Geologia Croatica	61/2–3	73–103	14 Figs.	1 Tab.		Zagreb 2008

Abiogenic, microbial and hybrid authigenic carbonate crusts: components of Precambrian stromatolites

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ABSTRACT

Authigenic seafloor carbonate crusts include fenestrate microbialite, thrombolite, and four types here designated: Fine-grained Crust, Sparry Crust, Hybrid Sparry Fine-grained Crust, and Sparry Crust plus Coarse Grains. Each of the latter four types includes at least some layered examples that have generally been regarded as stromatolites. Recognition and interpretation of these various deposits assists understanding of stromatolite development. Sparry Crust is common in the Late Archaean-Mesoproterozoic. It includes botryoidal fans and other crystal pseudomorphs, microdigitate stromatolite, dendrite, isopachous laminite, and herringbone calcite. Although differing in primary mineralogy and bedform, these are all characterized by coarse sparry, commonly radial fibrous, fabric and appear light coloured in thin-section. They have commonly been referred to as seafloor cement, although they formed at the open sediment-water interface rather than as void-fills. Two of them in particular, isopachous laminite and microdigitate "tufa", typically form isopachous layers with good vertical inheritance and have been regarded as stromatolites. In contrast to Sparry Crust, Fine-grained Crust has fine-grained (micritic, clotted, peloidal, filamentous) microfabric that appears dark in thin-section, and irregular uneven layering with relatively poor inheritance. Mixed crusts, composed of millimetric alternations of Sparry and Fine-grained crust, are here termed Hybrid Sparry Fine-grained Crust. Sparry Crust with coarse allochthonous grains – here termed Sparry Crust plus Coarse Grains – includes some examples that have been given formal stromatolite names, e.g., Gongylina and Omachtenia.

Sparry, Hybrid, and Fine-grained crusts are common components of Precambrian stromatolites. Their relative abundances change through time. Archaean stromatolite fabrics are commonly obscured by recrystallization, but their preserved lamina arrangements suggest that many of them could be composed mainly of Sparry or Hybrid crust. During the Palaeoproterozoic-Mesoproterozoic, Sparry Crust fabrics were common in peritidal stromatolites, whereas Hybrid Crust appears to have dominated large subtidal domes and columns. Fine-grained Crust may not have become generally abundant until the Neoproterozoic, when it commonly formed both stromatolites and thrombolites. Phanerozoic normal marine stromatolites are also typically composed of Fine-grained Crust.

Present-day analogues of Sparry Crust fabrics occur in some speleothem, hot spring, and splash-zone marine crusts, and of Fine-grained Crust in lithified microbial mats. Light-dark millimetric alternations of sparry and fine-grained crust that characterize Hybrid Crust have analogues in freshwater stromatolites. Taken together, these comparisons suggest that some Precambrian stromatolites are abiogenic, some microbial, and others are intimate hybrid mixtures of the two, and that – preservation permitting – these varieties can be distinguished using microfabric and lamina criteria.

Keywords: Archaean, carbonate, microbial, Proterozoic, stromatolite, thrombolite

1. INTRODUCTION

Stromatolites (KALKOWSKY, 1908) are often carbonate in composition and characteristically exhibit decimetric domical and columnar morphologies (HOFMANN, 1969). Based on present-day analogues (WALCOTT, 1914; BLACK, 1933; LOGAN 1961), they have long been regarded essentially as lithified microbial mats (AWRAMIK & MARGULIS, 1974). However, morphological similarities between stromatolites and a variety of other geological deposits and structures have confused their recognition and generated debate about how the term "stromatolite" should be defined (SEMIKHATOV et al., 1979; RIDING, 1999; AWRAMIK & GREY, 2005).

Uncertainty about KALKOWSKY's (1908) view of stromatolites has been created by a definition made by KRUMBEIN (1983, p. 499) and wrongly attributed to Kalkowsky: "stromatolites are organogenic, laminated, calcareous rock structures, the origin of which is clearly related to microscopic life, which in itself must not be fossilised". Although KALKOWSKY (1908) did not write this statement (see RIDING, 1999, p. 323), it has been repeated as if it were a literal translation from his paper (e.g., GINSBURG, 1991, p. 25; FELDMANN & MCKENZIE, 1998, p. 201; GROTZINGER & KNOLL, 1999, p. 316; McLOUGHLIN et al., 2008, p. 96). Compounding this mistake, the somewhat awkward wording employed by KRUMBEIN (1983) (use of "must not" rather than "need not") has been cited not only as "paradoxical", and "confusion" to be avoided, but also as an example of the deficiencies of such genetic definitions (GROTZINGER & KNOLL, 1999, p. 316; McLOUGHLIN et al., 2008, p. 96). In his 1908 paper Ernst Kalkowsky did not provide a specific definition of stromatolite, apart from repeatedly emphasizing that they he regarded them as laminated organic structures. He thought that the life forms involved were "*niedrig organisierte planzliche Organismen*" (simple plantlike organisms, KALKOWSKY, 1908, p. 125). It is reasonable to conclude that he regarded stromatolites essentially as laminated microbial deposits (RIDING, 1999).

During the century since KALKOWSKY (1908) introduced the term "*stromatolith"* (stromatolite), particular problems have centred on confident discrimination between lithified microbial mats and a variety of other geological deposits that can have broadly similar appearances, such as invertebrate skeletons, diagenetic concretions, deformation structures, and sub-aqueous abiogenic precipitates. The variety of these difficulties has been reduced as understanding of fossils and carbonate sediments has progressed. For example, it is now unusual for invertebrate skeletons or diagenetic concretions to be mistaken for lithified microbial mats, although confusion between deformed soft sediment and microbial domes was suggested relatively recently (LOWE, 1994). However, research (e.g., GROTZINGER 1989a, b) incrementally focused attention on the difficulty of discriminating between lithified microbial mats and sparry sub-aqueous authigenic carbonate crusts. This continuing problem (PERRY et al., 2007) can arise for several reasons. Firstly, essentially abiogenic seafloor crusts and lithified microbial mats can both create layered, often domical, structures of broadly similar appearance. Secondly, processes that drive seafloor precipitation and microbial calcification are not necessarily mutually exclusive, and their products may be intimately associated, raising the possibility that, in addition to lithified microbial mat and sparry crust end-members, there are deposits that represent complex mixtures of both. Thirdly, scarcity of present-day analogues for sparry seafloor crusts (GROTZINGER & JAMES, 2000, p. 9) has hindered their recognition as distinct deposits. The need to distinguish these components has been recently emphasized. PERRY et al. (2007, p. 169) noted that "microbially constructed stromatolites should not … be confused with abiotic, chemically precipitated carbonate crusts". POPE et al. (2000, p. 1139) regarded "isopachous stromatolites to have been dominated by chemogenic precipitation in the absence of microbial mats, and the growth of peloidal stromatolites to have been controlled by sedimentation in the presence of microbial mats", and suggested that "thinly laminated isopachous stromatolites are considered to have a largely abiotic origin" (*idem*, p. 1149). Here I explore this suggestion that microfabric details and lamina arrangement can be used to discriminate between ancient abiogenic deposits and those made by microbial mats, by reviewing published details of Precambrian authigenic carbonate crusts and their possible present-day analogues.

In addition to stromatolites, Precambrian authigenic subaqueous carbonate crusts include botryoidal crystal fans, dendrite, herringbone calcite, fenestrate microbialite, and thrombolite. Since these are often intimately associated with stromatolites and share similar components with them, I include them here. But the focus is stromatolites, and three generalizations arise from this overview. Firstly, Precambrian stromatolites basically consist of one or both of two components: fine-grained carbonate and sparry carbonate. Secondly, comparisons with present-day analogues suggest that Fine-grained Crust is lithified microbial mat, and that Sparry Crust is essentially abiogenic. Thirdly, Precambrian stromatolites generally consist of one of these components (Fine-grained Crust, Sparry Crust) or of millimetric alternations of both of them – Hybrid Crust. Tracing the secular distribution of these deposits reveals that Hybrid Crusts were very important in stromatolite formation during the Palaeoproterozoic and Mesoproterozoic. They are major components of large stromatolite domes that dominate subtidal facies of extensive Proterozoic carbonate platforms such as the ~1.9 Ga Pethei Group (SAMI & JAMES, 1996) and ~1.0 Ga Burovaya Formation (PETROV & SEMIKHATOV, 2001, fig. 6). The combination of microbial growth and abiogenic precipitation in Hybrid Crusts may have promoted rapid accretion of these large, locally decametric, stromatolites. Some Archaean stromatolites are equally large, e.g., in the Campbellrand-Malmani platform of South Africa (BEUKES, 1987) and at Steep Rock, Ontario (WILKS & NISBET, 1985). These examples are more difficult to interpret because discrimination between Sparry and Fine-grained crust relies on microfabric details that are readily obscured by poor preservation in old stromatolites. In the Campbellrand, large elongate stromatolite domes that are major components of extensive platform carbonates (SUMNER & GROTZINGER, 2004, figs. 2,10) have an overall appearance of smooth even lamination penetrated by crystal pseudomorphs (SUMNER & GROTZINGER, 2004, fig. 11a) consistent with essentially abiogenic precipitation. However, these "Boetsap laminae" contain both sparry and microcrystalline layers, and the latter could be interpreted as detrital silt or as microbial mat precipitate (SUMNER & GROTZINGER, 2004, fig. 3). If the microcrystalline layers are silt that was not microbially trapped, and the sparry fabrics are abiogenic crusts, then these large domes would be essentially abiogenic structures; but if they are mat precipitate then these deposits are Hybrid Crusts. Discrimination between Sparry and Hybrid crusts therefore focuses attention on whether such large Archaean domes are hybrid combinations of mats and abiogenic crusts, similar to those of the Pethei and Burovaya reefs, or are Sparry Crusts – possibly with detrital carbonate – and therefore essentially abiogenic? Proterozoic stromatolite development is more readily interpreted due to better overall preservation. Hybrid Crust dominated subtidal stromatolites during the early-mid Proterozoic, and Sparry Crust progressively declined (GROTZINGER & KASTING, 1993, p. 235; KAH & KNOLL, 1996, p. 81). By the Neoproterozoic, Fine-grained Crust stromatolites (and thrombolites) had probably surpassed Hybrid Crust deposits in abundance. This suggests that, whereas present-day microbial mats may provide analogues for most Phanerozoic stromatolites, their relevance is diminished in examples older than ~1000 Ma.

These considerations lead to a liberal view of the term "stromatolite" as broadly encompassing laminated authigenic crusts formed at the sediment-water interface in springs, rivers, lakes and seas. These characteristically can exhibit both large and small domical and columnar morphologies.

2. PRECAMBRIAN CARBONATE CRUSTS

Research into Precambrian stromatolites has revealed not only fine-grained lithified microbial mats (e.g., VOLOGDIN, 1962; WALTER, 1972; KOMAR, 1976) but also distinctive sparry fabrics. Radial spar is the dominant component of the small digitate stromatolites recognized by DONALDSON (1963) and described as microdigitate tufa by HOFFMAN (1975). These were given names such as *Pseudogymnosolen* (CAO & LIANG, 1974) and *Asperia* (SEMIKHATOV, 1978) and came to be generally termed microdigitate stromatolites. Larger stromatolites often exhibit sparry layers that alternate with finer ones (HOFMANN, 1969, p. 4, 16, fig. 13), as in *Conophyton* (KOMAR et al., 1965) (Fig. 1) and in botryoidal sparry crust fabrics of digitate stromatolites that BERTRAND-SARFATI (1972) compared with calcified cyanobacterial colonies. At the same time, evidence of early lithification was noticed in the localization of stromatolitic carbonates (SERYBRYAKOV & SEMIKHATOV, 1974), and in the support required by high-relief coniform stromatolites (GEBELEIN, 1976; DONALDSON, 1976).

John Grotzinger's research, beginning with the ~1.9 Ga Rocknest platform, was seminal in focusing attention on these seafloor precipitates. Recognition of the primary aragonite mineralogy of microdigitate stromatolites (GROTZINGER & READ, 1983) led to interpretation of large crystal botryoids as originally aragonite rather than gypsum, and to the suggestion that long-term decline in deposits such as microdigitate stromatolites could reflect progressive reduction in seawater carbonate saturation (GROTZINGER, 1989a, p. 96, fig. 15). GROTZINGER (1989b, p. 11) listed "substrate-parallel layers of neomorphic fibrous cement", "radial fibrous fabrics … that constitute microdigitate stromatolites", and "conoform stromatolites" as evidence for "in situ carbonate production".

The outcome was increased recognition of seafloor sparry crusts. The superposed radial fibrous botryoid fabrics of Mesoproterozoic *Tarioufetia* and *Tungussia*, first thought to be calcified cyanobacteria (BERTRAND-SARFATI, 1972), were compared with aragonite cements (FAIRCHILD et al., 1990, p. 61). In addition to botryoidal fans and microdigitate stromatolites, isopachous laminite (JACKSON, 1989), dendrites (SAMI & JAMES, 1996, fig. 6a), and herringbone calcite (GROTZINGER & KASTING, 1993), were distinguished, especially in Palaeoproterozoic and Archaean carbonates. As a result, GROTZINGER & JAMES (2000, p. 7) were able to summarize Precambrian marine "abiotic precipitates" as: (i) decimetric to metric radial fans (after aragonite), (ii) microdigitate stromatolites, (iii) isopachous millimetric laminites, (iv) isopachous layers of herringbone calcite, and (v) dendrites ("dendritic tufa"). GROTZINGER & KNOLL (1999, p. 329–330) cited "petrographic evidence not only for early lithification, but also for direct growth of encrusting marine cement directly on the growing stromatolite, particularly for stromatolites of Mesoproterozoic and older ages".

Figure 1: *Conophyton*. Stag Arrow Formation, Manganese Group, Bangemall Basin, Western Australia, ~1050–1100 Ma. Width of view, 5.5cm. Photograph courtesy of Kath Grey.

Sparry crusts occur thinly interlayered with fine-grained crust in coniform stromatolites (e.g., WALTER, 1972), and, for example, in Palaeoproterozoic Pethei stromatolites described by SAMI & JAMES (1996), in latest Mesoproterozoic and early Neoproterozoic *Baicalia* lacera described by KNOLL & SEMIKHATOV (1998) and PETROV & SEMIKHATOV (2001), and in the ~800 Little Dal "lamelliform elements" described by AITKEN (1989) and TURNER et al. (2000a).

Thus, the main components of Precambrian subaqueous carbonate crusts recognized here are sparry and fine-grained precipitates, and hybrid mixtures of the two. All three of these may incorporate allochthonous grains. Discrimination of mud- and silt-grade allochthonous grains is difficult, but coarse grains can be recognized. These components occur in five main combinations (Fig. 2): Fine-grained Crust, Sparry Crust, Hybrid Sparry Fine-grained Crust, Sparry Crust with Coarse Grains, and Fine-grained Crust with Coarse Grains. All of these include at least some deposits that have been generally regarded as stromatolites. Fine-grained Crust with Coarse Grains is common in Neogene coarse-grained stromatolites, such as Lee Stocking Island and some Shark Bay columns, but does not appear to be common in the Precambrian. Two additional seafloor crust categories that are locally common during certain periods in the Precambrian, but which do not contain stromatolites, are fenestrate microbialite and thrombolite. Accordingly, the categories of seafloor carbonate crust discussed here include Fine-grained Crust, Sparry Crust, Hybrid Sparry Fine-grained Crust, Sparry Crust with Coarse Grains, fenestrate microbialite and thrombolite (Table 1). These are outlined below.

Table 1: Categories of subaqueous authigenic carbonate crust common in Precambrian carbonates. Fine-grained Crust, Sparry Crust, Hybrid Sparry Fine-grained Crust and Sparry Crust with Coarse Grains all contain examples generally regarded as stromatolites. The following general interpretations, based on present-day analogues, are suggested: Fine-grained Crust, fenestrate microbialite and thrombolite represent lithified microbial mat; Sparry Crust and Sparry Crust with Coarse Grains are essentially abiogenic precipitates. Hybrid Sparry Fine-grained Crust results from submillimetric to millimetric alternations of Sparry (abiogenic) and Fine-grained (lithified microbial mat) crust.

1. FINE-GRAINED CRUST
2. SPARRY CRUST
Botryoidal fans and crystal pseudomorphs; Radial fibrous microbotryoids
Microdigitate stromatolite; Dendrite
Isopachous laminite
Herringbone calcite
3. HYBRID SPARRY FINE-GRAINED CRUST
Microcrystalline-peloidal carbonate
Conophyton
Baicalia lacera
Laminar fibrous crusts and micritic peloidal laminae
Clotted-bushy-peloidal micrite
Filamentous
Boetsap laminae: microspar crusts of uncertain origin
4. SPARRY CRUST PLUS GRAINS
Herringbone Calcite with coarse grains
Radial fibrous crust with silt and sand grains (e.g., *Gongylina, Omachtenia*)
Crystal fans with coarse grains
5. FENESTRATE MICROBIALITE
6. THROMBOLITE

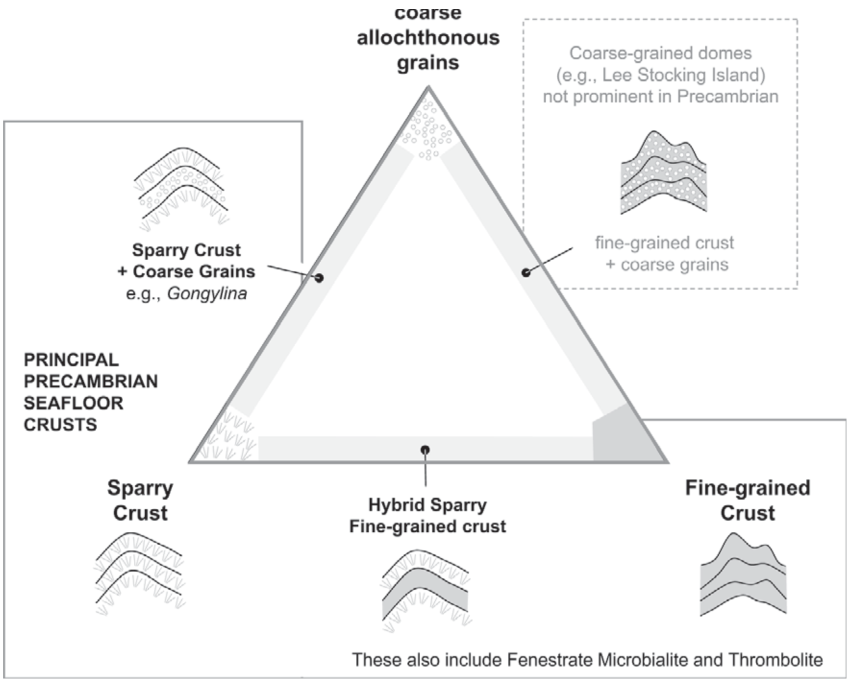

Figure 2: Authigenic sparry and fine-grained carbonate crust recognized here together with Hybrid Crust and coarse-grained admixtures. All crust categories in boxes (Fine-grained, Sparry, Hybrid, Sparry + Coarse Grains, and Fine-grained + Coarse Grains) all include at least some deposits that have been generally regarded as stromatolites. Note that fine-grained crust can include fine allochthonous grains as well as fine-grained *in situ* precipitate.

2.1. Fine-grained Crust

Fine-grained (micritic, clotted, peloidal, filamentous) microfabrics and irregular uneven layering with relatively poor inheritance are typical of microbial stromatolites (e.g., MONTY, 1976). These fabrics occur interleaved with other deposits in Hybrid Crusts, but on their own they also constitute the dominant components of many stromatolitic domes, columns and layers, as well as thrombolites. They may contain fenestrae and incorporate allochthonous grains. In older examples the micritic fabrics have often aggraded to microspar. Fine-grained Subaqueous Crust described here is regarded as the product of lithified microbial mats, and therefore as an essentially biotic deposit (see Present-day Analogues).

Proterozoic Fine-grained Crust, together with including Hybrid Crust, is figured extensively by VOLOGDIN (1962). Latest Ediacaran examples are figured by SCHMITT (1979, pl. 16, figs. 3, 4; pl. 22, fig. 2) from the Anti-Atlas Mountains, Morocco. Neoproterozoic examples (some of which are fenestral) with "streaky" microstructure occur in the ~800 Ma Bitter Springs Formation of Central Australia (WALTER, 1972, pls. 2, 3, 23, 25) and in the Little Dal reefs (e.g., TURNER et al., 2000a, fig. 15f). In the Little Dal, these locally also exhibit filamentous fabrics (e.g., AITKEN, 1989, fig. 10; TURNER et al., 2000a, fig. 8 e, f, g). JEFFERSON & YOUNG (1989, fig. 5a) show stromatolites underlying the Little Dal Group which have "clotted/grumous microfabric". GROTZINGER & KNOLL (1999, fig. 3f) figure filament moulds in "micritic stromatolite laminae" from the Neoproterozoic Chernya Rechka Formation, Siberia. RIDING & SHARMA (1998) found clotted microfabrics "irregular masses of micrite bounded by microspar and sparite" to be the common in late Palaeoproterozoic Vempalle stromatolites from southern India. In RIDING & SHARMA (1998), they dominate examples of both poorly (*idem*, fig. 2) and evenly (*idem*, figs. 3, 4) laminated forms in which sparry layers or fenestrae occupy a relatively minor volume of the structure. In general, however, fine-grained stromatolites – as opposed to Hybrid Crusts – appear relatively scarce in the Palaeoproterozoic, but this requires further verification.

2.2. Sparry Crust

Sparry Crust includes stromatolitic deposits (microdigitate stromatolite, isopachous laminite); large and small botryoidal fans as well as related crystal pseudomorphs; extensive herringbone calcite beds; and rarely recorded large dendrites.

2.2.1. Botryoidal fans and crystal pseudomorphs

These centimetric to metric pseudomorphs after crystals that formed at the sediment-water interface occur as layers and beds, commonly draped by fine-grained carbonate. Typically they are conical and fan-shaped with a convex upper surface (Fig. 3). They range from isolated skeletal crystals and widely spaced "fanning pseudomorphs" to extensive beds of juxtaposed botryoids of upwardly diverging radial crystal fans, e.g., in the Late Archaean Campbellrand-Malmani platform of South Africa (SUMNER & GROTZINGER, 2000, figs. 3a, 5; SUMNER & GROTZINGER, 2004, fig. 7).

The original mineralogy of these "giant botryoids" (GROTZINGER & KASTING, 1993, p. 234) has been interpreted as gypsum (BERTRAND-SARFATI, 1976; HARDIE, 2003) or aragonite (SUMNER & GROTZINGER, 1996a, p. 120). They also occur in the ~3.45 Ga Warrawoona Group ~50 km west of Marble Bar, Western Australia (HOFMANN et al., 1999, p. 1257); the ~2.8 Ga Steep Rock carbonate platform, Ontario; the ~2.6 Ga Carawine Dolomite, Western Australia; the ~2.9 Ga Uchi Greenstone Belt of Ontario (SUMNER & GROTZINGER, 2000, p. 139), and as "Coxco needle" fans in the ~1.64 Ga McArthur Group of the Northern Territory, Australia (WINEFIELD, 2000). At Steep Rock they may form the structure that WALCOTT (1912) named *Atikokania* (HOFMANN, 1971; SUMNER & GROTZINGER, 2000, p. 134). Fans up to 1.6m high that lack detrital sediment

Figure 3: Laterally juxtaposed botryoidal radial fans with convex internal bands. Late Archaean Campbellrand-Malmani platform, South Africa. Width of field ~12 cm.

indicate they "did not grow within the sediment" (SUMNER, 2002, p. 109). SUMNER & GROTZINGER (2000, p. 139) regarded "all the pseudomorphs as replacing aragonite with the exception of morphologically distinct gypsum pseudomorphs from the 2.6 Ga Carawine Dolomite (SIMONSON et al., 1993)" (SUMNER, 2002, p. 109).

BERTRAND-SARFATI (1976) interpreted Campbellrand-Malmai crystal rosettes as pseudomorphs after gypsum. MARTIN et al. (1980) considered similar "radiating crystal structures" associated with stromatolitic domes, in the ~2.6 Ga Cheshire Formation of the Belingwe Greenstone Belt, ~150 km east of Bulawayo, Zimbabwe, to be replacements of aragonite or gypsum. GROTZINGER & KASTING (1993, p. 235) cited "prolific precipitation of aragonite as giant botryoids up to 1 m in radius" as evidence that Archaean seawater was significantly oversaturated for $CaCO_3$. Well exposed fan beds occur in the Cambellrand-Malmani platform (SUMNER & GROTZINGER, 1996a, fig., 4; 2000, fig. 3). SUMNER & GROTZINGER (2000, p. 131–133) described cyclic sequences (approximately similar in age to those described by MARTIN et al., 1980) in Huntsman Quarry, ~50 km NNE of Bulawayo with layers of crystal fans after aragonite, herringbone calcite, large domical stromatolites (described by MACGREGOR, 1941), and fenestrate microbialite. They concurred with MACGREGOR (1941) that the environment was probably subtidal. HARDIE (2003) restated BERTRAND-SARFATI's (1976) interpretation that Late Archaean fans were after gypsum. SUMNER (2004) countered this with petrographic and trace element data that support their primary aragonite mineralogy (see also SUMNER & GROTZINGER, 2000, p. 1137–1139).

Radial fibrous microbotryoids. Small (~< 1 mm) radial fibrous botryoids, reminiscent of far larger "giant" botryoids (e.g., GROTZINGER & KASTING, 1993), form tussocky microfabric in some Mesoproterozoic stromatolites (BERTRAND-SARFATI, 1976). Similar but more irregular "fibrous precipitate masses" are principal components of some Palaeoproterozoic stromatolites (SAMI & JAMES, 1996, fig. 7c, d).

Tussocky microstructure ("*microstructure en touffes*") occurs as superposed radial fibrous botryoid fabrics in digitate Mesoproterozoic stromatolites such as *Tarioufetia hemispherica*, *Tungussia globulosa*, *Tungussia cumata* and *Serizia radians* in NW Africa (BERTRAND-SARFATI, 1972, p. 94, 103, 105, 131, fig. 26c, pls. 23–26). The columns are elongate to irregular and up to 8cm in diameter and 30 cm in height. The botryoids are sub-millimetric to millimetric and arranged from isolated irregularly superposed hemispheroids to laterally amalgamated layers of lenses. Locally botryoids are interlayered with micrite (*idem*, pl. 25, fig. 2) and scattered detrital quartz grains (*idem*, pl. 26, fig. 1). BERTRAND-SARFATI (1976, p. 253, fig. 2a) refigured *T. globulosa* and described *"microstructure en touffes"* as *"tussocks"* commonly interlayered by sparite cement, a dark film, or detrital quartz. She compared them with present-day calcified colonies of *Rivularia*, but it was subsequently noted that they are "strikingly similar to … originally aragonitic cements" (FAIRCHILD et al., 1990, p. 63). In these Atar examples intercalated micrite and quartz layers appear to be minor components and so they are here classed as essentially Sparry rather than Hybrid Crust. But in the Pethei Group, where they also create digitate columnar stromatolites, fibrous precipitate masses are associated with clotted micrite cores and voids filled by detrital micrite (SAMI & JAMES, 1996, figs. 7c, d, 8h) and they can be regarded as Hybrid Crust. SAMI & JAMES (1996, p. 218) noted that "digitate stromatolite heads composed of clustered fibrous cement fans formed a rigid framework analogous to Paleozoic reef fabrics".

2.2.2. Microdigitate stromatolites and dendrite

Microdigitate stromatolites are small stubby digitate laminated columns, typically <5 mm wide and <20 mm high, closely packed in extensive layered sheets that can dominate the shallow parts of peritidal cycles (HOFFMAN, 1975, p. 262), especially in the early-mid Proterozoic (Fig. 4). The laminae show good inheritance and may be traced through adjacent columns, and individual columns can exhibit radial fibrous fabric (HOFMANN & JACKSON, 1987, p. 964).

In the ~2.1 Ga Denault Formation of Labrador, DONALDSON (1963, p. 12, pls. 4–5) noticed very small "digitate stromatolites", "branching, finger-like structures 1 to 5 mm in

Figure 4: Microdigitate stromatolites, silicified after carbonate. Wumishan Formation, Mesoproterozoic, ~25 km north of Beijing. Width of view ~25 cm. Note well-developed overall layering, and large size variation of individual digitate forms.

diameter and less than 2 cm in height" that show regular layering and "correspondence of lamination thickness at coincident levels". HOFFMAN (1975, p. 262) recognized that similar deposits were important components of the shallow parts of Rocknest peritidal cycles and described them as "tiny arborescent stromatolites that resemble structures in modern algal tufa. Where silicified, microscopic filament molds are preserved in the stromatolites". He compared them with "crusts of calcareous tufa" in "brackish algal marshes, such as those in the Bahamas" described by SHINN et al. (1969). GROTZINGER & READ (1983, p. 712, fig. 1f) subsequently termed these Rocknest deposits "cryptalgal tufas", describing them as "cement laminae" that "commonly form discrete, tiny columnar structures (microdigitate stromatolites), 1–10 mm wide and with 0.1–5 mm relief". They followed HOFFMAN (1975) in interpreting them as tidal flat deposits but suggested that the environment was semiarid rather than humid, adding "cement crusts appear to have formed by precipitation of aragonite as sheet-like tufa layers and microdigitate stromatolites within mats on surfaces of tidal flats or shallow, evaporitic ponds" (GROTZINGER & READ, 1983, p. 712).

"Digitate stromatolites", "calcareous tufa" and "cryptalgal tufas" noted by DONALDSON (1963), HOFFMAN (1975), and GROTZINGER & READ (1983) have also since then variously been termed microdigitate tufa, microdigitate stromatolites, ministromatolites (HOFMANN & JACKSON, 1987), and tidal flat tufa (GROTZINGER & KNOLL, 1999, fig. 4a), as well as being assigned formal names (e.g., *Pseudogymnosolen* CAO & LIANG, 1974; *Asperia* SEMIKHATOV, 1978). GREY & THORNE (1985) regarded them as biogenic, but GROTZINGER (1986a, p. 842) considered that "the tufas are, in essence, evaporites", and suggested that they reflect "microbially influenced inorganic calcification (although it is possible that they are entirely abiotic in origin)" (GROTZINGER, 1986b). HOFMANN & JACKSON (1987) compared 1.9 Ga examples from the Belcher Supergroup in Hudson Bay with those described by DONALDSON (1963) from the Denault Formation, and discussed a variety of possible interpretations. They compared the radial fibrous fabric with "chemogenic carbonate crusts" including pisoids, aragonite cements and speleothems (*idem*, p. 969) and concluded "chemical precipitation played a significant role in the formation of the radial-fibrous fabric here described. Whether the precipitation was biologically mediated, or occurred within or on microbial mats is less clear" (*idem*, p. 970). GROTZINGER (1989b, p. 11) described them as "microbial tufa", but subsequently they have often been regarded as inorganic. SAMI & JAMES (1994, p. 116) described them as cement laminae up to 2 cm thick consisting of microdigitate "stalks" separated by thinner micrite layers, and GROTZINGER & KNOLL (1999, p. 347) wrote that microdigitate stromatolites are "pure precipitate structures".

Microdigitate stromatolites are common in late Archaean and early Proterozoic carbonates (RAABEN, 1980, 2005; LIANG et al., 1984, 1985; GREY & THORNE, 1985, p. 193–194, fig. 12; CAO, 1991; SHARMA & SHUKLA, 1998), and are also well-known in the Mesoproterozoic (RAABEN, 1980; KAH & KNOLL, 1996).

Dendrite. Closely spaced subvertical dendrites, often 3–5 cm in height and ~0.5 cm wide, form layers and irregular higher-than-wide mounds 50 cm or more in width that constitute beds up to ~3m thick; individual dendrites consist of micritic stalks and branches coated by fibrous spar (POPE & GROTZINGER, 2000, p.106, fig. 5).

These dendrites broadly resemble microdigitate stromatolites, but are larger and less well bedded. The Hearne Formation at the top of the Pethei Group remains the only described occurrence. They may have first been figured by SAMI & JAMES (1996, fig. 6a), and are shown as "dendritically branching tufa" by GROTZINGER & KNOLL (1999, fig. 6c; see also GROTZINGER & JAMES, 2000, fig. 5e). POPE & GROTZINGER (2000, p. 106–110) described them in detail. They considered the dendrites to be "chemically precipitated structures" formed "in a manner similar to laboratory deposition of zinc and copper dendrites" (POPE & GROTZINGER, 2000, table 1, p. 109). The dendrites are overlain by irregularly laminated stromatolites and then by isopachous laminites.

2.2.3. Isopachous Laminite

Isopachous Laminite forms stromatolites composed of even, laterally continuous, radial fibrous layers that grew "normal to the stromatolite surface, regardless of local curvature" (GROTZINGER & KNOLL, 1999, fig. 6a, b; POPE & GROTZINGER, 2000, p. 113) (Fig. 5). These stromatolites can form thin (e.g., 3–5 m) but extensive beds (JACKSON, 1989, p. 70) within shallowing sequences, associated with transition to evaporite conditions (POPE et al., 2000, p. 1140). In addition to smooth domical morphologies (e.g., GROTZINGER & KNOLL, 1999, fig. 3a), isopachous laminites can exhibit peaked crests (JACKSON, 1989, figs. 6, 13; SUMNER & GROTZINGER, 2004, fig. 4a) and angular asymmetry (POPE et al., 2000, figs. 2d, 4, 7a, 9b; POPE & GROTZINGER, 2000, fig. 8). POPE et al. (2000, p. 1142) found that "stromatolites with isopachous fine lamination" commonly have "radial fibrous texture". "Isopachous, evenly laminated stromatolites", described in detail from the uppermost Pethei Group, consist of dolomicrite and fine dolosparite (POPE & GROTZINGER 2000, p. 112–113).

In the ~2.6 Ga Cheshire Formation of the Belingwe Greenstone Belt, ~150 km ESE of Bulawayo, MARTIN et al. (1980, figs. 10, 12, p. 348, table 2) recognized "crinkle lamination" "with good inheritance" and synoptic relief up to 10 cm, forming metric beds, which they compared with *Stratifera*?. SUMNER & GROTZINGER (2000 p. 128) described these as "crinkly laminite facies" overlying pseudomorph fans and "composed of sub-millimeter to millimeter-thick microsparitic laminae that have a constant thickness normal to layering". JACKSON (1989, p. 70, figs. 6, 13) described "unusual, 5 m thick, ridged or peaked stromatolites" interpreted to form a laterally continuous subtidal bioherm in the 1.89 Ga Cowles Lake reef south of Coronation Gulf, Canada, and added "the laminations show very strong inheritance and have a maximum synoptic relief of about 1 m". GROTZINGER (1989b, p. 11) commented that these "show textural evidence for having been produced by *in situ* carbonate pro-

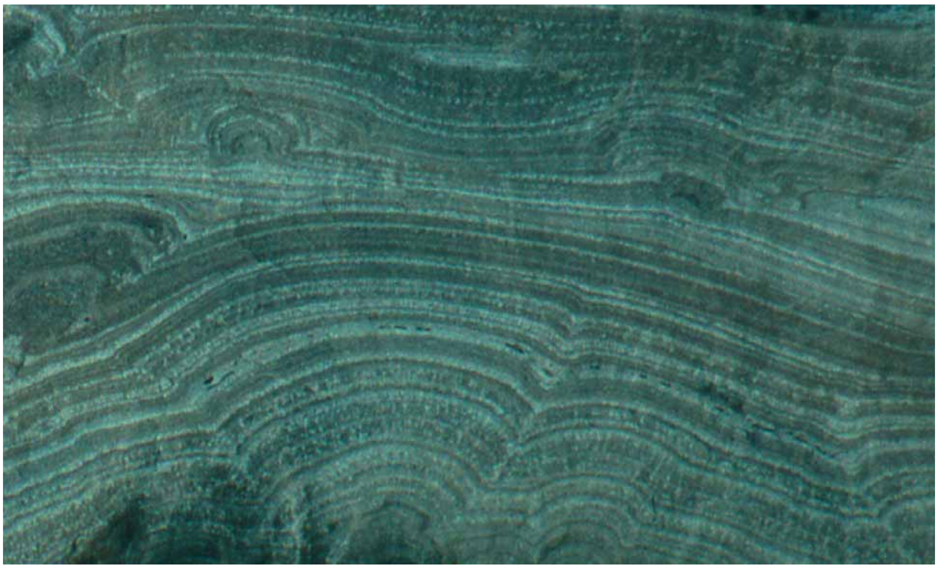

Figure 5: Peritidal isopachous laminite composed of fibrous dolomite. Society Cliffs Formation, Bylot Supergroup, ~1.2 Ga, White Bay, south of Bylot Island northern Baffin Island. Width of view, ~7cm. Note 1–2 mm very even layering and good inheritance. Photograph courtesy of Linda Kah.

duction". GROTZINGER & KNOLL (1995, p. 581) noted that "stromatolites formed by direct precipitation on the sea floor are a conspicuous feature of Archean and Proterozoic carbonates. Isopachous sparitic, fibrous and micritic layering, generally devoid of clastic carbonate, is the characteristic microstructure. These structures were fully lithified as they accreted".

TURNER et al. (2000a, p. 189, fig. 12g) described "cement-rich stromatolites" from the Neoproterozoic Little Dal of north-west Canada that form "a uniform veneer of domal stromatolites" (*idem*, fig. 11). They consist of millimetric "cement-rich grumous layers alternating with thin films (ca. 100 µm) of micrite"; "laminae are even and regular, and show a high degree of inheritance" (*idem*, p. 189). POPE et al. (2000) figured isopachous thinly laminated stromatolites from the ~2.55 Ga Malmani Fm of the Transvaal (*idem*, fig. 2d), ~1.9 Ga uppermost Pethei Group (*idem*, fig. 4), and Late Permian Zechstein deposits of NE England (*idem*, fig. 9). They interpreted these to have formed by carbonate precipitation at the sediment-water interface, stimulated by high saturation levels (*idem*, p. 1149), and concluded, "thinly laminated isopachous stromatolites are considered to have a largely abiotic origin, in that as part of the evaporite sequence, the inorganic process of evaporative seawater concentration was critical for their growth" (POPE et al. 2000, p. 1149–1150). Nonetheless, SUMNER & GROTZINGER (2004, p. 7, fig. 4a) figured the same isopachously laminated stromatolites of the Neoarchaean Cambellrand-Malmani platform and suggested that they formed by precipitation or trapping within microbial mats. Late Miocene-Pliocene (~6–4 Ma) lacustrine Furnace Creek stromatolites in Death Valley, California, have isopachous laminae composed of radiating crystal fans interpreted to be "indicative of predominantly abiotic precipitation" (CORSETTI & STORRIE-LOMBARDI, 2003, fig. 1).

2.2.4. Herringbone Calcite

Herringbone calcite occurs as void-filling cement but also, especially in the Late Archaean, has formed extensive decimetric to metric massive sheet-like seafloor crusts. It is characterized by distinctive delicate serrated or crenulated banding formed by light and dark couplets ~<1 mm in thickness (Fig. 6), and is thought to be derived from a Mg-calcite precursor (SUMNER & GROTZINGER, 1996b).

Herringbone calcite occurs as a cement in Palaeozoic reef and stromatactis cavities (e.g., KREBS, 1969; LEHMANN, 1978; MCGOVNEY, 1989; DE WET et al., 2004) and has been variously named (SUMNER & GROTZINGER, 1996b). GROTZINGER & KASTING (1993, fig. 1) recognized herringbone calcite beds as a feature of Late Archaean carbonate sedimentation. In the Campbellrand-Malmani platform, for example (SUMNER & GROTZINGER, 1996b), it is laterally extensive, forming decimetric beds traceable over 140 x 50 km in the deep subtidal transgressive Gamohaan Formation (SUMNER & GROTZINGER, 1996b, p. 420; SUMNER, 2002, fig. 2c). It is also closely associated with "plumose microbialites" and in "grainstone-precipitate" beds (SUMNER, 1997a, table 1, p. 464, 470), where it can be "repetitively interbedded with clastic carbonate on a centimetre scale" (SUMNER & GROTZINGER, 1996b, p. 420). It both fills voids and isopachously encrusts seafloor surfaces (SUMNER & GROTZINGER, 1996b, p. 420). GANDIN & WRIGHT (2007, p. 301) interpreted some Gamohaan herringbone calcite as a replacement of a precursor sediment "likely to have been a gypsum-mush", whereas SUMNER & GROTZINGER (1996a, b) suggested that herringbone calcite reflects anoxic conditions with low [Fe^{2+}] seawater values that inhibited calcite precipitation. Herringbone calcite ~2.6 Ga in age occurs in Huntsman Quarry, ~50 km NNE of Bulawayo, in decimetric layers associated with crystal fans, domical stromatolites, and "fenestrated microbialites" (SUMNER & GROTZINGER, 2000, fig. 9). SUMNER (2002, fig. 2b) termed herringbone calcite "serrate, fibrous marine cement".

2.3. Hybrid Sparry Fine-grained Crust

Hybrid Crust comprises alternations of light-dark layers. For example, BERTRAND-SARFATI (1972, p. 25–26) noted

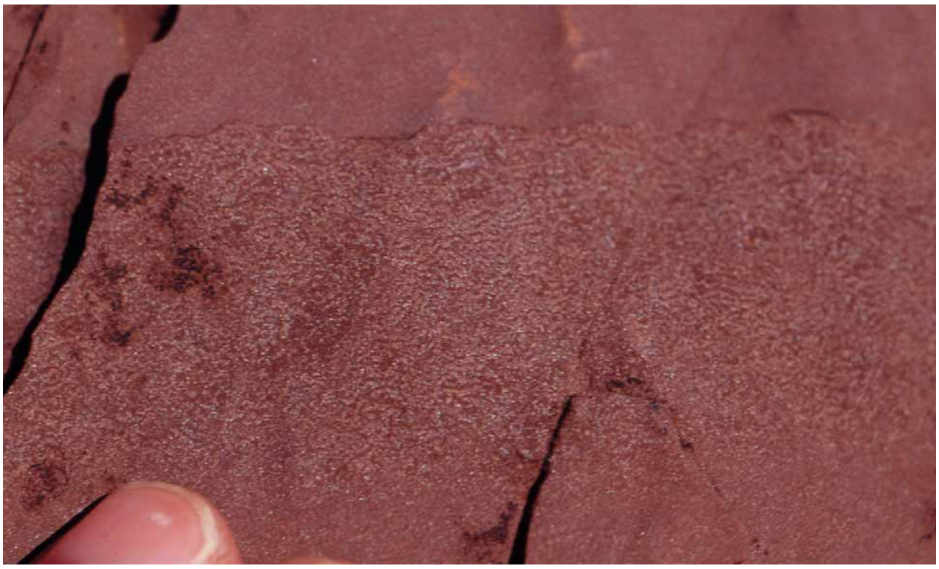

Figure 6: Herringbone calcite seafloor crust. Neoarchaean, Campbellrand-Malmani platform, South Africa. Note delicate sub-millimetric uneven, crenulated layering.

light-dark couplets ("*doublet: couche claire et couche sombre*") in some Atar and other African Proterozoic stromatolites. These include some members of the Crustophycaceae and Lopatinellaceae of VOLOGDIN (1962, p. 195–226), Zonalia and Arca microstructures of KOMAR (1989, pl. 3), and spar-micrite couplets of SAMI & JAMES (1996). The dark layers show a variety of micrite and/or microspar fabrics, including dense, peloidal, bushy, clotted, and/or filamentous. The light layers are sparry carbonate, often radial fibrous in form. Frequency curves of light and dark layer thickness have been used to routinely compare stromatolites with this microstructure (e.g., KOMAR et al., 1965; BERTRAND-SARFATI, 1972, p. 25–26). In English, this general fabric has variously been termed "ribboned" and "striated" (HOFMANN, 1969, p. 16, fig. 13), "streaky" (WALTER, 1972, p. 12), and "film" (BERTRAND-SARFATI, 1976, p. 253).

Three main types of Hybrid Crust are recognized here, based on fine-grained dark layer microfabric: microcrystalline-peloidal, clotted-bushy-peloidal, and filamentous. In addition, layer definition, thickness and evenness vary; typically from thinner (≤ 1 mm), better defined and more even, to thicker (≥ 1 mm), less well defined and less even. Layer definition, thickness and evenness appear generally to progressively decrease from microcrystalline-peloidal, through clotted-bushy-peloidal, to filamentous fabrics. However, fabric preservation complicates recognition of these sub-types, particularly of filamentous microfabric. For example, KNOLL & SEMIKHATOV (1998, p. 410) found that filmy microstructure in early Neoproterozoic *Baicalia lacera* "intergrades with a distinctly filamentous microstructure". In contrast, late Mesoproterozoic *B. lacera* shows distinctive micritic films but only "rare ghosts of filaments" (PETROV & SEMIKHATOV, 2001, p. 270, fig. 6). Whether well-preserved *Baicalia lacera* consistently exhibits filamentous microfabric remains to be determined. The categories and examples distinguished here are based on relatively well-preserved Proterozoic examples. They require further description, comparison and clarification.

2.3.1. Microcrystalline-peloidal carbonate

Conophyton. Laterally persistent, interleaved sub-millimetric to millimetric dark-light layers are common in Proterozoic coniform stromatolites (VOLOGDIN, 1962, pls. 24–25; KOMAR et al., 1965; BERTRAND-SARFATI, 1972, pl. 11(4); WALTER, 1972, p. 103–112) (Figs. 7, 8). The layering ranges from uneven with irregular thicknesses to even and regular. Thickness and configuration of these bands are among the features used to distinguish *Conophyton* species (CLOUD & SEMIKHATOV, 1969, fig. 2), and KOMAR et al. (1965) recognized general long term increase in dark relative to light laminae in *Conophyton* through the Riphean. It was suggested that dark laminae "represent originally alga-rich layers" (KOMAR et al., 1965, p. 67), and WALTER (1972, p. 86) commented that "presumably the pale laminae originally had less organic matter". Some coniform stromatolites show coarse sparry layers whose lateral variation in thickness suggests that they reflect recrystallization in addition to their primary character (e.g., VOLOGDIN, 1962, pl. 32, fig. 3, pl. 72, fig. 1; WALTER, 1972, pl. 10, fig. 2).

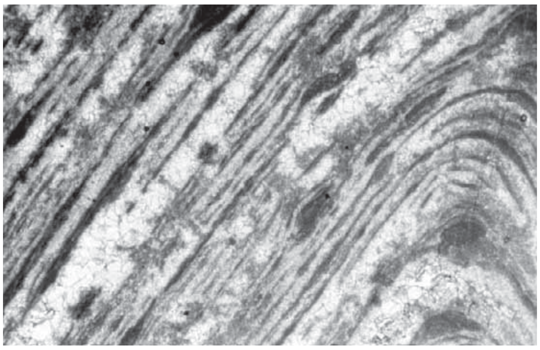

Figure 7: *Conophyton garganicum*, Middle Riphean, Russia. Stratigraphic unit and locality not known; specimen donated to Geological Survey of Canada by M.A. Semikhatov. Width of view 8 mm. Note laterally persistent, relatively even, submillimetric interleaved layering of thin fine-grained and light-coloured sparry layers, and good inheritance. Photograph courtesy of Hans Hofmann.

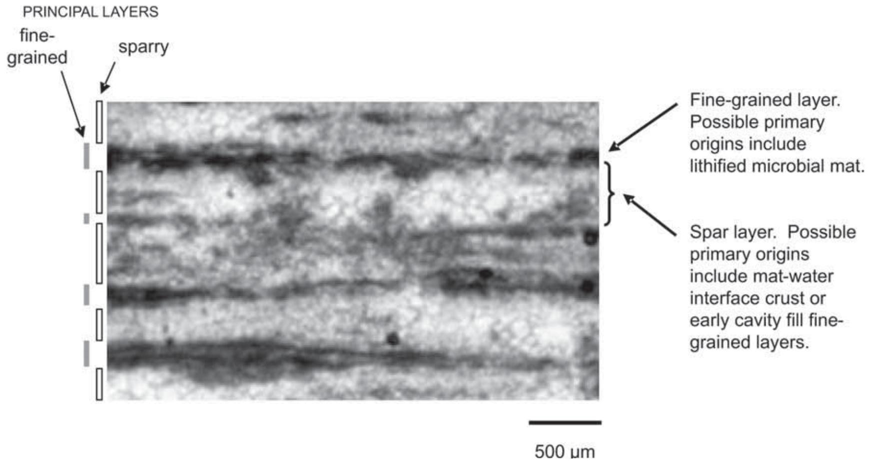

Figure 8: Hybrid Crust microfabrics (detail of Fig. 7, *Conophyton garganicum*). Sparry and fine-grained layers can be interpreted as Hybrid Crust composed of thin layers of lithified microbial mat (fine-grained) separated by thicker layers of surficial crust and/or early cavity fill (sparry) (cf. Monty & Hardie, 1976, fig. 2b, see Analogues, below). However, neomorphic spar aggradation cannot be ruled out.

Inzeria lindina. BERTRAND-SARFATI (1972, p. 155, fig. 58, pl. 22(2, 3)) described repeated millimetric alternations of dolomicrite-microsparite with dolospar in decimetric stubbily branched *Inzeria lindina* from the late? Proterozoic of Lindi, Zaire (now Congo). She suggested that these might include seasonal rhythmicity.

Baicalia. The bands are often laterally persistent and can occur on steep-sided coniform (e.g., WALTER, 1972, pl. 5, figs. 3, 4) and other (e.g., *Baicalia lacera*, PETROV & SEMIKHATOV, 2001, fig. 5a, b) stromatolites. The fine-grained material ranges from micrite to microspar and can be quite heterogeneous, including calcified filaments, clots, peloids and bush-like structures, as well as spongy "vermiform" fabrics. The spar is typically radial-fibrous or blocky. The laminae are submillimetric to millimetric, occasionally centimetric (e.g. WALTER, 1972, pl. 12, fig. 1) and range from isopachous with good inheritance to irregular and discontinuous. Proportions of light and dark bands range from predominantly dark to ~50% light. Where dark layers predominate and sparry bands are thin and few, spar can occur in irregular fenestrae. In some cases, filamentous fabrics are well developed, as in the case of *Baicalia lacera* which forms distinctive "platy" dark-light alternations (KNOLL & SEMIKHATOV, 1998; PETROV & SEMIKHATOV, 2001, fig. 6) (Fig. 9) (see Filamentous, below).

BERTRAND-SARFATI (1972, p. 112, pl. 13) described distinctive light-dark layers in Mesoproterozoic *Baicalia mauritanica* from Atar. The dark layers are thin, generally <0.1 mm, whereas the light layers range up to 0.75 mm (fig. 37). The dark layers are themselves composed of up to 5 or 6 thin leaves ("feuillets") with a platy appearance (*idem*, pl. 13(1–3)) that she compared with that of *Baicalia lacera* (*idem*, p. 113).

Tungussia nodosa. BERTRAND-SARFATI (1972, p. 99, p. 187, pl. 19(1–3)) described millimetric micrite-microspar (and locally sparite) alternations as "*microstructure en tapis*" ("micritic mat" in BERTRAND-SARFATI, 1976, p. 256) in *Tungussia nodosa* and *T. aff. nodosa* from Atar.

Laminar fibrous crust and micritic peloidal laminae. In the Pethei platform SAMI & JAMES (1994, p. 116; 1996, p. 216, fig. 6d) recognized "wavy microbialite" as a major component of peritidal facies. It consists of "stromatolites composed of cement laminae, 1–2 mm thick, separated by thin (< 1 mm), dark micritic surfaces and lenticular peloid grainstone laminae" (SAMI & JAMES, 1994, p. 116). The laminae are laterally persistent, smoothly undulose and isopachous, with good inheritance and intervening troughs are occupied by fine sand. Laminar fibrous crusts can be interbedded with detrital grains (SAMI & JAMES, 1996, fig. 5f) (and see *Gongylina*, below). They attributed accretion to "combination of cement precipitation and binding of peloids by smooth microbial mats" and interpreted it to form in lower intertidal and shallow subtidal conditions. SAMI & JAMES (1994, p. 116) considered fenestral microbial laminite to be a low energy, upper intertidal to supratidal equivalent of laminar fibrous crust, consisting of "thin (1–2 mm),

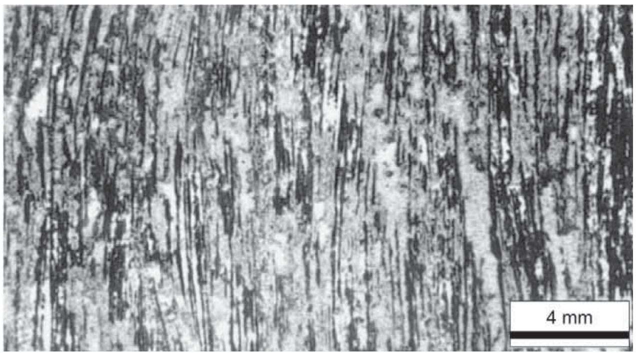

Figure 9: Hybrid Crust composed of submillimetric dark-light alternations. *Baicalia lacera*. Burovaya Fm, Turukhansk, Siberia, latest Mesoproterozoic (~1020 Ma). The delicate, gently curved thin, even and persistent appearance of the dark layers, characteristic of "platy" *Baicalia lacera* microstructure, may be filamentous in detail (KNOLL & SEMIKHATOV, 1998). Reprinted from PETROV & SEMIKHATOV (2001, fig. 6a), with permission from Elsevier.

irregular to continuous, micrite and spar laminae with thin (< 1 mm), dark, clay-rich drapes" and irregular spar-filled fenestrae. The clotted microfabric "may represent either peloids or micrite-cement". Based on SAMI & JAMES' (1994, p. 116) interpretation of combined "cement" precipitation and mat bound peloids it could be regarded as a hybrid of isopachous, essentially abiogenic, laminite and detrital carbonate, but if the peloids are in place microbial precipitates then this would essentially be a hybrid abiogenic-biotic precipitated crust.

2.3.2. Clotted-bushy-peloidal micrite

Clotted-peloidal-bushy micrite forms laminae interlayered with seafloor precipitate and detrital micrite. The irregular micrite aggregates are often interspersed with microspar and spar, giving the lamina a relatively light appearance in thin-section.

In addition to abundant synsedimentary "cement"-like precipitate, SAMI & JAMES (1996, p. 213) recognized peloidal clotted micrite as "a significant component (10–45%) of most stromatolitic laminae". The clots consist of poorly defined 50–100 μm peloids and together with fibrous and blocky spar form laminae in "prone stromatolitic laminite" (SAMI & JAMES, 1996, fig. 7a, b). "Prone microbial laminite" is a major component of Pethei carbonates where it contributes significantly to large elongate stromatolite domes (SAMI & JAMES, 1993, p. 405, table 1).

Clotted-peloidal-bushy micrite aggregates can be very irregular, but locally distinctive vertically elongate shrub-like structures occur that are similar to present-day calcified cyanobacterial sheaths (KAH & RIDING, 2007). The shrubs are typically separated by spar, giving the layers a broadly flocculent or palisade-like appearance. In the ~1200 Ma Society Cliffs Formation, laminae with shrubs form submillimetric laminae within isopachous laminite (KAH & RIDING, 2007). The shrubs consist of fine microspar and are up to 600 μm high and 200 μm wide and have irregular margins and tend show vertical orientation on sloping surfaces. They closely resemble the calcified thick irregular sheaths of present-day oscillatoriacean cyanobacteria (see RIDING & VORONOVA, 1982). The Society Cliffs shrubs are associated with calcified filaments that are currently the oldest examples of sheath-calcified cyanobacteria (KAH & RIDING, 2007). Somewhat similar fabrics have been figured from latest Precambrian stromatolites as *Vesicularia* (VOLOGDIN, 1962, pl. 39) and as "vermiform microstructure" in *Madiganites mawsoni* from Central Australia (WALTER, 1972, pl. 1, figs. 1,2) of Late Cambrian age (LINDSAY et al., 2005; see also BERTRAND-SARFATI, 1976, p. 255), but these do not appear to be elements of hybrid deposits.

2.3.3. Filamentous

Tangled to prostrate *Girvanella*-like filaments within spar-microspar cement form relatively persistent platy to curved flocculent submillimetric to millimetric layers. The filaments may be constant diameter tubes with thin even-thickness walls, conforming to the calcified cyanobacterial sheaths of *Girvanella* (see RIDING, 1977a) but more commonly are less regular and less distinctly tubiform. They are tangled and irregular, often prostrate, and interspersed among microspar-spar. Filamentous microstucture with *Girvanella* tubules, but without well developed interleaved sparite layers, occurs in some Phanerozoic oncoid cortices (e.g., GARWOOD & GOODYEAR, 1924; BIDDLE, 1983). In Proterozoic stromatolites, layers of filamentous microstructure are commonly interleaved with millimetric sparite layers. Some of these exhibit a distinctively striated "filmy" or "streaky" microstructure, as in *Baicalia lacera*, *Tungussia confusa* and other forms (KNOLL & SEMIKHATOV, 1998, table 1).

Microstructure with filament moulds was termed Canaliphorida and Filiformita by KOMAR (1976, 1989; see also BERTRAND-SARFATI et al., 1994, p. 182, fig. 18). AITKEN (1989) recognized "dendriform" and "lamelliform" fabrics as framework components of stromatolitic bioherms in ~835 Ma Little Dal Group of NW Canada. He remarked that these fabrics "are not typically stromatolitic" and that "sediment trapping may not have been the dominant process in their formation" (*idem*, p. 15). He described them as "cellular" and containing tubular and *Renalcis*-like structures (*idem*, figs. 10–13). Subsequently, TURNER et al. (1993, 2000a, fig. 10b; 2000b) compared the tubules with *Girvanella* and noted that the lamelliform fabric consists of alternating dark layers of "calcimicrobial filaments" and lighter "more cement-rich" areas. Little Dal "hollow tubules with micritic walls" are figured by BATTEN et al. (2004, fig. 9b).

KNOLL & SEMIKHATOV (1998, p. 410, figs. 3, 4) described well-preserved "filmy or platy" microstructure in early Neoproterozoic *Baicalia lacera* stromatolites from the Chernaya Rechka Formation, Igarka, Siberia. They found it to be associated with "a distinctly filamentous microstructure" in which "laminae comprising densely interwoven to scattered, vertically or subhorizontally oriented filaments are interspersed with layers of spongy or dense microspar". They interpreted the 8–10 μm tubes as "sheaths of LPP-type (*Lyngbya*, *Phormidium*, *Plectonema*) cyanobacteria and preserved as drusy microspar encrustations" (KNOLL & SEMIKHATOV, 1998, p. 411). Similar *Baicalia lacera* fabrics in the ~1Ga Burovaya Formation of west-central Siberia locally contain calcified tubes resembling *Siphonophycus* (PETROV & SEMIKHATOV, 2001, p. 270).

AITKEN (1989, p. 15–16) described "dendriform" and "lamelliform elements" as important components of Little Dal reefs in the Mackenzie Mountains. He regarded both as stromatolites with "unusual" or "unique" characteristics: thin-walled tubes and *Renalcis*-like objects in dendriform element, and a reticulate "ladder-rung" arrangement that "may be formed by a meshwork of tubes" in lamelliform element. Dendriform and lamelliform elements look quite similar in two of his illustrations (*idem*, figs. 10, 13). TURNER et al. (2000a, p. 185, 188) related these elements to growth stages in the reefs, with dendriform most common in Stage III and lamelliform in Stage IV. Their illustrations of dendriform elements

(TURNER et al., 2000a, fig. 8a, b, e) show irregular closely-spaced centimetric digitate stromatolites with laminar-reticulate cores and marginal *Renalcis*-like clots. They describe lamelliform elements as commonly steeply sloping (45–70°) and containing dark filamentous and more cement-rich light layers (TURNER et al., 2000a, fig. 10b). These resemble the distinctive "filmy" microstructure of similar age *Baicalia lacera* (PETROV & SEMIKHATOV, 2001, figs. 5b, 6a) which also has steeply dipping laminae and, as noted above, quite possibly filamentous microstructure too.

In the examples cited above, layers of filamentous fabric are generally interleaved with lighter, sparry, layers. If the sparry layers were lacking then the deposit would be indistinguishable from "skeletal stromatolite" (RIDING, 1977b) and "porostromate stromatolite" (MONTY, 1981). In addition to the Little Dal and Chernaya Rechka examples, calcified filaments reminiscent of *Girvanella* are relatively widespread elsewhere in the Neoproterozoic, e.g., in the ~750–700 Ma Draken Fm (SWETT & KNOLL, 1985; KNOLL et al., 1993), ~725–675 Ma Svanbergfgellet Fm (RAABEN, 1969), and ~700 Ma Upper Eleonore Bay Supergroup, Greenland (BERTRAND-SARFATI & CABY, 1976) (all references in KNOLL & SEMIKHATOV, 1998, p. 413). However, Mesoproterozoic examples reported from the ~1200 Ma Society Cliffs Fm are currently the oldest known *Girvanella*-like calcified filaments, and are associated with micritic bush-like structures also interpreted as calcified cyanobacteria (KAH & RIDING, 2007).

2.3.4. Boetsap laminae: microspar crusts

Well-developed relatively even lamination described from the Neoarchaean Campbellrand-Malmani platform of South Africa as Boetsap lamination (SUMNER & GROTZINGER, 2004) also represent a type of Hybrid Sparry-Microcrystalline Crust, but is difficult to interpret due to uncertainty regarding the origin of the layers, which appear to be entirely microspar, with no sign of clotted or peloidal fabric. The main question is whether the microspar is entirely primary, or includes altered micrite.

Giant elongate domes in the Campbellrand-Malmani platform are dominated by millimetric layers of fine-grained dolomite (red-brown) and calcite (grey) that SUMNER & GROTZINGER (2004, p. 14–16) termed "Boetsap lamination". They distinguished two main, equally abundant, components: (i) dark microcrystalline dolomite, varying 1–3 mm in thickness along a single lamina, commonly with peaked upper surfaces, (ii) thin (<1mm) uniform layers of light microcrystalline calcite and dolomite, showing a vertical fabric in thicker laminae. They interpreted the thicker layers with varied thickness as fine clastic carbonate, and the thinner uniform layers with vertical fabric as precipitated laminae. SUMNER & GROTZINGER (2004, p. 22) commented that "apparent paucity of micrite suggests that spontaneous precipitation of carbonate, i.e., whitings, was not common across seaward sides of the platform", and noted that "micrite beds were not observed in shallow subtidal depositional environments" and "most intertidal to deep subtidal stromatolites and microbialites contain fibrous calcite cements". But they also emphasized that extensive recrystallization made it difficult to interpret the fine-grained components (*idem*, p. 6, 8). At the Boetsap section (SUMNER & GROTZINGER, 2004, fig. 3) they estimated that elongate stromatolites are dominated by "microcrystalline" and "precipitated" fabrics, in which microcrystalline represents microspar to silt-sized crystals that "could have been either transported silt-sized carbonate or carbonate precipitated within microbial mats", and precipitated represents "cement-like crystal textures". They concluded that some elongate stromatolite mounds contain "a significant component of clastic carbonate" whereas others, especially those better preserved, have "more precipitated textures" (*idem*, p. 16). Boetsap laminae differ from isopachous laminite mainly by the presence of dark-light layering.

Interpretation of Boetsap laminae presents problems to similar those of laminar fibrous crusts and micritic peloidal laminae (the key components of SAMI & JAMES' (1994, p. 116) "wavy microbialite"). Both are hybrid deposits in which the origin of the fine-grained carbonate requires clarification. Boetsap lamination is regular but includes discontinuous layers (SUMNER & GROTZINGER, 2004, fig. 11a) and the microspar to silt-sized crystals could represent detrital grains or microbial mat precipitate (SUMNER & GROTZINGER, 2004, fig. 3). Until these possibilities are resolved it is not possible to tell whether Boetsap laminae, and therefore the "Giant" domes of which they are an important component (SUMNER & GROTZINGER, 2004, p. 14, 16) are essentially Sparry or Hybrid crust.

2.4. Sparry Crust plus Coarse Grains

Abiogenic precipitates both cement and surficially veneer particulate carbonate. These hybrid "grainy crusts" are most distinctive where the grains are coarse. In the Precambrian, examples of grains incorporated in seafloor herringbone calcite and in radial fibrous carbonate crusts have been described, and some have been given stromatolite names, e.g., *Gongylina*.

2.4.1. Herringbone Calcite with coarse grains

Herringbone calcite associated with grainstone forms laterally persistent centimetric to decimetric layers with scours and cross-lamination; the grainstone occurs as basal graded units or fills troughs between herringbone calcite domes (SUMNER, 1997a).

In centimetric to decimetric "grainstone-precipitate" cycles in the subtidal Gamohaan and Frisco formations of the Campbellrand-Malmani platform, basal grainstones pass up into "precipitate-rich" beds (SUMNER, 2002, fig. 2c), or grainstones fill troughs between stromatolitic "precipitate" domes (SUMNER, 1997a, table 1, p. 464–466). Grainstone beds have basal scours and contain wave ripples. Stromatolites are poorly laminated and dominated by herringbone calcite, which is also present between grains. Synsedimentary lithification is reflected in vertical ripple propagation.

2.4.2. Radial fibrous crusts with silt and sand grains (e.g., *Gongylina, Omachtenia*)

Alternating submillimetric layers of particulate carbonate and radial fibrous crusts, influenced by synsedimentary scouring and micro-crosslamination, create distinctive dark-light well laminated rippled microstructures in laterally persistent decimetric to metric beds (KNOLL & SEMIKHATOV, 1998, p. 414–418). The pseudocolumnar to stratiform deposits formed by these grainy crusts form have been given form names within groups such as *Gongylina* KOMAR, 1966 (Fig. 10) and *Omachtenia* NUZHNOV, 1967.

Omachtenia omachtensis with muddy to silty sediment, and *Gongylina differenciata* with silt and sand, are regarded as characteristic of the Mesoproterozoic (KNOLL & SEMIKHATOV, 1998, p. 418). HOFMANN (1969, table 13, p. 38) recognized that stratiform *Gongylina* "appears to be nothing more than a form dependent on the periodic influx of sand- or silt-sized material". KNOLL & SEMIKHATOV (1998, p. 417–418, fig. 11) agreed, and extended this interpretation to include *Omachtenia omachtensis*. They ruled out both trapping/binding and precipitation "by actively photosynthesizing mats", and regarded these deposits as "mechanically emplaced sediments" encrusted by thin veneers of "cements". They interpreted them as alternations of grains and seafloor precipitates on peritidal flats locally associated with "microdigitate precipitates". Nonetheless, they considered that microbial mats appeared to have "covered and stabilized event beds and provided sites for the nucleation of carbonate crystals after degradation (KNOLL & SEMIKHATOV, 1998, p. 418). A variant of this mixed deposit is where grainy sediment accumulated lateral to domes, as in Rocknest isopachous laminites where "precipitated laminae pinch out in adjacent depression, filled by both precipitated laminae and peloidal grains" (GROTZINGER & KNOLL, 1999, fig. 3a). SAMI & JAMES (1994, fig. 6) noted "ooid grainstone with thin microbial laminae draping climbing ripples" in Pethei shallowing cycles, and laminar fibrous crusts interbedded with detrital grains (SAMI & JAMES, 1996, fig. 5f). Whereas grainy herringbone calcite deposits are centimetric-decimetric, in *Gongylina* and *Omachtenia* the radiaxial carbonate and grainy layers are both submillimetric. These deposits evidently formed by alternation of Sparry Crust precipitation with sand and silt influx. They are likely to find analogues, albeit in shallower water, in present-day hot-spring travertines and cave flowstone.

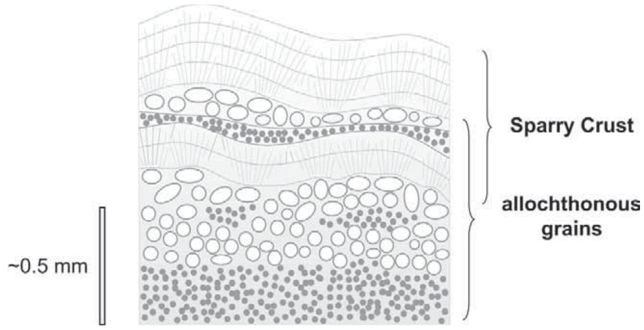

Figure 10: Diagrammatic representation of *Gongylina*: submillimetric interlayers of Sparry Crust and coarse grains (after KNOLL & SEMIKHATOV, 1998, fig. 11).

2.4.3. Crystal fans with coarse grains

Crystal pseudomorph fans also can be interbedded with cross-stratified grainstones, e.g., Cheshire Fm., Zimbabwe (SUMNER, 2002, fig. 1c).

2.5. Fenestrate Microbialite

These are thin beds of net-like masses of thin curved wispy dark layers, often rounded and contorted, that define millimetric to centimetric lensoid to irregular areas of light-coloured cement that includes radial, sparry and herringbone calcite fabrics (Fig. 11). The network is commonly structured by thinner dark layers draped from thicker dark subvertical "supports".

These distinctive deposits were recognized and described in detail from the Campbellrand-Malmani platform where they form thin (decimetric, SUMNER, 1997a, p. 462; SUMNER & GROTZINGER, 2004, fig. 12) but laterally very extensive (SUMNER, 1997b, p. 315) beds. SUMNER (1997a, b) interpreted them as delicate convoluted microbial mats forming open networks (SUMNER & GROTZINGER, 2004, p. 16), with the thicker supports and laminated drapes being due to different microbial communities; the delicate wispy sheets being encrusted by calcite as they grew. Varieties have been termed tented, cuspate, irregular columnar and plumose (SUMNER, 1997b) and, as a whole, fenestrate microbialites (SUMNER, 2000). They are typically closely associated with herringbone calcite, that preferentially veneers the vertical "supports", together with bladed and blocky calcite cements (SUMNER, 1997b, p. 313).

KERANS & DONALDSON (1989, p.85, fig. 6) described "massive accumulation of concave-upward, dish- or bowl-shaped algal plates ranging in size from 0.1 to 2 m" in the Dismal Lakes Group, and termed them "cyanobacterial plate bioherms" (*idem*, fig. 3). The plates, a few millimetres thick and a few centimetres long, are veneered by a few millimetres of "isopachous fibrous cement crust" (*idem*, fig. 6b). These show some resemblance to fenestrate microbialites, but lack the net-like organization. In Campbellrand-Malmani carbonates, SUMNER (1997a, p. 458, fig. 7) recognized "filmy laminae" draping over "supports creating complex microbial structures with complex voids" that combine to form cuspate, planar laminated, irregular columnar and contorted laminated structures, cemented and coated by herringbone calcite, in deep subtidal environments.

SUMNER (1997b, p. 313) interpreted fenestrate microbialite as delicate thin microbial mats that provided irregular substrates for herringbone calcite cements that "precipitated contemporaneously with microbial growth", and recognized that these deposits graded into herringbone calcite beds (SUMNER, 1997b, fig. 7) that precipitated directly on the seafloor. She suggested that present-day mineral encrusted floating substrate-attached mats may help understand fenestrate microbialites (SUMNER, 1997b, p. 311).

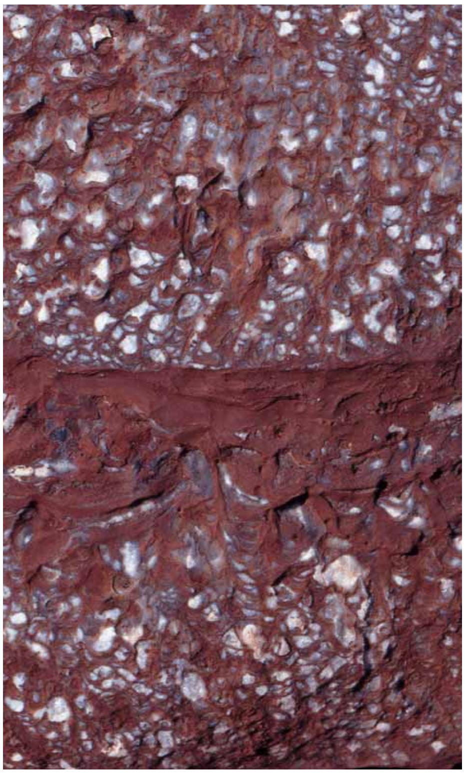

Figure 11: Fenestrate microbialite. Late Archaean Campbellrand-Malmani platform, South Africa. Width of field ~ 16 cm. Meshwork of rounded or angular to lunate fenestrae (white), generally <1cm in size, defined by thin curved dark layers, and crudely stacked in elongate, erect to sloping, masses a few centimeters in length.

SUMNER (2000) reported fenestrate microbialites from greenstone belt carbonates at Steep Rock, Ontario (~2.8 Ga) and Huntsman, Zimbabwe (~2.8 Ga) and regarded fenestrate microbialite essentially as "laminated mat encased in … fibrous marine cement" (SUMNER, 2002, fig. 2b). SUMNER & GROTZINGER (2004, p. 16–17) described spatial distributions of varieties of these deposits across the Campbellrand-Malmani platform, where they are most abundant in deeper water facies. They are associated with layers of "contorted laminated mat" (*idem*, fig. 12) and may grade into less distinctive by grossly similar "fenestral laminite" that in turn is associated with isopachous laminite (*idem*, fig. 9). BARTLEY et al. (2007, p. 216) reported, but did not figure, cuspate microbialite from the ~1300–1000 Ma Avzyan Fm of the southern Urals.

Fenestrate microbialites appear to lack filamentous microfabric (see SUMNER, 1997b, fig. 5) but show some broad resemblance to "dendriform" and "lamelliform" Little Dal microfabrics. Both essentially consist of thin wispy netlike layers that define cement filled voids, but fenestrate microbialite microstructure is generally significantly (~10–100 x) coarser than that of dendriform and lamelliform fabric (cf. SUMNER, 1997b, figs. 8, 10 with AITKEN, 1989 figs. 10, 13). Nonetheless, the fine structure of lamelliform "ladder-rung" fabric (AITKEN, 1989 fig. 12) and laminated mat (SUMNER, 1997b, fig. 5a) is not dissimilar.

2.6. Thrombolite

The dense, peloidal, clotted and/or filamentous, micritic and microspar microfabrics typical of Fine-grained Crust occurs in thrombolites as well as stromatolites. Thrombolites are distinguished by their lack of well-developed layering, and by their macroscopic patchy or clotted fabrics – typically millimetric to centimetric irregular dark masses (clots) in a lighter coloured matrix (AITKEN, 1967). They form beds and mounds, sometimes in association with stromatolites, and in the Proterozoic are rich in cement and/or filaments.

Calcified microbial thrombolites (RIDING, 2000, p. 192) are well known in the Early Palaeozoic (PRATT & JAMES, 1982; KENNARD & JAMES, 1986). The earliest reported thrombolites are in the ~1.9 Ga Rocknest Formation and are suggested to have formed "through the inorganic encrustation of probable microbial communities by marine cements" (KAH & GROTZINGER, 1992, p. 305). No Mesoproterozoic thrombolites have been reported, but there are several reports from the Neoproterozoic. AITKEN & NARBONNE (1989) described thrombolites from the ~800 Ma Little Dal Group and the Ediacaran Blueflower Formation of northwest Canada. In the lower two-thirds of the Little Dal reefs "dendriform" and "lamelliform" stromatolites (AITKEN, 1989) are interlayed with thrombolitic deposits with filamentous, clotted and spongy "cellular" fabrics (TURNER et al., 1993; 2000a, figs. 6e, 8h,i) comparable with those of Cambro-Ordovician thrombolitic bioherms (TURNER et al., 1997, p. 441, 449; BATTEN et al., 2004). Thrombolites also occur in the latest Neoproterozoic of Oman (MATTES & CONWAY MORRIS, 1990) and Namibia (GROTZINGER et al., 2000, 2005; JOHNSON & GROTZINGER, 2006).

Coincidence of relatively widespread Neoproterozoic development of thrombolites with the development of filamentous fabric supports the view (KENNARD & JAMES, 1986) that these thrombolites reflect microbial calcification. BATTEN et al. (2004, p. 264, fig. 10) suggested that Neoproterozoic and Early Palaeozoic thrombolites generally developed in relatively deeper water than associated stromatolites.

3. DISCUSSION

3.1. PRESENT-DAY ANALOGUES

The early search for present-day analogues for ancient stromatolites led from freshwater tufa (WALCOTT, 1914; RODDY, 1915) to marginal marine domes (BLACK, 1933) and columns (LOGAN, 1961). These discoveries strongly supported KALKOWSKY's (1908) inference that stromatolites are essentially microbial deposits. They stimulated widespread studies of lithified microbial mats, but optimism that such examples provide appropriate analogues for all ancient marine stromatolites diminished as studies of Precambrian examples advanced (e.g., SEREBRYAKOV, 1976, p. 633; GROTZINGER & KNOLL, 1999, p. 314). Although there may be no present-day examples that closely resemble the very large domes and columns of the Late Archaean and early-mid Proterozoic, nonetheless there are smaller examples in diverse environments that appear to contain comparable fabrics.

3.1.1. Fine-grained Crusts

Fine-grained Crusts typically contain complex, dominantly fine-grained, carbonate microfabrics that reflect precipitation in intimate association with organic matter, especially cell material and the extracellular polymeric substances that they produce, in microbial mats as a result of synsedimentary calcification associated with processes such as oxygenic photosynthesis and bacterial sulphate reduction (e.g., TRICHET & DÉFARGE, 1995; VISSCHER et al., 1998, 2000; REID et al., 2000; RIDING, 2000, table 1; ARP et al., 2003; KUHL et al., 2003; DUPRAZ et al., 2004; DUPRAZ & VISSCHER, 2005; BAUMGARTNER et al., 2006; KREMER et al., 2008). These fine-grained microfabrics range from dense, through clotted, to peloidal and filamentous (RIDING, 2000, figs. 6, 7). Individual, or associations of a few, micrite grains have been attributed to calcification of bacterial cells after death (MAURIN & NOËL, 1977; KRUMBEIN, 1979; FOLK, 1993) and during life (THOMPSON & FERRIS, 1990). Clotted (grumous) microfabrics have commonly been linked with microbial processes (KAISIN, 1925; PIA, 1927, p. 36; HOFMANN, 1969, p. 40; BERTRAND-SARFATI, 1976; MONTY, 1976, fig. 27, 1981, p. 2). Peloids – micritic aggregates of uncertain origin (MCKEE & GUTSCHICK, 1969) – include in place precipitates that have been variously interpreted as essentially abiogenic cements (MACINTYRE, 1984, 1985) and as bacterial aggregates (CHAFETZ, 1986). Associations of clotted and peloidal micrite develop in microbial organic matter (MONTY, 1976, p. 229, fig. 27e; ZANKL, 1993), including decaying sponges (REITNER et al., 2000), and are commonly preserved in fossil sponges (MOCK & PALMER, 1991; WARNKE, 1995). They have also been interpreted as products of calcified bacterial biofilm (RIDING, 2002). Although the presence of heterotrophic bacteria has been suggested to lead to cyanobacterial calcification (PENTECOST, 1991, p. 6; CHAFETZ & BUCZYNSKI, 1992) this may in part be related to the experimental growth medium used (ARP et al., 2002). Furthermore, such degraded sheaths are likely to be irregular in form and encrusted by carbonate to varying degrees, whereas fossils such as *Girvanella* exhibit regular tube morphology in which wall-thickness remains constant in individual specimens, suggesting *in vivo* sheath impregnation (RIDING, 1977a, 2006). Such sheath calcification is linked to photosynthetic carbon uptake (GOLUBIC, 1973; PENTECOST, 1987, p. 134) particularly of HCO_3^-. Some cyanobacterial sheaths are tubular and others are irregularly digitate and often show vertical orientation that creates a bush-like appearance (RIDING & VORONOVA, 1982). These diverse examples indicate that a wide range of fine-grained clotted-peloidal-shrub-like and filamentous fabrics, often co-occurring, characterize lithified microbial mats.

3.1.2. Sparry Crusts

Speleothem. Cave carbonate precipitates include a wide array of deposits that include sparry subaqueous crusts, e.g., phreatic pool deposits (FAIRCHILD et al., 2007, fig. 7.1b), and extensive flowstone (e.g., BURNS et al., 1999, p. 499) that can also incorporate allochthonous grains. Speleothem calcite exhibits palisade calcite (KENDALL & BROUGHTON, 1978). KENDALL & IANNACE (2001, fig. 6c) figured stromatolitic crusts from a Pleistocene rimstone dam from Sorrento, Italy, and also laminated dendrite crystals (*idem*, fig. 8). They suggested (KENDALL & IANNACE, 2001, p. 695) that these might assist interpretation of similar lamination in freshwater stromatolites such as described by FREYTET & VERRECCHIA (1999), and also the sub-millimetric micrite-microspar laminae typical of the problematic stromatolite-like structure *Archaeolithoporella*.

Travertine. Hot spring travertines can include crystalline crusts and shrub-like fabrics (CHAFETZ & FOLK, 1984; GUO & RIDING, 1992; RIDING, 2000, p. 196; PENTECOST, 2005, pl. 8c) that resemble some Precambrian isopachous laminites, and dendritic fabrics, as well as alternations of sparry crusts and allochthonous grains such as in *Gongylina* and *Omachtenia*.

Calcrete. Laminar calcretes include stromatolitic fabrics with sub-millimetric light-dark bands (READ, 1976, pl. 3). Some have been termed lichen stromatolites (KLAPPA, 1979) and terrestrial stromatolites (WRIGHT, 1989), and can include diverse fabrics (see references in RIDING, 2000, p. 196).

Alkaline lake crusts. GROTZINGER & JAMES (2000, p. 9) noted the scarcity of present-day analogues of seafloor precipitated calcite and aragonite. They suggested that partial analogues may exist in non-marine thermal springs and also in alkaline lakes such as those of Pyramid Lake, Nevada (e.g., BENSON, 1994). KAZMIERCZAK & KEMPE (2006, fig. 3, p. 124) illustrate partially silicified aragonite stromatolitic crusts from alkaline lakes of Niuafo'ou Island, Tonga, that have with laminated, arborescent and tussock fabrics. They compared them with Proterozoic and also Palaeozoic examples. The stromatolites contain cyanobacterial remains (KAZMIERCZAK & KEMPE, 2006, fig. 2) but do not appear to be precipitating at present (*idem*, p. 124).

Marine evaporative splash crusts. Intertidal-supratidal carbonate crusts have been termed “pelagosite”, after the Italian name Pelagosa for the Croatian island Palagruža (see PALACHE et al., 1951), and “coniatolite” (PURSER & LOREAU, 1973). These can be well-developed along evaporitive shorelines and intertidal radial-fibrous aragonite crusts up to 3cm thick on beach rock in the southern Persian Gulf (PURSER & LOREAU, 1973) form through repeated immersion and evaporation of slightly hypersaline seawater. Such indurated crusts have been termed “marine cements” and compared with travertine and Great Salt Lake cements (ALSHARHAN & KENDALL, 2003, pl. 2, p. 230, 237). Locally they are coated by cyanobacteria (ALSHARHAN & KENDALL, 2003 p. 214) and may therefore provide examples of Hybrid Crusts. HOFMANN & JACKSON (1987, p. 969) compared Proterozoic microdigitate stromatolite fabrics with the microstructure of the carbonate crusts described by PURSER & LOREAU (1973, p. 368). MONTANARI et al. (2007) described pelagosite from Palagruža and Hvar, Croatia, as “microstromatolite” and interpreted the light-dark laminae as annual layers.

Hypersaline stromatolites. In the marginal marine Sebkha el Melah of SE Tunisia, 5500 BP stromatolites that formed on beachrock and serpulid bioherms at the margins of a restricted lagoon have clotted and radial fibrous aragonitic microfabrics (DAVAUD et al., 1994, figs. 9, 10c, d). Metric stromatolitic domes composed of aragonite also occur in the present-day Great Salt Lake (EARDLEY, 1938; CAROZZI, 1962; HALLEY, 1976) and in Late Pleistocene Lake Lisan deposits of the Dead Sea (BUCHBINDER, 1981).

Beachrock. Aragonite cements are lithifying components in both beachrock and stromatolites near Lee Stocking Island, Exuma Cays (WHITTLE et al., 1993). Beachrock at San Salvador Island, while differing in morphology from Stocking Island stromatolites (REID & BROWNE, 1991; MACINTYRE et al., 1996) exhibits similar fenestral layering (KINDLER & BAIN, 1993, fig. 4b, p. 245). Microbial influences on beachrock formation (KRUMBEIN, 1979) suggest a connection with the formation of coarse-grained near beach stromatolites (e.g., Stocking Island and Highborne Cay, Bahamas) that should be explored.

Subtidal marine "cement" crusts. Research into marine lithification during the 1960's and 1970's revealed thick fibrous calcite crusts, for example in Late Palaeozoic reefs (OTTE & PARKS, 1963), that were subsequently compared with Holocene submarine cements (SCHROEDER, 1972; JAMES et al., 1976) and, in some cases, interpreted to have been precipitated directly on the seafloor (e.g., MAZZULLO & CYS, 1979, p. 918). These were often referred to as "cements" and this terminology has commonly been applied to similar Precambrian sparry seafloor precipitates. Present-day examples are typically subtidal botryoidal crusts of aragonite and Mg-calcite. Well-documented examples from the Belize fore-reef are restricted to millimetric to centimetric cavities (JAMES & GINSBURG, 1979, p. 117, figs. 6–5), and in some cases aragonite cement is intimately associated with peloidal silt (*idem*, figs. 6–15d, 6–17d).

3.1.3. Hybrid Crusts

Freshwater tufa. Partial analogues for Proterozoic stromatolitic Hybrid Crust are likely to exist in present-day evaporitic and freshwater carbonates. Freshwater "tufa stromatolite" (RIDING, 2000, p. 191) is characterized by light-dark banded cyanobacterial deposits that commonly consists of filamentous, shrub-like and coarse spar fabrics (e.g., PIA, 1933, p. 41–42; STIRN, 1964; IRION & MÜLLER, 1968; GOLUBIC, 1973; MONTY, 1976, fig. 7; PENTECOST, 1995; FREYTET & PLET, 1996; KANO et al., 2003; ANDREWS, 2005; PENTECOST, 2005, pl. 14c, d). These intimate associations of sheath impregnation and encrustation (e.g., RIDING, 1977a; MONTY & MAS, 1981, fig. 18b) preserve seasonal variations in microbial growth and associated precipitation.

BERTRAND-SARFATI (1972, p. 29, 169, 188; 1976, p. 253) compared light-dark "film" layering in Mesoproterozoic Atar stromatolites with present-day cyanobacterial mats from Andros Island (MONTY, 1965) and suggested that, for example in some *Conophyton* and *Inzeria* specimens, they may be seasonal (BERTRAND-SARFATI, 1972, pl. 11(4), pl. 22(2)) or even virtually daily (BERTRAND-SARFATI, 1976, p. 253). In this context, it is relevant to compare BERTRAND-SARFATI's (1976, fig. 1b) Mesoproterozoic film microstructure with superposed layers of *Schizothrix* (MONTY & HARDIE, 1976, fig. 2b) in present-day Andros mats. Similarly, BERTRAND-SARFATI et al. (1994, p. 178–184) compared "alternating micrite-microsparite laminae" and filamentous and tussocky fabrics in Palaeogene fluvio-lacustine stromatolites from France, with similar fabrics in Proterozoic stromatolites. In Late Pleistocene and Holocene marginal stromatolites of East African Rift lakes, CASANOVA (1994, fig. 10a) described "doublets" composed of "light-coloured sparitic laminae and dark micritic laminae" as the "most frequent microstructure observed in lacustrine stromatolites".

Although light-dark bands are widespread and often distinct in freshwater stromatolites, their interpretation may not be straightforward (PENTECOST, 2005, p. 38–40). MONTY (1976, p. 199–208) described the complexity of layering in Andros and also fluviatile mats. He noted that Andros mats essentially show alternations of "whitish calcareous layers and brownish organic ones", but emphasized their complexity, that can include layers that develop within mats (MONTY, 1976, p. 199, 204). Fluviatile *Rivularia* shows both broad seasonal bands that relate to inorganic precipitation and finer bands thought to relate to photosynthetic activity (PENTECOST, 1987, p. 125). As a result, the winter bands can be more heavily calcified and light-coloured (PENTECOST, 1987, fig. 6b; PENTECOST & SPIRO, 1990, p. 18). Similarly, in fluviatile tufas, IRION & MÜLLER (1968, fig. 3) recognized light sparry winter layers, and commented "as the algae do not grow in winter, pure layers of sinter are formed during this period" (*idem*, p. 165). On the other hand, in seasonal couplets from Lake Manyara and Lake Natron, Tanzania, CASANOVA (1994) interpreted the thinner (5–900 μm) organic rich micritic layers as forming during the dry season, and thicker (20–1500 μm) sparitic layers, with numerous erect ~1 μm diameter filaments, representing rainy season growth of filamentous cyanobacteria (CASANOVA, 1994, p. 212–213, figs. 10, 11). Thus, in the fluviatile tufas the light bands may be relatively inorganic sparry precipitates, whereas in the Lake Natron example the sparry layers represent rapid growth of erect cyanobacteria. In fact this latter case may also apply to some fluviatile tufa too; e.g., IRION & MÜLLER (1968, fig. 4) show "dark layers … deposited during the winter" and "white layers, formed during the summer".

Not surprisingly, therefore, there has been debate concerning controls on lamina formation in fluviatile tufas (KANO et al., 2003, p. 259; ANDREWS & BRASIER, 2005, p. 413; ANDREWS, 2005; PENTECOST, 2005, table 3). KANO et al. (2003, p. 255) report reversed seasonal patterns at different sites: dense winter and porous summer laminae at one, and dense summer and porous winter laminae at another. In contrast, many studies report denser/micritic winter-spring layers and more porous/sparry summer layers at both North American (e.g., CHAFETZ et al., 1991) and European (e.g., JANS-

SEN et al., 1999, fig. 2d; and other references in ANDREWS & BRASIER, 2005, p. 413). In addition to depositional processes, diagenetic effects are also probably important (ARP et al., 2001; ANDREWS & BRASIER, 2005, p. 419; PENTECOST, 2005, figs. 8, 9). For example, fossil tufas in Belgium possess "more sparry calcite laminae than the Recent precipitates" that have preferentially developed at particular horizons (JANSSEN et al., 1999, fig. 5). These studies suggest that interpretation of Hybrid Crust in ancient stromatolites will not be simple, although it remains possible that they too, in some cases, may be seasonal.

Travertine shrubs. The likelihood that microdigitate stromatolites are essentially inorganic has long been considered (GROTZINGER, 1986B; HOFMANN & JACKSON, 1987). However, based on similar structures (shrub travertine) in present-day hot spring travertines, they too may have combined inorganic and microbial components (CHAFETZ & FOLK, 1984; GUO & RIDING, 1994). These shrubs are typically a few millimetres to centimetres in size, but larger examples up to 8 cm long (CHAFETZ & FOLK, 1984, p. 305, fig. 8) resemble dendrites described from the upper Pethei Group by POPE & GROTZINGER (2000).

Cave crusts. Sparry cave crusts can be interleaved with fine-grained layers, e.g. fine dark laminae in cave popcorn, some of which may be microbial (THRAILKILL 1976; MELIM et al., 2001) in which case they could be regarded as Hybrid Crusts. Nonetheless, "much cave popcorn contains thick layers of clear calcite or aragonite with no indication of organic involvement" (THRAILKILL, 1976, figs. 7–12, p. 83). COX et al. (1989) described cyanobacterial speleothem as subaerial stromatolite.

Marine evaporitive splash crusts. Present-day Abu Dhabi crusts formed through repeated immersion and evaporation of slightly hypersaline seawater are ephemerally coated by cyanobacteria (ALSHARNAN & KENDALL, 2003 p. 214) possibly develop interlayered sparry and microbial fabrics, and alternations of pellet micrite and fibrous aragonite layers occur in sub-Recent Dead Sea stromatolites (DRUCKMAN, 1981, fig. 6).

Evaporite stromatolites. Microbial mats in hypersaline environments can be colonized and be encrusted by evaporite minerals (e.g. KENDALL & SKIPWITH, 1968; GERDES et al., 1993, pl. 13) and involved in the development of stromatolitic structures (AREF, 1998, figs. 4a, 6b). These can contain calcified microbial filaments and show well-defined even lamination (ROUCHY & MONTY, 1981, figs. 7, 9; 2000, fig. 1).

Miocene marine stromatolite. CONIGLIO et al. (1988, p. 102, 105, figs. 3, 7) described a mid-Miocene reefal platform veneered by a 1m thick dolomitized deep-water "stromatolite" bed, forming domes up to 10 m across, composed of micropeloidal and homogeneous mudstone that locally grades to fibrous fabric that they compared with calcitized aragonite cement.

3.1.4. Fenestrate microbialite

SUMNER (1997b, p. 311) envisaged that plumose and similar Archaean fenestrate fabrics originated by synsedimentary lithification of vertically tufted microbial films, as in hot springs (e.g., WALTER et al., 1976) and in the pinnacle, columnar and lift-off mats of ice-covered lakes in Antarctica (WHARTON 1994, fig. 3). Comparisons could also be suggested with cool and hot spring travertine fabrics, especially those with rounded millimetric to centimetric voids formed by precipitation on water and bubble surfaces; these (e.g., REIS, 1926, p. 181; GUO & RIDING, 1998, figs. 4, 5). GANDIN & WRIGHT (2007) interpreted Campbellrand-Malmani fenestrate fabrics as products of synsedimentary deformation of organic filaments "exerted by the growth of evaporite nodules, during the coalescence of enterolithic folds".

3.1.5. Thrombolite

Neoproterozoic thrombolites have been compared with Early Palaeozoic examples (TURNER et al., 1997), but present-day analogues of these types of thrombolite have not been confidently recognized. LAVAL et al. (2000) suggested that fabrics within freshwater tufa mounds from Pavilion Lake, British Columbia, might be analogous with those of Cambrian thrombolitic reefs containing *Epiphyton* and *Girvanella*.

This brief and very incomplete overview suggests that diverse partial analogues of Sparry and Hybrid crust deposits may be found in Quaternary evaporitic, alkaline lake, and freshwater environments. None of these present-day deposits is known to create sparry crusts on the scale observed in the Precambrian, e.g., in metric domes and cones. Nonetheless, some should provide analogues for small crusts, and in particular for their microfabrics.

3.2. RECOGNITION AND INTERPRETATION OF PRECAMBRIAN STROMATOLITIC CRUSTS

Abiogenic precipitated stromatolites. Awareness of the widespread existence of seafloor precipitates that could be confused with lithified microbial mats emerged gradually from studies of Proterozoic, and subsequently Archaean, stromatolites in the 1980's (e.g., KERANS, 1982; GROTZINGER, 1986a). This research led to critical reassessment of the nature and significance of Precambrian authigenic seafloor carbonate crusts. GROTZINGER & READ (1983) described microdigitate stromatolites as "cement laminae", and GROTZINGER (1986b) considered the possibility that they were "entirely abiotic". GROTZINGER (1989b, p. 11) drew attention to "the direct precipitation of stromatolitic laminae" and GROTZINGER & ROTHMAN (1996, p. 424) suggested that the growth of large Early Proterozoic stromatolites (JACKSON, 1989, fig. 13) could "be accounted for exclusively by abiotic mechanisms, particularly where growth by precipitation is thought to be important". GROTZINGER & KNOLL (1999, p. 343) noted that "the growth of abiotic marine crusts might substitute for mats and create the same end result" and GROTZINGER & JAMES (2000, p. 7) commented "abiotic precipitates are morphologically and mineralogically identical to marine cements of Phanerozoic age … with the striking difference that they do not simply fill voids but are widespread as direct precipitates on the sea floor itself". These abiogenic precipitates were commonly referred to as seafloor cements, and this usage continued even after GROTZINGER & KNOLL (1995, p. 579) pointed out that seafloor crusts/encrustations should be distinguished from "true cements which bind sediment particles and line voids" (e.g., KAH & KNOLL, 1996, p. 79; POPE et al., 2000, p. 1145).

These investigations led to realization that abiogenic seafloor precipitates were not only associated with stromatolites but also, in some cases, included them. Thus, GROTZINGER & JAMES (2000, p. 7, fig. 5) summarized "sea-floor encrusting precipitates" as including microdigitate stromatolites, large crystal fans, isopachous laminites, herringbone calcite, and dendritic tufa. Inclusion of isopachous laminites implied that abiogenic seafloor crusts had not only formed microdigitate stromatolites on peritidal flats, but were also responsible for larger subtidal stromatolites that included Palaeoproterozoic (JACKSON, 1989, figs. 6, 13; GROTZINGER & ROTHMAN, 1996, fig. 1b; GROTZINGER & KNOLL, 1999, fig. 3a; POPE et al., 2000, fig. 4; POPE & GROTZINGER, 2000, fig. 8) and late Archaean (GROTZINGER & KNOLL, 1995, fig. 1b; POPE et al., 2000, fig. 2d; SUMNER & GROTZINGER, 2004, fig. 4a) examples. As a result, POPE et al. (2000, p. 1149) considered "thinly laminated, isopachous stromatolites" "to have a largely abiotic origin".

Fine-grained and Sparry crust. The outline of previous research presented here suggests that three principal categories of well-preserved stromatolites can be recognized in the Proterozoic: Fine-grained, Sparry and Hybrid crust. Although no present-day large subaqueous domes and cones with comparable structure are known, smaller present-day deposits can guide interpretation by providing partial analogues on two levels: microfabric and lamina structure. Precambrian Fine-grained Crust stromatolites resemble present-day lithified microbial mats; in addition they conform to the great majority of Phanerozoic normal marine stromatolites. In contrast, Sparry Crust stromatolites have fabrics and structures that resemble present-day speleothem flowstone and hot-spring travertine crystalline crust. This suggests that Sparry Crust stromatolites are essentially abiogenic aqueous precipitates, in the sense that their formation does not require biotic processes and that they do not typically contain organically generated fabrics. Sparry and Fine-grained carbonate stromatolites can broadly resemble one another in stratiform to domical and columnar morphologies, but are generally distinct in fabric and lamina arrangement. Fine-grained stromatolites have micritic and microspar microfabrics and their layering is relatively uneven to discontinuous and usually shows poor inheritance. Sparry stromatolites have coarsely crystalline, equant spar or radial-fibrous, microfabrics and their layering is even to isopachous, and laterally persistent layers with good inheritance.

Hybrid Crust. Since Fine-grained and Sparry stromatolites differ in fabric and detailed structure and, as interpreted here, differ in origin (microbial as opposed to abiogenic) it could well be argued that they need not be grouped together as stromatolites. However, the gap between Fine-grained and Sparry crust stromatolites is bridged by Hybrid Crust stromatolites, which typically consist of millimetric alternations of

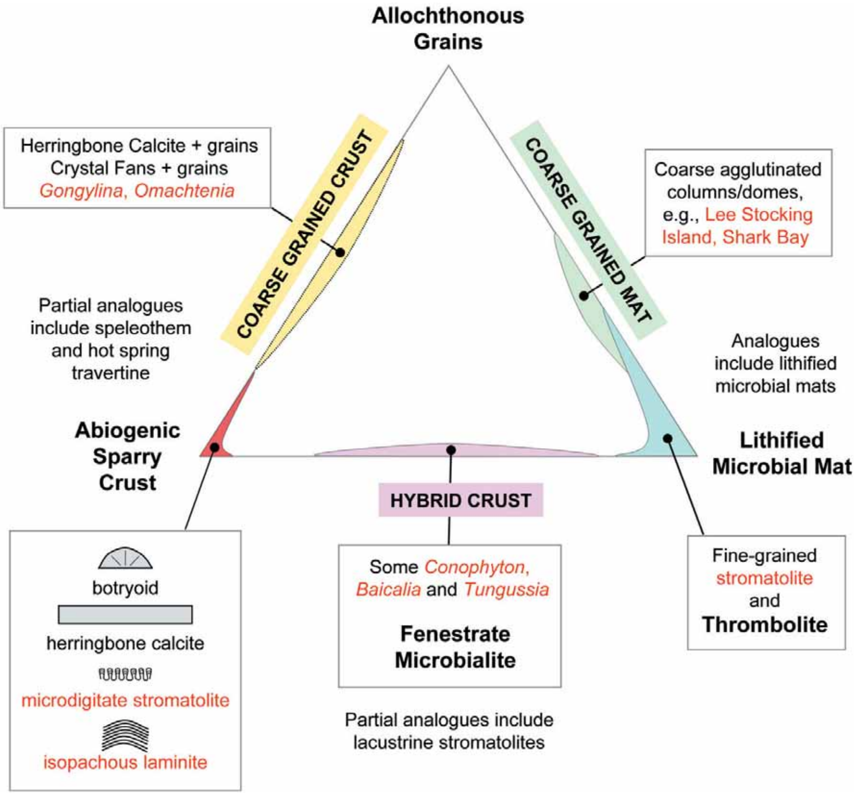

Figure 12: Interpretive summary of Precambrian authigenic crusts. Principal components: Sparry Crust (essentially abiogenic precipitate), Fine-grained Crust (lithified microbial mat), and allochthonous grains. Intermediates: Hybrid Crust, Coarse Grained Crust, and Coarse Grained Mat. Apart from allochthonous grains, each of the other five components and intermediates has at some time been regarded as containing examples of stromatolites. Examples of these stromatolitic deposits are indicated in red.

Sparry and Fine-grained crust. These alternations are interpreted here as more-or-less regular, possibly seasonal, fluctuations in microbial accretion and abiogenic precipitation. If this is correct then they reflect a relatively balanced mix of abiotic and biotic processes. In the early-mid Proterozoic, Hybrid Crust does not merely provide a link between Fine-grained and Sparry crusts, but – in many subtidal carbonate platform environments – it appears to supercede them in abundance. For example, giant decametric subtidal domes of the Palaeoproterozoic Pethei Group (SAMI & JAMES, 1996), and Mesoproterozoic Burovaya Formation (PETROV & SEMIKHATOV, 2001) are composed of Hybrid Crusts, and one of the most distinctive stromatolites, *Conophyton*, which locally forms decametric cones, also often has a Hybrid Crust composition (see WALTER, 1972).

Awareness of the importance of authigenic carbonate crusts in association with Precambrian stromatolites was presaged by recognition of the role of synsedimentary lithification in the formation of high-relief coniform stromatolites (DONALDSON, 1976; GEBELEIN, 1976). *Conophyton* and similar forms were already known to commonly contain distinctive streaky microstructure (KOMAR et al., 1965; CLOUD & SEMIKHATOV, 1969, fig. 2). Clearer understanding of the significance of these fabrics came from KERANS' (1982) (see GROTZINGER, 1989b, p. 10) suggestion that "cement crusts were precipitated on microbial laminae while stromatolites were growing". Similarly, GROTZINGER & KNOLL (1999, p. 329–330) later suggested that "the growth of abiogenic marine crusts might substitute for mats and create the same end result". It thus appears that some stromatolites, such as some forms of *Conophyton*, persistently had a dual abiogenic and microbial origin in which the fine-grained layers are essentially organic in origin (KOMAR et al., 1965, p. 67; see WALTER, 1972, p. 86) and the precipitated spar, as KERENS (1982) suggested, is essentially inorganic. Subsequently, SAMI & JAMES (1994, p. 120) suggested that spar-micrite couplets reflect alternation of "cement precipitation and microbial mat growth". There is therefore a need to distinguish not only between what PERRY et al. (2007, p. 169) regarded as "microbially constructed stromatolites" and "abiotic, chemically precipitated carbonate crusts", but also between these and Hybrid Crust stromatolites.

Crust discrimination. Against earlier expectation (e.g., GROTZINGER & ROTHMAN, 1996; GROTZINGER & KNOLL, 1995, 1999) it now seems possible to apply details of fabric and lamina arrangement criteria to the recognition of Fine-grained, Hybrid, and Sparry crusts (Fig. 12). These criteria draw on observations developed by GROTZINGER & READ (1983) in their recognition of the nature of microdigitate stromatolites, and by GROTZINGER (1989b, p. 11) when he drew attention to "the direct precipitation of stromatolitic laminae". Seafloor encrusting precipitates typically consist of fans and layers of elongated fibrous crystals or dendrites (GROTZINGER & JAMES, 2000, p. 7, fig. 5). Similarly, POPE et al. (2000, p. 1142) found that "stromatolites with isopachous fine lamination" commonly have "radial fibrous texture". POPE et al. (2000) interpreted "isopachous stromatolites to have been dominated by chemogenic precipitation in the absence of microbial mats, and the growth of peloidal stromatolites to have been controlled by sedimentation in the presence of microbial mats" (*idem*, p. 1139), and added "thinly laminated isopachous stromatolites are considered to have a largely abiotic origin" (*idem*, p. 1149). Thus, whereas lithified microbial mats are characterized by micritic (clotted-peloidal-bushy), and sometimes grainy, fabrics and uneven to irregular layering, crystalline seafloor precipitated crusts are characterized by sparry/radial-fibrous fabrics and more even and regular layering. Hybrid Crusts consist of millimetric alternations of these fabrics, in layers that are more regular than those usually present in Fine-grained stromatolites, and less regular than those of Sparry Crust stromatolites (Fig. 12). If these generalizations are valid, they signal an advance towards the Holy Grail of stromatolite studies – confident discrimination between abiogenic and microbial deposits. At the same time this recognizes Hybrid Crust as a key component of early-mid Proterozoic stromatolites. Realization of the existence of Hybrid Crust raises questions concerning its role in "giant" stromatolite formation, which may be significant, as well as the nature of Archaean stromatolites – specifically the relative importance of Sparry, Hybrid and Fine-grained crusts in their formation.

Sparry Crust with subordinate Fine-grained Crust. Hybrid Crust as defined here generally exhibits relatively regular alternations of Sparry and Fine-grained crust. But in some cases the proportions of Sparry and Fine-grained crust are less balanced, as in the ~1200 Ma Society Cliffs Formation (KAH & RIDING, 2007, p. 799) where fine-grained calcified cyanobacterial crust layers are subordinate to Sparry Crust. This raises questions, apart from terminological ones. For example, is there an overriding control on Hybrid Crust development? In fluviatile and lacustrine tufa stromatolites, dark-light layers appear to reflect seasonal controls on microbial growth and carbonate precipitation, and this might also apply to Precambrian Hybrid Crusts (see Analogues, Hybrid Crusts, Freshwater tufa, above). However, if subaqueous colonization of Sparry Crust by microbial mat were intermittent, in response to environmental factors operating on different and less regular time-scales, such as changes in water depth or salinity, then irregular alternations could be produced. These could include rare layers of Fine-grained Crust within Sparry Crust, and vice versa. Further exploration of these possibilities and their controlling factors is required.

3.3. GIANT STROMATOLITES

The volumetric importance of stromatolites in the construction of Precambrian carbonate platforms has long been emphasized (e.g., HOFFMAN, 1969; GROTZINGER, 1990, p. 96) and the sizes of individual domes and cones can be remarkable. KERENS & DONALDSON (1989, p. 84, figs. 4,5c) described upward transition from conical to domal stromatolites in the Dismal Lakes Group, with cones up to 6 m diameter and 12 m in synoptic relief, and domes up to 40 m in diameter and 10–15 m in synoptic relief. Whereas such large cones appear to be relatively rare, metric to decametric domes are locally important subtidal components of Precambrian carbonate platform (SUMNER & GROTZINGER, 2004, p. 16). Archaean examples include Steep Rock (e.g., NISBET & WILKS, 1989), Campbellrand-Malmani (e.g., YOUNG, 1932; TRUSWELL & ERIKSSON, 1973, p.6; ERIKSSON, 1977; BEUKES, 1987), and Carawine (e.g., MURPHY & SUMNER, 2008). Palaeoproterozoic examples include the Whalen Group, Wyoming (HOFMANN & SNYDER, 1985, p. 843) (now regarded as probably correlative with the lower Nash Form Fm., and therefore ~2.1 Ga, BEKKER et al., 2003, p. 311), Pethei Group (e.g., HOFFMAN, 1969), Rocknest (GROTZINGER, 1986b, p. 833) and Beechey Fm (PELECHATY & GROTZINGER, 1989, fig. 9). A late Mesoproterozoic example is the Burovaya Fm (PETROV & SEMIKHATOV, 2001). Neoproterozoic examples include Little Dal reefs (AITKEN, 1989), Boot Inlet Fm (NARBONNE et al., 2000), and Noonday Dolomite (CLOUD et al., 1974; CORSETTI & GROTZINGER, 2005).

In the latest Archaean Campbellrand-Malmani platform, elongate mounds up to 10m across and 40m or more in length (BEUKES, 1987, p. 9; SUMNER & GROTZINGER, 2004, figs. 10, 14) contain occasional pseudomorph fans, and grainstone and "cement" layers, but their principal constituents are "Boetsap-style lamellae" consisting of darker finely crystalline and lighter coarse sparry layers (SUMNER & GROTZINGER, 2004, p. 14, fig. 11). Archaean and Palaeoproterozoic "giant mounds" are commonly steep-sided, elongate – presumably in response to current influence – and associated with decimetric fans and crusts (GROTZINGER, 1986b, p. 833; SUMNER & GROTZINGER, 2004, p. 16). GROTZINGER (1986b, p. 833) described Rocknest stromatolitic mounds "5–40 m wide and with up to 4m of synoptic relief" locally "encrusted with layers of bladed, isopachous marine cement which may compose up to 50% of the bioherm". At the Groot Boetsap River section, 45 km WNW of Warrenton, South Africa, a 135 m section of Cambrellrand-Malmani carbonates shows elongate stromatolite mounds up to 10 m wide, 40 m long and 2.5m relief dominated by crinkled lamination with good inheritance (TRUSWELL & ERICKSSON, 1973, p. 6, fig. 3) (Fig. 13).

Where well-preserved microstructures are documented, these large domes often appear to be characterized by Sparry or Hybrid Crusts. SAMI & JAMES (1996, p. 217) emphasized the importance of "spar-micrite couplets" in Pethei subtidal stromatolites, and in the late Mesoproterozoic Burovaya PETROV & SEMIKHATOV (2001, fig. 6, p. 269) noted that "cement-based microstructures" interlayered with clotted micrite create parallel lamination that "is remarkable in the giant dome facies for its smoothness and lateral extent". It seems reasonable to infer that, in addition to providing increased strength and stability, a significant abiogenic Sparry Crust component enhanced stromatolite accretion, contributing to their size and relief. Conversely, it appears possible that few if any of the impressively large stromatolites that dominate the shallow subtidal areas of Proterozoic carbonate platforms was solely composed of lithified microbial mat.

At the present-day, coarse grained agglutinated stromatolites (RIDING, 1991, p. 30) can have metric dimensions, as at Lee Stocking Island (DILL et al., 1986), but none is known that compares in size with the largest Precambrian domes. Nonetheless, there are Phanerozoic examples where stromatolite size has increased with evaporative conditions. For example, metric domes occur in association with gypsum deposits in the mid-Miocene of the eastern Ukraine (PERYT et al., 2004, fig. 4). Dolomitized laminar crusts, usually regarded as stromatolites and often associated with early marine cements, form large reefal masses in the Late Permian Zechstein carbonate-evaporite cycles of northern Europe (PAUL, 1995), and POPE et al. (2000, p. 1143) drew attention to the similar age "very thinly and evenly laminated" metric stromatolites associated with evaporites in the Zechstein Basin of northeast England.

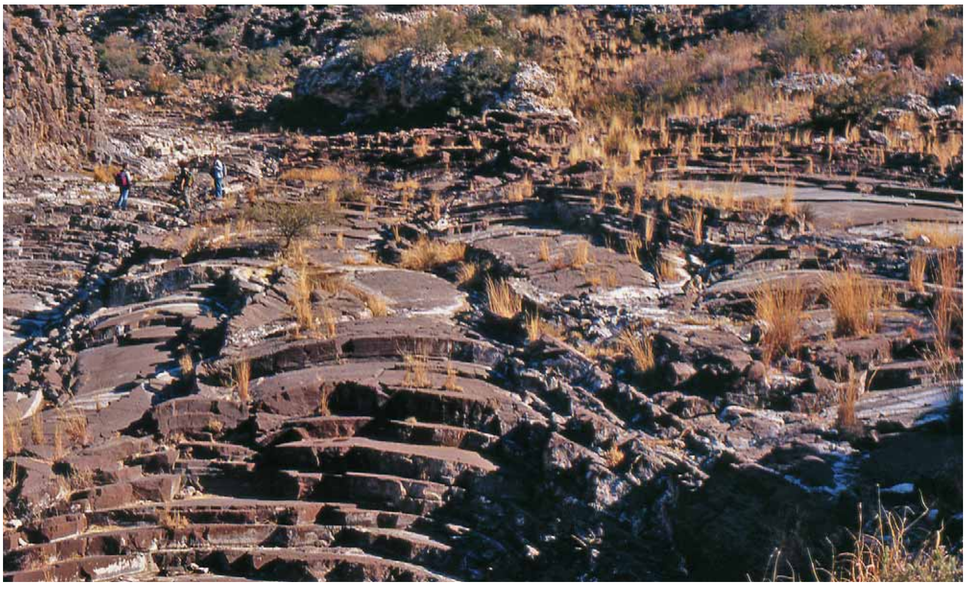

Figure 13: Stromatolite domes, tens of metres in extent, elongated in direction of view. Late Archaean Campbellrand-Malmani platform, dry bed of Groot Boetsap River, South Africa. Note generally even layers and good inheritance, even at this scale. Persons at upper left indicate size.

3.4. NATURE OF ARCHAEAN STROMATOLITES

Whether giant Archaean domes, such as those in Steep Rock and Campbellrand-Malmani carbonates, are also largely Hybrid Crusts remains uncertain. Their relatively even layering and good inheritance suggest that they are likely to be Hybrid and/or Sparry crusts. However, their microfabric preservation is generally poor and even in the relatively well-preserved Cambellrand-Malmani carbonates the nature of the Boetsap laminae that are major components of the large domes is unclear. SUMNER & GROTZINGER (2004, p. 16) concluded that some elongate stromatolite mounds contain "a significant component of clastic carbonate" whereas others, especially those better preserved, have "more precipitated textures". But whether this was microbially mediated or essentially abiogenic is uncertain. Thus, Campbellrand-Malmani giant domes may have been Hybrid Crusts; but there is also the possibility that they are more completely abiogenic.

Coniform stromatolites in the Warrawoona Group (~3.45 Ga) of Western Australia show fine continuous laminae (LOWE, 1980, 1983) and sparry microfabrics (HOFMANN et al., 1999, fig. 3), although these could well be secondary (HOFMANN et al., 1999, p. 1259). The origins of Pilbara stromatolites have been debated (e.g., LOWE, 1994, 1995; BUICK et al., 1995). HOFMANN et al. (1999, p. 1260–1261) argued that examples ~50 km west of Marble Bar should be regarded as having "a biogenic component" based on features such as greater uniformity of laminae in the columns than in intervening areas, second-order corrugation that appear to have accreted upward, continuity of non-isopachous laminae, extensive regular development, steep slopes – often >40° and up to 75° – not known to be formed abiogenically. ALLWOOD et al. (2006, p. 717) supported a biogenic origin, including in their reasoning the difficulty of accounting abiogenically for both the conical shape and the non-isopachous layering which has produced parallel-sided pseudocolumns, and also the more variable interspace laminae. Furthermore, the only known present-day analogues for coniform stromatolites are structures formed by the influence of "vertically motile" microbes in hot springs such as Yellowstone (WALTER et al., 1976; ALLWOOD et al., 2006, suppl. notes, p. 16). Thus, although some of these Pilbara structures superficially resemble isopachous laminites, they could differ from them in significant details: specifically conical form and non-isopachous laminae with near vertical rather than upward expanding margins to the pseudocolumns. Some Pilbara stromatolites show well laminated interspaces (see HOFMANN, 2000, fig. 3b), suggesting that these as well as the cones were seafloor crusts. Perhaps the outstanding question is whether coniform structures with vertical margins really cannot be produced by abiogenic precipitation.

3.5. SECULAR CHANGES AND CONTROLS

GROTZINGER & KASTING (1993, p. 235, figs. 1, 2) pointed out that "massive, thick beds of marine cements", common in the Late Archaean, gave way to "microdigitate stromatolites (tidal-flat marine cement crusts)" in the Palaeoproterozoic, and to "micritic whitings" in the Neoproterozoic. They argued that "prolific precipitation of aragonite as giant botryoids up to 1 m in radius and magnesian calcite as stratigraphic sheets up to several meters thick" in the Archaean reflected elevated over-saturation for $CaCO_3$ that subsequently declined over geological time (GROTZINGER & KASTING, 1993, 235–236). Subsequent research provided further details of this significant long-term trend (GROTZINGER & KNOLL, 1995; KAH & KNOLL, 1996; SAMI & JAMES, 1996; SUMNER & GROTZINGER, 1996a, b). On an even larger time-scale, JAMES et al. (1998, JSR) suggested that carbonate sedimentation was respectively dominated by massive seafloor precipitates (Archaean-Palaeoproterozoic), molar-tooth mudstones and grainstones (Meso-Neoproterozoic), and burrowed and fossiliferous limestones (Phanerozoic).

In this context it seems possible that the early-mid Proterozoic importance of Hybrid Crust stromatolites coincided with long-term transition from dominance of Sparry Crusts on Archaean seafloors to the rise to prominence of Fine-grained stromatolites and thrombolites in the Neoproterozoic. It may even be speculated that conditions favouring abiogenic Sparry Crust precipitation in the late Archaean tended to inhibit microbial growth and substrate colonization, and that Hybrid Crusts developed as these conditions gradually became more favourable to microbial growth. Perhaps conditions that alternately favoured microbial growth and abiogenic precipitation fluctuated at relatively regular intervals, perhaps even seasonally. As Sparry and Hybrid crust stromatolites declined, Fine-grained Crust stromatolites, together with thrombolites, increased and probably become dominant during the Neoproterozoic. From the mid-Mesoproterozoic onward they locally contain conspicuous – presumably cyanobacterial – filamentous fabrics.

The key long-term secular control on Sparry Crust development during the Archaean and Proterozoic has long been suggested to be seawater chemistry and its effect on carbonate nucleation and precipitation (GROTZINGER, 1990; GROTZINGER & KASTING, 1993; SUMNER & GROTZINGER, 1996a). Hybrid Crust development can be integrated with this view. As seawater carbonate saturation declined, Sparry Crusts declined and Fine-grained Crusts increased, and during this long transition Hybrid Crusts were volumetrically abundant. In addition, cyanobacterial sheath calcification could reflect induction of CO_2-concentrating mechanisms in response to declining atmospheric CO_2 level, and this may have been primarily responsible for the mid-Proterozoic appearance of widespread filamentous microbial fabrics in stromatolites and thrombolites (RIDING, 2006; KAH & RIDING, 2007). Thus, long-term patterns of stromatolite and thrombolite fabric development may be intimately related to large-scale changes in ocean-atmosphere composition.

Conditions of Sparry Crust formation, especially rapid accumulation, may have tended to inhibit microbial growth and colonization. As these conditions reduced, Sparry and Fine-grained crusts may increasingly have interacted to develop Hybrid Crust. Lithified microbial mat stromatolites may therefore have antecedents in Hybrid Crusts that formed in environments of intense seafloor carbonate precipitation. Certainly it appears that many stromatolites older than ~1000 Ma differ from present-day normal marine stromatolites characterized by Fine-grained Crust. Conversely, marine Sparry Crusts, as both stromatolitic and other deposits, have been generally scarce since the Mesoproterozoic (SUMNER & GROTZINGER, 2004, p. 2). However, they redeveloped briefly in Cap Carbonates associated with rapid Neoproterozoic deglaciation events (e.g., GROTZINGER & JAMES, 2000, fig. 7; SUMNER, 2002; NOGUEIRA et al., 2003) and also at times during the Phanerozoic when "massive carbonate precipitation was favored" (GROTZINGER & KNOLL, 1995, p. 578). POPE et al. (2000, p. 1139) suggested that isopachously laminated stromatolites "are dominated by chemogenic precipitation in the absence of microbial mats" and are "best developed atop Proterozoic and Paleozoic carbonate platforms that underlie major evaporite successions". Among several examples, they cited coatings on reefs in the Silurian Michigan Basin, and also Late Permian crinkly stromatolites noted by SMITH (1981) from the Zechstein Basin of northern Europe (POPE et al., 2000, table 1, figs. 7, 9). They described the Michigan isopachous stromatolites as commonly having "radial fibrous texture" (POPE et al., 2000, p. 1142) which suggests that they are Sparry Crust, but the precise nature of the "crinkly" Zechstein stromatolites remains uncertain.

4. SUMMARY

Seafloor carbonate crusts. Petrographic classifications emerging from the "carbonate revolution" of the 1950's (e.g., FOLK, 1959; DUNHAM, 1962) were primarily focused on Phanerozoic marine examples. Extensive research since then has shown that Precambrian seafloor carbonate crusts comprise a wide variety of deposits that accreted at the sediment-water interface at depths ranging from intertidal to deep subtidal. They occur as irregular sheets and also as domes and columns, some of which are decametric in scale. Based on the information reviewed here, six categories can be recognized (Table 1) of which four (Fine-grained Crust, Sparry Crust, Hybrid Crust, Sparry Crust plus Grains) include at least some examples that have been regarded as stromatolites. Interpretations based on partial present-day analogues suggest that Fine-grained Crust is lithified microbial mat, Sparry Crust is essentially abiogenic precipitate, Hybrid Crust is a mixture in which microbial mat and abiogenic crusts alternate, and Sparry Crust plus Grains forms where relatively large grains are incorporated into abiogenic crust (Fig. 14).

Fine-grained Crust is dominated by micritic and microsparitic (dense, clotted, peloidal, filamentous) microfabrics. These may contain fenestrae and incorporate allochthonous grains. In older examples micritic fabrics have often aggraded to microspar. It forms diverse stratiform, domical and columnar stromatolites with relatively uneven to discontinuous layers that usually show poor inheritance. It is also a key component of thrombolite. In the Proterozoic, Fine-grained Crust is interleaved with Sparry Crust to form Hybrid Crust. In addition, it is the dominant components of many, usually relatively small (typically centimetric–decimetric) stromatolitic domes, columns and layers. Palaeoproterozoic examples of these are less well-known, possibly due to poor fabric preservation. Fine-grained Crust thrombolites are relatively widespread in the Neoproterozoic. Present-day analogues of Fine-grained Crust are diverse as lithified microbial mats in non-marine and marine environments (see Analogues). On this basis, Proterozoic Fine-grained Crust is interpreted as an essentially biotic deposit resulting from *in situ* microbial mediation of carbonate precipitation, locally augmented by incorporation of allochthonous grains.

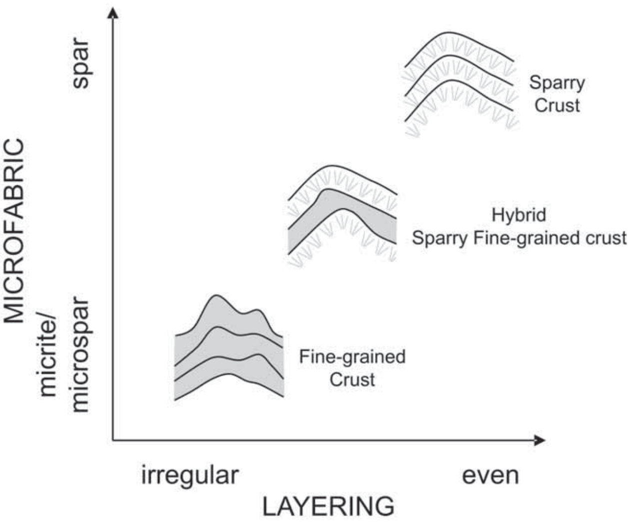

Figure 14: Key features of crust discrimination, based on microfabric (fine-grained or sparry) and layer arrangement (irregular, poor inheritance; even, good inheritance).

Sparry Crust has coarsely crystalline, often radial-fibrous, microfabric. Examples include large and small radial botryoids and crystal pseudomorphs, microdigitate stromatolitic "tufa", dendrite, isopachous laminite, and herringbone calcite. These variously form domes, vertical crystal growths, and extensive layers. At least two categories, microdigitate "tufa" and isopachous laminite, create structures that have been generally regarded as stromatolites. These Sparry Crust stromatolites are characterized by even, often isopachous, laterally persistent layers with good inheritance, and have been most widely recognized in the Palaeoproterozoic and Mesoproterozoic, with microdigitate forms occupying peritidal environments and isopachous laminite relatively deeper water facies. Large subaqueous Sparry Crust domes, comparable with those of the Proterozoic, are not known at the present-day. Nonetheless, there is a wide variety of potential present-day analogues for Sparry Crust fabrics in smaller scale deposits, e.g., speleothem flowstone, and hot-spring travertine crystalline crust (see Analogues). These analogues suggest that Sparry Crust is essentially abiogenic, in the sense that its formation does not require biotic processes and that it does not typically contain organically generated fabrics. Nonetheless, it can incorporate and veneer organisms and organic material.

Sparry Crust has often been termed "seafloor cement", although it has been pointed out that this conflicts with the general usage of cement as precipitate between grains and within voids (GROTZINGER & KNOLL, 1995, p. 579). It has also been referred as "seafloor crusts" and "inorganic crusts" (GROTZINGER & KNOLL, 1995, p. 578–579), "encrusting beds" (of bladed and herringbone calcite) and "microbialites coated by cements" (SUMNER & GROTZINGER, 1996a), "abiotic marine crusts" (GROTZINGER & KNOLL, 1999, p. 343), "encrusting marine cement directly on the growing stromatolite" (GROTZINGER & KNOLL, 1999, p. 329–330), "seafloor-encrusting marine cement" (POPE et al. 2000, p. 1145), and "seafloor encrustations" (SUMNER, 2002). Of the four general categories of subaqueous Sparry Crust recognized here, based on Precambrian examples (Table 1), three include stromatolitic deposits: (i) Botryoidal fans and crystal pseudomorphs include small radial fibrous millimetric microbotryoids that build *Tarioufetia* and *Tungussia* (BERTRAND-SARFATI, 1972); (ii) microdigitate stromatolites: small laminated columns of radial crystals (GROTZINGER & READ, 1983; HOFMANN & JACKSON, 1987); (iii) isopachous laminite (JACKSON, 1989, SUMNER & GROTZINGER, 2004). In addition, thin (millimetric and submillimetric) Sparry Crust interlayered with Fine-grained Crust is an integral component of Hybrid Crust (see below).

Hybrid Crust typically consists of light-dark, often millimetric, alternations of Sparry and Fine-grained crust. It builds stromatolites with well-developed even, although not usually isopachous, layering that is laterally quite persistent with generally good inheritance. This layering is therefore intermediate in regularity between that for Sparry Crust stromatolites and Fine-grained Crust stromatolites. Hybrid Crust appears to be a major component of Palaeoproterozoic and Mesoproterozoic stromatolites, which can include very large domical and conical examples. For example, metric to decametric stromatolite domes of Hybrid Crust are prominent components of some Palaeoproterozoic (e.g., Pethei Group) and Mesoproterozoic (e.g., Burovaya Formation) shallow subtidal carbonate platform sequences. Hybrid Crust exhibits a variety of Fine-grained Crust microfabrics, and filamentous microfabric is locally common in Hybrid Crusts from the mid-Proterozoic onward. Light-dark millimetric alternations typical of Hybrid Crust have long been recognized in many Precambrian stromatolites (e.g., VOLOGDIN, 1962; HOFMANN, 1969, fig. 13), particularly in coniform examples (e.g., KOMAR et al., 1965; WALTER, 1972, pls. 5, 6, 10, 12). For example, BERTRAND-SARFATI et al. (1994) noted that microstructure consisting of alternations of micrite-microspar laminae "is one of the most frequently found in Proterozoic stromatolites". In the Pethei Group, SAMI & JAMES (1994, p. 113; 1996, p. 217) emphasized the widespread importance of "spar-micrite couplets", which are generally 1–2 mm thick, and comprise two broad groups: "laminar fibrous crusts" interlayered with micritic laminae (*idem*, fig. 6d) and "clotted micrite precipitates arranged in vertical pillars and surrounded by fibrous and blocky precipitates" (*idem*, fig. 7a,b). Laminar fibrous crusts are here regarded as a possible hybrid form of isopachous laminite, and clotted micrite pillars are grouped with "bushy" microfabrics. KNOLL & SEMIKHATOV (1998), BARTLEY et al. (2000) and PETROV & SEMIKHATOV (2001) also drew attention to the contrast between fibrous and micritic synsedimentary precipitates in Proterozoic stromatolites.

Large subaqueous Hybrid Crust domes, comparable with those of the Proterozoic, are not known at the present-day, but potential analogues for their fabrics occur in freshwater stromatolites (see Analogues). These examples tend to support the SAMI & JAMES' (1994, p. 120) suggestion that spar-micrite couplets reflect alternation of "cement precipitation and microbial mat growth". Furthermore, layered alternations could reflect secular changes that in some cases may be seasonal (BERTRAND-SARFATI, 1972, pl. 11(4), pl. 22(2)). In present-day fluviatile examples, the dark – microbial – layers often have filamentous fabric produced by filamentous cyanobacteria. In the Proterozoic, Hybrid Crust appears to be responsible for some of the largest stromatolites known, with decametric dimensions. The size of these deposits might rapid accretion amplified by combined effects of abiogenic precipitation and microbial growth. However, interpretation of Hybrid Crust can be complicated by poor preservation that hinders discrimination between detrital and microbial micrite, and blocky and radial spar (SAMI & JAMES, 1994, p. 120). In particular, it can be difficult to decide (i) whether fine-grained carbonate represents primary silt- or micrite-grade material; (ii) whether it is detrital or precipitated, (iii) the extent to which spar is void-filling or precipitated directly on the seafloor, and (iv) the precise origins of putative microbial fabrics that may be clotted, peloidal, bush-like fabrics or filamentous.

Three broad categories of "spar-micrite couplet" are recognized here, according to the dominant fine-grained fabric: (i) relatively dense, but also peloidal, microcrystalline carbonate with either generally even and extensive laminae or uneven and discontinuous laminae, (ii) clotted-bushy-peloidal micrite, (iii) filamentous. These categories can intergrade and co-mingle, both in terms of components and of laminar evenness and continuity. Their discrimination is highly dependent on the quality of fabric preservation; micrite may be present locally (e.g., Pethei, SAMI & JAMES, 1996, p. 203) but even so is often converted to microcrystalline spar (SAMI & JAMES 1996, p. 210) and in other cases is absent or hard to recognize in others (e.g., Campbellrand-Malmani, SUMNER & GROTZINGER, 2004, p. 8). These categories should be regarded as preliminary generalizations, and the examples selected require further comparison and probably subdivision.

Sparry Crust plus Grains. Intercalation of Sparry Crust with allochthonous grains may prove to be a common deposit, but it has relatively rarely been reported. Nonetheless, stromatolitic examples from the Mesoproterozoic, in which radial fibrous sparry crust is interleaved with draped layers of silt and sand, have been given formal names, e.g., *Gongylina*, *Omachtenia* (SEMIKHATOV & KNOLL, 1998, figs. 9–11). These alternations of Sparry Crust precipitation with grainy sedimentation probably have partial analogues in hot-spring travertine and cave flowstone (see Analogues).

Abiogenic and biogenic stromatolites. Awareness of the existence of abiogenic stromatolites, emphasized by POPE et al. (2000), has led to uncertainties regarding stromatolite definition and interpretation and has made it difficult to assess their significance as indicators of both early life and environments. As CORSETTI & STORRIE-LOMBARDI (2003, p. 649) noted, "it has been underappreciated that inorganic processes can produce stromatolites", and PERRY et al. (2007, p. 169) recognized the need to discriminate between microbial stromatolites and abiotic carbonate crusts. POPE et al. (2000, p. 1149) showed the way forward by regarding "thinly laminated isopachous stromatolites" as largely abiotic. The overview presented here suggests that Precambrian stromatolites include not only essentially abiogenic (Sparry Crust) and lithified microbial mat (Fine-grained Crust) examples, but also intimate mixtures of the two (Hybrid Crust). Nonetheless, despite these complexities it seems likely that many Proterozoic stromatolites retain sufficient structural and fabric information to be distinguished as either Sparry, Hybrid or Microcrystalline crust. This may also apply to well-preserved Archaean stromatolites. If this is correct then it should be possible to use these distinguishing features to further elucidate the history of Precambrian stromatolites and increase understanding of their significance as environmental and biological indicators of past life and conditions.

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