Taxonomy and biogenicity of Archaean spheroidal microfossils (ca. 3.0 Ga) from the Mount Goldsworthy–Mount Grant area in the northeastern Pilbara Craton, Western Australia

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\textbf{ABSTRACT}

Microstructures recently reported from an Archaean sedimentary succession (ca. 3.0 Ga) in the Mount Goldsworthy–Mount Grant area in the northeastern Pilbara Craton meet the criteria for compelling evidence of biogenicity [Sugitani, K., Grey, K., Allwood, A., Nagaoka, T., Mimura, K., Minami, M., Marshall, C.P., Van Kranendonk, M.J., Walter, M.R., 2007. Diverse microstructures from Archaean chert from the Mount Goldsworthy–Mount Grant area, Pilbara Craton, Western Australia: microfossils, dubiofossil, or pseudo-fossils. Precambrian Res. 158, 228–262]. The structures are morphologically diverse. Although they were tentatively classified into five major morphological types (thread-like, film-like, small (<15\textmu m) and large (>15\textmu m) spheroidal, and spindle-like), the possible taxonomic significance of these groups was not discussed. Building on our earlier analysis, we focus on the morphology of the larger spheroids, as well as presenting further evidence relating spindles and several bizarre forms, and attempt to group them taxonomically and adduce additional evidence for their biogenicity.

Taphonomic features were identified in each of the various morphological groups, but the range of morphological diversity of the spheroids cannot be attributed solely to taphonomic alteration. Four subdivisions of spheroids are proposed: (1) simple single-walled spheroids, (2) thin-walled spheroids having a diffuse envelope, (3) thick-walled spheroids, and (4) spheroids having an extensively folded wall. Simple single-walled spheroids, 15–60\textmu m in diameter, with various wall textures but commonly lacking envelopes or appendages form the dominant subgroup. Other complex morphologies are present and include aligned or associated bodies of thin-walled spheroids with diffuse envelopes, and spindle-like structures containing inner spheroidal bodies. The degree of morphological complexity and associations between structures suggest the presence of reproductive phases. If correct, this implies that the early Earth (ca. 3.0 Ga) showed a higher level of biodiversity than is currently postulated.

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1. Introduction

Sugitani et al. (2007) reported a diverse assemblage of carbonaceous microstructures (threads, films, spheroids, and spindles) from an Archaean (ca. 3.0 Ga) sedimentary succession at Mount Grant and Mount Goldsworthy, northeastern Pilbara Craton, Western Australia. Analysis of the sedimentary origin of the host chert and the indigenous nature of the microstructures, their narrow size distribution, a composition that includes disordered carbon, and the presence of taphonomic features, such as flexible and/or breakable walls, folding and tearing, together with the presence of apparently colony-like aggregations, provided compelling evidence of biogenicity and that films, spheres and spindles (but not threads) can be classified as microfossils (summarised in Table 1). Multidisciplinary studies have confirmed initial investigations and provided new observations. Light-microscopy examination has revealed elaborate morphologies, including some suggestive of cell division (Sugitani et al., 2008). Nano-scale chemical mapping indicates enrichment in biologically important elements such as sulfur and nitrogen as well as carbon (Oehler et al., 2008, this issue). Morphologies identical to those observed in chert thin sections have been extracted through palynological maceration, indicating that some structures retain an integral organic wall (Grey and Sugitani, this issue). While these accumulating lines of evidence are con-
Simplified key features of the microstructures related to syngenicity and biogenicity.

<table>
<thead>
<tr>
<th>Criteria and interpretation</th>
<th>Note</th>
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<tr>
<td>I. Syngenicity</td>
<td>Threads are mainly from secondary cavity-fill silica precipitates so they cannot be regarded as syngenetic. Films, spheroids and spindles are syngenetic</td>
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<tr>
<td>Microstructures occur within sedimentary black chert that is characterized by spherulitic structure and locally displays lamination. Carbonaceous matter of microstructures and that of matrix show thermal maturity identical to background material and have been subjected to the same geochemical alteration (silicification and ferruginization). Microstructures, except for threads, do not occur within secondary phases such as vein and cavity-fill precipitates. They are sometimes cut by narrow quartz veins. They are randomly oriented, rather than being bedding aligned.</td>
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<td>II. Biogenicity</td>
<td>The sedimentary geological context is consistent with biogenicity</td>
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<td>Geologic context</td>
<td>Isotopic and Raman data are consistent with a biogenic origin</td>
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<td>Microstructures were found in a ca. 3.0 Ga-old sedimentary black chert layer of low metamorphic grade (&lt;lower greenschist facies). The black chert layer can be traced laterally over 7 km and is associated with an evaporite bed, suggesting a shallow-water, sedimentary environment.</td>
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<tr>
<td>Composition</td>
<td>All physical properties of the microstructures are consistent with biogenicity</td>
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<td>The carbonaceous composition of microstructures of all morphological types was identified by Raman analyses. They are composed mostly of carbon and silica. The structures are a mixture of ordered and disordered carbon, and exhibit a spectral pattern typical of chert-embedded kerogenous microfossils (e.g., Schöp et al., 2005).</td>
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<tr>
<td>Physical properties</td>
<td>Abundance and size distributions are similar to those of younger Precambrian microfossils, and are consistent with biogenicity</td>
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<td>Microstructures show wide ranges of morphologies. Taphonomic features, e.g., deformation, and fragmentation, suggest a composition of flexible but breakable matter and resemble similar features found in younger fossils and extant organisms.</td>
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<tr>
<td>Population and size distribution</td>
<td>More than 20 morphotypes can be identified including minor ones, but their taxonomy and biological affinities are not yet defined</td>
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<td>Microstructures are abundant (&gt;200 specimens may be present in a single petrographic thin section. Size distributions are not random, so similar to those for microbes: spheroids have a main peak at 5–15 μm with a smaller peak at 20–30 μm. Spindles have a sharp peak ca. 40 μm</td>
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<td>Morphological variation</td>
<td>Complex morphologies, aggregations, and associations are consistent with biogenicity</td>
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<td>Microstructures can be classified into five major morphologies (threads, films, two groups of spheroids (&lt;15 μm and &gt;15 μm), and spindles). Other minor morphologies are present. Four categories of spheroidal microstructures are recognized here</td>
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<td>Elaboration in morphology and in occurrence</td>
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<td>Spindles have flange-like appendages. Spheroids sometimes have inner bodies. Colony-like aggregations and associations of more than two morphological types occur</td>
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The microfossils described here were discovered in stratiform carbonaceous black chert in the Mount Grant and Mount Goldsworthy area, approximately 100 km east of Port Hedland in Western Australia (Fig. 1a). This area is composed predominantly of 3.02–3.01 Ga sedimentary rocks of the Gorge Creek Group of the De Grey Supergroup, which unconformably overlies dominantly volcanic and volcanioclastic rocks, part of the 3.53–3.17 Ga Pilbara Supergroup (Smithies et al., 2004; Van Kranendonk et al., 2006, 2007; Sugitani et al., 2003, 2006a,b, 2007; Hickman and Van Kranendonk, 2008) (Fig. 1b). The Gorge Creek Group comprises a lower clastic unit, currently assigned to the Farrel Quartzite and an upper cherty unit with banded iron formation assigned to the Cleaverville Formation. The stratiform black chert, in which the microfossils were discovered, occurs in the uppermost portion of the Farrel Quartzite (CE2 in Fig. 1c). This black chert, ca. 30 cm thick, is closely associated with silicified evaporite beds. The carbonaceous black chert and evaporite association can be traced laterally for ca. 100 m at Mount Goldsworthy and ca. 7 km at Mount Grant, despite significant variation in the thickness and lithology of the Farrel Quartzite. Black chert samples were collected from more than 10 sites at this horizon, and each contains a similar assemblage of carbonaceous microstructures.

The lateral extent of the microfossiliferous Farrel Quartzite chert, interbedding with clastic layers, a small local fault cutting both chert and clastic rocks, the presence of terrigeneous or volcanioclastic detrital laminae within the chert, the localized development

2. Geological context

The preliminary classification of the structures as thread-like, film-like, spheroidal or spindle-like was morphologically based and did not consider possible affinities of the structures. A classification is needed to advance investigations of possible phylogenetic. Morphological complexity suggests broad diversity, but it is unclear whether this represents biological diversity or is taphonomic.

Many structures are >20 μm, and occasionally up to 80 μm along their major axis. Modern prokaryotic organisms are in general smaller than 10 μm, so if these relatively large microstructures are fossils, their sizes are more consistent with eukaryotic than prokaryotic microorganisms. This is a critical issue when the extreme age of the host rocks is considered and in the light of current debate about the timing of the rise of the eukaryotes (e.g., Knoll et al., 2006).

The elaborate morphologies seem more complex by comparison with previously described Archaean microfossils and are difficult to compare directly with other fossils and modern organisms, although some structures, such as the flange in the spindles, do have counterparts.

In this study, we focus on the large spheroid subcategory (>15 μm in diameter) and their comparison with similar morphologies from younger rocks to try to determine whether their diversity is biogenic or taphonomic.
of angular chert clasts in the clastic layers indicative of post-depositional reworking of chert and the alignment in laminations of fine-grained carbonaceous particles and fossil-like objects, all point to a sedimentary origin for the chert (Sugitani et al., 2007). The close association between evaporite and the Farrel Quartzite black chert suggests deposition in a shallow, restricted basin in a continental margin setting (Sugitani et al., 2003, 2006a).

3. Samples, specimens and methods

Samples studied were collected from a stratiform black-chert layer, CE2, at three localities (Fig. 1b). Two hand specimens, samples ORW4B and NORW1, were collected from locality 1 in 2001 and 2002, respectively. Three hand specimens, samples GFWE2, GFWE3 and GFTE06-4, were collected from locality 2, 200 m east of locality...
Fig. 2. Photomicrographs of key specimens of spheroidal microstructures. Scale bars: 20 μm (a–f, h), 100 μm (g, i). (a) Representative specimen of simple single-walled spheroid. Slide GFWE3-E1, position R-N62. (b) Example of broken simple single-walled spheroid. Slide GFWE3-E8, position R-T60. (c) Example of deeply folded simple single-walled spheroid. Slide GFWE3-F3, position R-N37/4. (d) Spherical cluster composed of small spheroids, ca. 10 μm in diameter. Slide GFWE3-F3, position R-C45/3. (e) Cluster composed of spheroids of various sizes. Slide GTFE06-4-H1, position R-X52/4. (f) Irregularly shaped cluster composed of relatively large spheroids (12–20 μm). Slide ORW4B-8, position R-S64/2. (g) A large hollow spheroid (arrow) with abundant small spheroids ca. 10 μm in diameter. Slide GFWE3-F3, position R-N62/1. (h) Cluster composed of spheroids and spindle-like structures. Slide GFWE2-SS, position R-N64. The arrows show spindle-like structures. (i) Cluster composed of spheroids and spindles. Slide GFWE3-E6, R-J62.
4. Results and discussion

4.1. General features of spheroidal microstructures

The spheroidal microstructures described here include hollow, spherical to subspherical structures. Here the term hollow is used for structures that originally had a wall structure of one composition and an interior of a different composition. The wall is generally an integral, external, structure composed of resilient material that is preservable, whereas the internal contents presumably were not resilient enough to be preserved and in most cases were replaced as required under the Australian Protection of Movable Cultural Heritage Act.

1 in 2005. Three hand specimens were collected from locality 3: GWM11A in 2001, and NGWM1 and 3 in 2003.

By the use of a diamond saw, the samples were cut into several slabs, most of them perpendicular to the bedding planes. Multiple petrographic thin sections (2.5 cm × 3.4 cm wide and 30–35 μm thick) were made from each hand specimen (indicated by slide numbers with extensions, e.g. ORW4B-1). Microscopic examinations were carried out using a Leitz-DMPR with ×1000 magnification and digital camera system (Leica DFC280). Positions of microstructures in thin section were recorded using an England Finder and are cited in the figure captions.

Hand specimens, slabs, and thin sections are currently housed in the Nagoya University collection while studies are underway, but they will eventually be repositioned in an Australian collection

Fig. 3. Photomicrographs of key specimens of spheroidal microstructures. Scale bars: 20 μm. (a) A large hollow spheroid with multiple small spheroids ca. 10 μm in diameter. The small spheroids are present both inside and outside of the large one. Slide GPWE3-F3, position R-H44/4. (b) A large partly hollow spheroid with multiple small spheroids inside. Slide NORW1-05B, position L-F39/2. (c) Broken large hollow spheroid with multiple small spheroids. Slide NORW1Y-2, position L-K59. (d) Broken large hollow spheroid with an inner solitary hollow body. The white and black arrows show broken parts of the inner and outer sphere, respectively. Slide NGWM1X, position R-N40. (e) Large spheroid with an inner solitary body. Slide NGWM3, position R-Q38. (f) Partially broken large spheroid with a wrinkled wall. At the broken part, a relatively small hollow spheroid is present. Slide GPWE2-S7, position R-X61/2. (g) Partly hollow spheroid and possibly, a poorly preserved ellipsoidal outer wall. The inner spheroid appears to be partially broken, and is the locus for an aggregate of small opaque particles (arrowed). Slide GPWE2-2, position L-L61/4. (h) Spindle-like structure with an inner spherical body. Slide GPWE2-S5, position R-W62. (i) Spindle-like structure with two inner spherical bodies. Slide GPWE3-E6, position R-D63/2.
Fig. 4. Photomicrographs of key specimens of spheroidal structures. Scale bars: 20 μm. (a) Thin-walled spheroid with a diffuse envelope. Slide GFWE3-F7, position R-Z66. (b) Representative specimen of thin-walled spheroid with a diffuse envelope. Note the even wall. The arrow shows the deepening focal depth. Slide GFWE3-2et, position R-Z46/3. (c) Pair of partly hollow large spheroids with a diffuse envelope. Slide GFWE3-E10, R-U53. (d) Degraded specimen, probably of the same type as (c) and (e). Slide GFWE2-S1, position R-Z50/2. (e) Pair of dense large spheroids with a diffuse envelope. Slide GFWE3-F6, position R-Z48/2. (f) Cluster of large spheroids with a diffuse envelope. Slide GFWE3-F3, position R-J58. (g) Cluster of partly hollow large spheroids showing variously deformed shapes, with a diffuse envelope. Slide GFWE3-E11, position R-Q40/3. by chert. Some structures appear to have internal structures, here referred to as internal bodies.

Ovoids and spheroids with significant eccentricity (ellipsoids) are included in the category of spheroidal microstructures, whereas spheroids with small protrusions at both ends are not. Such structures, together with those showing a high degree of eccentricity, are classified as spindle-like structures. However, analyses of ovoids, ellipsoids and spindles will be discussed in subsequent publications. Here we focus only on the spheroids and classify them using four characteristics: (1) size, (2) wall texture, (3) internal texture, and (4) mode of occurrence.

4.1.1. Size

Spheroids range widely from 5 μm to 60 μm in maximum diameter (Fig. 2a–g). Specimens <5 μm in diameter are present, but their details are difficult to decipher. Small spheroids with diameters ranging from 5 to 15 μm predominate. Although a minor mode is present at 20–30 μm (Fig. 14 in Sugitani et al., 2007), the size distribution is approximately unimodal with a skewness towards the larger size of 60 μm. This resembles distribution patterns of some modern unicellular algae (Prakash et al., 1973).

4.1.2. Wall texture

Spheroid walls are composed of sheet-like arrangements of carbonaceous material. Thinner parts of the wall appear hyaline. Walls of hollow, relatively large spheroids (>15 μm) often appear folded, dimpled, or wrinkled (Figs. 2a–c and 5a–c). Broken walls are common (Fig. 2b). Thicker, granular or dense walls are also present (e.g., Fig. 3e). Although the wall textures of small spheroids (<15 μm), particularly those less than 10 μm, cannot always be clearly identified, they appear similar to those of larger spheroids. Most spheroids are single-walled (Fig. 2a–f), although some specimens have a single wall with a diffuse envelope (Fig. 4a–g) or a dense thick wall (Fig. 5d–f).

4.1.3. Internal texture

The interior of the spheroids is usually completely hollow (Fig. 2a–c), although variations occur (e.g., Fig. 4a, c and g). Some spheroids appear solid or partly solid, but usually this can be attributed to the presence of both proximal and distal walls within the plane of the slide, and to focusing on the outer wall. Most spheroids are now infilled with chert, which has a similar cloudy
appearance to the chert matrix beyond the microstructure and is made up of small silica spheres surrounded by finely disseminated carbonaceous particles. In some specimens, the particles may be dense enough to give the spheroid a partially solid appearance. Opaque particles, including possibly pyrite grains and larger carbonaceous grains, may also be present. The internal texture of small spheroids remains uncertain because it is too hard to examine it under a normal petrographic microscope.

4.1.4. Mode of occurrence

Spheroids are usually solitary (e.g., Figs. 2a–c and 4a and b), but they can comprise colony-like clusters or paired structures (Figs. 2d–g and 4e–g). They are also sometimes found in association with other morphological types (Figs. 2h and i, and 3h and i). Associations of structures could reflect a taxonomic relationship. Colony-like clusters of small (<15 μm) spheroids are very common. The number of spheroids in any one cluster ranges from <10 to 200. Some clusters of small spheroids are spherical (Fig. 2d), whereas others are irregularly shaped. Rarely, several small spheroids make up a geometrically arranged cluster. Rare clusters of large (>15 μm) structures generally contain less than 15 spheroids (Fig. 2f). Despite an abundance of small spheroids, they are rarely paired, whereas more than 10 examples of paired large spheroids have been identified (Fig. 4c–e).

4.2. Key features for taxonomic studies of the spheroidal microstructures

In addition to the general features described above, the spheroidal microstructures exhibit even more complex modes of occurrence, in which colony-like clusters are composed of spheroids of various sizes, or where spheroids coexist with other different morphotypes in a single cluster. Such modes of occurrence are expected to provide critical information about taxonomy of the assemblage and are described in detail below.

4.2.1. Coexisting spheroids of different sizes

Whilst size variation has often been used as a taxonomic criterion for Proterozoic spheroidal microfossils (e.g., Hofmann and Jackson, 1991; Butterfield et al., 1994) and potentially provides us with important information about phylogeny (Knoll et al., 2006), frequency peaks in size distribution of spheroidal microfossils may not always correspond to distinct species (Knoll et al., 1978); they could be attributed to life cycle variants of a single species (Sergeev, 1994). In the case of the Farrel Quartzite spheroids, the following two modes of occurrence have to be considered in the context of classification, particularly in the case of simple, single-walled spheroids in which the wall is folded to various degrees and free from any envelopes and appendages:

1. In addition to clusters of similar-sized spheroids, colony-like clusters composed of spheroids of various sizes are common (Fig. 2e). Sizes range from ca. 5 μm up to 60 μm, which corresponds to the similar range of the spheroid population as a whole.
2. An association of large hollow spheroids with multiple small spheroids is present (Figs. 2g and 3a–c). The large spheroids range from 40 to 60 μm in diameter, whereas the small ones range from 5 to 10 μm.

Such modes of occurrence suggest that spheroids of various sizes could be genetically related to each other. The association of one large hollow spheroid with multiple small spheroids (Fig. 3a–c) might represent multiple fission, comparable to that recorded for the spheroidal cyanobacterium Dermocarpa by Waterbury and Stanier (1978) where the small spheroids correspond to daughter cells and the large spheroid to the mother cell. This interpretation seems to be supported by the fact that paired occurrences suggestive of ordinary binary fission are rare for this type of large simple spheroid despite their predominance. In extant cyanobacteria, individual daughter cells do not always grow uniformly (Waterbury and Stanier, 1978), and this results in a cluster of spheroids of different sizes as in Fig. 2e.

A possible relationship between spheroids of different sizes is further inferred from the presence of a large hollow spheroid that contains an inner single spheroidal body (Fig. 3d–g). The outer structure is a simple single-walled, without any envelopes or appendages. The inner spheroid appears to be hollow and partially broken, like the outer spheroid.

Spheroidal microfossils with an inner solitary body are common in the Proterozoic fossil record, but the origin of inner bodies has been controversial. Some have been interpreted as well-defined nuclei with an outer membrane and thus they were asserted to be eukaryotic (Schopf, 1968). However, this interpretation has been criticized because the formation of internal spheroidal bodies may result from post-mortem degradation of prokaryotic cells (Knoll and Barghoorn, 1975; Hofmann, 1976; Golubic and Hofmann, 1976; Oehler, 1977). Ueno et al. (2006) reported coccoid carbonaceous structures that have an inner body from chert of the Cleaverville Formation (ca. 3.0 Ga) in the northwestern Pilbara Craton, Western Australia and interpreted the inner body as having a diagenetic origin. In the present case, the hollow nature of the inner body is not consistent with formation as degraded cell contents. Moreover, there are several specimens where a hollow inner spheroid appears to have been preserved in the process of being expelled from a broken outer hollow spheroid (Fig. 3f and g).

4.2.2. Coexistence of spheroids with different morphologies

Another problem in the classification of the Farrel Quartzite spheroids is the abundance of colony-like clusters composed of both spheroids and spindle-like structures (Fig. 2h and i). The repeated spatial association of these two morphotypes indicates a genetic relationship between them. Some associations may simply be the result of sectioning through different planes of orientation (a spindle structure would appear to be a walled spheroid in some transects perpendicular to the axial plane), but the association occurs too frequently for this to be the sole explanation. Further evidence for the relationship between spheroids and other morphotypes is that several specimens of spindle-like structures contain an inner spheroidal body (or bodies). There are two types: a spindle-like structure with a peripherally positioned single inner spheroid (Fig. 3h) and a spindle-like structure with two inner spheroids (Fig. 3i). In both examples, the diameter of inner body (10–15 μm) is almost the same width as the enclosing spindle. In the specimen shown in Fig. 3h, the outline of the outer spindle appears to be slightly deformed by the inner spheroidal body. These relationships suggest that the inner spheroids could be endospores within a spindle-shaped resistant outer wall.

4.3. Taxonomic framework for spheroidal microstructures

A puzzling feature of the microstructures is that they are considerably larger and more complex than might be expected for Archaean organisms. Based on the features described above, we propose the following classification for the microstructures.

4.3.1. Classification of typical spheroids

The dominant spheroid type in the Farrel Quartzite assemblage is the simple, single-walled kind (Fig. 2a–g). Although this type shows a continuous and wide range of variation in size and textures, variations in wall and internal textures can usually be attributed to preservation, as in many examples of Proterozoic microfossils...
Fig. 5. Photomicrographs of key specimens of spheroidal microstructures. Scale bar: 20 μm. (a) Representative specimen of spheroid with extensively folded wall. The white arrows show embayed portions of the sphericoid. The black arrow shows the deepening focal depth. Slide GWM11Asub1, position L-R46/4. (b) Spheroid with an extensively folded wall. The white arrow shows an embayed portion. Slide GFWE2-G4, position R-F48/2. (c) Spheroid with an extensively folded wall. Slide GFWE2-S6, position R-N54/1. (d) Representative specimen of a spheroid with a thick wall. Slide GFWE2-G6, position R-B61/3. (e) Spheroid with a thick wall. Slide GFWE2-H4, position R-H47/4. (f) Spheroid with a thick wall. Slide GFWE2-G2, position R-E43.

(Knoll et al., 1988; Kumar and Srivastava, 1992; Hofmann, 1976; Golubic and Hofmann, 1976). On the other hand, the size distributions cannot be attributed solely to taphonomic alteration. If the association between a large spheroid and multiple small spheroids described above is the result of multiple fission, most of the simple single-walled spheroids would represent a single species, regardless of their size. Variations in diameter within a cluster and between clusters (Fig. 2d–g) could reflect the non-uniform vegetative growth of daughter cells. Furthermore, spheroids with an inner body may represent a resting stage of the same taxon (Fig. 3d–g). This group of spheroids is here designated simple, single-walled spheroids, and is considered a potential counterpart of relatively large spheroids previously reported from Archaean chert (Schopf and Barghoorn, 1967; Schopf, 2006).

As discussed above, some spindle-like structures comprise colony-like clusters, together with simple single-walled spheroids (Fig. 2h and i). Such clustering appears to be genetic, because the spindles occasionally contain an inner spheroid or spheroids (Fig. 3h and i). One possibility is that the spindle-like structures correspond to a resistant outer wall of a resting stage (Walsh, 1992) of an organism that has spheroidal morphology in a vegetative and endospore stage. It is likely that this group of structures is unrelated to the spheroids reproducing by multiple fission.

4.3.2. Other categories of large spheroids (>15 μm)

Other categories of large spheroids (>15 μm in diameter) include forms having (1) a thin wall with a diffuse envelope, (2) a significantly thickened wall and (3) an extensively folded wall. Based on these features, we propose three additional categories besides the typical spheroid described above.

4.3.2.1. Thin-walled spheroids having a diffuse envelope (Fig. 4). Ten specimens have been recorded of spheroids ranging in diameter from 15 to 40 μm, with a thin, generally uniform wall with a diffuse envelope. Several specimens are paired or clustered, with the paired spheres apparently being connected. The degree of connection varies, although it is difficult to determine whether this is taphonomic or a result of the spheres showing different degrees of separation as in different stages of binary fission (Fig. 4c–e). Such binary fission could produce colony-like clusters of large spheroids enveloped by diffuse material (Fig. 4f and g). The mode of occurrence, cell diameter, and wall texture of the spheroids with a diffuse...
envelope are significantly different from the typical simple single-walled spheroids for them to be placed in a separate category.

4.3.2.2. Thick-walled spheroids (Fig. 5d–f). This category is based on five specimens that range from 30 to 40 μm in maximum diameter and that are commonly characterized by a thick, dense wall, 5 μm or more in thickness. The interior of the wall is darker in color than the exterior, reflecting a denser distribution of carbonaceous material that has aggregated to form irregularly shaped clots (Fig. 5e and f) or a partially continuous thin film-like structures (Fig. 5d and f), giving rise to an irregularly shaped inner space. Carbonaceous material is distributed heterogeneously within the wall, and the outer surface occasionally appears to be diffuse (Fig. 5d and f). The heterogeneous distribution of carbonaceous material is at least partially attributable to degradation and redistribution of organic matter during diagenesis. However, the dense nature of the wall implies an original resistant nature. No composite structures or paired spheroids and colony-like clusters have been found for this type of spheroid that resembles the outer wall of a resting spore.

4.3.2.3. Spheroids having an extensively folded wall (Fig. 5a–c). This group consists of more or less problematical spheroidal structures (8 specimens) that are characterized by a thin, deeply folded wall without any appendages. The photomicrographs in Fig. 5a, showing specimens having a spheroidal outline ca. 30 μm in diameter, actually represent sections around the upper 1/3 of the specimen. The structure’s outline is incomplete; the wall appears to be deeply embayed (also see Fig. 5b), to be partially tucked in (also see Fig. 5c), or to be blistered. Thus, this specimen could be interpreted as a crumpled film with a spheroidal outline. Although the category of simple, single-walled spheroid includes specimens characterized by a wide range of wall textures, the extent of wall folding of the extensively folded type is distinctive, and different from a thin-walled spheroid with a diffuse envelope and from a thick-walled spheroid. So far no associations of this type with the other spheroid types, clusters and other composite occurrences have been found.

5. Conclusions

In this study, we have attempted to classify some of the ca. 3.0 Ga putative microfossils from the Farrel Quartzite into morphological categories with the aim of developing a future taxonomic framework, here focusing on spheroidal microstructures larger than 15 μm. This classification is based on morphological similarities and variation as well as apparent repeated associations between structures. Much of the morphological diversity and elaboration here documented appears to be original, rather than a result of taphonomic alteration. Certain of the more elaborate morphologies are suggested as possibly representing reproductive cells, vegetative cells or endospores, providing compelling evidence for the biogenicity of the Farrel Quartzite assemblage. Four distinctive categories of spheroid-based fossil-like morphology are present:

(1) Simple single-walled spheroids: This category predominates over all other types of Farrel Quartzite spheroids. It consists of spheroids with features consistent with multiple fissions and that may have produced resistant endospores originally enclosed by a robust outer wall. The diameter of such spheroids ranges from 10 μm up to 60 μm. The walls are folded or wrinkled to various degrees and the spheroids’ interiors can be either hollow or partially filled, depending on differential degradation.

(2) Thin-walled spheroids having a diffuse envelope: This category of spheroids ranges from 20 to 40 μm in diameter and occurs in various colony-like clusters, possibly produced by binary fission. When well preserved, the wall is thin, even and enveloped in diffuse material.

(3) Thick-walled spheroids: This category of spheroid ranges 30–40 μm in diameter, and typically has a dense wall up to 5 μm or more in thickness. This morphology may represent a resting-spore stage, but the morphology of the corresponding vegetative cell is not known.

(4) Spheroids having an extensively folded wall: This morphology ranges from 20 to 40 μm in diameter and is characterized by a thin, extensively folded wall.

Regardless of how these suggested categories survive further analysis, these proposed groups represent only a small part of the biotic diversity of the Farrel Quartzite assemblage. For the present, however – and given the body of data that support the biogenicity of these objects (Table 1) and the additional evidence of their biogenic origin presented here and elsewhere (Oehler et al., this issue; Grey and Sugitani, this issue) – it seems clear that biota of the Achaean Earth ca. 3.0 Ga was appreciably more diverse than has previously been recognized.

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