in diamond. It also characterizes the degree of crystalline order in solids. However, it does not provide a list of elemental components or even ratios of carbon, hydrogen and oxygen, which might help to establish the biogenicity of a compound.

Most pertinent to the analysis of putative microfossils is the fact that the Raman spectrum of carbonaceous (that is, carbon-dominated) materials is sensitive to the degree of ordering of the carbon they contain (distinguishing, for example, between amorphous carbon, poorly ordered graphitic material and highly crystalline graphite)[3–10]. The Raman spectra of Schopf *et al.*[1] confirm that their samples consist of highly disordered carbonaceous material and are consistent with the spectra of kerogens[3,4]. However, their spectra are indistinguishable from those of many other types of structurally disordered carbonaceous matter generated from a wide range of starting materials by a wide variety of processes. Those processes (including high-temperature heating of organic or inorganic compounds[4–7], inorganic deposition from high-temperature synthetic fluids[3–5] and geological deposition from hydrothermal solutions[8]) and materials (for example, ion-bombarded graphite[9] and graphite-intercalation compounds[10]) may be strictly non-biogenic. There are no distinctive features in the spectra shown by Schopf *et al.*[1] that directly and unambiguously link them to kerogens.

Raman microprobe spectroscopy is useful for investigating the molecular structure of micrometre-sized features, such as putative microfossils, in rock. Showing that fossil-like objects consist of highly disordered carbonaceous material by Raman spectroscopy provides necessary, but not sufficient, evidence that the objects are biogenic. Although the microscopic objects analysed by Schopf *et al.*[1] may indeed be biogenic, we see nothing in their spectra that indicates the origin of their disordered carbonaceous material. The basic question remains unanswered: which measurable chemical and/or physical properties of a fossilized and/or altered material will unambiguously identify it as biological in origin?

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Schopf et al. *reply* — The criticism by Pasteris and Wopenka of our use of laser–Raman imagery to investigate the carbonaceous make-up of extremely ancient fossils[1] focuses only on their Raman signature; however, our interpretation that the carbonaceous matter that makes up these specimens is biogenic is based on several lines of evidence, of which Raman spectroscopy is only one.

We did not state, nor did we imply, that Raman spectroscopic analysis can by itself be used to establish the biological origin of geochemically highly altered carbonaceous matter present in ancient sediments. We believe that the biogenicity of such matter, whether in fossil-like objects or sapropel-like detritus, should be demonstrated by a combination of data drawn from independent but mutually reinforcing lines of evidence.

For fossils in each of the four geological units we analysed[1] — including those of the roughly 3,375-million-year (Myr)-old Kromberg Formation and 3,465-Myr-old Apex Chert, which are among the oldest fossils known — three lines of evidence are most compelling. These are their cellular morphology[2,3], their carbonaceous molecular-structural make-up[1–4], and the carbon isotope composition of such fossils[5] and/or of co-existing particulate kerogen[6,7], which have been shown by replicate analyses[5–7] to be well within the range established for Precambrian biological organic matter on the basis of over 1,200 measurements from hundreds of fossil-bearing units[7].

Our study[1], which focuses on the first two of these lines of evidence, is centred on the use of laser–Raman imagery (rather than on more conventional single-point measurements), a technique new to palaeobiology[1,4]. We showed that there is a one-to-one correlation of cellular morphology and carbonaceous make-up in individual microscopic fossils from each of the four units investigated. Our claim is that such an analysis based on a combination of morphology and chemistry together provides a powerful new means to investigate the biogenicity of putative fossil-like objects, a problem that for many decades has plagued the search for evidence of early life[8].

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COMMUNICATIONS ARISING

Palaeontology

Thermal alteration of the Earth's oldest fossils

Microscopic carbonaceous structures found in ancient rocks could provide clues to early life on Earth if they turn out to be genuine fossil microorganisms. Here we show that thermal alteration of microbial remains embedded in a mineral matrix may significantly change their original morphology and produce structures that resemble those of what are claimed to be the Earth's oldest fossils[1]. These observations may shed light on the controversy[2,3] that surrounds these microfossils from the 3,465-Myr-old Apex Chert of the early Archaean Warrawoona Group in northwestern Australia.

The biogenicity of these fossils has been called into question[3] on the basis of suggestions that the Apex Chert structures were formed from amorphous graphite within multiple generations of metalliferous hydrothermal-vein chert and volcanic glass, and that the carbonaceous composition and characteristically biological carbon-isotope make-up of the carbonaceous filaments could have been products of non-biological (Fischer–Tropsch) organic synthesis[3].

We have investigated structures that are present in silicified (chertified) cyanobacterial mats from the Bardo Mountains (Żdanów locality[4]) in southwestern Poland, which date to the early Silurian period (about 440 million years ago). The fossil mats occur in black, laminated radiolarian cherts, which have been interpreted as sediments that formed at moderate depths within the photic zone[5]. The mats are composed of cyanobacteria that are closely related to representatives of modern colonial chroococcaleans (particularly the

families Entophysalidaceae and Xenococcaceae[6]). Living colonies of these cyanobacteria are composed of globular subcolonies surrounded by thick mucous envelopes (Fig. 1a). The subcolonies are composed of minute cells (which in some species are less than 2 μm in diameter).

Post mortem degradation processes in modern mats composed of coccoid cyanobacteria[7] indicate that the components that are most resistant to decay are the thicker outer mucous envelopes that surround groups of cells, subcolonies and entire colonies. After burial, these partially biodegraded envelopes often remain preserved as a cobweb-like polysaccharide material. With time and progressive diagenesis, this material may undergo kerogenization and be transformed from a more-or-less structured biological material into amorphous organic matter.

The early-Silurian cyanobacterial mats we describe represent a kerogenized stage in which the outlines of the subcolonies and of even smaller groups of densely packed, minute cells are still recognizable in the chert matrix (Fig. 1e). Owing to compaction, the circular outlines of the subcolonies are best seen in petrographic thin sections made parallel to the bedding. The subcolonies reach 60–90 μm in diameter and occur as blackish, cobweb-like structures (Fig. 1b; and see Fig. 1c in supplementary information) or as yellow–brown circular or semicircular areas, which are bordered by blackish, continuous or discontinuous, irregularly segmented or porous zones (Fig. 1c, d; and see Fig. 1a, b in supplementary information).

The densely packed masses of small bodies that fill the interiors of many subcolonies (Fig. 1e) are likely to be remnants of cells that created the original colonies. In vertical thin sections, the blackish material is usually present as slightly curved or undulated, often segmented, filamentous structures (Fig. 1f) which are locally branched (see Fig. 2 in supplementary information).

All of these features make the blackish structures almost identical in appearance to the filamentous structures described from the Apex Chert. This similarity is particularly striking when the shapes of Archaean structures are compared to the porous and irregularly segmented structures from the peripheries of the Silurian cell aggregates. Their quasi-circular, C- and J-shaped outlines fit almost perfectly the morphologies described for the Apex structures[1,3]. The same is true for the size classes of both groups of structures.

The blackish, pseudo-filamentous Silurian structures probably represent thermally altered, kerogenized remains of coccoid cyanobacterial mats. The Silurian deposits in the Bardo Mountains were influenced by Caledonian and/or Variscic thermal events[8], as evidenced by generations of microcracks filled with hydrothermally precipitated microcrystalline chalcedony and quartz. The cyanobacterial remains distributed in the vicinity of these cracks have been markedly altered, but still preserve traces of their primary biological structure.

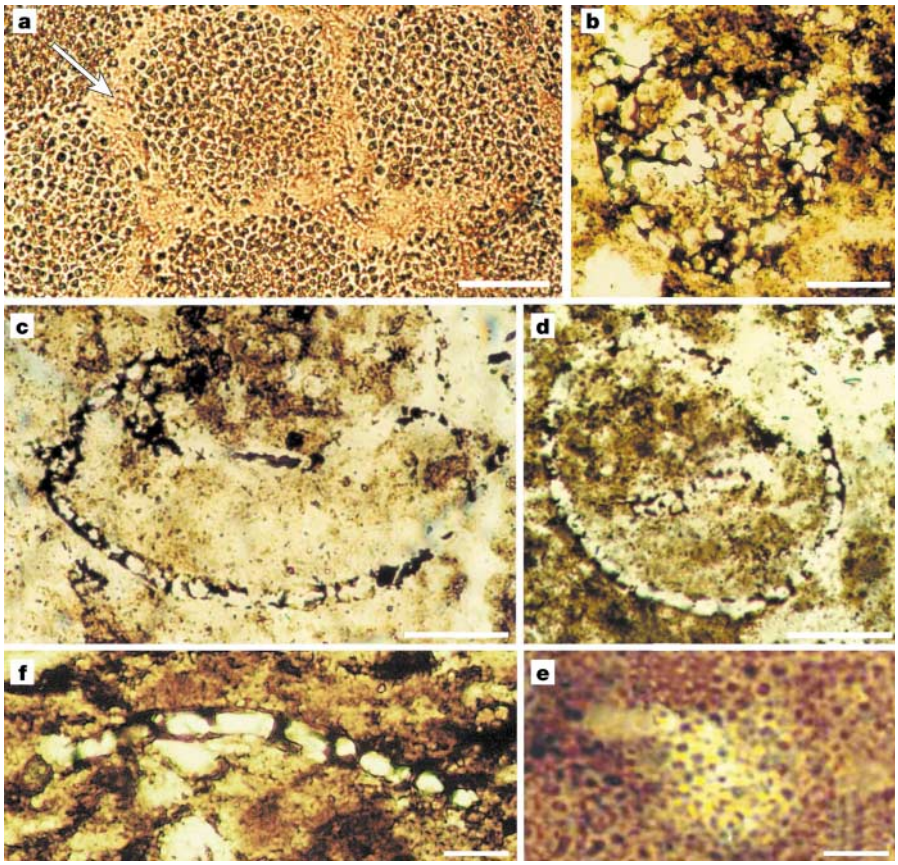

Figure 1 Light micrographs of mats of modern and early Silurian coccoid cyanobacteria. **a,** Modern mat of benthic coccoid cyanobacteria from Sulejów Dam, central Poland; the mat is composed of globular colonies surrounded by thick mucous envelopes (arrow). **b–f,** Examples of variously thermally altered colonies of Silurian coccoid cyanobacteria from Żdanów in the Bardo Mountains, Poland; these were originally composed of minute cells (magnified in **e**). Note the quasi-regular, segmented, blackish structures of thermal origin, which are strikingly similar to the purported Archaean Apex Chert microfossils. Scale bars: **a**, 50 μm; **b–d**, **f**, 20 μm; **e**, 5 μm.

Thermal alteration was apparently more advanced in the Apex Chert samples, leaving only isolated fragments in the chert background of much-changed ('carbonized') kerogen, and preserved pseudo-filamentous ghosts of the original biostructures. The generation of gaseous and bituminous hydrocarbons associated with thermal maturation and the conversion of kerogenous materials[9] could have been responsible for the apparent reduction in volume and partial relocation of the cyanobacterial material.

Several inferences can be drawn from our observations of chertified and slightly thermally altered early-Silurian cyanobacterial mats. First, the early Archaean Apex Chert filaments may have originated through late diagenetic (thermal or thermobaric) *in situ* alteration of kerogenized remnants of mucilage sheaths, capsules and extracellular polymer substances that originally enveloped groups of coccoid cells. Second, the Apex Chert microfossil-like filamentous structures could therefore be biogenic but may represent diagenetic ghosts of benthic mats composed of colonial microorganisms resembling some modern chroococcalean cyanobacteria. Third, what have been described from the Apex Chert as 11 filamentous microbial taxa[1] may rather represent remnants of a homogeneous (and most probably monospecific) microbial community, similar to modern benthic coccoid cyanobacteria, that is also known from later Precambrian and Phanerozoic strata.

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