The term stromatolite: towards an essential definition

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Kalkowsky regarded stromatolites as laminated and microbial. Recognition of unlaminated microbial deposits, and also of biogenicity problems, subsequently resulted in broader definitions of the term stromatolite: (i) microbial but not necessarily laminated, and (ii) laminated but not necessarily organic. The first of these definitions does not discriminate between microbial deposits with markedly differing macrofabrics (such as thrombolite, dendrolite, etc.). The second purposely disregards origins and would apply the term stromatolite to both inorganic and organic deposits. Subsequent recognition of cognate terms (thrombolite, dendrolite, leiolite), and the umbrella term microbialite, has not resolved the question of stromatolite definition. Consequently, at least three long-standing definitions of stromatolite are available. These respectively emphasize the following features: (i) laminated and microbial, (ii) just microbial, (iii) just laminated. It is proposed to stabilize usage by adopting Kalkowsky's key points of laminated and microbial, supplemented by the adjective benthic, as expressed in the definition: '*a stromatolite is a laminated benthic microbial deposit*'. This definition excludes non-laminated microbial deposits (e.g. thrombolites) that may have had a different accretion history, and also abiogenic laminites. Doubt concerning biogenicity can be expressed by the descriptors 'probable' and 'possible' stromatolite. The alternative to stipulating a microbial origin for stromatolites would defer, but not ultimately avoid, the key question of their origin. □ *Biogenicity, definition, lamination, microbial, microbialite, stromatolite.*

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Stromatolites are simultaneously fossils and sediments. Their geological significance engages palaeobiology, sedimentology and stratigraphy. They are the most conspicuous Precambrian fossils, they are significant components of Proterozoic carbonate platforms, and they are locally important in Phanerozoic reefs. Present-day examples have become metaphors for the survival and continuing importance of microbial deposits. Yet, anomalously, there is no agreed definition of stromatolite in current scientific usage.

Reports of what we now call stromatolites date at least from Steel's (1825) descriptions of Cambrian examples, to which Hall (1883) gave the name *Cryptozoön proliferum*. The term stromatolite, itself based on Triassic forms, was not proposed until 25 years later (Kalkowsky 1908). In contrast to previous workers, who thought that stromatolites were animal in origin (e.g., Hall 1883; Matthew 1890; Seely 1906; Gürich 1906), Kalkowsky (1908) believed they were formed by plants, although he could not identify the organisms responsible. Walcott (1914) used modern freshwater tufas to deduce a cyanobacterial origin for Proterozoic Belt Supergroup stromatolites in Montana. Calcified cyanobacteria, which can form laminated biscuit-like oncoids, were already well known from lacustrine environments (see references in Mawson 1929, p. 616). Black (1933) further implicated cyanobacteria when he discovered Recent agglutinated intertidal stromatolites on Andros Island in the Bahamas. Young (1935) applied Black's observations back to Proterozoic stromatolites in South Africa, while Fenton and Fenton (1931, 1937) further documented Walcott's Belt examples. During the 1920s and 1930s, Mawson (1925), Pia (1927) and Maslov (1938) were also engaged in deciphering the nature of stromatolites (see Glaessner 1972). These important but relatively sporadic advances continued until 1960, notably on modern (Ginsburg *et al.* 1954) and Proterozoic (e.g. Vologdin 1955, Maslov 1960) examples. During the 1960s and 1970s, stromatolite research accelerated rapidly (Fig. 1) as interest spread, not least in response to discovery of large modern columnar stromatolites at Shark Bay in Western Australia (Logan 1961).

The stromatolite literature is now vast. GEOREF (January 2000) lists 3830 papers with the word stromatolite/stromatolites as a keyword, and it is sufficiently well known to be included in ordinary dictionaries. But what precisely do we understand by the term stromatolite? As Ginsburg (1991, p. 25) aptly

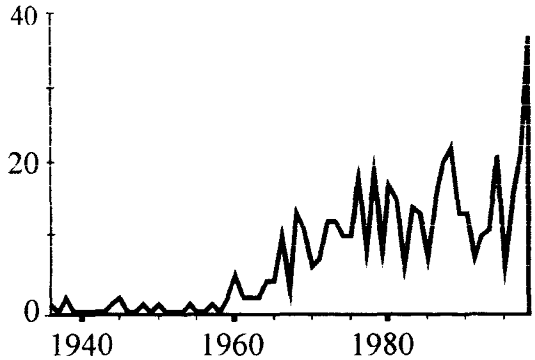

Fig. 1. Numbers of references per year to stromatolite and/or thrombolite from 1936–1998 (data from GEOREF August 1999). Note that GEOREF cites no references to stromatolite prior to 1936, or to thrombolite prior to 1975. The overall impression of the sharp increase during the 1960s and 1970s is probably correct, but these data are much less complete than the Awramik *et al.* (1976) bibliography (cf. Fig. 4).

noted, researchers encounter more difficulty in defining than in identifying stromatolites. Even a casual perusal of the literature reveals that whereas some specialists apply the term only to microbial deposits, others include abiogenic structures. Some insist that stromatolites are laminated; others employ the term to encompass clotted and dendritic, as well as laminated, macrofabrics. Which of these usages is correct, or preferable? What was the original meaning of stromatolite? What are the objects that we are attempting to characterize when we use the term?

Terminology matters. It is not necessary to argue that stromatolite should be clearly defined: scientific communication relies on clarity. The purpose of this paper is to outline how the term stromatolite became blurred, and to propose a solution by refining Kalkowsky's (1908) original definition.

Stromatolite definition

Kalkowsky

Ernst Kalkowsky (1908) coined the term stromatolith (Greek *stromat*, to spread out, Latin *stroma*, bed covering; Greek *lithos*, stone) for Lower Buntsandstein (earliest Triassic) lacustrine examples near the Harz Mountains in northern Germany (Kalkowsky 1908; Paul & Peryt 1985) (Figs 2 and 3). In fact, Kalkowsky (1908) devised two terms: stromatoid and stromatolith (see Appendix 1), which he used in parallel with ooid and oolith. Kalkowsky (1908) did not give a single comprehensive definition of stromatolite. There has been debate about what exactly he wished to convey by the twin terms stromatoid and stromatolith.

Fig. 2. Field example of one of the lacustrine stromatolites originally described by Kalkowsky (1908). The overall column height is 1.15 m. Bernburg Fm., Lower Buntsandstein (Scythian, Early Triassic), Heeseberg near Jerxheim, northern Germany.

Monty (1977, p. 18) has argued that 'stromatolite refers to the final resulting structure ... whereas stromatoid refers to what constitutes it, i.e. sets of laminae' (but see also Hofmann 1969, p. 3, 1973, p. 341). Stromatoid is not commonly used now.

However, there can be little doubt about Kalkowsky's view of the general structure and nature of stromatolites. Throughout his paper, Kalkowsky

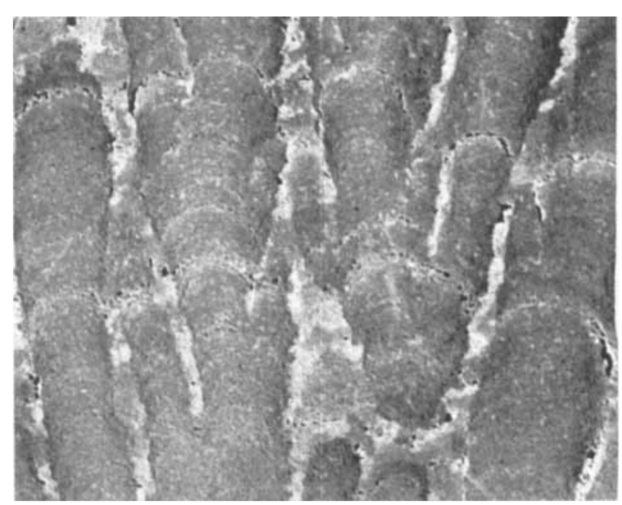

Fig. 3. Cut slab of one the lacustrine stromatolites originally described by Kalkowsky (1908). The width of the field of view is 9.2 cm. Bernburg Fm., Lower Buntsandstein (Scythian, Early Triassic), Heeseberg near Jerxheim, northern Germany. Specimen courtesy of J. Paul.

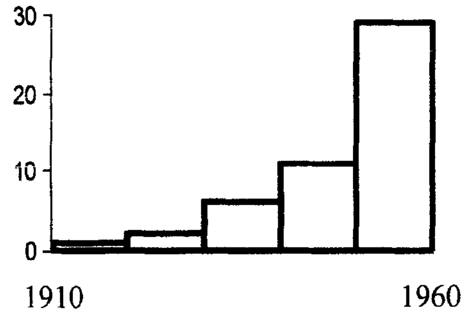

Fig. 4. Numbers, by decade, of pre-1960 papers with 'stromatolite' or 'stromatolith' in the title, not counting Kalkowsky's (1908) original paper and Reis's (1908) critical response. Data from Awramik *et al.* (1976).

(1908) repeatedly emphasized two aspects of stromatolites: their (i) laminated structure, implicit in the name, and (ii) organic nature. He stated that he could not be specific about the particular types of organisms involved in stromatolite formation, but he considered them to be 'niedrig organisierte pflanzliche Organismen' (simply organized plant-like organisms) (Kalkowsky 1908, p. 125). It is reasonable to conclude that Kalkowsky regarded stromatolites essentially as laminated microbial structures, and he had a similar view of the origin of ooids. Incidentally, the definition ascribed to Kalkowsky by Krumbein (1983, p. 499), 'stromatolites are organogenic, laminated, calcareous rock structures, the origin of which is clearly related to microscopic life, which in itself must not (need not) be fossilised', is not actually a direct quote from Kalkowsky's paper (W.C. Krumbein, pers. comm. 1999) even though it has been cited as if it were a literal translation (e.g. Feldmann & McKenzie, 1998, p. 201; Grotzinger & Knoll, 1999, p. 316). Nonetheless, it encapsulates Kalkowsky's overall view.

1908–1950s

The term stromatolite was not widely used until the 1950s. The earliest article on stromatolites after Kalkowsky's (1908) paper was Reis's (1908) immediate critical response in which, in contrast to Kalkowsky, he concluded that both stromatolites and ooids were formed inorganically by precipitation from gel. An impression of how the term stromatolite subsequently slowly came to gain acceptance can be obtained by counting the number of papers that gave it prominence by including 'stromatolite' or 'stromatolith' in their title. There appears to have been only one such paper in the 1910s, two in the 1920s, then six (1930s), eleven (1940s) and twenty-nine (1950s) (Fig. 4). The first stromatolite-titled paper in a language other than German (in fact in English) was by Høeg (1929), and not until the 1940s did a stromatolite-titled paper appear in North America (Cloud 1942).

1960–1970s

The marked increase in stromatolite studies that ultimately took place in the 1960s finally focused interest on Kalkowsky's work. During the 1970s several authors reviewed the development of stromatolite concepts (e.g. Walter 1972), and some quoted at length from Kalkowsky's 1908 paper (e.g. Monty 1977, pp. 16–19). This attention, together with additional studies of modern and ancient stromatolites, led to consideration of what the term should mean. Hofmann (1969, pp. 56–57) listed some pre-1969 usages of 'stromatolite'. He himself regarded stromatolites as 'a highly polymorphous group of internally laminated organosedimentary structures' (Hofmann 1969, abstract). More fully, he defined stromatolite as 'A millimetre- to dekametre-sized organosedimentary structure whose growth is recorded by a succession of laminae. The laminae represent intervals of accumulation of fine sediment on surfaces presumed to have been populated by a community of micro-organisms. The sedimentary material is accumulated by trapping or agglutination on the organic plexus, or by nonskeletal precipitation resulting from the metabolic activity of the micro-organisms' (Hofmann 1969, p. 58). This definition echoes Kalkowsky in its emphases on lamination and microbial origin.

However, in a significant step, Awramik & Margulis (1974) defined stromatolite 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'. Initially, only a suggestion in the informal Stromatolite Newsletter, Awramik & Margulis's (1974) definition was widely disseminated by being endorsed by M.R. Walter in the introduction to his seminal book (Walter 1976, p. 1). It followed Kalkowsky in prescribing organic (and microbial) origin, and it is thus a 'genetic' definition, but at the same time it abandoned lamination as an essential character of stromatolites. Awramik & Margulis (1974) removed lamination from the definition because research had revealed that some microbial deposits are either only crudely laminated, e.g. Shark Bay (see Logan 1961, p. 522) or not laminated at all (see Aitken 1967), and in order to emphasize that process was the significant factor (S.M. Awramik, pers. comm. 1999). However, this action substantially broadened the term and allowed stromatolite to be regarded as an umbrella term for any microbial organosedimentary structure regardless of internal structure. Thus, when Burne & Moore (1987) subsequently created the term microbialite to encompass microbial deposits regardless of macrofabric, they simply adapted Awramik & Margulis's (1974) definition to define microbialites as '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 & Moore 1987, pp. 241–242).

However, in addition to revealing macrofabric variations that needed to be accommodated by the developing terminology, stromatolite research was also exposing the difficulties of demonstrating biogenicity in ancient examples. In this case, the problem with Kalkowsky's (1908) definition lay not in lamination, but in the microbial nature inferred for stromatolites. The solution would be to remove the requirement that stromatolites be essentially biogenic. Consequently, four of the five authors of Semikhatov *et al.* (1979, p. 993) (the dissenter, not surprisingly, being S.M. Awramik) defined stromatolite as 'an attached, laminated, lithified, sedimentary growth structure, accretionary away from a point or limited surface of initiation. Although characteristically of microbial origin and calcareous composition, it may be of any origin, composition, shape, size or age.'

1980–1990s

Awramik (1982, p. 353) described stromatolites as 'characteristically ... layered sedimentary structures ... whose laminae are convex away from the substratum', although he noted that 'transition from laminated to unlaminated at times can be seen within a single stromatolite' (Awramik 1984, p. 3). Krumbein (1983) even more resolutely revived dual emphasis on lamination and microbial origin in a definition which, in its essence, was the same as Kalkowsky's: 'laminated rocks, the origin of which can clearly be related to the activity of microbial communities, which by their morphology, physiology and arrangement in space and time interact with the physical and chemical environment to produce a laminated pattern which is retained in the final rock structure' (Krumbein, 1983, p. 501). Riding (1991, p. 30) more simply, but to similar effect, merely added benthic and defined stromatolite as a 'laminated benthic microbial deposit'.

Paradoxically, therefore, decades of research into modern and ancient examples had substantially increased understanding of the formation, distribution and history of stromatolites, but at the same time had resulted in a perplexing choice of contrasting definitions, none of which was pre-eminent. By the early 1980s it was possible to variously regard stromatolites as (i) microbial and laminated (e.g. Kalkowsky 1908; Hofmann 1969; Krumbein 1983), (ii) microbial but not necessarily laminated (Awramik & Margulis 1974), or (iii) laminated but not necessarily organic (Semikhatov *et al.* 1979) (Table 1). A casual examination of subsequent publications indicates that the situation continues to be unclear, with some definitions emphasizing lamination while others do not. Rasmussen *et al.* (1993, p. 199) commented 'although strict definitions vary, stromatolites can generally be described as laminated organosedimentary structures'. In contrast, Coshell *et al.* (1998, p. 1014), describing Holocene thrombolitic deposits considered 'the broader generic definition of 'stromatolite' presented by Awramik & Margulis (1974) to be more suitable for these organosedimentary structures', whereas Grotzinger & Knoll (1999, p. 314) preferred the definition of Semikhatov *et al.* (1979).

Table 1. Respective emphases on lamination and biogenic/microbial in some definitions of stromatolite between 1969 and 1983, compared with Kalkowsky (1908).

	Lamination	Biogenic/microbial
1908 Kalkowsky	Yes	Yes
1969 Hofmann	Yes	Yes
1974 Awramik & Margulis	No	Yes
1979 Semikhatov et al.	Yes	No
1983 Krumbein	Yes	Yes

Non-laminated microbial deposits

The status of the term stromatolite has been further complicated by the addition of several other terms to distinguish types of benthic microbial deposits. Thrombolite (Greek: *thrombos*, clot; *lithos*, stone), defined on the basis of Cambro-Ordovician examples of the southern Canadian Rocky Mountains, has a macroscopically clotted fabric (Aitken 1967; also see Aitken 1966). Dendrolite (Greek *dendron*, tree; *lithos*, stone) (Riding 1991, p. 34), best known from the Palaeozoic, has a macroscopically bush-like fabric typically produced by calcified microbes. Leiolite (Greek *leios*, uniform or smooth, *lithos*, stone) has a relatively structureless, aphanitic, macrofabric lacking clear lamination, clots or dendritic fabrics, and is based on examples in the Late Miocene of SE Spain (Braga *et al.* 1995, p. 347). These are all essentially genetic terms in the mould of Kalkowsky (1908) that stipulate a biogenic origin but differ in terms of macrofabric. The existence of these terms emphasizes the need to circumscribe clearly the term stromatolite.

Stromatolite features and categories

The principal qualities that stromatolite definitions have alternately emphasized or purposely omitted are laminated structure and microbial origin.

Lamination. – Thin lamination, 2 mm or less in thickness (see McKee & Weir 1953, p. 384), is exhibited by Kalkowsky's (1908) examples, and is commonly emphasized in stromatolites descriptions, e.g. Défarge *et al. (1994, p. 14): 'stromatolitic structure* is created by the occurrence of sub-horizontal, millimetre thick carbonate laminae'. Such lamination is often readily visible in hand-specimen, and Kennard & James (1986) emphasized the meso-macroscopic scale of lamination in stromatolite, and of clots in thrombolite. However, some very small stromatolites (microstromatolites 20–200 µm across, and ministromatolites ~200 µm to 20 mm across, Hofmann & Jackson (1987, p. 963)) may have lamination that is not macroscopic.

Microbes. – Microbes are sometimes regarded as essentially just bacteria, although of course even these alone are extremely diverse, but are probably more correctly defined as microscopic organisms in general. They broadly encompass Archaea, Bacteria (including cyanobacteria), some fungi, small algae and protozoans. Because of their diversity and environmental tolerances, the sedimentary effects of microbes are noticeable in a wide variety of depositional settings.

Microbes often mediate mineral precipitation and sediment localization; hence the formation of microbial sediments (Riding & Awramik 2000). Stromatolites, as defined here (i.e., laminated benthic microbial deposits), form by a variety of processes, principally trapping of sediment particles (Black 1933) and precipitation (Walcott 1914; see Ginsburg 1991). On the basis of variations that include components, microfabric and quality of lamination, several varieties of stromatolite have been described. Many Precambrian examples are essentially micritic, but exhibit a wide range of complex microfabrics (Bertrand-Sarfati 1976), and there are microdigitate forms with a radial fibrous, apparently precipitated (Hofmann & Jackson 1987), microfabric. Stromatolites that have formed mainly by trapping of allochthonous particles are termed agglutinated stromatolites (Riding 1991) and may be very coarse grained. Subtidal examples include some of the famous Recent domes and columns at Shark Bay, Australia, and Lee Stocking Island, Bahamas. Parts of these are crudely laminated (see Logan 1961, p. 522) or unlaminated, and so are not entirely stromatolite, although it is debatable whether they can also be described as clotted (but see Feldmann & McKenzie 1998, fig. 8). Intertidal stromatolites also commonly incorporate coarse-grained layers. In addition to forming some thrombolites and dendrolites (Kennard & James 1986; Riding 1991), calcified cyanobacteria can create crudely laminated skeletal stromatolites (Riding 1977). Terrestrial (Wright 1989) (and subaerial stromatolites, Riding 1991) and tufa stromatolites have also been described (Riding 1991). Stromatolite has principally, but not exclusively, been applied to carbonate sediments. Siliceous (Walter *et al.* 1972), evaporite (Rouchy & Monty 1981; Gerdes *et al.* 1985), and siliciclastic (Martín *et al.* 1993; Bertrand-Sarfati 1994) stromatolites also occur (and see Hofmann 1973, p. 346).

The existence of these varieties of stromatolite, and the need to relate them to thrombolite and leiolite, as well as to an umbrella term such as microbialite, underlines the importance of clear definitions, not least for stromatolite itself.

Discussion

Kalkowsky's (1908) definition circumscribed stromatolites as laminated deposits that can reasonably be inferred to be microbial. The Awramik & Margulis (1974) and (Semikhatov *et al.* 1979) redefinitions, respectively, reflect realization that (i) not all microbial deposits are laminated and (ii) it can be difficult to establish biogenicity in ancient examples. Yet these attempts at terminological clarification in turn carry implications that limit their value. Three key questions are raised by these attempts to define and redefine stromatolite: (i) Are the new difficulties less than those posed by Kalkowsky's (1908) original definition? (ii) How substantial are the problems posed by Kalkowsky's definition of stromatolite as laminated and microbial? (iii) Is the solution to live with the problems or to attempt to stabilize usage?

New difficulties

Awramik & Margulis's definition. – Several practical implications arise from the Awramik & Margulis (1974) broad definition of stromatolite: (a) It makes no nomenclatorial distinction between stromatolite and thrombolite because it precludes stromatolite from being used solely for *laminated* microbial deposit. This clearly involves loss of terminological precision. (b) 'Stromatolite' as defined by Awramik & Margulis (1974) is now commonly expressed by the term microbialite. Usage of stromatolite to convey the same meaning would involve duplication and would leave no specific term for 'laminated stromatolite'. It is more straightforward in these instances to continue to use microbialite as the overall umbrella term for microbial deposits, and stromatolite for the laminated sub-category. After all, it is necessary to recognize subdivisions as well as overarching categories of microbial carbonates.

Semikhatov et al. definition. – This definition precludes stromatolite from being applied solely to *microbial* laminated deposits, because it applies to all 'attached, laminated, lithified, sedimentary growth structure(s), accretionary away from a point or limited surface of initiation' which 'may be of any origin'. This was not a new concept; Logan *et al.* (1964, p. 69) had already written of 'inorganic stromatolites'. But in avoiding the requirement for demonstrating – or at least reasonably inferring – biogenicity, this definition inevitably encompasses other sedimentary deposits, of whatever origin, that fit this geometrical pattern. These could include abiogenic surface precipitates, diagenetic concretions, as well as organic, but non-microbial, structures such as coralline algae.

The ostensible advantage of a descriptive definition would be that it could be readily applied in the field. But would such a term retain value? Many geological field terms are not purely descriptive; everyday sedimentary terms, e.g. bedding, sandstone, fossil are interpretive. The significance of many deposits relies on recognition of their origins, and this would seem to be true for stromatolite. A purely descriptive definition could be so broad as to have little value.

However, application of the Semikhatov *et al.* (1979) definition also has specific repercussions for microbial deposits. It stipulates that structures must be 'accretionary away from a point or limited surface of initiation'. This would encompass domical to digitate stromatolites, but could be interpreted to exclude stratiform stromatolites. Possibly the intention was to prevent the redefined term stromatolite from being extended to laminated sediments in general. Yet it still manages to encompass stalagmite and stalactite speleothems, other domical surface $CaCO_3$ precipitates, diagenetic concretions and some sedimentary metallic ores.

Multiple definitions. – As a compromise, Ginsburg (1991, p. 27) suggested applying a descriptive (i.e. laminated, organic or inorganic) definition to ancient stromatolites, and a genetic (microbial, laminated or non-laminated) definition to modern examples: in other words, co-existence of the Semikhatov *et al.* (1979) and Awramik & Margulis (1974) definitions. However, each of these definitions had broadened Kalkowsky's (1908) definition by omitting either microbial origin or laminated structure, respectively. Consequently, a dual approach that allows stromatolites to be both biogenic and abiogenic does not resolve the issues outlined above that arise from these less focused definitions. Researchers will still need to recognize subdivisions as well as overarching categories of microbial carbonates. And they will also still need to reach judgements on such a crucial question as biogenicity, and will require terminology to accurately convey their assessment.

Old problems

The key elements of Kalkowsky's (1908) stromatolite definition are laminated fabric and microbial origin.

Lamination. – Recognition of lamination presents no difficulties. It is already widely regarded as an important feature of stromatolites, enshrined in the name itself, and also given prominence by Semikhatov *et al.* (1979). Whether or not to include it within the definition is a matter of choice between a narrower or broader definition. The case has already been made that inclusion of lamination provides more precision and is the rationale for a series of other fabric-based terms (thrombolite, dendrolite, etc.). In contrast, exclusion of lamination relinquishes these possibilities and also creates synonymy between stromatolite and microbialite (see Awramik and Margulis's definition, above).

Biogenicity. – In contrast, the central question that has emerged from the continuing debate about stromatolite definition is whether it is reasonable to define stromatolites as microbial deposits. Establishing biogenicity has been a problem as long as the term stromatolite has existed, as Kalkowsky's (1908) soon discovered when his interpretation of them as organic was opposed by Reis (1908). In fact, it was a problem even before the term stromatolite was proposed. Avoiding this difficulty was the principal aim of Semikhatov *et al.* (1979). On the other hand, there seems little dispute that a genetic definition – if practical – is desirable. Stromatolite workers have long regarded stromatolites as organosedimentary structures, no modern analogue of a stromatolite has been suggested that is not microbial, and indeed Semikhatov *et al.* (1979, p. 993) themselves emphasized that stromatolites are 'characteristically of microbial origin'.

The problem of biogenicity is most starkly revealed when the interpretation is of critical importance. This is exemplified by the debate concerning the oldest putative stromatolites, dated at 3550 Ma in the Warrawoona Group of Western Australia. Lowe (1994) suggested that not only these examples, but all structures older than 3200 Ma that have been described as stromatolites, are inorganic in origin.

Although support remains for the view that these examples are probably microbial (e.g., Schopf 1994; Hofmann (2000), the ensuing exchanges (Buick *et al.* 1995; Lowe 1995) were reminders of the continuing need to apply biogenicity criteria objectively to ancient stromatolites (see Buick *et al.* 1981; Walter 1994, pp. 272–274; Hofmann *et al.* 1999).

The fundamental objection to including microbial in the definition of stromatolite is that it is in most cases inferential (see Grotzinger & Rothman 1996). It arises directly from the small size of microbes, and the fact that many stromatolites do not appear to preserve well-defined remains of the organisms responsible for them. How then can we demonstrate microbial origin in stromatolites? In addition to the overall geological setting (see Buick *et al.* 1981), specific criteria include fossils, macrofabrics and microfabrics.

(i) Preserved organisms. Although the mere presence of preserved microbes in stromatolites (biophoric stromatolites of Hofmann 1973, p. 350) does not indicate that they built these structures; microbes can be clearly constructional, as in skeletal stromatolites (Riding 1977) that contain abundant calcified microbes.

(ii) Macrofabric criteria based on comparisons with modern analogues whose origins are known to be microbial. These include crestal thickening of laminae, and irregularities within the laminae (see Buick *et al.* 1981; Walter 1983; Walter 1994, table 1).

(iii) Microfabrics. Although stromatolite microfabrics can appear inscrutable (Logan *et al.* 1964, p. 69) they are nonetheless complex and distinctive products of microbial mats as seen in modern examples (e.g. Monty 1976). Notwithstanding the difficulty of precisely elucidating the organisms and processes involved, these microfabrics can be regarded as microbial products and hence offer opportunities that could substantially assist biogenicity evaluation.

Solution

The biogenicity problems are not trivial, but neither are the difficulties of employing a descriptive definition (see *New difficulties*, above). Kalkowsky's (1908) emphasis of the laminated and microbial nature of stromatolites has been followed by many subsequent workers. Broadening the definition to include non-laminar deposits on the one hand (Awramik & Margulis 1974) or abiogenic (Semikhatov *et al.* 1979) structures on the other, does not ultimately resolve problems, either of categorization or interpretation. Stipulation of lamination avoids overlap with other categories of benthic microbial deposit, such as thrombolite, and avoids synonymy with microbialite. Lamination was emphasized by Kalkowsky, and is reflected in the name stromatolite. As H.J. Hofmann wrote: 'the fundamental feature of the stromatolite is the lamination' (Hofmann 1969, p. 4). However, Semikhatov *et al.* (1979, p. 994) were incorrect when they wrote that 'it was the lamination that Kalkowsky stressed, not its origin': Kalkowsky (1908) repeatedly stressed his conviction of the organic nature of stromatolites, in addition to emphasizing lamination.

The descriptive rationale of Semikhatov *et al*'s (1979) definition of stromatolite conflicts with the genetic rationale that is now well established for other microbial deposits. It negates the essential microbial nature of stromatolites, and it would include laminated domes as diverse as mineral deposits, diagenetic concretions, travertine crusts and speleothem, as well as microbial deposits, within the term stromatolite. Use of dual definitions of stromatolite, descriptive for ancient and genetic for present-day examples (Ginsburg 1991, p. 27) would not reduce these deficiencies, and could increase confusion.

Kalkowsky's (1908) definition requires having to demonstrate biogenicity. This is not a problem in stromatolites that preserve the organisms responsible for their formation, such as skeletal stromatolites, but it can be a challenge in other types. However, interpretation of microbial carbonate fabrics, including microfabrics, is improving and could provide the ability to achieve the level of confidence required to apply Kalkowsky's (1908) definition. There will of course be examples where preservation will be inadequate, and in these cases uncertainty can be indicated by 'possible, probable' prefixes. This is no different from the difficulties involved in recognizing other fossils; the fact that we cannot always confidently recognize fossils in all geological situations does not prevent us usefully defining them. But it remains necessary to realize the difficulties and to apply biogenic criteria rigorously. Stipulation of microbial nature avoids the unnecessary inclusion of essentially inorganic structures, such as speleothem and travertine crystalline crusts, in stromatolite. This emphasis does not of itself create biogenicity problems, which will exist in any case and cannot be avoided by definition. Defining a stromatolite to include abiogenic deposits only defers the question: 'so these deposits are laminated, but are they microbial?'

Emphases on microbial and lamination can be further refined by adding 'benthic', to remove the possibility of confusion with, for example, sedimented planktic diatom mats (see Pike & Kemp 1999). *It is* thus proposed to return to Kalkowsky's key concepts using the redefinition of Riding (1991): *A stromatolite is a laminated benthic microbial deposit.*

Implications

Definitions carry connotations, particularly where terminology has not been stable. The definition proposed here has implications for the terminological hierarchy of benthic microbial deposits, for ancillary terms, and in some cases for certain specific examples. These include:

1. Stromatolite and microbialite have distinctive and separate meanings. Stromatolite denotes only benthic microbial deposits with lamination. Benthic microbial deposits in general are encompassed by the term microbialite of Burne & Moore (1987).
2. Non-laminated microbialites are not stromatolites. Non-laminated microbialites that have been named include thrombolites (clotted), dendrolites (dendritic) and leiolites (aphanitic).
3. Doubt whether a stromatolite-like structure is microbial or not can be expressed by 'possible' or 'probable' stromatolite, as appropriate, and the same descriptors can be applied to other microbialites.
4. Stromatolites may or may not have primary relief. Layers without substantial relief, such as those formed on tidal flats, and reefal crusts, are stromatolites just as are those that form elevated domes and columns.
5. The concept of 'potential' stromatolite, i.e. unconsolidated stromatolite (Krumbein 1983, p. 501), is subsumed within the redefinition proposed here, which refers to a structure rather than a rock and therefore encompasses developing present-day stromatolites as well as ancient examples.
6. Modern microbial domes and columns at Shark Bay and Lee Stocking Island often exhibit varied internal structure, and can be composite, including stromatolite and other microbialite categories.

Conclusion

In the introduction to his seminal book on stromatolites, Malcolm Walter commented 'it is 68 years since E. Kalkowsky coined and defined the word 'stromatolith', yet there is increasing controversy and confusion as to its use' (Walter 1976, p. 1). Indeed, by 1979 three contrasting definitions of stromatolite were available: the original one 'microbial and laminated' (Kalkowsky 1908), a 'genetic' one 'microbial but not necessarily laminated' (Awramik & Margulis 1974) and a 'descriptive' one 'laminated but not necessarily organic' (Semikhatov *et al.* 1979).

As this is written, a further 24 years have elapsed. It is time to end the confusion. I propose that not only the oldest but also the best definition of stromatolite is that of Kalkowsky (1908), which can simply be restated: '*a stromatolite is a laminated benthic microbial deposit*' (Riding 1991). This adds stromatolite to the suite of microbial deposits distinguished according to their differing fabrics (stromatolite, thrombolite, dendrolite, leiolite), with microbialite as the overarching term. Qualifying terms, such as 'possible stromatolite' or 'probable stromatolite', linked to specific biogenicity criteria such as those summarized by Walter (1994, table 1) can be used to express degree of confidence concerning the microbial origin of particular examples.

Adoption of this redefinition would contribute to terminological stability and promote effective communication. Not least, it could further the task of deciphering the rich palaeobiological and sedimentary record archived in stromatolites and other microbialites.

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Appendix I

Terms similar to stromatolite

Stromatoid (Kalkowsky 1908, p. 101): '... jene dünnen Lagen von kohlensaurem Kalk mit eigener Struktur als Stromatoid eingeführt werden' [these thin calcium carbonate layers with characteristic structure can be introduced as Stromatoid]. In other words: 'the component laminae of stromatolites' (Monty 1977, p. 18).

Stromatolith (Kalkowsky 1908, p. 69): 'Kalkmassen ... die eine feine, mehr oder minder ebene Lagenstruktur besitzen' [limestone masses that possess a fine, more-or-less planar layered structure]. German equivalent of English stromatolite. A different usage of stromatolith ('a rock mass consisting of many alternating layers of igneous and sedimentary rocks in sill relationships') (Foye 1916, p. 791) is obsolete (see Hofmann 1969, p. 3).

Stromatolithi (Pia 1927, p. 37). A subdivision of the Spongiostromata of Gürich (1906); part of an early attempt to formalize the classification of microbial fossils.

Stromatoloid (Oehler 1972). Small laminated columnar structures that may lack biologic control.