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Discussion

CARBONACEOUS FILAMENTS FROM NORTH POLE, WESTERN AUSTRALIA: ARE THEY FOSSIL BACTERIA IN ARCHEAN STROMATOLITES? A DISCUSSION

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Some time ago Buick (1984) cast doubt on both the biogenicity and the age of the objects we described as Early Archean bacterial microfossils in a previous paper (Awramik et al., 1983). He presented new evidence significant to the interpretation of these objects, but his report also contains statements that may be misleading. We wish to comment on his new evidence and to correct the misleading statements.

Our initial report (Awramik et al., 1983) has been supplemented by a detailed discussion of all Archean microfossils and microfossil-like objects (Schopf and Walter, 1983). This latter paper describes the history of the discoveries at North Pole (Western Australia) and sets out in detail the evidence for biogenicity, syngenicity and age of the microfossils and possible microfossils. New observations have been presented by Awramik (1984), and additional relevant geochronological information has been published by Richards et al. (1981) in a paper that was not available to us when our initial reports were prepared.

Buick's new evidence is that apparently carbonaceous filaments occur in demonstrably secondary silica. We looked for such occurrences in our material (originally discussed in Awramik et al., 1983, p. 365; supplemented by discussion in Schopf and Walter, 1983, p. 234, and Awramik, 1984, p. 105) but in no case did we find apparently carbonaceous filaments in demonstrably secondary chert. Buick's (1984) interpretation of this unquestioned fact is, however, misleading and unconvincing when applied to the microfossils we described.

In response to Buick's (1984) comments, and questions raised by Cloud (1983, 1984, 1985), we (Awramik (SMA) and Walter (MRW)) have re-examined the thin sections containing the type and illustrated microfossils (SMA and MRW), prepared and studied additional thin sections from the original rock specimens from locality A (SMA), and have examined Buick's thin section U.A.W. 94219 (SMA and MRW). Supported by these supplementary observations we stand by our original conclusions that (1) the chert contains pseudofossils, dubiofossils and *bona fide* microbial fossils; (2) that the *bona fide* microfossils are syngenetic with respect to the first generation of chert (again we could not find apparently carbonaceous fila-

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ments in secondary silica); and (3) that the *bona fide* microfossils are of Warrawoona age.

There are two field localities, designated A and B by us; our *bona fide* microfossils occur only at locality A, whereas Buick's new observations relate only to locality B. From locality B, Buick described a patch of laminated, colloform, formerly chalcedonic silica, within which apparently carbonaceous filaments occur. He then wrote "These laminae are very similar in their alternating habit, relative thickness, relative grain size, degree of flexure and boundary styles to those in which Awramik et al. (1983) found their locality B filaments. The only differences between them are in composition (their laminae contained dolomite and apparently were not originally chalcedonic) and in lamina continuity (their laminae were lenticular)." This is confusing. What Buick says, in essence, is that what we described is very similar to his specimens but on the other hand differs in what we consider are significant characteristics. We present here once more (Fig. 1c), a photomicrograph of a portion of the thin section we studied (also see Awramik et al., 1983, fig. 2b). We have expressed before (Walter, 1983, p. 198; Schopf and Walter, 1983, pp. 234–235; Awramik et al., 1983, pp. 362–366) our reasons for interpreting the material as a stromatolite and will not repeat that reasoning here, but we must make it clear that Buick and ourselves are describing quite different objects, as a comparison of Fig. 1c with Buick's (1984) figs. 3 and 4 will demonstrate. We also use a different definition of stromatolite. Buick suggests that without detailed study the colloform chert he described may well have been interpreted as a stromatolite. It is frequently difficult to determine with confidence whether a structure is a stromatolite, but that is not the situation here: the colloform chert described by Buick is typical of that found in veins and cavity fillings of all ages and in many geological environments; it is not a stromatolite and it is most unlikely that it would be misinterpreted as such. Features that can be used to distinguish stromatolites from similar abiogenic structures are discussed by Walter (1983).

The evidently carbonaceous filaments we described from our locality B are in sedimentary rocks such as Buick also records from the same small exposure (only a few meters wide and high): "Several thin beds of coarse arenite are also present within the wedge, one lying 10 cm below the filament-bearing fissure [this refers to the filaments Buick discovered, not ours]. These are predominantly composed of scoriaceous grains but they also contain tabular clasts of a rock made up of alternating, undulose laminae of silicified lutite and amorphous kerogen, clasts that closely resemble fragments of stromatolites" (Buick, 1984, pp. 163–164).

Two of us (SMA and MWR) have examined one of Buick's specimens and agree that the filaments he has discovered closely resemble those we described from the same exposure. Therefore, the significant questions to be addressed are whether Buick's discovery eliminates the possibility that these filaments are microfossils and, secondly, if they are microfossils, whether they are 3.5 Ga old.

Readers of Buick's paper may have gained the impression that we interpreted the filaments from locality B as microfossils and that Buick refuted that interpretation. This could result from the fact that Buick discussed at some length the question of, and criteria for identification of, the biogenicity of these filaments, and only in the final sentence pointed out that we, in fact, had previously also reached the conclusion that the filaments from locality B are only "possible microfossils." Our reasoning for this is set out in detail in our previous papers. We pointed out that these filaments, designated for reference purposes as "Warrawoonella radia", "...are at least roughly similar to such rosette-forming modern colonial bacteria as *Thiothrix* and *Leucothrix*..." (p. 366) and are "...in some respects..." (p. 372) similar to the microfossil *Eoastrion simplex* (Awramik et al., 1983). So we do not agree that they "are quite unlike modern filamentous microorganisms or

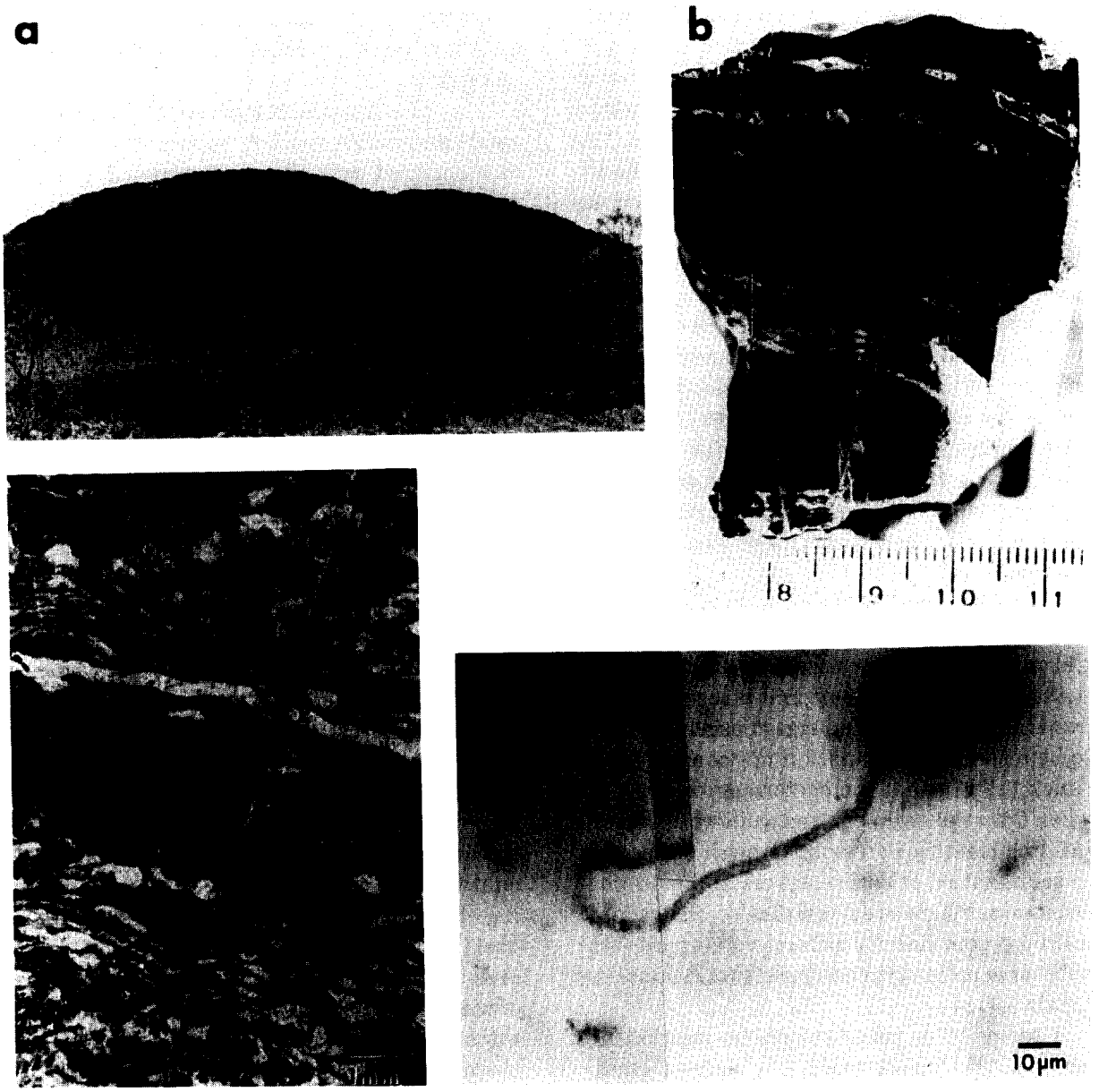

Fig. 1. (a) Exposure at locality A of Awramik (looking N). Samples come from the NE flank. (b) Hand specimen from locality A; the sample from which thin sections SMA 298 and SMA 299 containing the type and illustrated material (Awramik et al., 1983) and SMA 1483 (this discussion) were made. (c) Photomicrograph in transmitted light with crossed polars of a thin section of laminated black chert (sample 002-1-A) from locality B. This sample contains examples of the possible microfossil "Warrawoonella radiata" from this locality. The markedly lenticular laminae contrast with the regular, banded laminae of Buick's samples. Note also the easily recognizable chert-filled fissures, both discordant and, near the center, almost concordant. (d) Photomicrograph (photomontage) in transmitted light of an apparently aseptate, large ($\sim 1.5\ \mu m$ in diameter) *Eoleptonema australicum*-like tubular filament. Thin section SMA 1483, stage coordinates 15.7×14.4, housed in Preston Cloud Research Laboratory.

genuine filamentous microfossils..." (Buick, 1984, p. 167). The main problem in demonstrating their biogenicity lies in the fact that the filaments are neither demonstrably hollow nor demonstrably cellular. The word 'demonstrably' is important here because the filaments are $< 1\ \mu m$ wide, and in some examples much less, so we are working at or near the limits of optical resolution; at this scale it is frequently difficult to detect cellular characteristics, even in living bacteria. Moreover, it is not unreasonable to suggest that during crystallization of the enclosing silica, formerly broader, cellular filaments could have been compressed by growing crystals (particularly fibrous crystals) to produce somewhat irregular, more or less solid filaments. We maintain our view that these are "possible microfossils."

If it is assumed for the purpose of discussion that these filaments from locality B are bacterial microfossils, how can their occurrence in both laminated sediment and a secondary deposit be explained? We suggest, as a hypothesis to be tested, an explanation not considered by Buick (1984): that the bacteria grew at a time when both the sediment and a siliceous cement infilling cavities were soft. Growth of bacteria in sediment is, of course, a very common phenomenon. There are examples of chalcedonic infillings containing a rich microbiota presumably syngenetic with sedimentation (Cloud and Licari, 1972).

It seems to us that the genetic relationship between the "black and white banded chert" (with the carbonaceous (?) filaments) and the nearby chert–barite dike, as proposed by Buick (1984) and used to indicate a late secondary origin for the chert, has not been convincingly demonstrated. At the scale shown in Buick's (1984) fig. 5, where the geometric relationships at the locality are illustrated, the quality of exposure is not good and the details of interrelationships are very difficult to decipher with any confidence (although we have not revisited the exposure since Buick developed his current interpretation). The following issues need to be resolved before a genetic relationship can be accepted:

(1) The dike is composed of interlayered chert and barite and yet, apparently, no barite is associated with what is interpeted by Buick as concordant chert fissure fillings.

(2) The non-clastic layers in the rock unit containing the filaments are described as "white, black, black-and-white and clear" chert bands, and all are considered by Buick to have been intrusively emplaced from the dike. On the other hand, the only apparently demonstrable intrusive phase is black chert (Buick's fig. 5 and p. 165), and this is in the arenite bed beneath the filament-bearing bed. It is not clear why there should only be one variety of 'intrusive' chert in a bed only centimeters from a rock unit said to be predominantly composed of four varieties of such chert.

(3) It seems plausible to interpret the bulk of the 'black and white banded' chert wedge as a lithofacies of mixed detrital and chemical sediments (such as have been recognized in this and other formations in the Pilbara by Barley et al., 1979, Hickman, 1983, and Lowe, 1983). The diagenetic history of similar sediments in the region has included dissolution of early precipitates and replacement by silica, and the filling of cavities by secondary cements, including chert (Barley et al., 1979; Lowe, 1983). There undoubtedly are fissures filled with cherts, some of which may have formed late in the history of the rocks, but the sedimentary rocks have had a complex history and detailed work is still required to separate the different phases of silica cement that can be expected to occur.

(4) If the filaments formed or were emplaced when the chert–barite dikes formed, then they should also occur in the dikes. We have searched for them, and have found no evidence of their occurrence (samples are listed in Walter et al., 1983). We presume that Buick has done the same and we infer from his lack of comment on this matter that he similarly lacks such evidence.

(5) Buick's (1984, p. 166) final reason for relating the banded cherts to the dike is that "the kerogen content of the wedge decreases away from the dyke." No data are presented to support this assertion, and in any event its significance is not clear. Does it mean that the kerogen content of the 'intrusive' cherts decreases away from the dike, that the proportion of the 'chert wedge' made up of such cherts decreases away from the dike, or both?

The origin of the chert dikes and chert–barite dikes in the North Pole area is not yet understood (Hickman, 1983, p. 82). They were first described by Hickman (1973), who recognized that they occur in joints and faults related to the formation of the North Pole dome. He considered (Hickman, 1973, p. 60) that during uplift of the dome, "Joints and faults belonging to the dome's fracture system were locally invaded by diapiric folds of the bedded barite." He interpreted the interlayered barite and chert as of sedimentary origin. Hickman (1983, p. 82) states that it has been considered that "the chert was fumarolic and the intrusions represented feeders to bedded sedimentary chert units" but he concludes that "A minority of the discordant chert units may be fumarolic but most would appear to have formed in response to stress during doming." He goes on to suggest that "the sedimentary chert was still relatively plastic at the time of deformation". Although the main phase of doming seems to have occurred ~2.95 Ga ago, locally it began 3.50–3.45 Ga ago, i.e., contemporaneous with deposition of the Warrawoona Group (Hickman, 1983, p. 163). There appears to be only one direct isotopic date for chert–barite dikes at North Pole: it is a model Pb age on galena from several dikes, and is not considered definitive by its authors who, nevertheless, state that "It would be hard to find an interpretation, however, which involves an age of final deposition much less than the model age 3.4 Ga..." (Richards et al., 1981, p. 18).

Therefore we would make the following points: (1) A genetic relationship between the 'black and white banded chert' (with the filaments) and the adjacent chert–barite dike has not been demonstrated; (2) the origin of the chert–barite dikes is not understood; (3) parts, at least, of the dikes may be almost as old as the sedimentary rocks they intrude.

This discussion so far relates to our locality B, to which Walter, J.M. Hayes and H.J. Hofmann were originally guided by R. Buick and J.S.R. Dunlop (the circumstances are described by Schopf and Walter, 1983). Locality A was discovered by Awramik; Buick (1984) correctly states that the exact field relationships of the samples collected are not known for locality A (as we have previously noted; Awramik et al., 1983; Schopf and Walter, 1983). We should make clear the limits of the uncertainties: the samples (Fig. 1b) were collected by Awramik in 1977 from exposure (not float, as mistakenly reported by Knoll (1984)) low on the NE flank of a small hill (roughly 200×200 m wide; Fig. 1a; see Awramik et al., 1983; for location of exposure and index map, fig. 1). The initial collection was made soon after a bush fire had burnt off the normally extensive grass cover. When Awramik returned in 1980 to check the field relationships (after the fossils had been found, and accompanied by J.S.R. Dunlop and later R. Buick) it was at a time when the grass had regrown, and he was unable to recognize the precise location of and the specific horizon in this exposure from which the small amount of sample ($\sim 150\ cm^3$) was collected three years earlier. Awramik briefly revisited the exposure in 1985 and was again unable to locate the exact spot where the small samples were collected. Schopf, Walter and others visited the hill in 1982 after another bush fire had burnt off the grass, and they were able to determine that only a single sedimentary formation is exposed on the hill and that, in contrast to locality B, no chert–barite dikes are recognizable (nor does Buick (1984) report any).

Secondary, formerly chalcedonic, silica is abundant at locality A, as Awramik et al. (1983) and Schopf and Walter (1983) reported, but no microbial remains have been found in cracks,

in void fillings or in the formerly chalcedonic silica.

Cloud (1983, 1984, 1985) was struck by the pronounced ribbon-like morphology of some *Archaeotrichion contortum* filaments he observed in our thin sections from this locality. He noted their resemblance to the extant Fe oxidizing bacterium *Gallionella ferruginata* and this, along with the numerous fractures present in the samples and the weathered nature of the exposure, led him to conclude that there was a distinct possibility that these microbes were late introductions into the rock. Once again, we must point out that the microfossils occur only within the homogeneous cryptocrystalline chert matrix. No microfossils have been found in cracks or chalcedony in these samples. Furthermore, the resemblance of these filaments to extant bacteria does not suggest that they are contaminants. Many demonstrably syngenetic and indigenous Proterozoic microbial fossils preserved in chert have a striking resemblance to extant prokaryotes: for example, *Eoastrion simplex* Barghoorn from the Gunflint Iron Formation (Barghoorn and Tyler, 1965), *Palaeolyngbya barghoorniana* Schopf from the Bitter Springs Formation (Schopf, 1968), *Eucapsis*(?) from the Paradise Creek Formation (Licari and Cloud, 1972) and *Eoentophysalis belcherensis* Hofmann from the Belcher Islands (Hofmann, 1976; see also Golubic and Hofmann, 1976).

Buick (1984, p. 170) suggests that *Archaeotrichion contortum* filaments described from locality A might be better referred to as dubiofossils because they fail to satisfy Cloud's (1976) criteria for biogenicity: that they do not exhibit cellular, microstructural or biogeochemical differentiation comparable with that of living organisms. *A. contortum* is a solitary, unbranched, non-septate, non-tapering, thread-like filament, <1 μm in diameter (commonly 0.3 μm) with individuals reaching lengths of up to 180 μm (Awramik et al., 1983). Frequently, the filaments appear cylindrical, but in some cases they are ribbon-like. We have not recognized individual cells and such recognition may be impossible because the filaments are very narrow, at the limit of optical resolution. No pyrite or other mineral grains have been found at the ends of filaments making it unlikely that they are mineral trails. In one example, a filament wraps around the tubular segmented microbial fossil *Primaevifilum septatum* (Awramik, 1984, fig. 2). *A. contortum* has been detected only in non-chalcedonic chert at locality A. None has been found in cracks, void fillings, formerly chalcedonic silica or other post-Warrawoona features, or at locality B. Comparable fossils are well known from non-chalcedonic cherts of the Late Proterozoic Bitter Springs Formation (Schopf, 1968). Although the small size of *A. contortum* stretches the resolution limits of optical white light microscopy, there is another attribute of these Warrawoona filaments that supports our conclusion that they are microfossils. That is the ribbon-like form of some of them. These morphological variants are uncommon, comprising $<10\%$ of the filaments. In one or two examples, cylindrical filaments are locally flattened. Ribbon-like filaments can represent the original ribbon-like morphology of a microorganism, such as that found in the Fe oxidizing bacterium *Gallionella ferruginata*, or result from the compression or flattening of an originally hollow tubular structure such as the sheaths of narrow cyanobacteria or filamentous sheathed bacteria, as apparently is the case with the Warrawoona examples.

The other three filamentous taxa, *Siphonophycus antiquus, Eoleptonema australicum* and *Primaevifilum septatum*, have sufficiently complex morphologies to amply justify their interpretation as genuine microfossils. The apparently carbonaceous composition and the complex, curved segmented organization with hollow cell-like units of *Primaevifilum septatum* and *Eoleptonema australicum* satisfy the rigorous criteria for biogenicity summarized by Buick. Inexplicably, Buick does not accept this, preferring to regard all these microstructures as dubiofossils. *Siphonophycus antiquus* does not

have the morphological complexity of partitioned tube, but its size, shape, comparability with the encompassing sheaths of extant filamentous prokaryotes, the demonstrably hollow nature of the apparently kerogenous filament and its usual occurrence within the dark, thicker laminae argue persuasively for biogenicity. In addition, the discovery by Schopf and Packer (1987) of cellularly preserved filamentous and colonial microfossils from bedded carbonaceous chert of the Apex Basalt and Towers Formation of the Warrawoona Group helps to substantiate our claim that the filaments we described in 1983 are *bona fide* microfossils.

In summary, at locality A there are definite microfossils in chert laminae that can reasonably be interpreted as being of sedimentary origin and, in addition, unlike locality B, no chert–barite dikes have been recognized.

Buick's (1984) discovery of possibly carbonaceous filaments in secondary chert is a new observation with potentially significant palaeontological implications. However, neither the origin nor the age of that chert has yet been established, and as we have indicated it could well be penecontemporaneous with the enclosing sedimentary rocks, which also contain carbonaceous filaments. Buick's observations from locality B do not, contrary to his claim, invalidate our interpretations based on either of the two collecting localities. A diverse assemblage of morphologically convincing microfossils occurs at locality A in cherts of the Warrawoona Group.

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