
<tr>
<td>V.63164 [6]</td>
<td>P. amoenum paratype</td>
<td>Schopf (1992b), Fig. 1.5.5E</td>
<td>64C20, Fig. 12k</td>
<td>B</td>
<td>B</td>
<td>A1</td>
<td>sa</td>
<td>5.0</td>
<td>144</td>
<td>–</td>
</tr>
<tr>
<td>V.63164 [7]</td>
<td>Un-named type A broad filament</td>
<td>Schopf (1992b), Fig. 1.5.6A</td>
<td>64C1, Fig. 11g</td>
<td>B</td>
<td>B</td>
<td>A1</td>
<td>sa</td>
<td>5.0</td>
<td>150</td>
<td>–</td>
</tr>
<tr>
<td>V.63164 [8]</td>
<td>Un-named type C narrow filament</td>
<td>Schopf (1992b), Fig. 1.5.6D</td>
<td>64C30</td>
<td>B</td>
<td>B</td>
<td>A1</td>
<td>sa</td>
<td>5.0</td>
<td>330</td>
<td>–</td>
</tr>
<tr>
<td>V.63164 [9]</td>
<td>P. conicoterminatum</td>
<td>Schopf (1993), Fig. 4G</td>
<td>64D1</td>
<td>B</td>
<td>B</td>
<td>A2</td>
<td>–</td>
<td>–</td>
<td>380</td>
<td>–</td>
</tr>
<tr>
<td>V.63164 [10]</td>
<td>P. latitellus/amoenum holotype</td>
<td>Schopf (1993), Fig. 5A</td>
<td>64C19, Fig. 12f</td>
<td>B</td>
<td>B</td>
<td>A1</td>
<td>sa</td>
<td>5.0</td>
<td>331</td>
<td>–</td>
</tr>
<tr>
<td>V.63164 [11]</td>
<td>P. latitellus/amoenum</td>
<td>Schopf (1993), Fig. 5B</td>
<td>Not confirmed</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>V.63164 [12]</td>
<td>A. minutum holotype</td>
<td>Schopf (1993), Fig. 6F</td>
<td>64B1, Fig. 16e</td>
<td>R</td>
<td>R</td>
<td>A1</td>
<td>sa</td>
<td>2.4</td>
<td>7</td>
<td>–</td>
</tr>
<tr>
<td>V.63165 [1]</td>
<td>Un-named degraded cellular filament</td>
<td>Schopf (1992b), Fig. 1.5.4B</td>
<td>65H2, Fig. 15m</td>
<td>B</td>
<td>B</td>
<td>A1</td>
<td>sa</td>
<td>2.1</td>
<td>343</td>
<td>–</td>
</tr>
<tr>
<td>V.63165 [2]</td>
<td>P. delticatum holotype</td>
<td>Schopf (1992b), Fig. 1.5.4G</td>
<td>65H6, Fig. 15g</td>
<td>B</td>
<td>B</td>
<td>A1</td>
<td>sa</td>
<td>2.1</td>
<td>248</td>
<td>–</td>
</tr>
<tr>
<td>V.63165 [3]</td>
<td>P. amoenum paratype</td>
<td>Schopf (1992b), Fig. 1.5.5D</td>
<td>65P3, Fig. 16e</td>
<td>B</td>
<td>B</td>
<td>A2</td>
<td>–</td>
<td>–</td>
<td>10</td>
<td>–</td>
</tr>
<tr>
<td>V.63165 [4]</td>
<td>Un-named type B broad filament</td>
<td>Schopf (1992b), Fig. 1.5.6B</td>
<td>65G1, Fig. 13l</td>
<td>B</td>
<td>B</td>
<td>A1</td>
<td>sa</td>
<td>2.1</td>
<td>289</td>
<td>–</td>
</tr>
<tr>
<td>V.63165 [5]</td>
<td>Microfilamentous clast</td>
<td>Schopf (1992b), Fig. 3A and B</td>
<td>65A1, Fig. 14-e</td>
<td>B</td>
<td>B</td>
<td>A1</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>V.63165 [6]</td>
<td>P. minutum</td>
<td>Schopf (1993), Fig. 3H</td>
<td>65A35, Fig. 14i</td>
<td>B</td>
<td>B</td>
<td>A1</td>
<td>r</td>
<td>1.8</td>
<td>160</td>
<td>–</td>
</tr>
<tr>
<td>V.63165 [7]</td>
<td>P. delticatum</td>
<td>Schopf (1993), Fig. 3J</td>
<td>65A18, Fig. 14p</td>
<td>B</td>
<td>B</td>
<td>A1</td>
<td>r</td>
<td>1.8</td>
<td>133</td>
<td>–</td>
</tr>
<tr>
<td>V.63165 [8]</td>
<td>A. disciformis</td>
<td>Schopf (1993), Fig. 3N</td>
<td>6SP4, Fig. 16-l</td>
<td>B</td>
<td>B</td>
<td>A2</td>
<td>–</td>
<td>–</td>
<td>88</td>
<td>–</td>
</tr>
<tr>
<td>V.63165 [9]</td>
<td>Un-named solitary unicell-like microfossil</td>
<td>Schopf (1993), Fig. 5K</td>
<td>6SP4, Fig. 16l</td>
<td>B</td>
<td>B</td>
<td>A2</td>
<td>–</td>
<td>–</td>
<td>113</td>
<td>–</td>
</tr>
<tr>
<td>V.63165 [10]</td>
<td>A. disciformis paratype</td>
<td>Schopf (1992b), Fig. 1.5.4A</td>
<td>65H1, Fig. 15b</td>
<td>B</td>
<td>B</td>
<td>A1</td>
<td>sa</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>V.63166 [1]</td>
<td>A. amoenum holotype</td>
<td>Schopf (1992b), Fig. 1.5.4B</td>
<td>66B1, Fig. 17g</td>
<td>B</td>
<td>B</td>
<td>A2</td>
<td>–</td>
<td>–</td>
<td>315</td>
<td>–</td>
</tr>
<tr>
<td>V.63166 [2]</td>
<td>Un-named type A broad filament</td>
<td>Schopf (1992b), Fig. 1.5.4C</td>
<td>66B5, Fig. 17h</td>
<td>B</td>
<td>B</td>
<td>A2</td>
<td>–</td>
<td>–</td>
<td>298</td>
<td>–</td>
</tr>
<tr>
<td>V.63166 [3]</td>
<td>Un-named type</td>
<td>Schopf (1992b), Fig. 1.5.4D</td>
<td>66B5, Fig. 17g</td>
<td>B</td>
<td>B</td>
<td>A2</td>
<td>–</td>
<td>–</td>
<td>5</td>
<td>–</td>
</tr>
<tr>
<td>V.63167 [1]</td>
<td>A. amoenum paratype</td>
<td>Schopf (1992b), Fig. 1.5.4E</td>
<td>27C8</td>
<td>B</td>
<td>W</td>
<td>A1</td>
<td>sa</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>V.63167 [2]</td>
<td>P. conicoterminatum holotype</td>
<td>Schopf (1993), Fig. 1.5.4F</td>
<td>27D1, Fig. 18e</td>
<td>B</td>
<td>B</td>
<td>A2</td>
<td>–</td>
<td>–</td>
<td>266</td>
<td>–</td>
</tr>
<tr>
<td>V.63167 [3]</td>
<td>A. disciformis</td>
<td>Schopf (1993), Fig. 3L</td>
<td>28A2</td>
<td>G</td>
<td>G</td>
<td>A2</td>
<td>–</td>
<td>–</td>
<td>252</td>
<td>–</td>
</tr>
<tr>
<td>V.63167 [4]</td>
<td>P. amoenum</td>
<td>Schopf (1993), Fig. 3C</td>
<td>28B1</td>
<td>B</td>
<td>B</td>
<td>A2</td>
<td>–</td>
<td>–</td>
<td>75</td>
<td>–</td>
</tr>
<tr>
<td>V.63167 [5]</td>
<td>E. apex holotype</td>
<td>Schopf (1993), Fig. 3F</td>
<td>29B1, Fig. 19f</td>
<td>B</td>
<td>B</td>
<td>A2</td>
<td>–</td>
<td>–</td>
<td>150</td>
<td>–</td>
</tr>
<tr>
<td>V.63167 [6]</td>
<td>P. minutum holotype</td>
<td>Schopf (1993), Fig. 3G</td>
<td>29C2, Fig. 19e</td>
<td>B</td>
<td>B</td>
<td>A2</td>
<td>–</td>
<td>–</td>
<td>112</td>
<td>–</td>
</tr>
<tr>
<td>V.63167 [7]</td>
<td>A. disciformis holotype</td>
<td>Schopf (1993), Fig. 3M</td>
<td>30A2, Fig. 20d</td>
<td>B</td>
<td>B</td>
<td>A3</td>
<td>–</td>
<td>–</td>
<td>47</td>
<td>–</td>
</tr>
<tr>
<td>V.63167 [8]</td>
<td>A. amoenum holotype</td>
<td>Schopf (1993), Fig. 3N</td>
<td>31F2, Fig. 21b</td>
<td>B</td>
<td>B</td>
<td>A2</td>
<td>–</td>
<td>–</td>
<td>18</td>
<td>27</td>
</tr>
<tr>
<td>V.63167 [9]</td>
<td>A. amoenum paratype</td>
<td>Schopf (1993), Fig. 3O</td>
<td>31F2, Fig. 21b</td>
<td>B</td>
<td>B</td>
<td>A2</td>
<td>–</td>
<td>–</td>
<td>75</td>
<td>–</td>
</tr>
<tr>
<td>V.63168 [1]</td>
<td>P. conicoterminatum</td>
<td>Schopf (1993), Fig. 3P</td>
<td>34B1</td>
<td>W</td>
<td>W</td>
<td>A1</td>
<td>sa</td>
<td>50</td>
<td>208</td>
<td>–</td>
</tr>
<tr>
<td>V.63168 [2]</td>
<td>P. amoenum</td>
<td>Schopf (1993), Fig. 3Q</td>
<td>34C1</td>
<td>B</td>
<td>B</td>
<td>A2</td>
<td>–</td>
<td>–</td>
<td>146</td>
<td>–</td>
</tr>
<tr>
<td>V.63168 [3]</td>
<td>Poorly preserved ichthome</td>
<td>Schopf (1993), Fig. 3R</td>
<td>34C3</td>
<td>B</td>
<td>W</td>
<td>A1</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>
Table 1 (Continued)

<table>
<thead>
<tr>
<th>No.</th>
<th>Sample Label</th>
<th>Description</th>
<th>Ac</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>e</th>
<th>f</th>
<th>g</th>
<th>h</th>
<th>i</th>
<th>j</th>
<th>k</th>
</tr>
</thead>
<tbody>
<tr>
<td>V63744</td>
<td>Unnamed 'Type C' microfossil</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V63745</td>
<td>P. corroboratorium</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V63746</td>
<td>Poorly preserved trichome</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V63751</td>
<td>A. divorsus</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V63752</td>
<td>Poorly preserved trichome</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V63753</td>
<td>Poorly preserved trichome</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V63756</td>
<td>P. corroboratorium</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V63773</td>
<td>A. grandis holotype</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V63798</td>
<td>P. laterella-non</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes:
1. Slide numbers, Natural History Museum, London. The slides were cut from three separate blocks: block 1 = V. 63744-6 and V. 63727-30; block 2 = V. 63731-3; block 3 = V. 63734-38. (b) Figure(s) was cut from these separate blocks. (c) reference: (a) Oxford; NBM digital database number and (d) reference: (e) and number: (f) colour in transmitted light: B = black; G = grey; R = red; D = brown; Y = yellow; W = white; f. colour in reflected light: g. fabric: (A) = diatomaceous; (A) = chalcedonic) and inferred generations (1, 2, or 3) as worked out from samples in each block—equivalence between different blocks is possible but not assumed. (d) Shape of clasts in which the 'microfossils' occur (in A1 only, since microfossils in later fabrics do not occur in clasts)—a, subangular-b, rounded; c, rounded s, maximum diameter (mm) of the clast; A1 only) i, distance in mm to the nearest clear spherulitic radial structure (of the clast; A1 only) j, distance in mm to the nearest clear radial structure (of the clast; A1 only) k, distance in mm to the nearest clear radial structure (of the clast; A1 only)
dilute and thicken the stratiform Apex chert near each ‘vent’, through emplacement of numerous black chert sills (Fig. 3). Comparable cherts occur as clasts within the pyroclastic breccias at the base of overlying unit 5.

(4) Dyke cherts are rare in the Central Block where stratiform Apex cherts of unit 4 are thin or absent. This is consistent with a model in which the thickness of the stratiform cherts is controlled by the volume of silica supplied at depth, including underplating and intraplating.

(5) Mafic extrusives adjacent to the dyke (Figs. 3 and 5) yield sulphates rich in Al, K, Fe and As (e.g. from hydrothermal reactions involving sulphuric acid, feldspars, zeolites or sulphides). These sulphates resemble both ‘alunite’ KAl(SO₄)₂(OH)₂ and ‘jarosite’ KFe₃(SO₄)₂(OH)₆ (in SEM-EDX, e.g. relict minerals from hydrothermal leaching of adjacent basalts) plus Al- and K-rich phyllosilicates (in SEM-EDX, e.g. from hydrothermally altered feldspars).

(7) The black stratiform cherts (Figs. 3 and 5) yield sulphates rich in Al, K, Fe and As (e.g. from hydrothermal reactions involving sulphuric acid, feldspars, zeolites or sulphides). These sulphates resemble both ‘alunite’ KAl(SO₄)₂(OH)₂ and ‘jarosite’ KFe₃(SO₄)₂(OH)₆ (in SEM-EDX, e.g. from hydrothermal reactions involving sulphuric acid, feldspars, zeolites or sulphides). Bedding is overprinted near the dyke by rhombic crystal ghosts, now of both chaledonic quartz, containing relict grains of barite and alunite, suggestive of hydrothermal brines.

(8) Oxygen isotopes of +13.7 to +14.7‰ from within SiO₂ are less δ¹⁸O-enriched than many Archaean sedimentary cherts (Robert, 2000). Along with the inferred presence of native metals (Robert, 2000), this might be taken to imply that comparatively high (ca. 250–350 °C) hydrothermal temperatures were reached (Robert, 2000). If it may also reflect the temperatures reached during low grade metamorphism. Fluid inclusion work is being undertaken to resolve these two options.

(9) We find no evidence for surficial sedimentary structures or textures (e.g. sorting, rounded quartz, grain sorting or sedimentary laminae) in the ‘microfossiliferous’ clasts (see below).

We conclude from these studies that the Chinaman Creek chert that yielded the famous ‘microfossils’ (e.g. Robert, 2000) does not have a depositional setting comparable with a wave-washed beach or the mouth of a stream or river (Robert, 2000). It has a context consistent with a hydrothermal feeder dyke, much like that inferred for the barite-chert beds of similar age at nearby North Pole (Robert, 1999). If estimated surface water temperatures of ~70 °C are correct for the early Archaean ocean (e.g. Robert, 2000), temperatures within the dyke system at the level of the Apex ‘microfossils’ (some 100 m down the dyke system) are likely to have reached ~50 °C or higher, which would today be taken to indicate marginal extremophiles conditions.

5.2. Rounded grains

Are the microfossils found only in detrital clasts? Original reports describe the ‘microfossils’ as occurring ‘within clasts that were deposited in this unit prior to its lithification’ (Robert and Robert, 1987) but later interpreted as rounded grains of chert transported a great distance before redeposition in a bedded grainstone conglomerate (Robert and Robert, 1987).

Field mapping, sampling (Robert, 2000) and fabric mapping (Robert, 2000) reveal that the ‘microfossiliferous’ chert at Chinaman Creek (Robert, sample CC4), is not part of the bedded succession. It is part of a chert breccia that infills one of a series of dykes that feed upwards into overlying stratiform cherts (Robert, samples CC6–8). Fabric mapping also reveals that the majority of figured ‘microfossils’ do not occur exclusively in first generation fabrics, nor in rounded clasts as previously suggested (e.g. Robert, 1999). Only 40% occur within rounded to angular clasts of generation A1. The majority actually occur within
larger areas of A2 and A3 (57%) and some clearly occur within later chaledonic chert (B1; 3%), see The.
Comparable structures also occur within carbonaceous clasts and chaledonic matrix of the stratiform cherts (Dundas, 1993; Fig. 4p), within the carbonaceous runs of the volcanic glass shards (ibid., Fig. 4h) and in the chaledony cement between glass shards (ibid., Fig. 4j) and thus calling their indigenous and biogenic origin into question.

We conclude that the microfossils do not occur in a 'petrographically distinctive population of clasts', nor are they absent 'from all other clasts or the surrounding matrix' (see also Section 4 below). This means that the inference that filaments predate deposition of the chert unit and were initially preserved in older rocks, some part of which was eroded as a detrital component of the bedded chert (Dundas, 1993; 1998), is not sustained.

5.3. 'Stromatolite-like clasts'

Are 'stromatolite-like clasts' present in the 'microfossil'-bearing samples and could they support a biogenic interpretation? Such an association of putative Archaea microfossils with stromatolitic laminae could be regarded as a mutually supportive criterion for biogenicity. It is important to note, however, that the biogenicity of stromatolitic structures cannot be assumed (see Hurtubise et al., 1993; Wadhwa et al., 1997), and that abiogenic origins must be falsified. These challenges are especially great when only small fragments <1 mm across are preserved, as here.

We have re-examined the siliceous structures with undulose laminations (Fig. 3a–f) labelled as 'stromatolite-like clasts' by Dundas (1993; Fig. 3). Our observations indicate that this structure is intergrown with enclosing A1 to A3 and B1 to B3 fabrics, forming void filling drapes and overhangs (Figs. 3a–d). This, and associated 'stromatoloids', contain lithoclasts, phyllosilicates, metallic oxides, pyrite and rhombic ghosts exactly like those of the enclosing fabric. We find that these 'stromatoloids' are indistinguishable from other shards of chaledony with laminae of uniform thickness (B1 to B3) that grew and fragmented within the dyke system (Figs. 4h and 4j) and we reinterpret them as such. The biogenicity of these 'stromatoloids' should not be assumed and from our studies appears questionable.

5.4. The distribution of 'microfossils'

Does the distribution of microfossil-like structures (at the micrometer to kilometer scale) reflect any signs of biogenic behaviour? Typical populations of Proterozoic to modern cyanobacteria reveal trichomes that are commonly occur clustered together in layers, often with a distinctive orientation relative to bedding. That distribution pattern may be attributed to photo or chemotactic growth and is well known, for example, in the 1000 Ma Gunflint chert (Vernon and Schopf, 1974), and has therefore been proposed as a biogenicity criterion (Grotzinger and Knoll, 1995). Our micrometer scale fabric studies of the Apex chert microfossiliferous populations (Figs. 1b–d) clearly confirm that the 'microfossils' occur as isolated, irregularly distributed and randomly orientated solitary filaments (as acknowledged by Dundas, 1993).

We also find that the 'microfossil'-like structures occur throughout the dyke system, and at depths of up to 1500 m below the palaeoshore. These examples of dendritic to arcuate filaments are indistinguishable from those observed at the 'Microfossil' site. They occur in botryoidal chert of fabric B, regarded as integral to the hydrothermal system at depth. We find no evidence that sediment or microfossils could have fallen some 1500 m down the dyke system. We con-

Fig. 10. (a) Macroscopic view showing the core of NBM slide Y835164 showing area 64B1 discussed in the text, scale in mm; (b) closer view of area 64B1 (a) showing the iron-stained, angular shard of fabric A1 that contains object 64B1, regarded as the holotype for A. maxima (Dundas, 1993; Fig. 5f) surrounded by fabric A2, plus the objects illustrated in Figures 'f', 'g' and 'h' below; (c) closer view of the patch of iron stained spherulitic mullion fabric in area 64B1 associated with object 64B1 (arrowed) plus the objects illustrated in figures 'd' below; (d) detailed view of spherulitic mullions giving rise to two septate dendritic mullion pseudofossils (objects 64B2, arrowed); (e) detailed view of arcuate and septate object 64B1, the holotype for A. maxima (Dundas, 1993; Fig. 5f); (f) detailed view of spherulitic mullions giving rise to three septate arcuate mullion pseudofossils (objects 64B3, arrowed); (g) detailed view of spherulitic mullions giving rise to three septate arcuate mullion pseudofossils (arrowed, objects 64B3); (h) objects 64B4 formed as artefacts where the ink of a marker pen has infiltrated into arcuate cracks on the surface of the slide, forming numerous pseudofossils. Labels are as described in the text. Scale bar: 40 µm (d–h); 100 µm (b); 400 µm (b).
Fig. 11. (a) Macroscopic view showing the core of slide NHM V.63164 showing areas 64C and 64D discussed in the text, scale in mm; (b) closer view of area 64C (‘east’); (c) view of area 64C (‘mid-east’); (d) closer view of area 64C (‘northeast’); (e) view of area 64C (‘west’); (f) view of area 64C (‘south’); (g) object 64C1, described as un-named ‘Type A’ broad filament (Schopf, 1992b; Fig. 1.5.6A); (h) non-septate, arcuate object 64C7; (i) septate and non-septate objects 64C8. Scale bar: 40 μm (g–i); 100 μm (d); 400 μm (b, c, e and f).
Fig. 12. Slide NHM V.63164, Area C. (a) Object 64C2, erected as *P. conicoterminatum* holotype (Schopf, 1992b, Fig. 1.5.4C; Schopf, 1993, Fig. 4H); (b) object 64C3; (c) object 64C16; (d) object 64C9; (e) a morphological cascade of objects (64C3); (f) object 64C19, erected as *P. latellulatum* holotype (Schopf, 1993, Fig. 5A); (g) object 64C33 (‘little ballerina’); (h) object 64C9; (i) object 64C22; (j) object 64C23; (k) object 64C20, erected as *P. amoenum* paratype (Schopf, 1992a, Fig. 2.5E; Schopf, 1992b, Fig. 1.5.5E; Schopf, 1993, Fig. 4B); (l) object 64C21, erected as *P. amoenum* paratype (64C21; Schopf, 1992a, Fig. 2.5C; Schopf, 1992b, Fig. 1.5.5C); (m) object 64C10; (n) object 64C14; (o) object 64C18 (‘trousers’). Scale bar 40 μm (a–o).
5.5. Filament branching

Are the filaments really simple and unbranched as described? We use the term ‘branched’ to describe any feature of variable diameter, visibly connected to the main ‘microfossil’ axis and arising in some way from it. We find that many of the previously figured filamentous structures are ‘branched’ or formed in ways not evident in the original descriptions and illustrations because of the choice of focal depth and/or illustrated field of view (see Fig. 5C). We highlight here some conspicuous examples from the holotypes. The holotype of *Primaevifilum amoenum*, found within fabric A2 and interpreted as a prokaryote cellular trichome, is seen to have a small continuous side branch (Fig. 13e) compared with modern Oscillatoriaceae (Fig. 1.5G), is part of a complex structure involving a continuous upper side branch. Such branching is inconsistent with an oscil- latoriacean affinity and not confirmed in the fossil record until ca. 900–800 Ma (Fig. 5D). The tiny thread-like holotype of *Archaeotrichion septatum* (Fig. 13f) is part of a larger branched structure, deflected along polygonal planes between quartz crystals in an area of pervasive iron staining within fabric B3. One end of the holotype of *Primaevifilum attenuatum* (Fig. 13b) has been reconstructed (Fig. 5G) to incorporate a contiguous iron-stained fracture. A complete, montaged image of this “microfossil” shows it to be a strongly arcuate structure within fabric A2 (Fig. 13). We also find a continuum between such
filaments and comparable but unreported pseudoseptate forms near by with multiple branches of markedly varying diameter (e.g. Figs. 4a, 4d, j and o, Figs. 5a and 5b) and with multiple strings that radiate from a bulbous central body (e.g. Figs. 6a, b). The holotype of \textit{Eoleptonema apex} (Figs. 4a and 5a) compared with modern bacterium \textit{Beggiatoa} \cite{Griffin et al., 1993} is found to be part of a larger, sharply angular, sheet-like structure together (c) and d) consistent with formation around rhombic crystal ghosts within fabric A2.

In summary, our re-imaging of the holotypes reveals that many of the structures are more simious than previously illustrated, and many have side branching features not previously described. Furthermore, reinterpretation of some filaments as ‘folded’ (Schopf in \textit{Eoleptonema} and \textit{Giobelloa}) would call into question the use of ‘terminal cell shape’ as a diagnostic criterion \cite{Schopf, 1993} for each of the 11 ‘microfossil’ taxa.

5.6. Filament diameter

Can the criterion of filament diameter be used to characterise 11 different species of bacterial microfossils in the Apex chert? Can the large range of microfossil diameters (<20 μm at least) be used to infer the presence of oxygen-releasing cyanobacteria at 3.45 Ga \cite{Schopf, 1978, Schopf, 1993, Schopf, 1994} or can a study of the size distribution of the supposed microfossils be used to reject evidence for their biogenic origin?

Systematic re-measurement has been undertaken on all the figured microfossils, together with measurements of populations of microfossil-like structures within previously illustrated ‘microfossiliferous’ clasts in the Apex chert (see Section 4.2 above). We find no evidence to support the previously reported polymodal pattern of filament width distribution \cite{M.D. Brasier et al. (2005), 23} for each of the 11 ‘microfossil’ taxa. Nor do we find evidence for clustering of the filament width data to support the distinction between 11 separate ‘microfossil’ taxa. Our measurements reveal that natural populations of microfossil-like structures within the ‘microfossiliferous’ clasts produces a smooth morphological continuum, with the mode falling at ca. 4.1-6 μm and decreasing logarithmically with size. We also report an extension to the unusually large range of Apex chert filament diameters \cite{Schopf, 1978} (Fig. 7), with branched pseudoseptate structures that range up to 36 μm in diameter \cite{Schopf, 1978}.

For comparison, microfossil filament populations, such as \textit{Gunnifinis} filaments from the 1900Ma old Gunnifinis chert, have well-defined modal widths and small standard deviations, as indeed, do our (unpublished) studies of degraded remains of \textit{Escentophylassis} colonies from the ca. 900 Ma old Boorhanah chert. In contrast, abiotic pseudofossil populations formed by the devitrification of glassy silica in the Proterozoic Gwa Group hydrothermal cherts exhibit a logarithmic pattern of maximum width attenuation, accompanied by large standard deviations very much like those for the Apex chert ‘microfossils’. These studies show that simple biometry \cite{Schopf, 1978} cannot readily distinguish biological filaments from non-biological populations of spherulitic artefacts. A mathematical methodology will be needed for the mapping of morphospace of microbial and pseudofossil structures.

5.7. Pseudoseptate filaments

Can the phenomenon of ‘septation’ and ‘bifurcated cells’ \cite{Schopf, 1978, Schopf, 1993, Schopf, 1994} be accepted as evidence in favour of the biogenicity of the Apex filaments? Those authors have interpreted the darker mineral of these filaments to be kerogen and the transecting paler areas to be of cellular origin, taken together to reflect a trichomnic organization like that of Proterozoic to modern bacteria and cyanobacteria. Features interpreted as terminal and medial cell shape, cellular diameter and the degree of trichomnic attenuation were then used to distinguish the 11 taxa of filamentous ‘microfossils’ \cite{Schopf, 1978, Schopf, 1993}

Raman spectroscopy and thin section petrography suggest that the septate appearance of the filaments is caused by microcrystalline quartz grains (ca. 1-10 μm) interspersed with darker amorphous carbon that makes up the bulk of the filament \cite{Schopf, 1978}, a feature which can also be seen in associated rhomboid ghost reaction rims (e.g. Figs. a and j). The filaments are not hollow but composed of solid to discontinuous carbon \cite{Schopf, 1978}. The appearance of numerous thin septa (e.g. Figs. a, b, and j) is caused by closely packed plates of carbon alternating with thin fibres of quartz, a feature which can be seen in associated abiogenic chaledony structures \cite{Schopf, 1978} and even within asso-
ciated volcanic glass (Brasier et al., 2002, Fig. 2e and k), calling biogenicity into question.

The impression of supposed ‘bifurcated cells’ or ‘cell pairs’ in the process of division (Brasier et al., 1993) is brought about by irregular alternations of darker, platy carbon with paler quartz. Significantly, the same phenomenon can be seen in comparable reaction rims around rhombic crystal ghosts (Figs. 14 and j and k). The impression of septation is weakest in those cases where the filament is thicker and the quartz grains are more randomly scattered through the carbon (Fig. 2b). In the presumed holotype of Archaeoscellas tortispos grandis (Fig. 2a), the crudely septate appearance is explained by rhombic crystal ghosts. Chains of tiny cell-like blobs in the holotype of A. septatum (Fig. 1, black arrow) are re-interpreted as small mineral grains trapped between the planar interfaces of quartz crystals.

The features of ‘septation’ and ‘bifurcated cells’ are not readily distinguishable from similar features found in associated spherulitic artefacts and crystal rims (see Figs. 4, 5 and 6). Nor does the septation result in hollow structures, taken by Buick (1993), a major criterion for biogenicity. Hence, an abiotic, mineralised origin for the supposedly biog-

logical septation and bifurcation cannot be falsified using present evidence.

Can the microfossil-like structures be reinterpre-
tated, alternatively, as the degraded remains of a monospecific assemblage of coccolid microfossils, as proposed by Buick (1993)? Have they have made comparisons with degraded cyanobacteria-coccolid cell colonies in Silurian cherts (ca. 0.35 Ga old) that lived in a hydrothermal setting, and have gone on to speculate that the Apex microfossil-like structures could have formed in a similar way. We find no evidence, however, to suggest that the Apex structures arose from a degradational gradient of large, cyanobacteria-like coccolid cell colonies (see Buick and Schopf, 1993).

5.8. Carbonaceous composition of filaments

Can high-resolution laser Raman spectroscopy be used to determine whether the Apex chert structures are composed of abiotic graphite or of biogenic kerogen (Buick and Schopf, 1992; Buick et al., 1992; Schopf et al., 1992)? Our laser Raman results (Brasier et al., 2002) suggest that both the Apex chert ‘microfossils’ and carbonaceous groundmass are composed of amorphous carbonaceous matter. Our preliminary examination concluded that there was no strong signature for any other carbon-based material present other than amorphous graphite. The nomenclature can be confused in the geological literature by the use of “organic” and “kerogen”, implying higher order carbon compounds, whereas they also resemble graphite. Exhaustive work by Schopf et al. (1992) indicates that the graphitic signature is a widely observed feature of many rock types. Like Buick and Schopf (1993), we conclude that micro-Raman spectra, when used alone and without control studies (e.g. experiments on abiotic materials) should not be taken to imply or exclude biogenicity (Brasier et al., 2002).

6. Discussion

6.1. Pseudofossil formation

Detailed “microfossil” observations, when inte-
gated with chert fabric studies and geochemistry leads us to conclude that the Apex ‘microfossils’ and coexisting abiological fabrics share a common origin. Designated ‘holotypes’ lie close to patches of spherulitic chaledony that display graphic rims of identical mineralogical appearance, composition and particle size (Brasier et al., 2002) contradicting a major criterion for biogenicity (Buick, 1993). Together, they form part of a morphological continuum or a ‘symmetry-breaking cascade’ (see Buick, 1993).

We propose that the ‘microfossil’ structures formed around grain and crystal boundaries by the displacement of amorphous carbon during the growth of diagenetic chaledonic quartz crystals and the replacement of rhombic carbonate. Spheroidal fabrics occur commonly in the Apex chert where the concentration of impurities is high and secondary spherulites of silica are surrounded by sub-spherical masses of accessory minerals (see Figs. 6b, 6c, 5b and 5c). The dendritic to arculate “microfossils” appear to occur between spherulites in regions where the concentration of impurities is lower. These reaction rims can have a pseudosclerite appearance owing to the contraction and microfracturing of amorphous carbon or to the presence of radiating fibres of quartz. Variations
Table 2
Criteria previously used for determining the antiquity and biogenicity of putative microfossils

<table>
<thead>
<tr>
<th>Antiquity</th>
<th>Biogenicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contextual characteristics required by features to be considered ‘ancient’</td>
<td>Contextual characteristics required by features to be considered biogenic</td>
</tr>
<tr>
<td>Present or absent—petrographic details exhibited by specific structures in optical thin section</td>
<td>Petrographic details exhibited by specific structures in optical thin section</td>
</tr>
<tr>
<td>Occur in rocks of known provenance, confirmed by replicate sampling</td>
<td>Relatively abundant occurrence and members of a multi-component biologic assemblage</td>
</tr>
<tr>
<td>Structures should not be enclosed in metastable mineral phases (e.g. amorphous opaline silica)</td>
<td>In petrographic thin section, “microfossils” like objects should be the primary source of palaeontological data, verified by use of independent analytical techniques</td>
</tr>
<tr>
<td>Occur in rocks of established Archaean age</td>
<td>In petrographic thin section, “microfossils” like objects should exhibit all the characteristics listed above</td>
</tr>
<tr>
<td>Structures should occur in randomly extinguishing micro-quartz crystals</td>
<td>Of carbonaceous composition or, if mineral, be a result of biologically-mediated mineral precipitation or a product of mineral replacement</td>
</tr>
<tr>
<td>Demonstrably indigenous to the primary deposition of the enclosing rock</td>
<td>Exhibit “biological morphology” - characterized by a range of (statistically demonstrable) variability (rather than uniformity), including life cycle variants, comparable to that exhibited by morphologically similar modern and/or fossil micro-organisms</td>
</tr>
<tr>
<td>Demonstrably syngentic with the primary deposition of the enclosing rock</td>
<td>Occur in a geological context plausible for life</td>
</tr>
<tr>
<td>“Microfossils” from planar, infilled-mineral veins, or concentrated at mineral grain boundaries rather than along primary depositional laminae, or exhibiting cross-cutting relationships in which they have disrupted primary features of the lithified rock fabric, subject to question</td>
<td>Fit within a well-established evolutionary context</td>
</tr>
<tr>
<td>Pre cambrian “microfossils” should exhibit a significantly different colour from that of the particulate finely laminated kerogenous component of the rock matrix</td>
<td>Be dissimilar from potentially coexisting abiotic organic bodies (e.g. proteinoid microspheres, carbonaceous “organized elements”, and products of organic synthesis)</td>
</tr>
<tr>
<td>Filaments (or colonial unicells) should exhibit an orientation and distribution indicative of their role in the formation of stromatolitic laminae</td>
<td></td>
</tr>
</tbody>
</table>

in the size and shape of the filaments (Schopf, 1980) are attributed to localised differences in primary texture, spherulite size and shape. We suggest the Apex clasts can be generated by the following ‘substrate neutral’ algorithmic process: (1) mix one amorphous mineral within another amorphous mineral (e.g. amorphous carbon within silica glass); (2) allow the second (host) mineral to crystallise out as sphaerules, variolites, rhombs or other crystal forms, around discrete nuclei; (3) expel the first amorphous mineral (carbon) as filamentous reaction rims around the newly forming sphaerules or rhombs; (4) allow the first mineral to become interpersed with the second mineral, to form pseudoseptate reaction rims.

A full taxonomic re-description and re-interpretation of each of the figured “microfossil” holotypes will be given by us elsewhere (Buick et al., 2005). Of the 11 holotypes of prokaryotic “microfossils” defined from the Apex chert (Schopf and Whittington, 1994; Schopf, 1996, 1981), we regard those of E. apex (Figs. 6.1a and 6.2a) and A. septatum (Figs. 6.1b and 6.2b) to be mineral rims that formed around sub-rhombic crystal margins, while the other nine can be explained as arcuate, sinuous and branched mineral rims of spherulitic origin. We point out that similar (but non-septate) filamentous pseudofossils are mimicked by pencil graphite found artificially infilling the arcuate fractures around chalcedony spherulites near figured specimens (Fig. 6.1d). The model we propose above is close to those suggested for pseudomicrofossils from other Archaean and Proterozoic horizons (Buick et al., 2005).

6.2. Criteria for biogenicity

While Proterozoic rocks are full of microfossils whose biogenicity cannot be seriously challenged, the situation in Archaean rocks is less straightforward. In (Buick, 2004) we list major criteria previously suggested for testing both the age and biogenicity of putative Archaean microfossils. The comprehensive scheme put forward by Schopf and Whittington (1994) rightly held a major place in such discussions during the 1980’s. This scheme was abbreviated and adapted for a series of later papers describing putative microfossils from the Warrawoona Group (Whittington and Buick, 2003) though the biogenicity of these “microfossils” was hotly disputed by (Buick, 1997, 1995). A recent years, these criteria and their associated debates have tended to slip from view. Many other early Archaean “microfossils” that have been published over the last decade (e.g. Schopf, 1987; Schopf et al., 1987; Schopf, 1987; Schopf et al., 1987) are promising and worthy of re-examination (see also (Buick et al., 2005)). Here, we suggest that the testing of biological signals in very ancient rocks address the three main criteria: geological context, biology-like morphology and biology-like processing.

6.2.1. Geological context

The context for potential biosignals should be mapped and studied at a wide range of scales from outcrop to thin section. Evidence for, and interpretation for, the context should be clearly separated. Any potential biological signals should be referable to a well-defined history within this context, to show if they are early or late, indigenous or exogenous. Plausibility of the context for early life (e.g. temperature limits) can then be assessed.

6.2.2. Biology-like morphology

Ideally, there should be evidence for biology-like morphology in the form of cell aggregates, cell envelopes, microborings or waste products. These should occupy a restricted morphospace that pertains to biology alone, and not occupy the morphospace for distinct categories of abiological pseudofossils. The null hypothesis (of an abiological origin for this morphology) should be falsified. While biology-like morphology of this kind is highly desirable, it overlooks the difficulty of distinguishing the earliest true cells from their prebiotic precursors, and should only be obligatory for microfossils themselves.

6.2.3. Biology-like processing

Evidence for ancient, biology-like processing in space and time should be put forward for testing. More than a single tier of biology-like processing ought to be present. These steps may take the form of extracellular polymeric substances (EPS) plus organominerals (Buick et al., 1987) that show micro-tiers or zonation in morphology and geochemistry. Petrographic ‘thin sections’ seem likely to remain fundamental to the mapping of such potential bioproducts. We emphasize that these multiple lines of evidence should be available (as with the Schopf, 1987 material) for sci-
entific loan, for scientifically repeated tests, and for public scrutiny. The null hypothesis (of an abiogenic origin) should be addressed and falsified in all case histories.

7. Conclusions

Our study of the Apex chert 'microfossils' reveals that the majority is part of a morphological continuum (a 'symmetry-breaking cascade') ranging from spheroidal through bulbous and radiating to arcuate and branching forms (cf. Schopf, 1992a; Brasier et al., 2001). We do not accept this to be true. Nor do we accept that filamentous structures described as 'microfossils' from the Apex chert are demonstrably biogenic. They fail to meet a wide range of criteria for biogenicity and their occurrence in a geologically plausible context (especially for cyanobacteria) is doubtful. They intergrade morphologically with a range of coexisting abiological bodies, mainly formed as reaction rims around chalcedony spherulites or crystal (e.g. barite) margins during silification and diagenesis.

We do not accept that the filamentous structures described from the Apex chert are biogenic microfossils, including cyanobacteria, for the following reasons:

(1) Mapping (Brasier et al., 2001) shows that putative 'microfossil'-bearing clasts were formed by fracturing and pulverization of earlier fissure-filling deposits and chert, and consistent with formation as hydrobreccia under hydrothermal conditions (Brasier et al., 2001).

(2) More than half of the previously illustrated specimens (Brasier et al., 2001) occur in fabrics mapped as late stage fissure-filling and secondary chalcedony (Brasier et al., 2001).

(3) The filaments are distributed in a way that is consistent with their formation as secondary artefacts of crystal growth (Brasier et al., 2001).

(4) The filaments are not hollow but composed of solid to discontinuous carbonaceous material, wrapped around quartz crystals.

(5) Arcuate and branched filamentous are reinterpreted as mineral 'reaction rims' formed by displacement and/or accretion of mineral impurities during the devitrification and recrystallization of hydrothermal silica (Brasier et al., 2001) and compare with other well-known pseudofossils from Archaean and Proterozoic rocks (Schopf, 1992; Brasier et al., 2001). Septation and features regarded as cells in the process of cell division (Brasier et al., 2001) are both explained by the interleaving of accessory minerals with quartz crystallinites within reaction rims.

Ancient filamentous structures should not be accepted as of biological origin until all possibilities of their non-biological origin have been exhausted (Brasier et al., 2001). Complex structures can result from simple physical processes (Brasier et al., 2001). Reinterpretation of the Warrawoona structures as pseudofossils raises serious questions about the presence of a cyanobacterial biota at 3.56 Ga. Instead, we find evidence consistent with a hydrothermal setting for the Apex cherts at Chinaman Creek. While carbon isotopic values (Figs. 18-20) have traditionally been interpreted as indicating a significant biological contribution to the carbon cycle, perhaps from otherwise unobserved hyperthermophile bacteria like those thought to occur as microfossils in younger Archaean rocks (Schopf et al., 1992; Brasier et al., 2001), we suggest that redox buffers such as native metals, sulphides and iron oxides and present in abundance within the carbonaceous dyke cherts (Figs. 6-8) could have encouraged the transformation of CO2 into organic compounds via Fischer-Tropsch type synthesis (cf. Butterfield, 1994). Such compounds, together with freely available sulphur species and H2, conceivably provided the carbon and energy sources for hyperthermophile bacteria (cf. Butterfield, 1994). This hypothesis is consistent with evidence from bacterial rRNA sequencing, which indicates that hyperthermophile methanogenic archaeabacteria branch most deeply in the tree of life and are arguably of much greater antiquity than cyanobacteria (Schopf, 2001). The Apex chert may provide evidence for a cradle of life, nurtured not by the energy of sunlight but by the thermal energy and mineral resources of the early crust.
Acknowledgements

Franco Pirajno (GSWA), Arthur Hickman (GSWA) and Martin Van Kranendonk (GSWA) provided generous advice and assistance. We are also grateful to the Geological Survey of Western Australia for extensive logistical support of our field program. The Royal Society and NERC supported fieldwork for MDB and NMcL.

Appendix A. Petrography of ‘holotype’ slides

The slides stored at the Natural History Museum in London have been cut from three blocks: block 1 gave rise to slides labeled V. 63164–63166 and 63727–63730; block 2 gave rise to slides 63731–63733; block 3 gave rise to slides 63734–63738. The slides are therefore described according to the blocks from which they were cut, using the general model for rock fabric genesis outlined in Section 6 above (see Fig. 3).

A.1. Block 1

Slides V.63164–63136 and 63727–63730 have been cut from the same elongate block. Distinctive features of this block include the very complex and intense brecciation of fabric A1, the deep black colouration of the core of the rock, but with a distinctly bleached and reddened marginal zone that reaches deep into the rock in places. Ten holotypes and six paratypes were erected from slides taken from this material (see Fig. 3).

A.1.1. Description of slide NHM V.63164

Slide NHM V.63164 is an important slide that contains twelve previously illustrated putative microfossils, including three holotypes. The main features of the slide are as for slide NHM V.63165 described below, with a marginal weathered zone plus abundant evidence for fracturing, veining, brecciation and fissure filling by carbonaceous chert. Two main areas, here called Areas 64B and 64C, contain the previously illustrated microfossil-like objects (Fig. 3). All of these lie within the marginal leached zone (Fig. 3), with each key area illustrated by a plate of photographs described in detail below.

Area 64B occurs near the margins of the slide within the leached zone (Fig. 3d and e, label 64B). Here, the angular clast, which abuts a broken margin of the slide, is reddish brown in transmitted light and bright red in reflected light, consistent with bleaching and oxidation of iron-rich carbonaceous silica within the weathering zone. Its rather dense fabric (A1) is cut by small, elongate, chaledony-filled vugs (fabric B1) and displays patches of conspicuous spherulitic chalcedony, where the matrix is very iron-rich and a deep red colour (Fig. 3e and f, arrow). These spherulitic patches typically have fringes of septate dendritic to arcuate filamentous pseudofossils, formed as reaction rims (Fig. 3f and g). This spherulitic fabric is less easily seen in areas of lower pigmentation but its ghosted presence can be seen where the ink of a marker pen has infiltrated into arcuate cracks on the surface of the slide, forming numerous pseudofossils (Fig. 3).

Object 64B1 is the holotype of Archaeosillanocystis maximia (Fig. 3b and c, label 64B1). This pseudoseptate arcuate structure lies immediately adjacent to an artefact-rich patch of reddened spherulites. Geochemical analysis (SEM/EDX) shows that the “holotype” is indistinguishable in mineralogy from the adjacent spherulitic mass. The septate fabric of object 64B1 clearly preserves radiating fibres of chaledonic silica interleaved with iron oxides, giv-
ing the false impression of cellular fabric. It is here reinterpreted as an arcuate ‘mullion’, the latter being an architectural word for the rib that separates two panes of glass in a mediaeval church window. Here, we use ‘mullion’ for those ribs (usually circular to arcuate) that arise as reactions rims during devitrification and recrystallization of an amorphous silica matrix to fibrous spherulitic chalcedony.
Fig. 14. (Continued).
Area 64C within the slide (Fig. 1.F) contains many of the figured ‘microfossils’ including three holotypes and five paratypes, and comprises an angular, polygonal clast of flinty fabric A1 (Fig. 1.A and B). One margin of the clast (close to label B in Fig. 1.C) comprises an especially dark, carbonaceous flinty fabric that can be seen to spill into grainy fabrics A2 and A3, forming small voids between the grains that are infilled with botryoidal chalcedony (Fig. 1.D–E). These botryoids show clear arcuate reaction rims. Similar botryoidal cements infilllurate numerous irregular fractures within the main body of the clast and have helped to form the ubiquitous sphenoidal to arcuate millons of carbonaceous matter, through the process of reaction rim growth during devitrification and recrystallization of a silicified, glassy protolith. It is this process which has given rise to the numerous pseudofossils described below.

The range of microfossil-like structures from clast C is shown in Figs. 1.G and 1.H; filamentous objects are scattered through the clast (Figs. 1.G and 1.H) and are commonest near to patches of carbonaceous sphenoidal chalcedony. The forms range widely in shape from complex dendritic forms (Fig. 1.H) 1, 11, 11 to common arcuate forms that may appear septate (Figs. 1.G and 11). The appearance of septation is due to scattered crystals of quartz within the carbonaceous matter that is fibrous (e.g. Figs. 1.H and 11). A smaller number of microfossil-like objects arise from incomplete carbonaceous reaction rims that have grown around the margins of rhombic crystal ghosts (Fig. 1.H). These artefacts include three illustrated holotypes: Primavellum conicoterminatum holotype (64C2; Fig. 1.5.4G; Paratype 64C2; Fig. 1.5.4H), Primavellum laticellulatum holotype (64C19; Fig. 1.5.4A), Primavellum laticellulatum paratype (64C19; Fig. 1.5.4B). Five paratypes: P. amoeno paratype (64C21; Paratype 64C21; Fig. 1.5.4C; 1992b, Fig. 1.5.5C); P. amoeno paratype (64C20; Fig. 1.5.4F; 1992b, Fig. 1.5.5E; Fig. 1.5.5G; Fig. 1.5.4F), P. conicoterminatum paratype (64CplanM3; Fig. 1.5.4B), P. delica- tuition paratype (64CplanM3; Fig. 1.5.4D), P. delica- tuition paratype (64CplanM3; Fig. 1.5.4H), plus figured examples of P. conicoterminatum (64D1; Fig. 1.5.4A; 1992b, Fig. 4D), P. laticellulatum (Fig. 1.5.4B; Fig. 5B), un-named ‘Type A’ broad filament (64C1; Fig. 1.5.6A) and un-named ‘Type C’ narrow filament (64C30; Fig. 1.5.6C, Fig. 1.5.6D).

A.1.2. Description of slide NHM V.63165 (Area A)

Slide NHM V.63165 contains nine previously illustrated putative microfossils, including one holotype (P. delica- tus), one paratype (P. amoeno) and three clasts labeled as ‘microfossiliferous’ (Fig. 1.5.4A, 1993, Fig. 3A and B). On one side of the slide (nearest to the largest label), and at the top of Fig. 1A, there is a conspicuous weathered marginal zone that cuts across all fabrics (Fig. 1A, label W). This leached margin tends to be pale grey to white in reflected and there is conspicuously reddened, oxidised zone where it abuts against the darker and more carbonaceous rock matrix, consistent with bleaching of the carbonaceous matter. All the ‘microfossil-like’ objects described below come from zones where this carbon has been partly or largely leached. The core of the slide (Fig. 1A) lower edge) consists of brecciated and angular shards of relatively compact grey to black fabric A1, often with jigsaw-puzzle fit, set within a matrix of paler, less compact, fissure-filling fabrics of generations A2 and A3 (e.g. 1992b, c, labels A1, A2, A3). Angular grains of laminated chert can also occur within fabric A1 and resemble microclasts of fractured vein chert. Less opaque areas within fabric A1 can reveal grey or brown chert with a mottled texture of scattered small elliptical grains, layered sericite flakes and iron oxide wisps, suggestive of a volcanic or volcanoclastic protolith that has been secondarily silicified. These rather homogenous clasts of fabric A1 can be blackened (‘melanized’) around their margins and along thin fractures that penetrate into the interior of the clast. The majority of the clasts of A1 fabric appear to have been pervasively melanized in this way.

In places, shards of fabric A1 are clearly seen to spill at the margins via sheet-like or irregular (‘ciscumgranular’) cracks, to form a dense to loosely packed, assorted microbreccia of fabric A2, comprising pale grey to black grains of angular to subrounded, lobate or elliptical shape, plus sparse angular to subrounded grains of clear and laminated vein chert (fabric B1) and conspicuous grains of pyrite. These are set within a clear chert matrix that in places can be traced laterally into elongate vugs lined with layers of clear botryoidal chalcedony (Fig. 1.B and b, fabric B2). There
is also a later generation of fissure-filling related to geotonal void fills, having a finer-grained or dusty fabric (Fig. 65A, label A3) that can be traced into botryoidal and geotonal chaledony (Fig. 65B, label B3). The slide is also cut across by later, narrow veins filled with chalcedony (fabric B4), commonly margined by grey or reddened rhombic ghosts or voids after iron carbonate. Wider veins and vugs can show a final stage of infilling with later megaquartz (Fig. 65A, label C). These veins have mostly grown parallel with the short axis of the slide. Adjacent fabrics of A1 and A2 can show remarkably abrupt changes in colour from black to pale grey, suggestive of local bleaching, across these veins.

The slide contains several previously illustrated ‘microfossiliferous’ clasts in two main areas, here called Clast 65A and Clasts 65B to H. All these lie with the marginal leached zone (Fig. 65A, label W). Each of these key areas is illustrated by a plates of photographs (Fig. 65C–65H) described in detail below. Clast A is rounded and brown coloured. Clast N is angular and yellow stained, and lies within a marginal area of the slide. Clast 1 is angular and red coloured. Clast A is rounded and brown coloured. Microfossiliferous clast H is subrounded to angular and brown coloured. It lies within a marginal area of the slide. Clast I is angular and red coloured. Clast N is angular and yellow stained, and lies within a marginal area of the slide. On one side is a large vein margined by epiaxial cement with rhombic ghosts, infilled with drusy quartz and cubic ghosts. Area 65A is of paramount interest because it contains the example most frequently illustrated of a putatively microfossiliferous clast, with rounded margins (inset, Fig. 65A, Fig. 3A and B). Common objects (Fig. 4A and B). In terms of context, this rounded slipper-shaped clast, here called 65A, occurs near the margins of the slide, within the leached zone described above (Fig. 65A and B). This clast is pale brown in transmitted light but grey to white in reflected light, suggestive of intensive silicification plus bleaching of the carbonaceous matter in the weathering zone. Clast 65A is surrounded by a pale, fine-grained microbreccia (fabric A3) that can be seen to grade directly into a botryoidal clear chert cement (fabric B3) that, in places, coats the margins of this clast, as well as the margins of adjacent more melanized clasts of fabrics Al and A2 (Fig. 65A, labels A1, A2, A3, B3). The chalcedonic nature of this enveloping B3 cement is shown by dendritic spherulitic mantles left by the crystalization of amorphous carbonaceous glass to fibrous chalcedonic silica botryoids and spherulites (Fig. 65A, black arrow). Clast 65A is made of fabric A1 comprising relatively homogenous grey brown chert containing numerous scattered, unsorted black carbonaceous microclasts (see Fig. 65A, B, and C). These microclasts typically show a distinctive alveolar mullion fabric within, and a dendritic mullion fabric on their margins (cf. Fig. 65A, black arrow) and accurate mullions in their hinterland (Fig. 65B, white arrows), mainly brought about by spherulitic crystallization of the silica matrix. The chert matrix between these microclasts contains irregularly scattered and unsorted carbonaceous objects of highly variable shape, ranging from simple blobs (e.g. Fig. 65A, n, o and p) and pseudoboloblasts (Fig. 65A, g), through to pseudosapoite filaments that appear to be wrapped around the margins ghosted rhombic crystals (Fig. 65A, s, t, u and v), of arcuate ghosted botryoids or spherulite margins (Fig. 65A, l, m, n, p, q, r and w). Many show multiple limbs of solid carbonaceous matter or rendered ‘pseudosapote’ by the interleaving of plates and/or equant grains of microcrystalline silica (Fig. 65A, by and g). Of these structures, the 11 objects shown with white arrows in Fig. 65A were previously been regarded as sufficiently microfossil-like as to warrant labels (Fig. 65A, W, Fig. 3A and B).
or Linnaean names. Objects 65A, 18 (Fig. 14) arrowed has been regarded as an example of P. delicatum (Fig. 3j) and occurs alongside an identical arcuate structure. Object 65A, 4 (Fig. 14) arrowed has been regarded as an example of Primacium minutum (Fig. 3g).

A.1.3. Description of slide NHM V63165 (Areas B to H)

Areas B to H occur towards the right of the slide, again within the marginal bleached zone (Fig. 14A) label 65B to H in area label W). Here is found a cluster of mainly angular to subangular clasts of fabric A1, many of which have been lithified in the process of being fractured and broken apart, to be infilled by clear chert veins of fabric B2. These clasts are enclosed within fissure-filling fabric A2 and/or associated botryoidal silica of fabric B2, which has a later void-filling phase of megaquartz. Of these, two clasts here called 65G and 65H have previously been illustrated as 'microfossiliferous' (Fig. 13A) and by see (Fig. 1.5.4A). These comprise subangular sherd of grey-brown fabric A1, fractured by numerous small, straight, anastomosing and arcuate veinlets of fabric B2. The margins of these chert veins can be preferentially coated with carbonaceous matter (e.g. clast 65G). The wider examples of these chert-filled fractures can contain floating masses of carbonaceous matter that has crystallised into a distinctive, alveolar mullion fabric (caused by the crystallization of an amorphous glassy silica phase to form small spherules of chalcedonic silica surrounded by reaction rims of carbon). Similar spherulitic carbon structures are also seen around the margins of the veins, near the edges of the clasts and within the surrounding fissure-filling of fabric A2. It is notable that the microfossil-like structures appear within these areas of spherulitic mullion fabric.

Clast 65G is a subprismoidal, subangular grain of rather homogenous, grey fabric A1 (Fig. 13A). It contains abundant scattered grains of sericite, suggestive of a volcanic or volcanoclastic protolith, and is cut across by two parallel, late stage veins of clear chert. Its left margin appears to spall into smaller clasts of fabric A2 (Fig. 13B). The range of carbonaceous objects is much as in clast 65A described above, and includes pseudoseptate dendrititc mullions (Fig. 1.5.6D) and angular crystal rims (Fig. 1.5.6G). Object 65G11 (Fig. 1.5.6H) is a grey-brown structure with an iron stained microfabric of mesh-like lamellae interleaved with larger quartz grains, and has been described as an 'un-named Type B broad filament' (Fig. 1.5.6K).

Clast 65H occurs immediately to the right of clast 65G. This near-equant, subangular to subrounded grain of grey fabric A1 (Fig. 13A) is broken into smaller patches by numerous curving 'circum-granular' cracks infilled with clear chert, and its upper margin appears to spall into the fissure filling of fabric A2 with scattered reaction rims of opaque iron oxide. Clast 65H also contains scattered grains of sericite, suggestive of a volcanic or volcanoclastic protolith, and is cut across by a late stage vein of clear chert. The carbonaceous structures described below are sparsest within a zone about 200 μm wide on either side of this late stage vein. The range of carbonaceous objects seen here is much as in clast 65A described above, and includes blobs, angular crystal rims, arcuate, dendritic and alveolar mullions (Fig. 1.5.6K). The context for two previously figured objects (65H6 and 65H12), taken to be evidence for early life (Fig. 1.5.6A, 1.5.6B) shown in Fig. 16A (black arrows). These objects occur within a region of the clast that has abundant spherulitic mullion structures (Fig. 16A, B, C, D). The holotype for P. delicatum (Fig. 1.5.5) is illustrated as an un-named uncoll-like microfossil (Fig. 1.5.5A) and includes as an example of A. disciformis (Fig. 1.5.5B) but here seen to be much more complex.

Fig. 16. (a) Magnified view of clast 65B, 65C and area 65Q in NHM slide V63165, with labelled features as discussed in the text, and a black arrow showing the position of (b). (b) Magnified view of area 65Q with spherulitic and botryoidal features discussed in the text and a white arrow showing the position of (c). (c) Cluser view of the preceding figure, showing carbonaceous strings (black arrows). (d) Magnified view of clast 65P and the adjacent area, with labelled features as discussed in the text, and black arrow showing the position of following (h–o). (e) Object 65P, (f) Object 65P, illustrated as an un-named uncoll-like microfossil (Fig. 1.5.5). (g) Four successive images through the plane of focus object 65P, regarded as an example of A. disciformis (Fig. 1.5.5A) but here seen to be much more complex.
3). Our photograph reveals a more complex structure than originally shown, including the presence of an angular side ‘branch’ at the top (black arrow), and its intersection with a carbonaceous, spherulite-filled microfabric (white arrows). Object 65H12 (Fig. 13b) has been interpreted as an unnamed degraded cellular filament or wrinkled sheath (Schopf, 1993, Fig. 1.5B). Our new photograph shows its proximity to a galaxy of abiogenic, carbonaceous spherulites (Fig. 13a and m, white arrows) and the presence of an angular termination (black arrow).

A.1.4. Description of slide NHM V.63165 (Area P)

Clasts 65B, 65C and 65D occur within the Area B to R, towards the right of the slide, and within the marginal bleached zone (W in Fig. 12). Each comprises a subangular to subrounded, prismatic clast of relatively homogeneous, pale to dark grey fabric A1, enclosed within granular, fissure-filling fabric A2 (Fig. 12, white arrow). The spherulitic to botryoidal nature of the silica cement for fabric A2 is well shown around these clasts, especially in area 65Q, to the top left (black arrow). At higher magnification (Fig. 12, g–m) can be seen a zone with spherulitic fabrics of carbonaceous chert clustered around a fluffy carbonaceous microclast. These fabrics include rounded spherulitic rims and arcuate botryoidal rims (h–i) plus scattered ramifying objects that are partly broken into strings of dark blobs (o). These relationships suggest that the carbon around the spherulites was originally expelled from the microclast when the amorphous silica cement of fabric A2 later crystallised into microcrystalline spherulitic chert. Similar structures can be seen adjacent to clast 65C (Fig. 12, black arrow pointing towards A2) and scattered through clasts 65B and 65D (Fig. 12, black arrows). These structures include dendritic and arcuate millions, strings, blobs and angular crystal rims (e–i) and e).

Clast 65P lies within the Area B to R and along the margins of the bleached zone (W in Fig. 12). Here can be seen a dense black prismatic clast of fabric A1 that has spilled around its margins to form angular to subrounded and lobate microclasts set within a clear chert matrix, typical of fabric A2. Complex carbonaceous objects can be seen within this region of fabric A2, especially within the bleached zone, and include dendritic and arcuate millions, strings, spherules and angular crystal rims (o).

Of these structures, three objects (65P2, 65P3 and 65P4) have been put forward as possible evidence for early life. Object 65P4 (Fig. 16b) has been regarded as an un-named solitary unicell-like microfossil (Schopf, 1993, Fig. 5k). It resembles an isolated spherulite rim (Fig. 16a and c) and lies precisely along the edge between fabric A2 and botryoidal silica cement of associated fabric B2. Object 65P2 (Fig. 16g–m) has been regarded as an example of Primaevifilum disciformis (Schopf, 1993, Fig. 3). Examination in three dimensions reveals that the described object comprises two conjoined and arcuate strings of carbon that are wrapped around a microclast. The appearance of cells here is brought about by quartz grains of widely varying shape and form, scattered within the carbonaceous string. Object 65P3 (Fig. 16a and o) has been selected as a paratype for P. amoenum (Schopf, 1993, Fig. 1.4.5D). Examination in three dimensions herein shows that this object has a contiguous side branch of solid carbonaceous matter and that the whole structure is, again, wrapped around a microclast. When all the structures around this object are pulled into view (Fig. 16e–o), one can see a galaxy of structures that includes other pseudoseptate carbonaceous strings, some of them apparently wrapped around the margins of grains and ghosted crystals.

A.1.5. Description of slide NHM V.63166

Slide NHM V.63166 contains three previously illustrated putative microfossils, including the holotypes of P. amoenum (Fig. 1.5A), A. segatum (Schopf, 1993, Fig. 3D) and an un-named Type C narrow filament (Schopf, 1993, Fig. 1.5C).

Like the other slices from Block 1, one of the two longer sides of the slide (nearest to the larger label) shows a conspicuous weathered marginal zone that cuts across all fabrics (cf. Fig. 12b, label W) and extends as a finger across the middle of the slide. This leached zone tends to be pale grey to white in reflected and there is conspicuously reddened, oxidised zone where it abuts against the darker and more carbonaceous rock light, consistent with bleaching of the carbonaceous matter. All the ‘microfossil-like’ objects described below come from zones where this carbon has been partly or largely leached. The fabrics of the slide show features exactly like those described from slide NHM V.63165 above.
These include dense grey to black fabric A1, fracturing and spalling to form generations paler fissure-filling microbreccias of fabrics A2 and A3, associated chert cements that infill fractures and voids (fabrics B1 to B3) plus late stage megaquartz (fabric C).

Two main areas, here called areas 66B and 66F, contain the previously illustrated microfossil-like objects and both lie with the leached zone. Area 66B lies towards the right hand margin of the slide, and shows a boundary within a subangular, dense black and carbonaceous shard of fabric A1 which is fractured and spalled on its margins to form the paler, more fluffy microclasts of fabric A2 (Fig. 1c, black arrow) set within a botryoidal silica cement of fabric B2. The chert matrix between these microclasts contains irregularly scattered and unsorted carbonaceous objects of highly variable shape, ranging from simple blobs (e.g. Fig. 1a, b), through to pseudoseptate filaments that appear to be wrapped around the margins ghosted botryoids or spherulite margins to form single arcuate strings (Fig. 1d and e), sinuous strings (Fig. 1f) and even rare 'W' shaped strings (Fig. 1g). The false appearance of 'septation' in these carbonaceous strings is due to the interlaving of silica plates (e.g. Fig. 1h, c and f). Of these structures, object 66B1 (Fig. 1a) occurs between microclasts in fabric A2 within cement of fabric B2 (i.e. it does not occur within a clast). It has been erected as the holotype for *P. amoenum* (Schopf, 1982, Fig. 1.1.5A). It shows a hitherto undescribed solid side branch (white arrow). Arcuate object 66B5 (Fig. 1b, white arrow) with a similar setting, has been regarded as an example of an un-named Type C narrow filament (Schopf, 1982, Fig. 1.5.6C).

Area 66F is nearby and shows numerous comparable arcuate and branched filaments that occur only upon the surface of the slide (Fig. 1d). These filaments have been formed accidently from the pencil graphite used by previous researchers to mark this part of the slide. The graphite has here infilled the arcuate surface depressions within the chert, which are brought about by its recrystallized, spherulitic fabric. Immersion oil used by us for the high power (<100) microscope objectives has caused then these graphite molds to float about on the surface of the slide. Note the similarity in size and shape to the associated arcuate pseudofossils described above.

Area 66F lies near the bottom margin of the slide (black arrow), within a region of bleached chert and very close to a strongly iron-stained crack (white arrow). The fabric here is dominated by pale microcrystalline chert of fabric B3 with a scattering of iron oxide grains (black arrow) and tiny, reddish-brown, blob-like mineral growths arranged into strings. These strings commonly show hints of a polygonal arrangement, reflecting the margins of quartz crystal rims (white arrows). Of these structures, object 66F4 (black arrow) has been erected as the holotype for *A. sepanum* (Schopf, 1982, Fig. 3D). This extremely small object is reddish brown (iron oxide?) in both transmitted and reflected light. It appears to pass, at an angle, into two discontinuous strings (white arrow). The holotype is not distinguishable in either form or colour from the associated crystal rim mineral strings.

A.1.5. Description of slide NHM V63727

The core of NHM slide V. 63727 (Fig. 1a) consists of dark, brecciated and angular shards of fabric A1, often with jigsaw-puzzle fit, set within a flocculent matrix of fissure-filling generations A2 (e.g. Fig. 1a, label A2) and A3. On one side (nearest to the label, and at the top of Fig. 1a) there is a weathered marginal zone of leached, paler fabric A1 to A3 that extends as a distinctive pale ‘finger’ towards the right of the slide (label W). This leached zone in places shows a reddened, oxidised margin where it abuts against the darker-lesser-altered fabric. The slide contains numerous irregular vugs that are infilled with chaledony (fabric B; e.g. Fig. 1b, and label B). These tend to be elongated along the longer axis of the slide. The sample is cross-cut by a number of conspicuous veins filled with chaledony (fabric B) and by later megacrusts (fabric C). These veins have mostly grown parallel with the short axis of the slide (white arrows). It shows a chard (ca. 2.86 mm × 2.13 mm in diameter) of fabric A1 (D) that has highly irregular margins. The shard is deeply invaded by veins and vugs of chaledony (label B) that mainly lie parallel with the long (E-W) axis of the slide. The paler colour in the lower part of the shard indicates the marginal zone of leaching referred to above. Outside of the leached zone, spherulitic fabrics are hard to see because of the dark, almost black fabric. Within the leached zone, however,
Fig. 17. (a) Magnified view of area 66B (west) in slide NHM V.63666, with labelled features as discussed in the text and a black arrow showing the position of objects in following (b–h). (b) Object 66B4; (c) objects 66B7; (d) objects 66B2; (e) object 66B3; (f) object 66B6; (g) object 66B1, previously erected as the holotype for P. amoenum (Schopf, 1992b, Fig. 1.5.5A); (h) object 66B5, previously illustrated as an example of an un-named Type C narrow filament (Schopf, 1992b, Fig. 1.5.6C); (i) magnified view of area 66F (west) with labelled features as discussed in the text, and a black arrow showing the position of objects in (j) and (k); (j) objects 66F4; (k) object 66F5, previously erected as the holotype for A. septatum (Schopf, 1993, Fig. 3D). Labels are as described in the text. Scale bar: 40 μm (b–h, j–k); 400 μm (a and i).
Fig. 18. (a) Macroscopic view showing the core of slide NHM V.63727 with labelled features as discussed in the text, scale in mm; (b) closer view of Area D in (a); (c) closer view of Area C in (a); (d) and (g) magnified view of carbonaceous spherulitic mullion fabric and pseudofossils, from area shown by white arrow in (c); (e) object 27D1, described as the holotype of *P. attenuatum* (Schopf, 1993, Fig. 5G); (h) object 27C8, illustrated as an example of *P. conicoterminatum* (Schopf, 1993, Fig. 4F); (f, i and j–o) detailed digital montages of dendritic to arcuate pseudofossils, from around white arrow in (c). Labels are as described in the text. Scale bar: 40 μm (c, f and b–o); 100 μm (d and g); 1 mm (b and c).
dark carbonaceous matter becomes conspicuous and forms linear bands that clearly follow the E–W veins of chaledonic (a) arrow. When viewed at greater magnification, these carbonaceous bands exhibit a distinctive spherulitic fabric (arrow) that we think have been brought about by the recrystallization of silica gel to spherulites of radiating microcrystals of chaledonic silica. The carbonaceous impurities have been left as relics ‘mullions’.

A spectacular array of complex graphic objects can be seen in the immediate vicinities of the carbonaceous bands (e.g. a and b) or lie at some small distance from them. They range in shape from dendritic forms with multiple branches, often of greater varying diameter (e) and a through to simpler c-shaped (f) and nearly circular forms (g). These pseudofossils are interpreted here as the relics of spheroidal recrystallization plus some selective leaching. Some of the pseudofossils have a septate appearance brought about by the interleaving of small granules (h) or plates of quartz (i) with solid ribs of carbonaceous matter. These solid ribs predominate in some examples. 

Slide NHM slide V.63727 contains two objects previously interpreted as microfossils: object 27C8, illustrated as an example of P. conicentrum (label c, Fig. 4F), and object 27D1, described as the holotype of P. attenuatum (label e, Fig. 5G). The first of these (a) lies within Area C described above (b). It differs in no obvious way from other spherulitic mullions in the vicinity. Graphitic spherulitic mullions lie all around the object (d) of ca. 266 μm. Object 27D1 (e) lies in Area D, again within the zone of leaching (f, g). Here, a large patch of flocculent fabric A2 is seen to contain darker, scattered and more coherent clasts of earlier fabric A1. Both are sharply cut by a vein of chaledony (h) and the object of interest lies within a small elongate shard of fabric A2 (ca. 840 μm x 280 μm) that floats within this vein (i) arrow. Graphitic spherulitic mullions lie all around the object (d) of ca. 270 μm. Object 27D1 lies along a later, iron-stained fracture (j) arrow, part of which was mistaken (k) for the attenuated cellular termination of the ‘holotype’. The new digital images show that the object is tightly incurved and shaped like a cross-salt pan, and is indistinguishable from other arcuate pseudo-fossils in the slide.

A1.7 Description of slide NHM V63729

NHM slide V.63727 shares many features with slide V.63727, suggesting the rock slices were adjacent and mounted on the glass slide in a similar orientation. The core of the slide consists of dark, brecciated and angular shards of fabric A1, often with jigsaw puzzle fit, set within a flocculent matrix of ferricrite filling of generations A2 (e.g. , label A2) and A3. On one side (furthest from the label, and at the top of there is a weathered marginal zone of leached, paler fabric A1 to A3 that extends as a distinctive pale ‘finger’ towards the right of the slide (label W). This leached zone in places shows a reddened, oxidised margin where it abuts against the darker-less-altered fabric. The slide also contains numerous irregular vugs that are infilled with chaledony (fabric B); e.g. (label b) and (label b). These veins have mostly grown parallel with the short axis of the slide (label A3, white arrow). 

Slide V.63729 shows a detail of Area B in (label B). At left can be seen the dark and dense carbonaceous fabric of a clast made up of fabric ~A1 (1D), with irregular margins. The bulk of the image reveals paler, flocculent tissue-filling fabric A2 (4–6D). The mullions seen in adjacent Area C (label white arrows) form part of a continuously varying cascade of spherulitic artefacts, ranging from spheroidal, through dendritic to arcuate (label , white arrows). They include pseudo-septate filamentous, often of highly variable diameter (label). The filamentous object 29C2 (label, black arrow) was selected as the holotype for P. minutum (label, Fig. 3G) but in terms of shape, composition and association is more plausibly regarded as relatively simple, diagenetic mullion structure.

A distinctive feature of Area B is that they are not of rounded form (i.e. not of spherulitic origin alone) but are markedly polygonal. Both microscopic examination and digital montage reveal that these carbonaceous filaments form part of a continuous, ramifying network, wrapped around angu-
Fig. 19. (a) Macroscopic view showing the middle part of NHM slide Y63729, containing Areas B and C, scale in mm; (b) closer view of Area B in (a) showing location of (f) plus angular carbon artefacts; (c) montage of the lower part of Area C, showing castellated artefacts (black arrows); (d) detail of (c), (e) digital montage of object 29C2, previously described as the holotype of P. minutum (Schopf, 1993, Fig. 3G) plus associated spherulitic artefacts (white arrows); (f) object 29B1, previously described as the holotype for E. aper (Schopf, 1993, Fig. 3F); (g) object 29C3 from Area C. Labels are as described in the text. Scale bar: 40 μm (d, f and g); 100 μm (c) and 1 mm (b).

Lar crystal margins (probably once of barite and now replaced by silica), to give a castellated effect (c, d, arrows). It is important to emphasize that these polygonal graphite reaction rims incorporate small grains of quartz (b, c, to left of arrow). Viewed in isolation, these could be credulously regarded as evidence for biological septation.

Object 29B1 (Fig. 19f) has indeed been erected as the holotype of E. aper (29B1, Schopf, 1993, Fig. 3F). It lies within the middle of Area B (label f), and is surrounded by a galaxy of polygonal reaction rims of the type mentioned above (Fig. 19c, white arrows). Features not mentioned in the type description include the way the filament balloons
out into a much thicker, polygonal and pseudoseptate structure (between the black arrows). Three-dimensional reconstructions suggest that this filament is likewise wrapped around the margins of a rhombic crystal ghost. The object is not, therefore, readily distinguishable from closely associated diagenetic artefacts such as those noted in and d.

A.1.8. Description of slide NHM V.63730

Slide NHM V.63730 is the smallest of those cut from this block. It presumably forms the end member of the series. The core of the slide consists of dark, brecciated and angular shards of fabric A1, often with jigsaw-puzzle fit, set within a flocculent matrix of fissure-filling generation A2 (labels A1, A2). This appears to have spilled off in situ via circumgranular cracks. A weathered marginal zone of leached, paler fabric A1 to A3 extends as a 1–2 cm wide zone all around the margins of the slide (label W). This leached zone often shows a reddened, oxidised margin where it abuts against the darker, less-altered fabric and along laterally orientated cracks (label R). The slide also contains numerous irregular vugs that are infilled with chalcedony (fabric B). Fissure-filling fabric of generation A3 is closely associated with these vugs as geopetal infillings and shadow zones (label A3). The slide is cross-cut by later chalcedony-filled veins seen in the other slides from this block, and the wider ones infilled with later megaquartz of fabric C.

A3 shows a closer view of Area A (label A). This 'microfossiliferous' patch lies in the zone of oxidized weathering and reddening around the blackened and less altered core. The complex, flocculent appearance of fissure-filling fabric A3 is clearly seen (label A3). A small dark grain from this secondary fissure-filling fabric is enlarged in (white arrow). Here, the graphite is seen to have become especially concentrated along polygonal boundaries between quartz crystals following crystallization (white arrow). Note that this 'coating' of carbonaceous matter has become incoherent to form a worm-like pseudofossil (arrow), again as the probable result of recrystallization.

Fig. 20. (a) Macroscopic view showing the middle part of slide NHM V.63730, containing Area A, scale same as (c and d); (b) closer view of Area A in (a) showing location of (c and d); (c) digital image of a dark grain within Area A, showing the outer coat of graphite, which is concentrated along polygonal quartz crystals and locally broken down into a worm-like pseudofossil (black arrow); (d) detail of Area A, showing the late-stage fissure-filling context for the pseudoseptate, branched object (W3A), described as the holotype for A. discoides; (e) detail of Area A (W3M) note the associated rhombic crystal ghosts (labelled 'rhomb') and the scattering of less coherent spherulitic mullions. Labels are as described in the text. Scale bar: 40 μm (c and d); 400 μm (b).
The weathered zone of Area A (Fig. 20, label A) is notable for containing the object 30A3 (Fig. 21), erected as the holotype for the taxon Archaeosclerito-
riopora disciformis holotype (Schopf, 1993, Fig. 3M). It clearly lies within a very late and rather pale tissue-
filling fabric of A3 type (Fig. 21d) in which float large rhombic ghosts (Fig. 21e, labelled ‘rhomb’), which are especially concentrated near the junction of fabric A3 with void-infilling white chalcedony of generation B3 (Fig. 21f, label B3). Incoherent carbonaceous objects float all around the object, which is found by microscopy to be much more complex than illustrated or described in the original type descriptions. Not only does it have an incoherent extension at one end (Fig. 21g, lower arrow) but branches angularly continu-
ously into a second structure at the other end (Fig. 21h, upper pair of arrows). This means that what had been regarded as a diagnostic termination of the ‘holotype’ is not in fact the ends of the structure at all, and is certainly not diagnostic. Both the filamentous limbs of object 30A3 broadly follow the outline of the adjacent rhombic ghost, suggesting that the crystal (possibly once barite, and since replaced by quartz) was helped to control its shape and hence, conceivably, its growth. Three-dimensional likewise confirms that the limbs are arranged along twin sides of a polygon. The structure can be reinterpreted as a dendritic murillon structure formed as the result of the recrystallization of amor-
phous, carbonaceous silica, at a late stage of fissure filling.

A.2. Block 2

Slides NHM V.63731-63733 all appear to have been cut from the same elongate block. Distinctive features of this block include brecciation and fissure filling which are more uniform and somewhat easier to study than in block 1. The slides are cross-cut by parallel, rather linear veins filled with fabric C. Previ-
ously figured, supposedly fossiliferous material, from these slides includes three filamentous taxa, a solitary unicell-like structure and a stromatolite-like structure (Schopf, 1993).

A.2.1. Description of slide NHM V.63731

Slide NHM V. 63731 (overview not shown) consists of dark, brecciated and angular shards of fabric A1, often with jigsaw-puzzle fit, set within the more floccu-

lent matrix of fissure-filling generations A2 to A4 (e.g. Fig. 21i, labels A1, A2). There is no obvious leached zone around the slide. The bulk of the slide appears to comprise paller fabric A3 but there are also quite large areas of fabric A4 in the centre. Fabric A4 tends to have a less fine-grained matrix, to be grain-supported, and to show a clear, geotopal relationship with the late stage chalcedony-filled vugs (of fabric B4). The slide contains many irregular such vugs infilled with botry-
oidal chalcedony (fabric B; e.g. Fig. 21a, label B2) which tend to be elongated along the longer axis of the slide. These botryoids can be coated with graphite. The sample is obliquely transected by three linear veins infilled with chalcedony (Fig. 21b and B, label B4) which are cross-cut by five linear veins parallel with the short axis of the slide and filled with later megaquartz (fabric C). This shows the context for the ‘clast with stromatolite-like laminae’ reported and figured by Schopf, 1993 (Fig. 3C). The darker fabric here consists of small grains of dense, and mostly very black fabric A1, set within a more flocculent matrix of fissure-
filling generation A2 or A3 (Fig. 21i, labels A1, A2). The whispy, white areas comprise void-filling botry-
oidal chalcedony of fabric B2 or B3. A faint linear vein, probably of B3, transects the lower half of the slide and the whole is cross-cut by a linear vein of late stage fabric B4. Closer inspection of the ‘stromatolite-
like clast’ reveals that the basal laminae thin over flocculent grains of A2 (Fig. 21k, white arrow) but are essentially continuous across the asymmetrical peaks and troughs (Fig. 21l). Most importantly, they can be seen to wrap around the enclosing flocculent matrix of fabric A2 (Fig. 21l, white arrow), implying that they formed at roughly the same time, i.e. that they are part of a laminated cavity-fill of fab-
ric B2. This interpretation is supported by the pres-
ence within the laminae of a suite of minerals iden-
tical with those of the enclosing matrix, including hematoxilin (Fig. 21o, and e, black arrows), phyllosili-
cates (Fig. 21p, black arrow) and flocculent grains of fabric A2 (Fig. 21p, white arrow). Especially interest-
ing is the formation of a dark filamentous structure along the boundary between this grain and the chal-
cedony. We regard this as a pseudofossil that formed as a reaction rim around the grain during crystal-
ization of the silica, as noted elsewhere (cf. Fig. 21m). By way of contrast, Fig. 21q shows an angular shard
of fabric B, with undulating laminae and dark carbonaceous layers. This has clearly been brecciated and incorporated within flocculent fabric A3, which was later cut by veins chaledony (fabric B4) and megaquartz (fabric C). The undulating laminae resemble those reported from geysers sinter (cf. Walter, 1976, Fig. 19).

A.3. Block 3

Slides NHM V, 63734–63738 have been cut from the same rather triangular block. The features of brecciation and fissure filling are very clear and relatively simple, showing a large, angular and fractured shard of darkish fabric A2, transected by a broad vein filled
with pale grey fissure-filling of fabric A1. There are no obvious cross-cutting veins filled with megaquartz of fabric C. Previously figured and supposedly fossiliferous material from these slides include eight examples of six filamentous taxa, plus three examples said to be poorly preserved trichomes showing bifurcated cells and cell pairs (see Schopf, 1992b, 1993).

Description of slide NHM V.63737. Slide NHM V.63737 (Fig. 22d) shows a further slice through the same relatively large angular shard of fissure-filling microbreccia fabric A2, consisting of a mudstone to poorly sorted, wackestone matrix of indistinct grains with darker and denser clasts of fabric A1 together with subangular to subrounded clasts of clear and banded chert (fabric B1). The cross-cutting vein of fissure filling fabric A3, seen clearly in the other rock slices from block 3, is here confined to a small corner of the slide (Fig. 22d), and contains angular shards of A2. The slide...
is transected by several thin and rather irregular veins infilled with botryoidal chalcedony, some stained red with iron oxide.

Area A in slide NHM V63737 lies within a small subangular clast of fabric A1 set within fissure filling fabric A2 (large black arrow). This area is transected by later veins containing clear chert and by darker zones caused by localised pressure solution (EPMA labels B3 and R, respectively) while the primary fabric is scattered with rhombic ghosts and carbonaceous reaction rims (EPMA). Elongate object 37A1 lies within this area (EPMA black arrow) and is taken to be the holotype of A. grandula. (Photograph Fig. 5D). It is black in transmitted light but white in reflected light. Septation here is brought about by the impingement of several thin rhombic ghosts into the carbonaceous matter (EPMA black arrows).

References


Brasier, M.D., Green, O.R., Lindsay, J.F., McLaughlin, N., Jephcoat, A., Kleppe, A.K., Steele, A., Synes, C., Wacey, D. Contextual redescription of Earth’s oldest putative fossil assemblage from the ~3.5 Ga Apex chert, Chinaman Creek, Western Australia. Geological Survey of Western Australia Publication, in press.


