The Nature of Stromatolites: 3,500 Million Years of History and a Century of Research

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1 Introduction

Stromatolites are widely regarded as layered, early lithified, authigenic microbial structures – often domical or columnar in form – that developed at the sediment water interface in freshwater, marine and evaporitic environments (Fig. 1). In addition to this unusually wide environmental distribution, the exceptionally long geological record of stromatolites spans at least 3,500 million years (Ma) (Vologdin 1962; Hofmann 1969, 1973; Walter 1976a; Grotzinger and Knoll 1999; Riding and Awramik 2000). Most of these examples, together with those described by Kalkowsky (1908), are essentially originally carbonate in composition. More than a century of research has revealed many details of their diverse fabrics and complex history, but much still remains to be understood about stromatolites. This is not surprising considering their wide distribution in time and space; and it helps to account for a continuing problem with their definition. Kalkowsky (1908) considered stromatolites to be microbial sediments, but it has become increasingly difficult to maintain this view for all ancient examples, especially those more than ~1,000 Ma old. The aim of this article is to evaluate progress in understanding what stromatolites are, since they were first described in the 1800s. This makes it impossible to avoid the thorny problem of how they should be defined.

The nature and definition of stromatolites have been persistent difficulties ever since Kalkowsky introduced the name. At first, the main question posed was "are stromatolites biogenic or abiogenic?" With time, the focus has shifted to whether all stromatolites are biogenic, or whether some are biogenic while others are abiogenic. Kalkowsky's (1908) microbial interpretation of stromatolites was

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Fig. 1 Loaf-shaped stromatolite in oolite. Early Triassic, Bernburg Fm, Heeseberg Quarry, Jerxheim, 50 km west of Magdeburg, Germany. Width of view 1.6 m

immediately challenged by the suggestion that they are abiogenic precipitates (Reis 1908). The subsequent century of research provided support from present-day and ancient examples for both of these views. In particular, persuasive evidence that some Precambrian stromatolites are essentially abiotic seafloor crusts grew out of pioneering studies of early Proterozoic examples in Canada (e.g., Kerans 1982; Grotzinger and Read 1983).

The challenge of defining stromatolites reflects the diversity and complexity of the structures they represent. The scarcity of present-day marine analogues for abiogenic seafloor crusts (Grotzinger and James 2000a, p. 9), such as those that occur in the Palaeoproterozoic, has hindered appreciation of the inorganic processes that can produce marine structures that have been described as stromatolites (Pope et al. 2000, p. 1149; Corsetti and Storrie-Lombardi 2003, p. 649; Perry et al. 2007, p. 169). The marine stromatolite record can be read as long-term change from less to more biogenic (Grotzinger and Kasting 1993, p. 235; Kah and Knoll 1996, p. 81; James et al. 1998). As a result, the time period from which stromatolites are viewed is critically important. It is not difficult to regard most Phanerozoic examples as essentially lithified microbial mats. In contrast many Precambrian examples regarded as stromatolites, especially those older than ~1,000 Ma, appear to contain, and in some cases entirely consist of, precipitated abiogenic crust. Furthermore, there is evidence that many late Archaean and early Proterozoic stromatolites consist of intimate interlayering of both lithified microbial mat and essentially abiogenic precipitated crust (Bertrand-Sarfati 1972, p. 155; Sami and James 1996, p. 217; Petrov and Semikhatov 2001, fig. 5a, b; Riding 2008, p. 95) that has been termed Hybrid Crust (Riding 2008). Interpretation of these deposits is hindered – especially in very old deposits – by recrystallization, but even in the Neoarchaean, relatively well-preserved examples retain clear indications of even and laterally very continuous layers that appear to consist of thin alternations of sparry and microcrystalline fabrics (Sumner and Grotzinger 2004, fig. 3). These “Boetsap laminae”, named after a locality on the Boetsap River in South Africa, could be Hybrid Crust stromatolites (Riding 2008, p. 84) (Fig. 2). If so, Hybrid Crust is likely to be a major component of late Archaean and early Proterozoic

Fig. 2 Broad flat-topped stromatolite domes separated by a narrow shallow steep-sided depression. The well-developed layering is even and smooth, and can be traced from dome to dome across the intervening depression. Late Archaean Campbellrand–Malmani platform, Groot Boetsap River. South Africa. Width of view ~1.5 m

stromatolites. Boetsap laminae stromatolites are widespread in the extensive Neoarchaean Campbellrand-Malmani carbonate platform (Sumner and Grotzinger 2004, pp. 14–15).

Taking the long history of stromatolites as a whole, this suggests that some stromatolites are biogenic (e.g., lithified microbial carbonate), others are abiogenic precipitated crust, and that some are hybrid mixtures of the two. The concept of abiogenic stromatolites is not new. Logan et al. (1964, pp. 68–69), for example, recommended recognition of "inorganic stromatolite". The problem it presents is that it broadens the term stromatolite to potentially include speleothem and hot spring sinters, deposits that have not generally been regarded as stromatolites. As Walter (1976b, p. 1) recognized, if stromatolite definition is "so broad as to include a wide-range of non-biogenic structures" . . . "the term would cease to be useful". Here layered authigenic microbial and hybrid crusts – but not abiogenic crusts – are regarded as stromatolites. A definition is proposed: *Stromatolites are macroscopically layered authigenic microbial sediments with or without interlayered abiogenic precipitates*.

This definition avoids the difficulty of encompassing abiogenic sinter within stromatolite. However, Hydra-like, and characteristic of stromatolite studies, it raises new challenges. If stromatolites are not biogenic, then how are ancient examples to be distinguished from abiogenic crusts and, specifically, what criteria can be used to confidently establish biogenicity? These are the perennial problems that led Logan et al. (1964), for example, to recognize abiogenic stromatolites. I suggest that it is now possible to use macro- and microfabric details to distinguish microbial and Hybrid Crust stromatolites from abiogenic crusts, where they are sufficiently well-preserved.

2 Stromatolites and Spongiostromids

2.1 Stromatolith

Kalkowsky (1908) introduced the term *Stromatolith* – layered stone – to describe columns and domes of well layered carbonate within beds of Early Triassic lacustrine oolite that occur near the Harz Mountains of northern Germany (see Paul and Peryt 2000) (Fig. 3). Bowl-shaped weathering products of these near Winnrode (probably Wienrode – near Blankenburg on the northern edge of the Harz) had earlier been called *Napfstein* (bowl-stone) (Naumann 1862, p. 741; Kalkowsky 1908, p. 69). Kalkowsky (1908, p. 125) suggested that *Stromatolithe* were formed by "*niedrig organisierte pflanzliche Organismen*" (simply organized plant-like organisms). In essence, he regarded stromatolites as laminated microbial structures (Riding 1999, p. 323), and he held a similar view for the ooids with which they are associated (Kalkowsky 1908, p. 68). But he was not the first to propose a general name for the structures that came to be termed stromatolites. Examples with well-preserved spongy microstructures in the Mississippian (Viséan) of Belgium had been named *spongiostromides* by Gürich (1906), who had placed them in new genera such as *Pycnostroma* and *Spongiostroma*. Gürich (1906) thought they were protozoans. Heim (1916, p. 566) introduced the term oncoid (*onkos* – nodule) for grains in the Jurassic of Switzerland. Pia (1927, pp. 36–37) may have intended to reflect the priority of Gürich's work over Kalkowsky's when he classified "Stromatolithi" and "Oncolithi" as sub-groups within the Spongiostromata, but this usage did not gain support. Instead, stromatolite became widely adopted as the general term, whereas spongiostrome is now (and more rarely) used to refer to the distinctive clotted fabrics found in many Phanerozoic stromatolites.

2.2 Eozoön, Cryptozoon, Archaeozoon

Furthermore, neither Kalkowsky nor Gürich was the first to recognize the structures that came to be called stromatolites. Similar, and also geologically older, examples

Fig. 3 Contact of oolite/ pisolite (*left*) and stromatolite dome (*right*). Early Triassic, Bernburg Fm, Heeseberg Quarry, Jerxheim, 50 km west of Magdeburg, Germany

had long been recorded in North America. Steele (1825, pp. 17–18, pl. 2) described specimens in the Late Cambrian of New York State as "calcareous concretions" (Fig. 4). These were later named *Cryptozoon* by Hall (1883) (Fig. 5) who regarded them as the skeletons of simple animals. This opinion reflected Dawson's (1865) interpretation of *Eozoön*, from the Proterozoic of Québec, as a giant foraminifer. Dawson's claim of evidence for life in such ancient rocks attracted both interest and controversy. The "most instructive specimens of *Eozoön*", noted by Dawson (1876), are alternating laminae of serpentine or pyroxene and calcite in Grenvillian contact metamorphosed limestone from near Ottawa (Dawson 1865) (Fig. 6). *Eozoön* was keenly debated for many years and by the late 1900s most specimens were generally thought to be inorganic (O'Brien 1970; Hofmann 1971, p. 12; Adelman 2007).

Fig. 4 Engraving of Late Cambrian stromatolites at Saratoga Springs, New York State, described as "calcareous concretions" (Steele 1825, p. 18, pl. 2). Compare Fig. 5

Fig. 5 Horizontal outcrop section of the stromatolite described by Steele (1825) and named *Cryptozoon proliferum* by Hall (1883), showing irregular and impersistent layering. Late Cambrian, Hoyt Limestone, Petrified Gardens, 5 km W. Saratoga Springs, New York State. Width of view ~2 m. Compare Fig. 4

Nonetheless, Dawson's idea that layered domes could be animal remains was perpetuated in the *zoon* suffix of the names given to other broadly similar specimens, such as *Cryptozoon* (Hall 1883). At the time that Dawson was studying *Eozoön*, Bell (1870, p. 324) was describing Palaeoproterozoic Gunflint stromatolites (Fig. 7) in western Ontario as "small coral-like siliceous concretions" that "show fine concentric rings" (see Hofmann 1969, p. 5). Similar "concentric nodular masses" were discovered by Bailey and Matthew (1872) in the Proterozoic of New Brunswick. Matthew (1890a) named them *Eozoön acadiense*, but immediately changed this to *Archaeozoon* (Matthew 1890b). These specimens resemble *Baicalia* and similar taxa

Fig. 6 *Eozoön canadense*, showing domical layering consisting of alternations of serpentine (*dark*) and calcite (*light*). Mesoproterozoic, Côte St. Pierre, north of Papineauville, 55 km ENE of Ottawa, Canada. GSC specimen 1992-234B collected by T.C. Weston (see Dawson 1876). Width of view ~11 cm. Photograph courtesy of Brian Chatterton

Fig. 7 Contact of silicified stromatolite dome (*right*) and adjacent *red-brown* carbonates. Basal Gunflint Formation, Palaeoproterozoic (1,880 Ma), 1 km. of Kakabeka Falls, Ontario, Canada

(Hofmann 1971, p. 58). Thus, Kalkowsky (1908) was neither the first to describe stromatolites nor to propose a general name for them, although of course he did create the name stromatolite that has been universally adopted. He may have been the first to regard them as microbial, although not by very long, because 6 years later Walcott (1914) compared them with cyanobacterial tufa.

3 Stromatolites as Lithified Microbial Mats

Understandably, interpretation of stromatolites has been closely linked to present-day deposits that could shed light on their origins. Although it is not clear exactly what reasons led Kalkowsky (1908) to regard stromatolites as microbial, they may include the close association of stromatolites with ooliths (which Kalkowsky named Ooide). At the time of Kalkowsky's (1908) article there was already an extensive literature suggesting that ooliths and similar grains might be organic (e.g., Linck 1903). This view was pioneered by Rothpletz (1892) who had found coccoid cyanobacteria in Great Salt Lake ooliths. A role for cyanobacteria in carbonate precipitation was further supported by Walcott's (1914) comparisons of *Collenia* and *Cryptozoon* with present-day lacustrine tufas. During the half-century or more since Kalkowsky's (1908) and Walcott's (1914) articles, the search for present-day analogues led from cool-water calcareous freshwater lakes and streams to subtropical marshes and shorelines, tidal flats and, eventually, deeper marine environments. It provided irrefutable evidence linking many ancient stromatolites, especially those in marine Phanerozoic environments, to lithified microbial mats.

3.1 Cyanobacterial Lacustrine Tufas

C.D. Walcott, studying Proterozoic sediments in the western United States, had found Neoproterozoic specimens at Nankoweap Butte in the Grand Canyon (Walcott 1895, p. 319) that he regarded as stromatoporoids, but which Dawson (1896, p. 208) thought were *Cryptozoon* and compared to foraminifers (Dawson 1896, pp. 211–212). Walcott (1906) encountered more examples as he extended his studies to the Mesoproterozoic of Montana, and he described them as new genera, including *Collenia*, named after a rancher in the Big Belt Mountains (Walcott 1914, p. 111). Walcott had seen *Cryptozoon* much earlier at Saratoga Springs in 1878 (Schopf 1999, p. 25; Lindemann and Yochelson 2005) but did not adopt the view that it was of animal origin. Instead, he compared it with present-day freshwater tufas in lakes in New York State (Walcott 1914) (Fig. 8). He argued that Proterozoic and Cambrian *Collenia* and *Cryptozoon* were "deposited through the agency of algae similar in type and activity to the (Cyanophyceae) Blue–green Algae" (Walcott 1914, p. 100). Therefore, although he appears to have been unaware of Kalkowsky's work and of the name *Stromatolithe*, Walcott's (1914) comparisons with tufa provided the first present-day support that stromatolites could be microbial. This was also the first

Fig. 8 Freshwater lacustrine microbial tufa domes, broadly similar to deposits in Green Lake, New York State, that C.D. Walcott (1914) compared with Mesoproterozoic stromatolites. Poza Azul, 8 km south-west of Cuatro Ciénegas, Coahuila, northern Mexico. Domes are ~0.5 m high

link between stromatolites and cyanobacteria: a connection confirmed by many subsequent researchers. It stimulated further studies, such as Roddy's (1915) of tufas in Little Conestoga Creek, Pennsylvania. Immediately, Wiman (1915) described late Proterozoic *Collenia* in Sweden as "cyanophycean", although Hadding (1927) subsequently regarded this specimen as inorganic (Vidal 1972).

3.2 Andros Marsh

Nearly 20 years after Walcott's comparison with tufa, the stromatolite connection with cyanobacteria was strongly reinforced by Black's (1933) study of laminated "blue-green algal" deposits at the margins of lakes and tidal creeks on Andros Island in the Bahamas. These both supported and differed from Walcott's approach. Although Black did not refer to Walcott, he new Roddy's work and pointed out that Andros mats do not closely resemble freshwater tufas, which generally show much stronger early lithification. Black's (1933) examples are relatively poorly lithified and he commented that they are "best developed in regions of low salinity", adding that Andros examples have little in common with the "hard, stony cyanophyceous limestones" that form in hardwater lakes and streams such as those described by Roddy (1915) (Black 1933, p. 185, p. 191). He wrote, perhaps with some understatement, that "Bahamian sediments show a certain resemblance" to "Precambrian and early Palaeozoic stromatolites" (Black 1933, p. 186). Some Andros mats are much more similar to Walcott's (1914) Mesoproterozoic Belt stromatolites than are freshwater tufas. This can be seen by comparing Black (1933, fig. 3) and Monty (1972, fig. 22) with *Collenia undosa* (Walcott 1914, pl. 13). Black's (1933) work provided support for a microbial interpretation at a time when there was considerable doubt about stromatolite biogenicity (e.g., Seward 1931). As a result, Fenton (1943, p. 95) was able to summarize "several lines of evidence which indicate that stromatolites are both organic and algal". Further, and unexpected, support for a cyanobacterial interpretation of stromatolites later came from some very old examples, when silicified cyanobacteria were reported in Palaeoproterozoic Gunflint stromatolites (Tyler and Barghoorn 1954; Barghoorn and Tyler 1965) (Fig. 7).

3.3 Coarse-Grained Thrombolitic Stromatolites

Black's specimens came from ponds and tidal creeks in the interior of northern Andros Island and, at most, are only marginal marine (Black 1933, p. 191). The search for marine stromatolites and oncoids was pursued in back-reef environments in Florida (Ginsburg et al. 1954; Ginsburg 1960) and Andros (Monty 1965), but these specimens too were mainly poorly lithified (Monty 1972, p. 745). Breakthrough came with the discovery of large (generally up to ~0.5 m high) well lithified microbial domes and columns along the shoreline of seasonally hypersaline Shark Bay in Western Australia (Fig. 9). These now famous stromatolites were noted by geologists in 1954 (Playford and Cockbain 1976, p. 389), and described by Logan (1961) who emphasized their cyanobacterial mats and resemblance to *Cryptozoon*. The columns on the beach at Shark Bay are thought to have formed subtidally and then been exposed by recent relative sea-level fall (Playford and Cockbain 1976, p. 399). Externally these columnar microbial carbonates can closely resemble some

Fig. 9 Individual and laterally amalgamated thrombolitic stromatolite columns, ~50 cm high. Intertidal zone, Carbla Point, Hamelin Pool, Shark Bay, Western Australia. Photograph courtesy of Eric Mountjoy

very ancient examples such as 1,800 Ma Pethei elongate columns (Hoffman 1989, fig. 9b), but internally they are often less well layered and coarser grained. Crudely layered columns at Shark Bay, illustrated by Logan (1961, pl. 1, fig. 4) and described by Aitken (1967, p. 1171) as "thrombolitic stromatolites", are largely composed of fine sand (Logan et al. 1974).

Large columnar and domical stromatolites are very rare in present-day marine environments. Apart from Shark Bay, the only other region in which they have been reported are the Bahama Banks (Dravis 1983; Reid et al. 1995, 2000), where they are especially well-developed in the tidal channel between Lee Stocking Island and Norman's Pond Cay in the Exuma Cays (Dill et al. 1986; Riding et al. 1991a) (Fig. 10). Shark Bay and Lee Stocking columns occur in wave- and current-swept environments. Their formation can be attributed to factors that include the mat communities, water movement, and grainy conditions. Strong waves and currents raise sand to the accreting mat surface, and the grainy environment deters overgrowth by reefal encrusters (Dill et al. 1989, p. 10). Seasonal hypersalinity at Shark Bay also limits competitors. Accretion rates are high due to the combined presence of thick soft microbial mats that contain abundant EPS (extracellular polymeric substances) (Decho et al. 2005), and rapid grain supply. In addition to cyanobacteria, the mats contain diatoms and filamentous green algae that enhance trapping (Awramik and Riding 1988; Dill et al. 1989; Riding et al. 1991a). The upper mat

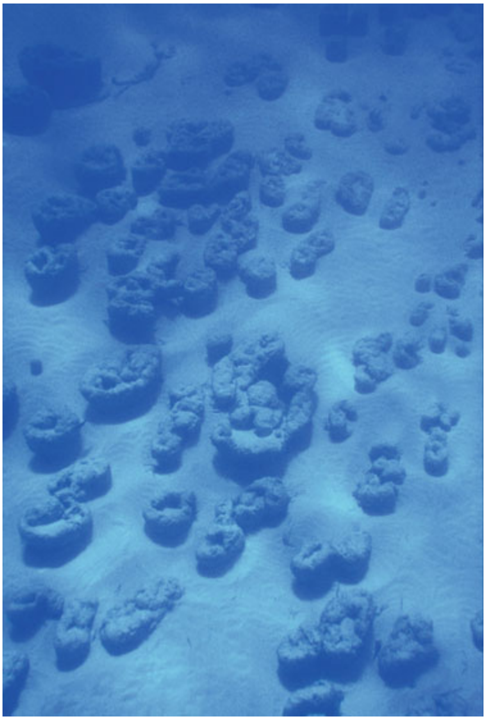

Fig. 10 "Molar tooth" thrombolitic stromatolite domes surrounded, and half-buried, by rippled ooid sand. Domes have exposed heights of ~0.5–1 m. Depth ~10 m in tidal channel between Lee Stocking Island and Norman's Pond Cay, Exuma Islands, Bahamas

remains soft and sticky because it is largely uncalcified, and the early lithification necessary to support these large columns mainly occurs in, or below, the lower part of the mat. Microbial lithification by sulphate reduction (Visscher et al. 2000) is limited to very thin micritic crusts (Reid et al. 2000), cyanobacterial sheaths are uncalcified (Reid et al. 2000, p. 992), and calcification of algal filaments mainly occurs in cavities (Dravis 1983; Whittle et al. 1993, p. 224). Thus, grainy current swept conditions, thick soft surface mats, and early subsurface lithification allow decimetric, and locally metric, columns to develop. Similar coarse-grained thrombolitic stromatolite domes are well developed in the late Miocene of SE Spain (Riding et al. 1991b; Braga et al. 1995; Feldmann and McKenzie 1997) but have not been reported from older rocks.

3.4 Tidal Flats

In contrast to the scarcity of large subtidal domes and columns, low relief – often poorly lithified – microbial mats are often widespread in many muddy-sandy intertidal and supratidal habitats, in both carbonate and siliciclastic environments, as well as in natural and artificial saline lakes (Fig. 11). Complex layered algal-bacterial communities develop on these intermittently illuminated and wetted sediment surfaces, and microbial energy cycling and physicochemical gradients generate vertical zonation (e.g., Revsbech et al. 1983; Cohen and Rosenberg 1989; van Gemerden 1993; Des Marais 2003; Stal 2000). This can be seen in distinctive millimetric colour bands produced by the microbes and their mineral products. Examples from Danish tidal flats were illustrated in Flora Danica (Hornemann 1813, pl. 1485) and reported from Trindelen in Odense Fjord (Ørsted 1842). Similar deposits in northern Germany were described as “Farbstreifen-Sandwatt” (colour-banded sand-flat) (Schulz 1936; Kremer et al. 2008, fig. 2c), and varicoloured mats

Fig. 11 Thick soft layered microbial mat on sediment. Coloured layers from the top down are: *yellow* EPS-rich layer with scytonemin; *green* cyanobacterial layer; *red* sulphur bacteria layer; *grey* sulphate reduction layer (although there is likely to be highest activity of sulphate reducers in the *green* layer). Salt pan the western side of Lagoa Pitanguinha, 85 km east of Rio de Janeiro, Brazil. Width of view 10 cm

are also well known at Great Sippewisset saltmarsh on Buzzard's Bay, Massachusetts (Nicholson et al. 1987).

These environments are stressed by physical and chemical factors (Cohen and Rosenberg 1989; Decho 2000) such as desiccation, ultra-violet radiation, temperature, and salinity that deter invertebrate competitors. As a result, cohesive microbial mats are generally much more extensive in present-day marine intertidal than shallow subtidal environments (Browne et al. 2000, p. 236). Following description of Shark Bay columns (Logan 1961), the accessibility of intertidal mats made them a focus of the geological search for marine stromatolites, e.g., in Andros (Monty 1967), the southern Persian Gulf (Kendall and Skipwith 1968), at Shark Bay (Davies 1970; Logan et al. 1974), and near the Coorong Lagoon in South Australia (Walter et al. 1973). This coincided with increased geomicrobiological research on microbial mats in hypersaline lagoons such as Solar Lake, adjacent to the Gulf of Aqaba (Por 1967; Jørgensen and Cohen 1977; Krumbein et al. 1977) and adjacent to the Pacific coast near Lázaro Cárdenas in northern Baja California, Mexico (Horodyski and Vonder Haar 1975; Horodyski 1977; Horodyski and Bloeser 1977; Javor and Castenholz 1981).

3.5 Wrinkle Marks

Present-day tidal flat mats typically form poorly lithified low relief structures that contrast markedly with Shark Bay columns (Kendall and Skipwith 1968). Aitken (1967, pp. 1163–1164) gave stratiform mats a different name – "cryptalgal laminite" – to describe "planar-laminated carbonate bodies bearing evidence of algal-mat activity". Whereas Aitken (1967) nonetheless continued to recognized these stratiform deposits as stromatolites, some authors have distinguished them from stromatolites because they lack characteristic "columnar, branched, and hemispheroidal structures that accrete from a single point" (Ginsburg and Planavsky 2008, p. 177); presumably because this makes it more difficult to interpret them as biogenic (e.g., Schieber 1998, p. 106). Nonetheless, cohesive mats can preserve the effects of synsedimentary deformation to which they are particularly prone on tidal flats, and these can impart distinctive features that aid their recognition in the rock record. In arid conditions, desiccation causes cracking and fragmentation (Gerdes et al. 1993, 2000, p. 205) (Fig. 12), whereas wet flexible mats are bent and folded by waves and currents, as well as gas bubbles (Cameron et al. 1985). Early lithification can preserve such synsedimentary mat deformation structures (Kendall and Skipwith 1968, p. 1056), but research has shown that mats can also leaves traces in sediments that are not strongly affected by early lithification, such as siliciclastic sand. As a result, deformed and imprinted mats have an extensive although often subtle geological record. From near White Sulphur Springs in central Montana, where he had collected Mesoproterozoic *Collenia*, Walcott (1914, p. 107, pl. 11, fig. 3) described *Kinneyia* and *Newlandia*, which have patterned

Fig. 12 Desiccated cohesive microbial mat, patterned by broad polygonal shrinkage cracks. Salt pan on the western side of Lagoa Pitanguinha, 85 km east of Rio de Janeiro, Brazil

ribbed or ripple-like surfaces. This original *Kinneyia* is in carbonate (the Newland Limestone) but was compared with somewhat similar structures in siliciclastic sediments (Martinsson 1965; Bloos 1976; Seilacher 1982). In the past, both *Newlandia* (Holtedahl 1921) and *Kinneyia* (Fenton and Fenton 1936, pp. 612–615; Fenton 1943, p. 86) have been regarded as inorganic, but more recently *Kinneyia*, in particular, has been linked to "Runzelmarken" (wrinkle marks), originally described from Jurassic siltstones of northern Germany (Häntzschel and Reineck 1968).

Horodyski (1982) drew attention to bedding plane markings in silty siliciclastic mudstones of the Mesoproterozoic Snowslip Formation in Glacier National Park, Montana, interpreting them as "impressions of thin, wrinkled algal mats" by comparing them with present-day mats in Florida Bay. Detailed studies of present-day intertidal siliciclastic mats (Cameron et al. 1985; Gerdes et al. 1985) revealed numerous delicate but distinctive structures (Gerdes and Krumbein 1994) that have subsequently been recognized in ancient sediments and interpreted as evidence for ancient mats. For example, Schieber (1986) interpreted carbonaceous silty shales in the Mesoproterozoic Newland Formation as remnants of benthic microbial mats, and found further evidence for microbial mats in shales and sandstones of similar age in the Belt Supergroup (Schieber 1998). Thus, "wrinkle marks" and other distinctive folds and elevated and depressed patterns on bedding planes, together with *Kinneyia*-like structures, are now widely linked to synsedimentary deformation of flexible cohesive sediment binding mats (Hagadorn and Bottjer 1997). These "microbially induced" (Noffke et al. 1996) or "microbially mediated" (Hagadorn and Bottjer 1997) "sedimentary structures" (MISS) (Noffke et al. 2001) have also been reported from Archaean rocks (Noffke et al. 2003, 2008). They can therefore be important indicators of mats in very old rocks where other indications of microbial life are uncertain. In addition to deformation structures, organic matter and filamentous fabrics can be preserved (Noffke et al. 2006), although these interpretations are not without the difficulties of distinguishing mat-related from other sedimentary structures (Porada and Bouougri 2007; McLoughlin et al. 2008; Porada et al. 2008).

3.6 Reef Crusts

Late Cenozoic reefal microbial crusts are much less well known than intertidal and hypersaline stromatolites and mats, but are locally important deposits in reef cavities and on fore-reef slopes. They typically occur as cryptic veneers on corals and other skeletons in framework cavities and closely resemble some of the thick clotted, peloidal stromatolitic crusts that are locally common in reefs in the Palaeozoic and Mesozoic. In a series of important papers, Macintyre (1977, 1984, 1985) drew attention to fine-grained peloidal crusts in Holocene Caribbean reefs and reef caves. Their non-skeletal fabrics are evidently precipitated. Together with other examples in the Great Barrier Reef (Marshall and Davies 1981; Marshall 1983), they attracted attention as examples of submarine lithification (James and Ginsburg 1979; Land and Moore 1980; Macintyre and Marshall 1988). Similar crusts occur in Messinian coral reefs in the western Mediterranean (Pedley 1979) and in some cases crust volume exceeds that of coral (Dabrio et al. 1981). Their clotted-peloidal fabrics were interpreted as calcified bacterial organic matter containing grains trapped in adhesive biofilm (Riding et al. 1991b). Similar crusts were found in reef caves at St Croix (Zankl 1993) and Lizard Island (Reitner 1993), and in late Quaternary reefs in the Pacific (Montaggioni and Camoin 1993; Cabioch et al. 1999; Webb et al. 1998). They have been studied in detail by Gilbert Camoin and colleagues at Tahiti (Camoin and Montaggioni 1994; Cabioch et al. 1999; Camoin et al. 1999, 2006, 2007).

Reefal microbial crusts are millimetric to decimetric in thickness (Cabioch et al. 2006, p. 304) with irregular, domical or dendritic surfaces (e.g., Land 1971; Macintyre 1977, pp. 507–508; Marshall 1986; Sherman et al. 1999; Camoin et al. 1999, 2006) (Fig. 13). Smooth domes usually show better internal layering than the columns. Silt-size peloids, generally <50 μm across, are characteristic crust components (Macintyre and Marshall 1988) (Fig. 14) and appear to "float" in fenestral microspar. Chafetz (1986) proposed that such peloids form in semi-isolated cavities in present-day reefs by bacterially-induced precipitation around suspended bacterial colonies, and many researchers have inferred a generally bacterial origin for fine-grained reef crusts (Pedley 1979; Brachert and Dullo 1991; Jones and Hunter 1991; Riding et al. 1991b; Montaggioni and Camoin 1993; Zankl 1993; Webb et al. 1998). More specifically, bacterial sulphate reduction (BSR) is suggested by the typically magnesian calcite composition, stable isotope values, and biomarkers. Crust values of magnesian calcite in the range 12–18 mole % Mg (Macintyre et al. 1968) are difficult to obtain inorganically (Morse and Mucci 1984, p. 287) and suggest bacterial activity (Pigott and Land 1986, pp. 355–356) such as BSR (Malone et al. 2001, p. 891, and fig. 10). BSR has also been inferred from carbon and oxygen isotope values of peloidal crusts and fills (Land and Goreau 1970; Pigott and Land 1986, figs. 9–11; Reitner et al. 2000, p. 153). Acidic macromolecules including diaminopimelic acids (Reitner et al. 1995) and biomarker evidence for anaerobic heterotrophs (Reitner et al. 2000, pp. 158–159) were found in Lizard Island and St Croix peloidal crusts. In Tahiti reef crusts, Camoin et al. (1999,

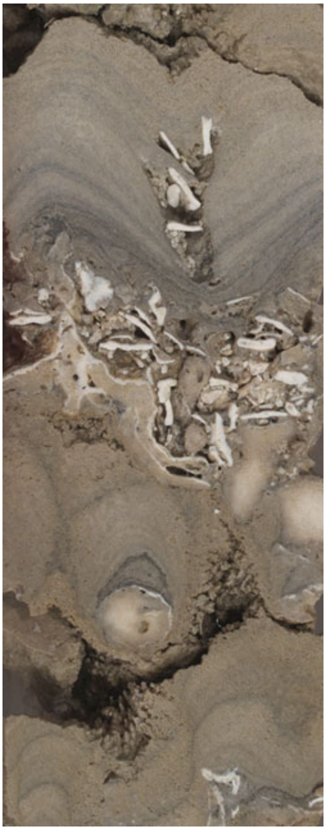

Fig 13 Reefal microbial stromatolite crusts (laminated *grey-brown*) on lighter coloured coral skeletons and bioclasts. Core through late Pleistocene-early Holocene reef, SW Tahiti, IODP 310, Maraa eastern transect, Hole M0015A, Last Deglacial Sequence, Subunit 1C, interval 310-M0015A-21R-01, 19–31 cm (Expedition 310 Scientists 2007, fig. 44). Width of view, 5.5 cm. © IODP/ECORD

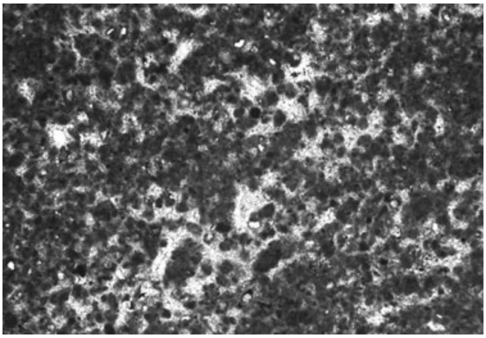

Fig. 14 Microfabric of reefal microbial crust. Peloid microspar with irregularly amalgamated dark peloidal masses in a light microspar, locally fenestral, matrix. Pleistocene −988 m drowned reef, Kohala, NW Hawaii; approx. age 375,000–400,000 years. Sample T302-R34, provided by Jody Webster. Width of view 1.4 mm

p. 297) found muramic and diaminopimelic acids characteristic of bacterial cell walls, and Heindel et al. (2009) found fatty acids typical of sulphate reducers.

In Late Pleistocene–Holocene reefs, crusts occur on wave-swept reef margins in dark enclosed framework cavities and on deep dark fore-reef slope surfaces

(Land and Goreau 1970; James et al. 1976; Macintyre 1977, p. 513; James and Ginsburg 1979, fig. 6-2e, fig. 6–17d; Marshall and Davies 1981; Lighty 1985; Marshall 1986; Camoin and Montaggioni 1994; Webb et al. 1998; Camoin et al. 2006). Their position between sciaphilic encrusters (e.g., corallines, foraminifers) and overlying reef or pelagic sediment reflects their formation in the closing stage of framework growth. As light diminishes, reef surfaces are colonized by a succession of increasingly sciaphilic (shade-loving) skeletal organisms (Garrett 1969; Martindale 1992, fig. 7): coralline algae, bryozoans, sclerosponges, foraminifers, and serpulids. The ability of the crusts to form in dark environments is consistent with them as products of essentially heterotrophic bacterial communities. Preference for wave-swept reef margins suggests the effect of seawater flushing on precipitation (e.g., James et al. 1976, p. 541; Macintyre 1977; Marshall 1986, p. 23). This too is consistent with a microbial origin since bacterial calcification is strongly dependent on environmental factors that promote precipitation (Riding 2000).

4 Stromatolites as Abiogenic Structures

Whereas biogenic interpretations of stromatolites, from Kalkowsky (1908) onwards, focused entirely on microbial sediments, abiogenic interpretations have been much more wide-ranging. In addition to sub-aqueous precipitates, such as hot spring sinters and, eventually, seafloor crusts, they involved post-depositional structures such as folds and diagenetic concretions. Organic interpretations of stromatolite-like structures were not new in the early 1900s. Most descriptions of *Cryptozoon*, *Spongiostroma* and similar deposits in the late 1800s and early 1900s regarded them as fossil remains. But whereas controversy enveloped *Eozoön*, there appears to have been little initial resistance to interpretations of *Cryptozoon* and *Spongiostroma* as simple animals. In contrast, the views of Kalkowsky (1908) and Walcott (1912, 1914) aroused some strong opposition. Possibly this was because Kalkowsky (1908) interpreted not only stromatolites but also ooids as microbial. In the case of Walcott (1912, 1914) criticism centred on his algal-cyanobacterial interpretations of Archaean and Proterozoic specimens that could convincingly be compared with inorganic structures such as crystal fans and diagenetic concretions. These questions created widespread uncertainty about the nature of stromatolites that continued for 20 years (Seward 1931, pp. 83–89) until the tide turned with Black's (1933) recognition of present-day stromatolitic microbial mats on Andros Island. Fold structures have also been drawn into the debate, especially for some Archaean stromatolite-like structures (Hofmann 1971, p. 58; Lowe 1994, p. 389).

4.1 Sinters

Kalkowsky's (1908) suggestion that both ooids and stromatolites are microbial was immediately challenged by Reis (1908), who argued that they are inorganic precipitates. Bucher (1913) supported Reis, observing that both stromatoliths and oolites had "a structure of delicate layers". Later he stated: "stromatoliths are the sedimentary equivalent of the calcareous and siliceous 'sinter' of the hot springs" and he contrasted them with "the coarse calcareous crusts which are formed by thick, felted masses of fresh-water algae and mosses" (Bucher 1918, p. 608). This was echoed by Bradley (1928) who, in marginal facies of the lacustrine Eocene Green River Formation in Wyoming, interpreted coarse fabrics similar to those of spongy Green Lake tufa fabrics as algal, contrasting them with finely banded and radial fibrous layers which he regarded as inorganic (Bradley 1928, p. 209, p. 217, pl. 34a,c; pl. 45a).

4.2 Concretions

Walcott (in Lawson 1912, pp. 16–23) gave the name *Atikokania* to Archaean structures found by A.C. Lawson in Archaean Steep Rock carbonates, and also identified a specimen as *Cryptozoan*? (NB, not *Cryptozoon*). Walcott suggested that *Atikokania* might be a sponge, but retracted this when Abbott (1914) compared it with Permian concretionary carbonates in north-east England (Hofmann 1971, p. 25). The idea that *Atikokania* might be a sponge persisted (de Laubenfels 1955) but it has generally been regarded as inorganic (Glaessner 1962, p. 472), for example as crystal fans (Hofmann 1971) precipitated on the seafloor (Sumner and Grotzinger 2000, p. 134).

Following Abbott's (1914) example, Holtedahl (1921) compared some of Walcott's (1914) Mesoproterozoic specimens from the Belt Series with concretions in the Permian Magnesian Limestone of the Zechstein evaporite basin in north-east England. Holtedahl (1921, p. 202) agreed with Sedgwick (1829) that these Permian structures were diagenetic and he particularly compared them with Walcott's (1914) *Greysonia* and *Newlandia* from the Newland Limestone of Montana. Holtedahl (1921) considered that they "must have had a similar origin" (p. 201) and were "inorganic and secondary" (p. 203). However, he concluded: "The discovery of algae and bacteria in pre-Cambrian strata, reported by Walcott, has therefore lost none of its importance, even if it should be found that these organisms are not responsible for the many curious structures found in the Algonkian Newland limestone" (p. 206). Nonetheless, as a result of these comparisons with Zechstein concretions, Seward (1931, pp. 83–89) was sceptical that *Cryptozoon* and similar structures were organic. Seward recognized that blue-green algae were associated with nodules, such as those described by Mawson (1929) from South Australia, but he was hesitant to infer "that their presence is essential" to nodule formation (Seward 1931, p. 83), and he also doubted that they could have produced "reefs of *Cryptozoon*" (Seward 1931, pp. 86–87). But Goldring (1938, p. 21) pointed out that the irregularity of *Cryptozoon* contrasted with the regularity to be expected from inorganic precipitates, and in a footnote Seward (1931, p. 86) himself recognized that bacterial deposits could closely resemble *Cryptozoon*. Although Fenton

(1943, p. 93, fig. 7) considered that it does not closely resemble *Newlandia*, some of Holtedahl's Zechstein specimens are stromatolitic in appearance. Fenton (1943, p. 86) too, considered that some of Walcott's (1914) Newland samples were inorganic products of "segregation of calcite and dolomite during deformation".

4.3 Folds

At Steep Rock Lake in Ontario, Jolliffe (1955, pp. 380) suggested that Walcott's (in Lawson 1912, pp. 16–23) "*Cryptozoan*? fragment probably came from what are much the most common organic-like forms in the Steeprock carbonate – the so-called 'algal' structures". These include large stromatolitic domes (Wilks and Nisbet 1985). However, Hofmann (1971, p. 58 and pl. 22, fig. 1) noted that "The sample appears to be deformed, and it is probable that the lamination of this particular specimen is a tectonic foliation and not stromatolitic". Lowe (1994, fig. 3d, p. 389) considered that a domical structure interpreted as a ~3,450 Ma stromatolite at Pilbara, Australia (Walter et al. 1980), had formed by soft-sediment deformation. Furthermore, he suggested that all three of the well-documented reports of stromatolites older than 3,200 Ma known at that time "probably formed through non-biological processes" such as deformation or evaporitic inorganic precipitation (Lowe 1994, p. 390).

4.4 Seafloor Crusts

Reliance on non-marine deposits for examples of abiogenic stromatolite-like structures continued into the 1970s (e.g., Read 1976; Thrailkill 1976; Walter et al. 1976). In the 1980s, a significant new development occurred when petrographic studies suggested that well-preserved Palaeoproterozoic stromatolites in Arctic Canada could be interpreted as essentially abiogenic precipitates (Kerans 1982; Grotzinger and Read 1983). Although these deposits were often at first described as "fibrous marine cements" (Grotzinger 1989b, p. 10), they were evidently seafloor crusts. Grotzinger (1986a) considered the possibility that microdigitate stromatolites are "entirely abiotic", and Grotzinger and Rothman (1996, p. 424) proposed that "abiotic mechanisms" could account for the growth of large Palaeoproterozoic stromatolites such as those described by Jackson (1989, fig. 13) (Fig. 15). Thus, some Proterozoic deposits described as stromatolites appear, from petrofabric evidence, to be essentially abiotic seafloor precipitates. Literature survey indicates at least four general categories of subaqueous Sparry Crust based on Precambrian examples (Riding 2008, table 1); three of which include stromatolitic deposits: (1) Botryoidal fans and crystal pseudomorphs include small radial fibrous millimetric microbotryoids that build *Tarioufetia* and *Tungussia* (Bertrand-Sarfati 1972); (2) "microdigitate stromatolites": small laminated columns of radial crystals (Grotzinger and Read 1983; Hofmann and Jackson 1987); (3) isopachous laminite (Jackson 1989; Pope and Grotzinger 2000, fig. 8e; Sumner and Grotzinger 2004).

Fig. 15 Isopachous laminite forming “peaked stromatolitic carbonate”, interpreted as potentially abiogenic by Grotzinger and Rothman (1996, p. 424). Cowles Lake Formation (~1,900 Ma). Width of view 45 cm. Jackson (1989, fig. 13), CSPG© 1989, reprinted by permission of the CSPG whose permission is required for further use

Fig. 16 Small, partly silicified, domical to cuspate stromatolites showing even and laterally continuous, smooth lamination. Late Archaean Campbellrand–Malmani platform, near Groot Boetsap River. South Africa

This made it clear that essentially abiogenic laminated crusts had precipitated on the floors of seas in the geological past, as well as forming in non-marine lakes and pools at the present-day. Recognition of these abiogenic marine deposits justified Hoffman’s (1973) apprehension that at least some “ancient stromatolites” … “might not be biogenic at all”. They emphasized the importance of clearly discriminating between these crusts and lithified microbial sediments. Appropriately, it was the petrographic descriptions of these seafloor crusts themselves that contributed significantly to resolving the dilemmas of stromatolite definition, by providing fabric criteria that can be used to distinguish biogenic and abiogenic layered authigenic carbonates.

5 Stromatolite Fabrics

Regular, as opposed to uneven, layering is a distinct feature of some stromatolites (Fig. 16). Pope et al. (2000, p. 1139) 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” and considered “thinly laminated, isopachous stromatolites” … “to have a largely abiotic origin” (p. 1149). These insights benefited from decades of research that had helped elucidate the structure of present-day

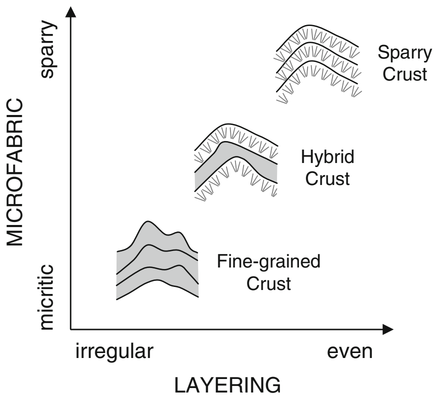

Fig. 17 Conceptual representation of Fine-grained, Hybrid and Sparry Crust, comparing their layering and microfabric. Fine-grained and Sparry Crust are interpreted as essentially microbial and abiogenic, respectively; Hybrid Crust is a mixture of the two. Fine-grained and Hybrid crust are here considered to be stromatolite; Sparry Crust is not. From Riding (2008, fig. 14)

sinters and lithified microbial mats, and of similar ancient examples that included abiogenic seafloor crusts that appeared to lack modern marine equivalents. Although these deposits as a whole are complex, it is possible to identify a few principal components. Two distinct fabrics are Fine-grained Crust with uneven layering, and Sparry Crust with regular layering, which can be interpreted as lithified microbial carbonate and abiogenic carbonate respectively (Riding 2008, pp. 77–80, p. 90). These two fabrics occur separately, but also in intimate association as Hybrid Crust (Fig. 17).

5.1 *Fine-Grained Biogenic Crust*

Fine-grained biogenic crust is characterized by fine-grained microfabric and irregular or poorly layered macrofabric. The microfabrics can be dense, clotted, peloidal, and/or filamentous (Riding 2000, figs. 5–7). They are dominated by micrite and microspar, and may contain fenestrae and allochthonous grains. Macroscopically, Fine-grained Crust stromatolites typically exhibit uneven to discontinuous – sometimes poorly defined – layers, usually with poor inheritance (Figs. 5 and 18). In some cases the incorporated grains are sand size, as in Shark Bay and Lee Stocking columns, but the matrix remains fine. In these cases, the larger grains can make the macrofabric correspondingly more uneven. Fine-grained crust stromatolites are widespread in the Neoproterozoic and Phanerozoic (Riding 2008, p. 73).

5.2 *Sparry Crust*

Sparry Crust typically has coarsely crystalline, often radial-fibrous, microfabric. The macrofabrics may consist of even, approaching isopachous, laterally persistent layers with good inheritance. There are diverse varieties, two of which are

Fig. 18 Small steep-sided stromatolite dome, showing uneven and discontinuous layering. Early Cambrian, Série Lie de Vin, Tiout, near Taroudant, Anti-Atlas Mountains, Morocco

microdigitate "tufa" (Hoffman 1975, p. 262; Grotzinger and Read 1983, p. 712, fig. 1f; Hofmann and Jackson 1987, p. 964) and isopachous laminite (Jackson 1989, figs 6, 13; Grotzinger and Knoll 1999, fig. 6a, b). Sparry Crust stromatolites were widespread in the Palaeoproterozoic and Mesoproterozoic, with microdigitate forms typically in shallower (Hoffman 1975, p. 262) and isopachous laminite in deeper water environments (Jackson 1989). In the Phanerozoic, Sparry Crust deposits locally occur in evaporite basins (Pope et al. 2000, p. 1139).

5.3 Hybrid Crust

Hybrid crust consists of interlayered Fine-grained and Sparry Crust (Riding 2008, p. 74). Detailed descriptions (e.g., Vologdin 1962; Komar et al. 1965; Hofmann 1969, fig. 13; Walter 1972, pls 5, 6, 10, 12; Bertrand-Sarfati et al. 1994; Sami and James 1996, p. 217; Petrov and Semikhatov 2001, fig. 6, p. 269) suggest that many Proterozoic stromatolites consist of intimate alternations of both microbial and Sparry Crust fabrics (Riding 2008, p. 95). For example, in large *Conophyton*, Kerans (1982) noted that "bladed cement crusts were precipitated on microbial laminae while stromatolites were growing" (see Grotzinger 1986b, p. 840). These do not appear to be minor occurrences. Examples with Hybrid-like "Boetsap lamination" are locally widespread in the Neoarchaean (Fig. 2). The subsequent very long interval represented by the Palaeo- and Mesoproterozoic,

~2,500–1,000 Ma ago, was the "Golden Age" of large and abundant stromatolites (Awramik and Riding 1986). An extensive literature (see references in Riding 2000) suggests that many of these Palaeo- and Mesoproterozoic stromatolites consist of Hybrid Crust and may exceed other coeval stromatolites in abundance (Riding 2008, p. 91). The often delicate alternations in Hybrid Crust (Petrov and Semikhatov 2001, fig. 6a; Riding 2008, fig. 9) may reflect seasonal changes (Bertrand-Sarfati 1972, p. 155). It could be that combination of microbial growth and abiogenic precipitation enhanced the growth rates of these deposits, some of which exhibit exceptional size and relief (Grotzinger and Knoll 1999, p. 352; Sumner and Grotzinger 2004, fig. 10; Riding 2008, pp. 91–92).

6 Stromatolite Definition

Stromatolites are regarded here as layered benthic microbial deposits (Kalkowsky 1908; Burne and Moore 1987; Riding 1999). The three types of authigenic carbonate crust outlined above can all form layered deposits (both biogenic and abiogenic) that have at various times been described as stromatolites (Riding 2008, fig. 12). Fine-grained Crust (typically unevenly layered and with complex clotted and peloidal microfabrics) and Hybrid Crust (thin alternations of Sparry and Fine-grained crust) are here regarded as essentially biogenic and therefore as stromatolites. Sparry Crust (typically with regular, even layering and sparry microfabric) is here regarded as essentially abiogenic and is not regarded as stromatolite.

Proposed definition: *Stromatolites are macroscopically layered authigenic microbial sediments with or without interlayered abiogenic precipitates*.

Stromatolites therefore include microbial and hybrid types; they can form domes and columns, but also commonly occur as sheet-like masses. In the definition, *with* abiogenic precipitates can refer to Hybrid Crust, and *without* abiogenic precipitates can refer to Fine-grained Crust. In contrast, thrombolites, dendrolites, and leiolites are categories of non-layered microbial deposits characterized by clotted, dendritic and aphanitic macrofabrics, respectively.

Definition of stromatolites as *microbial* is consistent with Kalkowsky's (1908) view which has been widely supported (e.g., Awramik and Margulis 1974; Walter 1976b, p. 1; Monty 1977, p. 23; Burne and Moore 1987; Riding 1999). It is also consistent with stromatolites being regarded as microbialite, as Burne and Moore (1987) intended, which has been widely adopted. Furthermore, this definition emphasizes genetic nature, which is a major interest in the study of stromatolites. Much of the interest in very old stromatolites, for example, centres on whether or not they are biogenic (e.g., Lowe 1994; Hofmann et al. 1999; Allwood et al. 2006). A definition that does not address this misses a crucial point. No abiogenic present-day deposits have generally been regarded as stromatolites, and although strong arguments have been expressed in favour of a descriptive definition that recognizes abiogenic as well as biogenic stromatolites (Logan et al. 1964; Hofmann 1973, p. 342, p. 346; Semikhatov et al. 1979) these appear to be essentially designed to

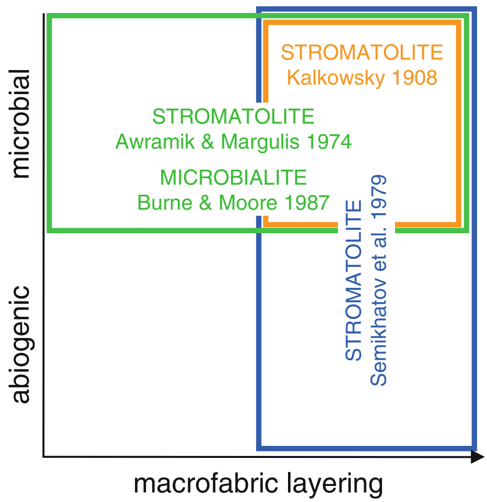

Fig. 19 Diagrammatic summary of contrasting stromatolite definitions, as they relate to degree of macrolayering and microbial/abiogenic origins. Circumscription of microbialite (Burne and Moore 1987) corresponds with Awramik and Margulis's (1974) definition of stromatolite. Kalkowsky's (1908) definition (supported by Burne and Moore 1987; Riding 1999) is supported here

avoid the difficulty of discriminating between abiogenic and biogenic examples in ancient deposits. Such a broad definition has the disadvantage that it could "cease to be useful" (Walter 1976b, p. 1). For example, "abiogenic stromatolites" could encompass deposits such as speleothem, travertine, and hot spring sinter.

Definition of stromatolites as *layered* is also consistent with Kalkowsky's (1908) definition, but is more restricted than either Awramik and Margulis's (1974) or Semikhatov et al.'s (1979) definitions which also permitted stromatolites to be unlayered or abiogenic respectively (Fig. 19).

Since this definition reaffirms that of Kalkowsky (1908), it raises the same question that has been at the centre of the stromatolite debate for over a century: if stromatolites are biogenic, how are ancient examples to be distinguished from abiogenic crusts? I propose to base this on the macrofabric and microfabric criteria outlined above (Stromatolite Fabrics). Macrofabric mainly involves evenness, regularity, and persistence of the layers. Microfabric ranges from sparry to fine-grained (clotted and peloidal) and filamentous. Hybrid Crust consists of thin alternations of Sparry and Fine-grained crust. Application of these criteria, especially microfabric, necessarily relies on good preservation. The extent to which this proposal will be useful remains to be seen.

7 Discussion

Timelines show how concept development tracked fieldwork and research progress discoveries among ancient examples and potential present-day analogues (Fig. 20). In this context, the "definition difficulty" that has hindered stromatolite studies reflects several factors. One of these is the availability of present-day analogues. Stromatolite studies could not have progressed without the comparative

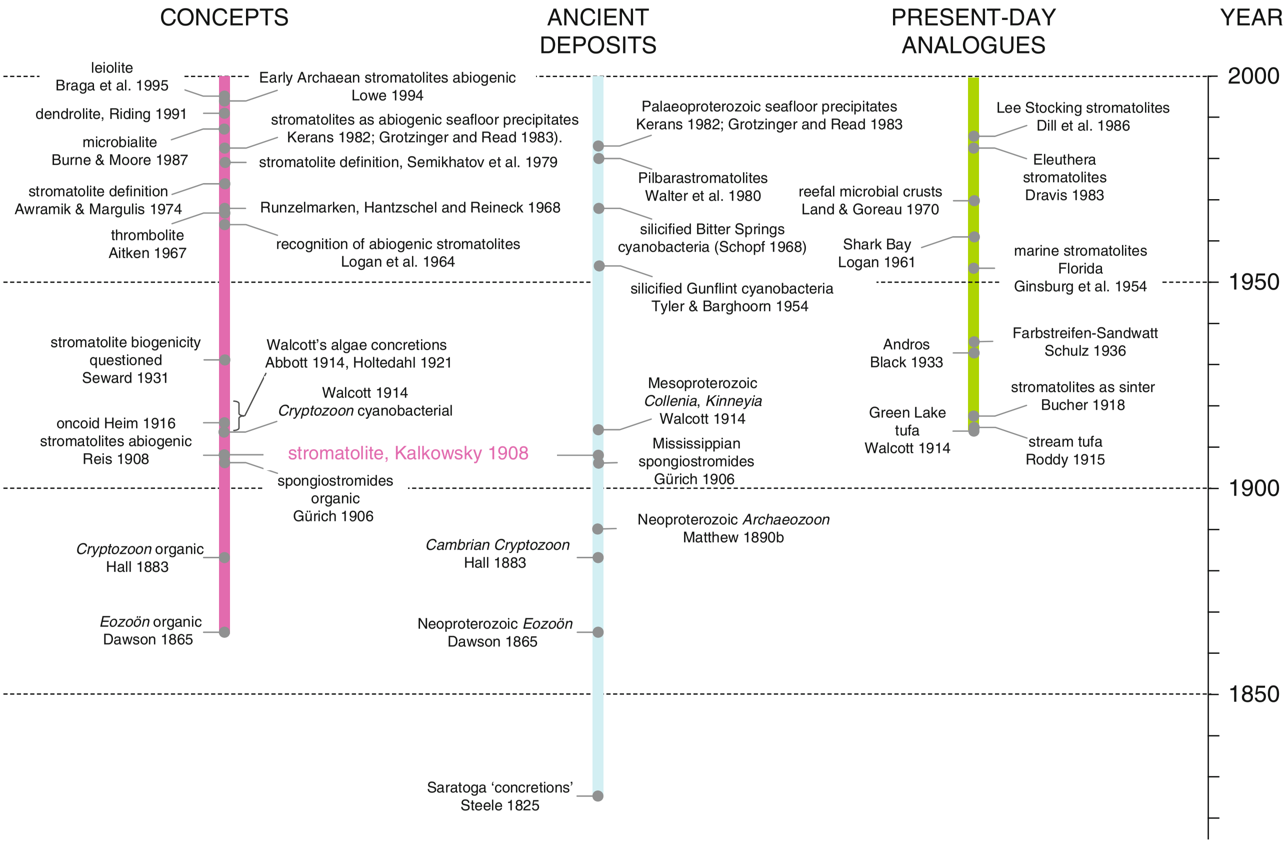

Fig. 20 Time-lines of stromatolite concept development and related ancient and present-day deposits mentioned in the text, from 1825 to 2000, beginning with recognition of *Cryptozoon* and *Eozoön*

information provided by the wide variety of present-day abiogenic and microbial mat deposits briefly summarized above. But despite this extensive research, efforts to base stromatolite interpretation entirely on present-day analogues have not been altogether successful. This is because not all ancient stromatolite-like deposits are well-represented today; most notably the abiogenic seafloor crusts first clearly recognized in the Proterozoic by Kerans (1982), Grotzinger and Read (1983), and Grotzinger (1989a, b) and others. Stromatolites have had such a long geological history, influenced by major changes in both biology and seawater chemistry, that finding good examples of all types of stromatolite today might hardly be expected. Another factor is the geological origin of the stromatolite concept, rooted in specimens that are hundreds of million years old (Kalkowsky 1908; Hall 1883). Stromatolites have been reported to be most abundant 2,000 Ma ago (Grotzinger 1990), and the term has been widely applied to specimens as old as 3,500 Ma (Allwood et al. 2006). Because stromatolites were first described and defined in the rock record, their genesis was not immediately demonstrable and demanded resourceful interpretation. This question of origins has become the motif of stromatolite studies, focused on the difficulty of distinguishing abiogenic crusts from microbial carbonates.

The paradox presented by stromatolites is conveyed by Ginsburg's (1991, p. 25) impish comment that "few observers have any difficulty identifying archetypical stromatolites . . . yet defining stromatolites is controversial". This is like saying that everyone knows what stromatolites look like, but no one can agree what they are. It was this daunting prospect, which threatened to leave stromatolite definition in a state of perpetual limbo, that led Semikhatov et al. (1979) to propose a descriptive definition. Yet, broad definitions encompassing both biogenic and abiogenic structures avoid the central question of how stromatolites have formed (Walter 1976b, p. 1). This brings the debate full circle, back to trying to find ways to make a microbial definition work (Burne and Moore 1987).

Nonetheless, there are clear pointers to be drawn from the considerable advances derived from studies of present-day deposits. One is that the term stromatolite is only very seldom applied to present-day deposits known to be inorganic (an exception is Maliva et al.'s (2000, p. 934) description of modern stromatolites "formed largely by inorganic precipitation"). This suggests that researchers have tended to view stromatolites as essentially biogenic, and that the only reason for grouping abiogenic and microbial crusts in ancient deposits is inability to distinguish them (Semikhatov et al. 1979). Another is that there are distinct fabric differences between abiogenic and microbial crusts, as was recognized very early (Bucher 1913). The pace of development of limestone petrography accelerated in the 1960s, but focused more on young and grainy carbonates than on old and authigenic ones. But substantial progress has been made in distinguishing laminated authigenic crusts of microbial and abiogenic origin. The argument here is that fabric criteria can resolve these questions, and that it is important to develop them inorder to overcome issues that impede stromatolite studies. It should be possible not only to formulate a microbial definition of stromatolite, but also to confidently apply it sufficiently widely in the geological record.

7.1 Abiogenic and/or Biogenic Stromatolites?

Despite all the difficulties, in many respects the sometimes contentious half-century of debate vindicated the views of both sets of early contenders; Kalkowsky (1908) and Walcott (1914), on the one hand, and of Reis (1908) and Bucher (1913) on the other. By the 1960s there was growing acknowledgement of the existence of both organic and inorganic stromatolites. A decade or more prior to Awramik and Margulis (1974), Logan et al. (1964, p. 68) succinctly stated: "Stromatolites are laminated structures that have been previously termed fossil algae. It is now recognized that such structures may be formed by a number of different processes and organisms." They did not offer a general definition of stromatolite, but their recommendation was clear: "To be useful, the term stromatolite should be preceded whenever possible by an adjective signifying the kind of stromatolite under consideration, for example, algal stromatolite, foraminiferal stromatolite, inorganic stromatolite, and so forth" (Logan et al. 1964, p. 69). This was echoed by Hofmann (1973), who emphasized that stromatolites need not be biogenic (p. 342) and recognized chemogenic stromatolites (p. 346) and the need to distinguish "biogenic stromatolites from chemical and mechanical ones" (p. 350).

These calls by well-known researchers did not lead to peaceful reform of stromatolite definition. Instead they precipitated a schism between those who regarded stromatolites as essentially biogenic, and those who believed it was necessary for the term stromatolite to encompass both biogenic and abiogenic laminated structures. In addition to discovery of cyanobacteria in ~1880 Gunflint stromatolites (Barghoorn and Tyler 1965) (Fig. 7), similar – and impressive – fossils had been found in the ~850 Ma Bitter Springs silicified stromatolitic mats (Schopf 1968; Knoll and Golubic 1979), emphasizing the biogenicity of Proterozoic stromatolites. Against this background, two definitions were published expressing these contrary convictions. Awramik and Margulis (1974) adhered to Kalkowsky's (1908) view that stromatolites are microbial, whereas Semikhatov et al. (1979) followed Logan et al.'s (1964) lead and recognized both biogenic and abiogenic stromatolites (Fig. 19).

Awramik and Margulis (1974) defined stromatolites as "megascopic organosedimentary structures produced by sediment trapping, binding and/or precipitation as a result of growth and metabolic activity of organisms, primarily blue-green algae". This genetic approach was endorsed in the introduction to Walter's (1976b, p. 1) seminal stromatolite volume. Its advantage was its straightforward restatement of Kalkowsky's (1908) microbial view. But it required biogenicity to be demonstrated, and this was difficult for ancient examples. Hoffman's (1973) had frankly admitted that "Something that haunts geologists working on ancient stromatolites is the thought that they might not be biogenic at all". This question of confidently establishing biogenicity in ancient examples is the enduring central problem of stromatolite studies. Reis (1908) used it to challenge Kalkowsky (1908). It was clearly expressed by Seward (1931, pp. 83–89) and Logan et al. (1964), and preoccupied Semikhatov et al. (1979), Ginsburg (1991, pp. 25–27), Grotzinger and Knoll (1999), and Brasier et al. (2006, p. 894). It led Buick et al. (1981) to suggest that "structures of uncertain origin that resemble stromatolites should be called 'stromatoloids'" and Awramik and Grey (2005) to term abiogenic stromatolite-like structures *pseudostromatolites*.

Semikhatov et al. (1979, p. 992) (but with S.M. Awramik dissenting), proposed to define stromatolites as "laminated, lithified, sedimentary growth structures that accrete away from a point or limited surface of attachment. They are commonly, but not necessarily, of microbial origin and calcareous composition". The operative words here are "commonly, but not necessarily", that permit some stromatolites to be abiogenic. They supported this descriptive, rather than genetic, approach to stromatolite definition by stating that "it was the lamination that Kalkowsky stressed, not its origin" (Semikhatov et al. 1979, p. 994). This was misleading; Kalkowsky (1908) emphasized organic origin as well as layering in describing stromatolites. But Semikhatov et al. (1979) were correct to point out the difficulties of confidently applying a genetic definition: "if a biological origin had to be demonstrated before a geological object could be called a stromatolite the term would in most instances be inapplicable (or at best provisional)" (Semikhatov et al. 1979, p. 994). Their approach was bold and realistic, a clear departure from Kalkowsky (1908), and an attempt to express a dual view of stromatolites in which many were microbial, but some could be abiogenic. It aroused criticism for exactly this reason. It appeared to be an all-encompassing definition that failed to either readily separate different structures or to circumscribe related ones. Walter (1976b, p. 1) had already perceptively foreseen that if non-genetic definitions "are so broad as to include a wide-range of non-biogenic structures", "the term would cease to be useful". Subsequently, Ginsburg's (1991, p. 27) opinion was that the Semikhatov et al.'s (1979) definition "includes structures of a variety of origins ranging from tufa domes . . . to laminated structures of mineralized organisms . . . and even some of the laminated zones of caliches and calcretes as well as certain speleothems." It could perhaps even be considered to include diagenetic concretions. A disadvantage with its specific wording is that it appears designed to exclude laterally extensive deposits such as Aitken's (1967) cryptalgalaminates. But the main difficulty can be summed up by the question, if stromatolites are "laminated, lithified, sedimentary growth structures that accrete away from a point or limited surface of attachment" (Semikhatov et al. 1979), then what exactly is *not* a stromatolite?

7.2 Microbialite

The name stromatolite purposely emphasized layered structure; *Stroma* and *stromat* – indicate a bed coverlet in Greek and Latin. Kalkowsky (1908, p. 102) stated: "*Alle Stromatolithe zeigen im vertikalen Schnitt deutliche Lagenstruktur*" "All stromatolites show distinct layering in vertical section". As geological studies progressed it eventually became clear that there are deposits that resemble stromatolites in external form but which appear to lack internal layering. Aitken (1967, p. 1164) introduced *thrombolite* "for cryptalgal structures related to stromatolites, but lacking lamination and characterized by a macroscopic clotted fabric" to describe structures that were common in the Late Cambrian and Early Ordovician. During the 1970s, growing awareness of the local importance of thrombolites led to doubts about the value of requiring layering as an integral part of stromatolite description. For example, Awramik and Margulis (1974) defined stromatolites as "megascopic organosedimentary structures produced by sediment trapping, binding and/or precipitation as a result of growth and metabolic activity of organisms, primarily blue-green algae". This required stromatolites to be microbial, but not necessarily layered, and therefore permitted thrombolite to be regarded as a type of stromatolite. But this left no specific term for laminated stromatolites. This deficiency was resolved when Burne and Moore (1987) applied the essence of Awramik and Margulis' (1974) definition of stromatolite to a new term: *microbialite*. "Microbialites are organosedimentary deposits that have accreted as a result of a benthic microbial community trapping and binding detrital sediment and/or forming the locus of mineral precipitation" (Burne and Moore 1987, pp. 241–242). This then allowed stromatolites to be regarded as macro-laminated microbialites, and thrombolites as macro-clotted microbialites. It also encouraged subsequent additions to the microbialite family, such as dendrolite (dendritic; Riding 1991, p. 34) and leiolite (aphanitic; Braga et al. 1995, p. 347). Since then, macrofabric has been a fundamental descriptor for these structures and stromatolites (Riding 2000, pp. 189–195).

Burne and Moore (1987) carefully evaluated the processes that might contribute to the formation of microbialites and associated deposits. As Hofmann (1973, fig. 5) and Riding (1977, fig. 1) had done, they noted the importance of sediment trapping, inorganic calcification and biologically influenced calcification (Burne and Moore 1987, figs. 1 and 2, pp. 243–244). Accordingly, they recognized three types of microbialite to reflect these processes respectively: microbial boundstone, tufa and framestone (Burne and Moore 1987, pp. 242–243). Microbialite was therefore designed as a broad term to encompass deposits formed by both grain trapping and mineral precipitation associated with benthic microbes, and this specifically included "microbial tufa – formed when microorganic material is incorporated during inorganic precipitation of carbonate" (p. 243). In detail, this could be considered to differ from Awramik and Margulis (1974) who defined stromatolites as "megascopic organosedimentary structures produced by sediment trapping, binding and/or precipitation as a result of growth and metabolic activity of organisms, primarily blue-green algae". The reasoning is that "precipitation as a result of growth and metabolic activity of organisms" emphasizes organic processes whereas "incorporated during inorganic precipitation of carbonate" emphasizes inorganic processes. However, these nuances are not evident in Burne and Moore's (1987, pp. 241–242) actual definition of microbialite, "organosedimentary deposits that have accreted as a result of a benthic microbial community trapping and binding detrital sediment and/or forming the locus of mineral precipitation", which is closer to that of Awramik and Margulis (1974). Furthermore, Burne and Moore (1987,

p. 249) advocated "a return to Kalkowsky's original meaning for 'stromatolite'" and used it "to refer to one possible internal structure of a microbialite".

The point of this rather protracted discussion is that – whatever the intention – in practice microbialite provided a necessary umbrella term for stromatolites, thrombolites and similar deposits and it became widely used. As the name obviously indicates, all these deposits are considered microbial. Thus, the train of events that led Burne and Moore (1987) to base microbialite on Awramik and Margulis's (1974) definition of stromatolite, strengthened the view that stromatolites are essentially microbial. This in turn tended to undermine the conviction, expressed by Logan et al. (1964) and Hofmann (1973) Semikhatov et al. (1979), that it was necessary to also recognize abiogenic stromatolites. But not everything was going in the direction of a microbial definition. Already, in the 1980s, studies of Proterozoic carbonates were interpreting some stromatolites as abiogenic seafloor crusts. This looked set to rebalance the debate, because it presented stromatolites as genetically heterogeneous structures.

7.3 Seafloor Crusts

The realization that some Proterozoic stromatolites are essentially abiogenic seafloor precipitates, set in train by Kerans (1982) and Grotzinger and Read (1983), was a break-through; arguably comparable in significance to the discovery of Shark Bay stromatolites 20 years previously. It revealed fundamental differences between Precambrian and present-day carbonate sedimentation (Grotzinger 1990; Grotzinger and Kasting 1993), and it provided good reason to recognize abiogenic stromatolites. But appreciation of its importance took time to spread. One reason for this may have been a lack of terminological clarity. Grotzinger and Read (1983, p. 712, fig. 1f) described the components of Rocknest microdigitate stromatolites as "cement laminae" and "cement crusts". Use of "seafloor cement" to describe microdigitate stromatolites and isopachous Sparry Crust continued for more than a decade (Kah and Knoll 1996, p. 79; Pope et al. 2000, p. 1145), even after Grotzinger and Knoll (1995, p. 579) pointed out that seafloor crusts/encrustations should be distinguished from "true cements which bind sediment particles and line voids". There was also an element of restraint. Grotzinger described microdigitate stromatolites as "in essence, evaporites" (Grotzinger 1986b, p. 842) but cautiously interpreted them as "microbially influenced inorganic calcification (although it is possible that they are entirely abiotic in origin)" (Grotzinger 1986a). Whatever the reasons, it was 15 years before more outspoken statements were expressed about the origins of these seafloor crusts. At the end of the century, Grotzinger and James (2000a, p. 7) included microdigitate stromatolites and isopachous millimetric laminites (i.e., Isopachous Sparry Crust) in their summary of Precambrian marine "abiotic precipitates", and Pope et al. (2000, p. 1149) considered "thinly laminated isopachous stromatolites" to be "largely abiotic". Thus, this research revealed a wide

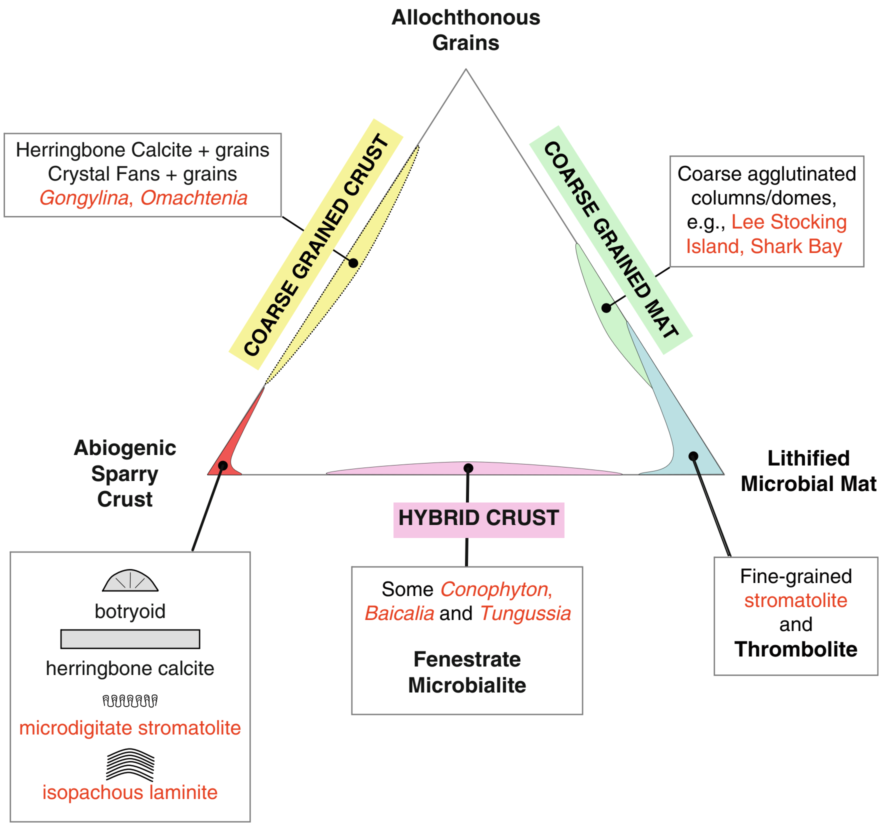

Fig. 21 Interpretive summary of Precambrian authigenic crusts, with layered deposits (both biogenic and abiogenic) that have been described as stromatolites indicated in *red*. Principal components are Sparry Crust (essentially abiogenic precipitate), Fine-grained Crust (lithified microbial mat), and allochthonous grains. Intermediate categories are Hybrid Crust, Coarse Grained Crust, and Coarse Grained Mat. From Riding (2008, fig. 12)

range of authigenic seafloor crusts (e.g., Sumner and Grotzinger 2004), and layered varieties have often, at one time or another, been termed stromatolite (Fig. 21).

7.4 *Biogenicity Criteria*

Recognition of abiogenic seafloor crusts reinforced the key question first pinpointed by Reis (1908): if stromatolites are biogenic, as Kalkowsky (1908) believed, then how are ancient examples to be distinguished from abiogenic crusts and, specifically, what criteria can be used to confidently establish stromatolite biogenicity. Progress in addressing these questions had been fitful. Following studies of microbial fabrics and fossils in stromatolites (Gürich 1906; Garwood 1913, Pia

1927, pp. 36–40) was able to distinguish filamentous (porostromate) and clotted (spongiostromate) microfabrics, and Black (1933) began to relate microbes to sedimentary structures in present-day stromatolites. But research on these two fronts advanced at different rates and cross-fertilization tended to be limited. For example, Johnson (1946) documented the microfabrics of Late Palaeozoic oncoids and *Cryptozoon* long before Shark Bay columns were discovered and described as *Cryptozoon* by Logan (1961). Considerable efforts were made to relate microbes to microfabric development in the 1970s (e.g., Golubic 1976; Monty 1976) and to document abiogenic fabrics (e.g., Gebelein 1974; Walter 1976c) and Semikhatov et al. (1979, pp. 1004–1005) were able to summarize microbial effects on carbonate grain/crystal relationships, lamina thickness and relief, and early diagenesis. But applying these to the interpretation of ancient examples was not straightforward. Buick et al. (1981, pp. 165–167) suggested eight biogenicity criteria for ancient stromatolites. Yet Lowe (1994, p. 389) was able to argue that five of these "are common not only to three-dimensional stromatolites but also to many if not most inorganic precipitates" and that the remaining three features "characterize <5% of stromatolites of any age". These final three all involve the presence of microfossils. By the early 1990s this approach showed surprisingly little advance on the work of Bucher (1913). In the Archaean, for example, Buick (1992, p. 255) used complex branching, tufted microfabric, and trapped grains to argue that Tumbiana stromatolites "are clearly biogenic", and Lowe (1994, p. 388) used fine, smooth, continuous lamination to question a biological origin for Barberton stromatolites.

It was at this stage that petrographic studies began to add important new microfabric detail to augment biogenicity criteria. Well-preserved Proterozoic microfabrics (e.g., Sami and James 1996; Knoll and Semikhatov 1998) allowed Grotzinger and Knoll (1999, fig. 3, pp. 320–323) to distinguish microbial mat from sea-floor precipitated crusts. In spite of this, Grotzinger and Knoll (1999, p. 316) were pessimistic about applying a genetic definition of stromatolite. Their focus was on numerical simulations that could reflect stromatolite growth processes, but they recognized the difficulty of distinguishing between mat growth and "the growth of abiotic marine crusts", and concluded with Grotzinger and Rothman (1996) that "morphology may well be a non-unique parameter" (Grotzinger and Knoll 1999, p. 343). Nonetheless, their insights into fabrics, together with those of Pope et al. (2000), put biogenicity into a broader perspective: the requirement now was for criteria not simply to establish the nature of biogenic deposits, but of abiogenic deposits too. This was advanced by articles in Grotzinger and James (2000b). Riding (2000, pp. 186–188) summarized the peloidal, clotted and filamentous fabrics of Phanerozoic microbial carbonates, and Corsetti and Storrie-Lombardi (2003, p. 652, fig. 1c–f) emphasized isopachous lamination and radiating crystal fan fabrics as indications of abiotic precipitation in non-marine stromatolites. At this point, criteria were available to distinguish two distinct types of layered authigenic crust: essentially microbial and essentially abiogenic (Pope et al. 2000; Perry et al. 2007, p. 169).

The presence of Hybrid Crusts complicates the otherwise simple view of stromatolites based on two basic fabric types that do not generally co-occur. Hybrid

Crusts are composed of intimate alternations of Fine-grained and Sparry Crust and are therefore partly biogenic and partly abiogenic. But here again, petrofabric studies enable these to be deciphered. Already, Bertrand-Sarfati (1972, pl. 11(4), pl. 22(2)) had suggested that layered alternations in stromatolites might reflect seasonal changes in accretion, and Kerans (1982) (see Grotzinger 1989b, p. 10) had pointed out that “cement crusts were precipitated on microbial laminae while stromatolites were growing”. Locally, Hybrid Crusts appear to be extensively developed in Proterozoic stromatolite reefs such as ~1,000 Ma *Baicalia* reefs in Siberia (Petrov and Semikhatov 2001) (see Riding 2008, p. 82). Similarly, in the Pethei Group (~1,850 Ma) of northern Canada, Sami and James (1994, p. 120) suggested that millimetric spar-micrite couplets reflect alternation of “cement precipitation and microbial mat growth”.

7.5 Fabric Criteria Through the Geological Record

Macro- and microfabrics are the keys to deciphering stromatolites (Riding 2000, p. 206). The three principal fabric types are interpreted to be essentially biogenic, mixed and abiogenic (Fig. 22), and have created a variety of layered and unlayered deposits (Fig. 23). These criteria, proposed here to discriminate between these diverse deposits, build fundamentally on the observations first emphasized by Reis (1908) and subsequent researchers when they compared the delicate layering and radial structures of sinters with the coarse spongy fabrics of microbial deposits (Bucher 1913, 1918; Bradley 1928). These have since been examined in detail. See, for example, the following publications and their contained references on

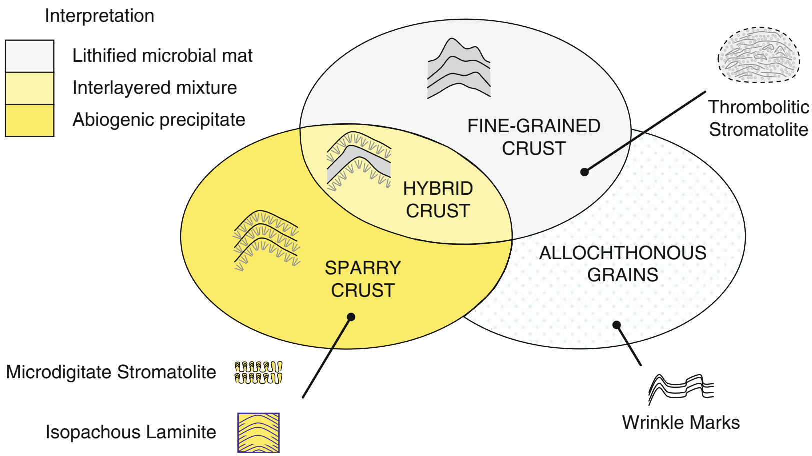

Fig. 22 Representation to show how Sparry and Fine-grained Crust, as well as incorporated allochthonous grains, contribute to the formation of Hybrid Crust, thrombolitic stromatolite, other macrolayered authigenic carbonate crusts, and wrinkle marks

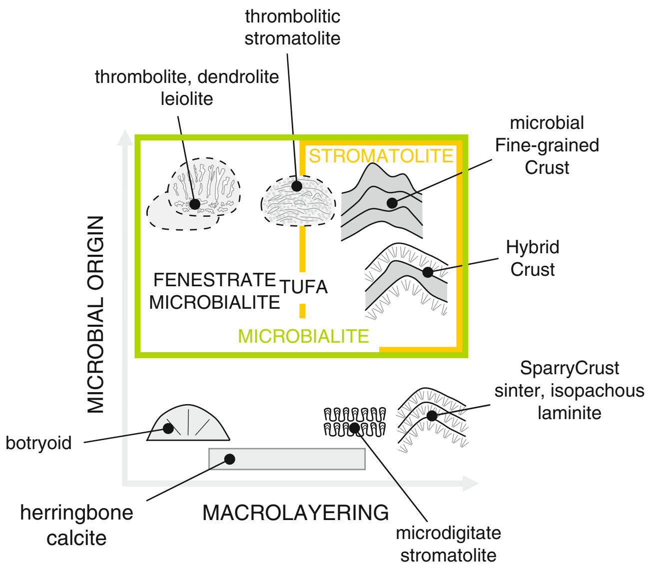

Fig. 23 Major categories of authigenic carbonate crust deposits compared with regard to degree of microbial origin and macrolayering. Principal microbial groupings are stromatolite [as defined by Kalkowsky (1908), and also here] and thrombolite (Aitken 1967), together with related non-layered microbial carbonates (dendrolite, leiolite). These are circumscribed by microbialite (Burne and Moore 1987). Examples of abiogenic crust, shown in the lower part of the diagram, include botryoids, herringbone calcite, microdigitate stromatolites and Sparry Crust deposits [for summary details see Sumner and Grotzinger (2000, 2004) and Riding (2008)]

Phanerozoic (e.g., Monty 1981; Bertrand-Sarfati and Monty 1994) and Precambrian (Grotzinger and Knoll 1999; Grotzinger and James 2000b; Pope et al. 2000; Sumner and Grotzinger 2004; Riding 2008) marine stromatolites and crusts, present-day microbial mats (e.g., Monty 1976; Arp et al. 2003, 2010; Dupraz et al. 2009) and hot spring carbonates (Pentecost 2005). Sparry Crust, Fine-grained Crust, and Hybrid Crust are recognizable in sufficiently well-preserved deposits. Proterozoic and especially Archaean deposits are especially challenging due to often poor preservation, but in these too fabric details allow cautious interpretation:

Sparry Crust may be present in the Palaeoarchaean, e.g., in the Warrawoona Group (~3,450 Ma) of north-western Australia, in stromatolites exhibiting continuous laminae (Lowe 1980, 1983; Hofmann 2000) that have sparry microfabrics (Hofmann et al. 1999, fig. 3), but these could well be secondary in origin (Hofmann et al. 1999, p. 1259). Thinly layered isopachous Sparry Crust appears to be present as “crinkly laminite facies” in the ~2,600 Ma Cheshire Formation of Zimbabwe (Sumner and Grotzinger 2000, p. 128). It is definitely present in the ~1,800 Ma Pethei Group of north-west Canada (Jackson 1989; Pope and Grotzinger 2000, p. 112). Isopachous Sparry Crust remained common in marine environments until the late Mesoproterozoic (Kah and Knoll 1996, fig. 4; see Riding 2008, fig. 5). It is associated with Hybrid Crust into the Neoproterozoic (see Hybrid Crust, below), and is probably present in evaporite basin sequences during the Phanerozoic (Pope et al. 2000).

Fine-grained Crust appears to be present in 2,724 Ma Tumbiana stromatolites from north-western Australia (Buick 1992, fig. 3e; Lepot et al. 2008, fig. 1b), and is definitely present in the ~1,800 Ma Pethei Group as peloidal clotted micrite (Sami and James 1996, fig. 7). It remains common in present-day marine stromatolites.

Hybrid Crust may be present as "Boetsap lamination" in the latest Archaean (2,550 Ma) Campbellrand-Malmani platform of South Africa (Sumner and Grotzinger 2004; see Riding 2008, p. 84), and again is definitely present as "spar-micrite couplets" in the ~1,800 Ma Pethei Group (Sami and James 1996, p. 217). Hybrid Crust remained common in marine environments to the latest Mesoproterozoic, e.g., in *Baicalia lacera* of the ~1,020 Ma Burovaya Fm of Turukhansk, Siberia (Petrov and Semikhatov 2001, fig. 6a). In the early Neoproterozoic it may be represented by some of the "lamelliform elements" described by Aitken (1989, pp. 15–16) in the ~800 Ma Little Dal reef (see Turner et al. 2000, fig. 10b).

This documentation needs to be extensively developed, fabric criteria require detailed refinement, and many aspects of biogenic and abiogenic influences on mineral precipitation in stromatolites require elucidation (e.g. Arp et al. 2010). These will also benefit by being augmented by analytical and modelling approaches to stromatolite macrofabric that build on previous work (e.g., Grotzinger and Rothman 1996; Batchelor et al. 2000, 2003; Corsetti and Storrie-Lombardi 2003; Storrie-Lombardi et al. 2004; Dupraz et al. 2006). In addition to providing important new insights into long-lived and wide-ranging deposits, fabric recognition provides the keys required to stabilize stromatolite definition.

8 Conclusions

1. Kalkowsky's (1908) microbial interpretation of ancient stromatolites was at first vigorously challenged due to their resemblance to hot spring crusts and other present-day laminated precipitates that were regarded as essentially abiogenic, and due to confusion between stromatolites and diagenetic concretions. During the following decades, criticism diminished as microbial stromatolites were recognized in present-day lake, marsh and shallow-marine environments. Logan et al. (1964) suggested recognition of both microbial and abiogenic stromatolites. This was opposed by support for the original microbial view. Awramik and Margulis (1974) proposed a modified definition that required stromatolites to be microbial, but not necessarily thinly layered. When Burne and Moore (1987) used this concept to define microbialite, stromatolites became a sub-group within microbialites, and reverted to being laminated microbial deposits. Meanwhile, Semikhatov et al. (1979) had proposed a descriptive definition of stromatolite that included both microbial and abiogenic deposits,

so long as they were thinly layered. This history of concept development resulted in at least three alternative views of stromatolites: (a) laminated and microbial (Kalkowsky 1908; Burne and Moore 1987; Riding 1999); (b) just microbial (Awramik and Margulis 1974); (c) laminated and microbial or abiogenic (Semikhatov et al. 1979). None of these approaches has gained unanimous support and there is currently no generally accepted definition of stromatolite.

2. Problems of stromatolite definition arise from the difficulties of distinguishing laminated authigenic crusts of microbial and abiogenic origin in ancient examples. Similarities in layering and external morphology between these deposits raise doubts about their interpretation, and confuse stromatolite definition by encouraging inclusion of abiogenic as well as microbial structures. Present-day crusts that have been regarded as essentially abiogenic, e.g., in cave and hot-spring sinters, have not normally been regarded as stromatolites. The only justification for grouping abiogenic and microbial crusts is the difficulty of distinguishing them in ancient deposits.
3. The geological record of layered marine authigenic carbonate crusts includes three distinctive types of deposit that have all been regarded as stromatolites: (a) Isopachous Sparry Crust – abiotically precipitated well-layered crust with sparry microfabric; (b) Fine-grained Crust – lithified irregularly, sometimes poorly, layered microbial carbonate, generally with fine-grained, (e.g., clotted, peloidal) but also sometimes coarse-grained microfabrics; (c) Hybrid Crust – thinly interlayered combinations of both preceding fabrics, with generally well-developed layering. Further work is required, but these fabric criteria can be used to broadly distinguish essentially abiogenic from essentially microbial crusts (Pope et al. 2000), provided that these are sufficiently well preserved.
4. The definition proposed here is: *Stromatolites are macroscopically layered authigenic microbial sediments with or without interlayered abiogenic precipitates*. This recognizes at least two types of stromatolite: (a) microbial, characterized by Fine-grained, locally coarse, Crust and (b) hybrid, composed of Hybrid Crust (i.e., alternations of Fine-grained and Sparry Crust). In contrast, thrombolite, dendrolite and leiolite are microbial carbonates distinguished from each other, and from stromatolites, by clotted, dendritic and aphanitic macrofabrics, respectively.
5. Thus, it is possible to use carbonate fabric criteria to distinguish essentially abiogenic crusts from essentially microbial ones. This ability permits practical application of a microbial definition of stromatolite, as Kalkowsky (1908) intended.

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