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A guide for microscopic description of fossil stromatolites

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Abstract

Stromatolites are laminated biosedimentary structures of great importance for paleobiological, paleoecological, and paleoenvironmental analyses, mainly in Precambrian rocks. Their value is related to the glimpse of past life recorded in their lamination, fabric, and, eventually, due to the preservation of organic matter, including microfossils, and because their deposition is directly influenced by environmental conditions. Although stromatolites are widely described in microscopic scale, there is a lack of standardization of their nomenclature, precluding better paleoenvironmental and paleobiological interpretations. In this study, we propose a guide for the microscopic analysis of fossil stromatolites and, possibly, thrombolites, and provide a review of specialized literature and the bibliometric context of main terms. The goal is to contribute to the improvement of their application through systematization of microscopic data, in the face of novel paleoecological and paleobiological approaches and for astrobiological prospection for microbialites in therock record of Mars.

KEYWORDS: stromatolites; microscopy guide; carbonates; paleobiology.

INTRODUCTION

Stromatolites are laminated biosedimentary deposits formed by benthic microbial mats (Burne and Moore 1987, Riding 2000) and are the most abundant category of microbialite in the geological record (Grotzinger and Knoll 1999). The development and lithification of stromatolites depend upon complex interactions between the environment and microbial communities at and below the mat–water interface (i.e., Des Marais 1990, 1991, Défarge *et al.* 1996, Dupraz and Visscher 2005, Visscher and Stolz 2005). The physical–chemical and metabolic processes involved in these interactions result in the lithification of laminated structures, but only very rarely in the preservation of the mat community (see more details in Défarge *et al.* 1996 and Spadafora *et al.* 2010). Stromatolites record geobiological interactions between the environment and the consortium of various biological groups that make up microbial mats (Walter 1977).

As biosedimentary structures, stromatolites may be analyzed at different scales, from regional to nanometric, and from paleobiological and sedimentological perspectives. Such approaches can potentially reveal the geologic, paleogeographic, and stratigraphic contexts and paleoenvironmental conditions in which stromatolites thrived, as well as aspects of microbial metabolism and lithification processes responsible for their development and preservation (Table 1). Field observations at the meter to kilometer scale allow characterization of the local to regional geological context of the stromatolite-bearing strata (e.g., stratigraphy, lateral distribution, paleoenvironment, and deformation like compressional or shear stresses). Analysis in outcrops and hand samples, usually at the submeter to centimeter scale (occasionally smaller), furnishes information on stromatolite macrostructure, that is, the shapes and relief of individual stromatolites and stromatolitic buildups, as bioherms and biostromes. Closer observation, on the scale of centimeters to millimeters, commonly employing magnification (hand lens or stereomicroscope) allows initial characterization of the internally laminated stromatolite mesostructure (Fairchild and Sanchez 2015).

At higher magnification, the microscopic internal characteristics of laminae allow to do inferences about the biological and environmental contributions to mat stabilization and subsequent sustained development. At this scale, in generally rare circumstances of very early diagenetic preservation by silica (chert), organic vestiges of the original mat, including remains of microorganisms, may be preserved, thereby permitting ecological inferences regarding the mat-building paleobiota or its

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Table 1. Scales at which stromatolites may be analyzed.

Level and scale of analysis	Focus of analysis	Nature of inferences
Outcrop to regional (m to km scale)	Lateral and vertical distribution of microbes and their relationships with other strata	Stratigraphic and paleogeographic distribution, paleoenvironmental/depositional settings (facies, hydrodynamics, bathymetry, etc.)
Macrostructure in outcrop and hand samples (mm to m scale)	Stromatolite shape, morphometry, spacing, and relationships with other sediment and sedimentary structures (facies analysis)	Paleoenvironment, paleocurrents, bathymetry, and the role of mat construction in sedimentary dynamics
Mesostructure in outcrops and laboratory (μm to cm scale)	Description of laminar morphology and architecture, and recognition of patterns in laminar accretion	Sedimentary dynamics, and lateral and vertical community growth and development
Microstructure using optical and electronic microscopy (μm to sub-mm scale)	Identification of primary and diagenetic constituents of laminae, including minerals, microfossils, texture, and fabrics	Relationships of sediment with microbiota and within microbiota (paleoecology) Diagenesis and taphonomy
Nanometric features in specialized laboratories with accelerator facilities (sub-μm to μm scale)	Extreme details of minerals, microorganisms, and organized and amorphous organic matter (when available)	Ultrastructural details of biogenic and mineral components and their relationships

palimpsestic overprint (Hofmann 1969). Depending on the quality of preservation, such preserved microbiotas may provide a window onto auto-(species), syn-(communities), and demoecological (populations) relationships (*lato sensus*) within and among the paleobiota and abiotic factors in sustaining mat production and stromatolite buildup.

As stromatolites are complex, different approaches to their description have been suggested, some even predating the term *stromatolite*. According to Hofmann (1969), John H. Steel was the first to describe stromatolites in 1825, from Saratoga County, New York, USA, referring to them as "lithographs." In 1908, the term *stromatolite* was proposed by Ernst Kalkowsky (1908) for structures from the Triassic Buntsandstein of Germany. With the application of stromatolites in geological studies, new proposals for illustration and description emerged, especially since the mid-twentieth century, for example, the three-dimensional reconstruction methods of Krylov (1959), Raaben (1969), and Hofmann (1976) and guides to the description such as those by Hofmann (1969, 1976), Preiss (1976), Grey (1989), Riding (2011a, 2011b), Fairchild and Sanchez (2015), and Grey and Awramik (2020). However, they all have two aspects in common that impose a serious limitation for the comparison of different outcrops and studies: little or no approach to stromatolite description at the microscopic scale and the lack of a focus or consensus in the microscopic description. Nevertheless, present technology now allows stromatolite research at nanoscale levels (i.e., Wacey *et al.* 2013, Maldanis *et al.* 2020), an important advance, especially for taphonomic and paleobiological analyses of Precambrian microbiotas. Even so, a significant lacuna still remains in protocols for the microbialite description at the microscopic level.

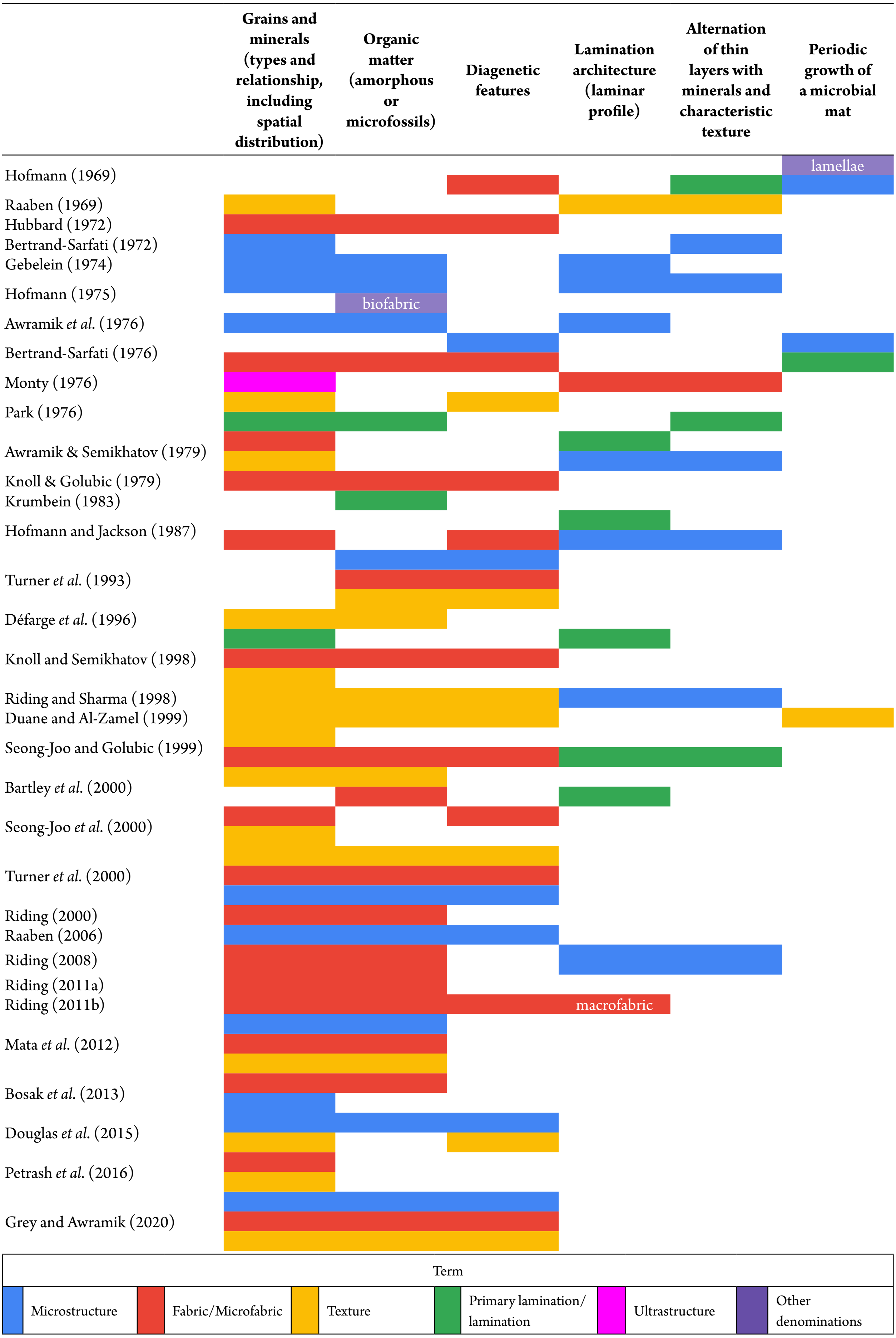
The specialized literature brings varied uses of terms for the microscopic description of stromatolites, such as microstructure, microfabric, fabric, and microfacies, that contribute little towards fulfilling the potential of microscopic evaluation of stromatolites (see references in Table 2). On the contrary, concept disorder and even semantic misinterpretation appear in the varied applications of these terms (Grey and Awramik 2020). For example, while some authors identify the components of laminae such as the paleobiota and sediments (i.e., Riding 2000, Mata *et al.* 2012, Bosak *et al.* 2013), others identify laminar components based on post-lithification products, such as micrite originating from the decay of cells and mucilage (i.e., Bertrand-Sarfati 1976, Knoll and Golubic 1979, Riding and Sharma 1998). Studies are frequently limited by the lack of clear definitions of concepts (i.e., Bartley *et al.* 2000, Riding, 2008, 2011a, Mata *et al.* 2012). Although the literature is very extensive (Grey and Awramik 2020), efforts at a holistic approach to description must begin with the establishment of a consensual and definitive glossary applicable to stromatolites on Earth, as well as to suspect structures on rocky surfaces elsewhere in the solar system, such as the lake and playa-lake deposits targeted for paleobiological exploration on current and future missions to Mars (i.e., Bianciardi *et al.* 2014, Rizzo 2020).

To reconcile the problems of the lack of a descriptive key for stromatolitic microscopic analysis, we review the main terminologies and propose a tentative guide for characterizing stromatolites (and possibly thrombolites) at the microscopic scale to improve stromatolite-based paleobiological, paleoecological and paleoenvironmental interpretations.

THE MEANING OF STROMATOLITE LAMINATION

The lamina is the fundamental unit of any stromatolite, the main feature that differentiates them from other types of microbialites (Riding 2011a). Lamination results from the interaction among microbial consortia in thin (< mm) metabolically stratified benthic mats, ambient sediments, and the surrounding physical–chemical environment. It is preserved by penecontemporaneous lithification and subsequent diagenesis (Stal 2012, Bolhuis *et al.* 2014, Prieto-Barajas *et al.* 2018). Therefore, stromatolites only exist where physical and chemical conditions allow both their establishment and sustainment. Such conditions are not necessarily constant nor uniform, and stromatolites grow in successive phases of biologically induced and biologically influenced (Dupraz *et al.* 2009) organomineralization (*sensu* Défarge *et al.* 1996, 2009). This process is

Table 2. Nomenclature applied to stromatolitic microscopic analysis and the comparison of the meaning of each term.



*Note the overlapping of meanings and how it constantly repeats. When interpreted as isolated terms, they are comprehensive (although with some exceptions); however, the overview of the literature is a mixed, confusing glossary. This may operate as a threshold for the full exploration of stromatolite potential, other than paleoenvironmental and, eventually, paleobiological application.

promoted by decomposers in the mat, mainly sulfate-reducing bacteria, in accordance with the local carbonate saturation state (van Lith *et al.* 2003, Dupraz and Visscher 2005, Spadafora *et al.* 2010). Factors that may complicate lamina formation and preservation are abrupt hydrodynamic changes, terrigenous influx, light incidence, nutrient availability, carbonate saturation state, as well as destructive interferences by metazoans, benthic algae, exposure, and erosion.

Microbial mat formation and growth

Microbial mat development comprises the starting point for stromatolite lamination, yet intrinsic and extrinsic factors influence mat growth, development, and complexity (Des Marais 1991, Stal and Calmette 1994, Noffke 2010, Noffke and Awramik 2013, Suarez-Gonzalez *et al.* 2019). For example, in shallow water stromatolites, a greater influence in mat complexity is favored by intrinsic factors, such as high microbial diversity, and extrinsic factors, such as availability of nutrients and key elements for biogeochemical reactions (Dupraz *et al.* 2009). On the contrary, extrinsic factors such as the sedimentary dynamics (e.g., currents, waves, sediment supply, and burial) and the action of grazing invertebrates or colonization by algae and invertebrates may influence the mass growth of the microbial mat and the equilibrium between destruction and regeneration of the biofilms necessary for sustained stromatolite development. The environment also determines the accretion process: for example, a combination of diversity of electrolytes, tides, and grains occurs, and it drives to the agglutinated accretion style (Suarez-Gonzalez *et al.* 2019). External factors can even define whether precursor biofilms will give rise to a microbial mat or promote the growth and regeneration of the microbial mats. When the microbiota regeneration exceeds the mechanical stressor, the microbial mats are, overall, minimally developed (Stolz 2000, Dupraz *et al.* 2009, Noffke 2010, Callefo *et al.* 2021, Barbieri and Cavalazzi 2022).

Seen in detail, microbial mats are vertically stratified benthic microecosystems that are initiated by the adherence of cyanobacteria to the sediment–water interface, followed by the introduction of members of other domains, including some Archaea and, more rarely, eukaryotic algae (Pedrós-Alió 2006, 2007, Bolhuis *et al.* 2014, Prieto-Barajas *et al.* 2018). Viruses may also occur among mat dwellers (Brüssow *et al.* 2004, Bolhuis *et al.* 2014). Once established, the mat becomes a self-sustaining ecosystem immersed in extracellular polymeric substances (EPS) (Bolhuis *et al.* 2014, Prieto-Barajas *et al.* 2018) and speckled by minerals, mainly carbonates and terrigenous grains (Stal 2012). The microbial mat organizes itself following several physicochemical gradients that will sustain and be sustained by the microbiota according to their physiology (Bolhuis *et al.* 2014), to light incidence and balance between O_2 and H_2S (i.e. Jørgensen *et al.* 1979, Vincent *et al.* 2000), the efficiency of absorbed irradiance (Al-Najjar *et al.* 2010), besides other factors inherent to life, such as temperature, pH, water availability, nutrients, and energy sources (Konhauser 2009). In practically all cases, cyanobacteria compose the mat surface due to their demand for light, N_2, and CO_2 (Bolhuis et al., 2014). Below them, a layer of aerobic heterotrophs may occur, followed downwards by anaerobic heterotrophs and purple, green sulfur and green non-sulfur bacteria, and finally by methanogen and sulfate-reducer bacteria (Prieto-Barajas *et al.* 2018). This high diversity is possible because of the microenvironmental heterogeneity imposed on the microbial mat, mainly by light, salinity, oxygen, carbon, sulfur, and nitrogenous compounds, as well as tide effect, precipitation, vegetation, bioturbation, and other factors (Bolhuis *et al.* 2014, Prieto-Barajas *et al.* 2018).

According to Noffke (2010), three types of biostabilization of microbial mats may be defined:

(i) Type I: A smooth layer of EPS is formed on the surface upon which the mat is growing, which increases the benthic mat's resistance to fair-weather friction and erosion, such as those related to waves and currents, but not to severe storm conditions;

(ii) Type II: Increase in the resistance to mechanical stresses acting on endobenthic microbial mats as sediment becomes entangled by trapping or binding by cyanobacterial filaments, being less effective than type I biostabilization;

(iii) Type III: Unlike the previous two types, type III produces aggregates of biotic and abiotic components, such as precipitates encompassed by biofilms, which can remain in suspension, preventing their burial.

After the establishment and biostabilization of the microbial mat, the accretion process occurs, leading to the deposition of a stromatolite. Following the ideas by Burne and Moore (1987) and Riding (i.e., 2008), the accretion process may happen through passive (physicochemical driven) mineral precipitation, biomediated mineral precipitation, agglutination (after Suarez-Gonzalez *et al.* 2019), also referred as trapping and biding, of terrigenous grains, or an alternate style between agglutination and precipitation, as demonstrated in stromatolites from paleolake settings (Fedorchuk *et al.* 2016, Wilmeth *et al.* 2019). This last accretion style seems to be more common in the modern stromatolites, although Middle to Late Proterozoic examples have already been demonstrated (Suarez-Gonzalez *et al.* 2019). The accretion through mineral precipitation comprises the most common accretion style in geological time and results in the formation of stromatolite structure and its preservation. Due to its importance, this process is better discussed in the next session.

Concerning the relationship between microbial mats and grain influx, particulate sediment dispersed in the surroundings may be incorporated into it by adhering or binding to the ubiquitous EPS in the mat, dropping in between upright microbial filaments (baffling), or being overgrown by microbes (trapping) (Cohen 1989, Des Marais 1990, 1991, Dupraz and Visscher 2005, Noffke

2010). The baffling and trapping (Dupraz *et al.* 2009) processes seem to be selected as a survival strategy in order to avoid burial under normal conditions of sediment flux. Baffling occurs in mats in which filamentous cyanobacteria orient themselves vertically to take advantage of available sunlight (phototaxis), thereby reducing current velocity and inducing the settling of particles in suspension. Trapping is the mechanism by which mineral particles become attached to EPS at the surface of microbial mats resulting in an entanglement of cells and minerals and in a growth incorporating sediment. In lower supratidal zones, for example, trapping and baffling prevent burial. In upper intertidal zones, cyanobacteria move (for details, see Overman and Wells 2022) in all directions once the sediments are transported laterally. Under such conditions, binding reestablishes the mats (Noffke 2010, Cuadrado 2017, Callefo *et al.* 2021).

Microbial mats may cover extensive areas, over which the ambient dynamics may differ. Such a situation gives rise to biofilm-catenae (sensu Noffke 2010), a lateral succession of different types of microbial mat adapted to local differences in environmental dynamics, such as currents, subaerial exposure, sedimentation rate, and hydraulic dynamics, among others (an example can be seen in Ricardi-Branco *et al.* 2018).

Although found worldwide in a wide range of sedimentary environments, three different modern microbial mats, which have been studied in detail, reveal important representative aspects of composition, diversity, molecular profile, and ecology of microbial mats: hypersaline environments, intertidal flats, and hot springs (Stal and Caumette 1994, Bolhuis *et al.* 2014). Cyanobacteria usually comprise the dominant forms, along with purple sulfur bacteria, followed by bacteroidetes and acidobacteria (Gobet *et al.* 2012, Burow *et al.* 2013, Bolhuis *et al.* 2014). The physical–chemical gradient of these life forms in the intertidal areas plays an important role in the nitrogen and sulfur cycles (i.e., DesMarais and Canfield 1991, Gao *et al.* 2022).

In this sense, many ecological aspects that once operated in microbial mats can be accessed through stromatolites (Fig. 1). For example, demoecological information concerning the functional groups, their interaction, life cycle, and physiological reactions that result in mat development can be accessed by analyzing preserved microfossiliferous assemblages (composition, life cycles, distribution within laminae) and the mineral framework, as well as the isotopic profile of unmetamorphosed or non-recrystallized samples. Also, the lamination and growth patterns of stromatolite morphology provide insights into populations (demoecology) and community development related to the environment (synecology). Even autoecological information may be obtained, regarding individual species, although it may be difficult to distinguish biological species on the basis of the limited morphological information preserved in stromatolites.

Preservation of lamination

Stromatolites are preserved by processes strikingly different from those of other fossil types. Whereas an organism passes through temporally separate and distinct stages of growth and development (biocenosis) and then death and preservation (thanatocenosis, taphocenosis, and orictocenosis), this cannot be said of stromatolites. For example, while the alive microbial mat at the upper surface of a stromatolite is still growing, all the rest downwards is already in various stages of degradation, burial, lithification, and preservation, making the field of stromatolite taphonomy something peculiar.

Studies of modern stromatolites worldwide, from a wide range of subaqueous environments and chemical conditions, have been crucial to understanding how the preservation of laminae happens. Several occurrences have provided important insights, for example, French Polynesia and Line Islands in the Pacific Ocean (Défarge *et al.* 1996); Rio de Janeiro, Brazil (Vasconcelos *et al.* 2006, Spadafora *et al.* 2010); Cayo Coco in Cuba (Pace *et al.* 2018); and the classical well-documented occurrences of Exuma Cay, Bahamas, and Shark Bay, Australia. According to Visscher and Stolz (2005) and Dupraz and Visscher (2009), microbial mats become lithified through two processes, one related to microbial metabolism, with special attention to rates of photosynthesis, day and night metabolisms, and through sulfate-reducing metabolism of some taxa. Empty sheaths and dead cells play an important role in mat lithification and stromatolite build-up, as they furnish abundant sites for carbonate or silica precipitation during burial (i.e., Golubic 1973, Oehler 1976, Défarge *et al.* 1996, Spadafora *et al.* 2010).

However, microbial mats may not necessarily be preserved as stacked laminated structures. The development of lamination depends on cyclic regimes (e.g., annual, seasonal, and diurnal) of variation in environmental parameters, biological components, and behavior, as well as the microbial capacity for trapping and binding sediments (Dupraz and Visscher 2009) and organomineralization (Noffke and Awramik 2013). Such processes guarantee the edification of laminated three-dimensional structures, or stromatolites, which is distinct from the two-dimensional biofilm of the microbially induced sedimentary structures (MISS), resulting from very short-lived microbial colonization, and is visible only in plain view (Noffke and Awramik 2013).

In general, the micro- and meso-structural analysis of a stromatolite can lead to insights into the ecology of the microbial mat (demoecological groups and their physiology, following Gabelein 1974; and synecological and demoecological aspects, as proposed by Monty 1976) and its lithification process. These factors will, in turn, originate from different primary microstructures with well-delimited vertical distribution (Gabelein 1974), but with broad geographical distribution, usually determined by oceanic currents, tidals, and wind patterns (Monty 1976). Finally, those primary microstructures can be subjected to wide

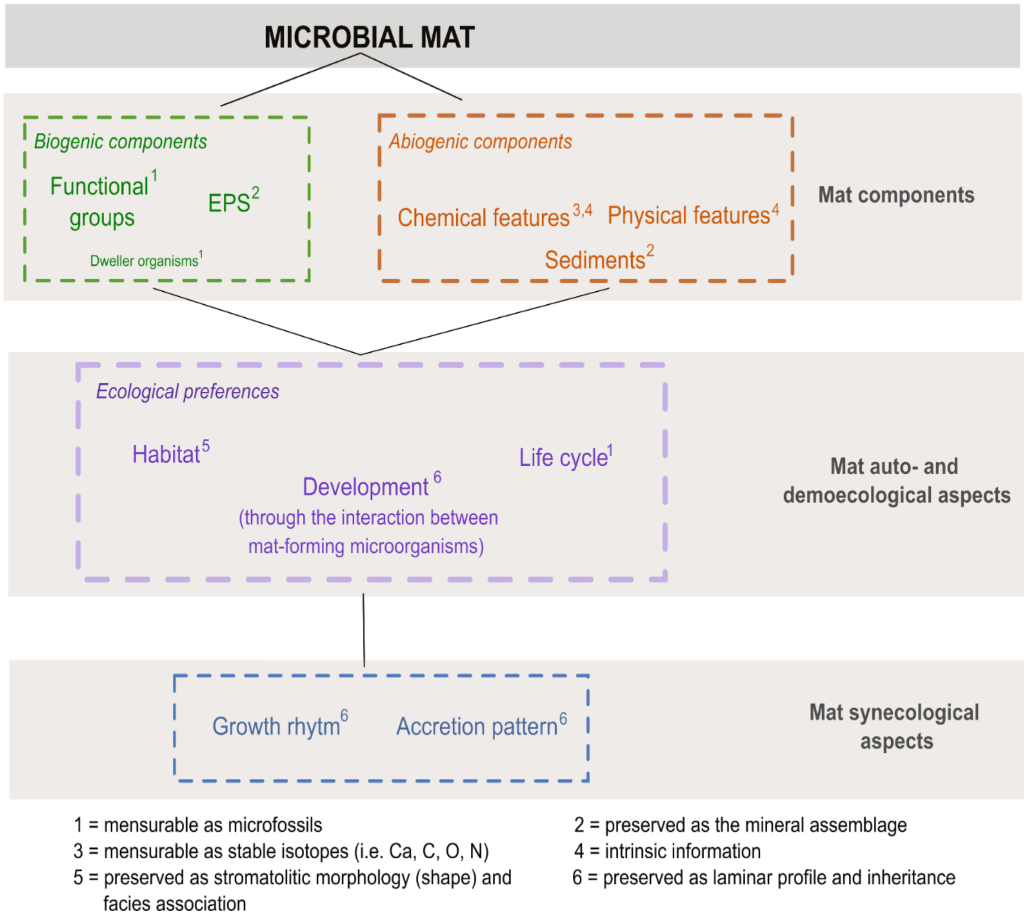


Figure 1. A simplified summary of microbial mat structure, its development, and the different levels of relationship with the environment. Much of this information is preserved in stromatolites and can be analyzed in different scales, for example, the mesoscopic analysis of the growth rhythm and accretion pattern, and the microscopic analysis of biological components and their life cycle.

chemical and physical diagenetic processes and, sometimes, metamorphic obliteration, which will result in a secondary microstructure (Fig. 2).

MATERIALS AND METHODS

For the literature review, public databases and specialized sites for articles and book search were consulted. Keywords were applied and combined for material search, like stromatolite, carbonate, fabric, microstructure, lamination, lithification, texture, ultrastructure, and microscopic. In total, 299 articles and 6 books were evaluated. From those works, we selected the ones that strictly dealt with the systematization of microscopic aspects of stromatolites, going beyond the description, but also created categories that could be applicable to the fossil record. A total of 33 works fitted these conditions.

After the establishment of the data source, information was inserted in tables comprising the term(s), original idiom, the meaning of each term, the geological features related to each meaning and to each term, the interpretation attributed to each term, and the geological material. Data were organized in chronological order to check the temporal occurrence of each term. However, no temporal tendency for the application of a preferred term was noted. The last step was to assemble the acquired data into a graphical representation, which is shown in Table 2.

To test how representative our sampling was, a bibliometric analysis was performed (Fig. 3), which utilized the Scopus database and the following search terms with the number of results in parentheses: stromatolites AND fabric (254 results); stromatolites AND texture (203 results); stromatolites AND microtexture (5 results); stromatolites AND factory (18 results); stromatolites AND microfacies (79 results); and stromatolites AND microstructure (86 results). These terms were limited to some parameters, such as Title, Abstract, and Keywords, and complemented by other publication restrictions, as articles with final versions published in the English language. For a more content-based approach, the geographic terms and references to geological units were removed, although chronostratigraphic terms were preserved. The software used in the elaboration of the illustrations was VOSViewer 1.6.18, which allows the creation of maps based on bibliographic database files. Aiming to avoid biased linkages, the keywords did not receive different weights, and all terms that

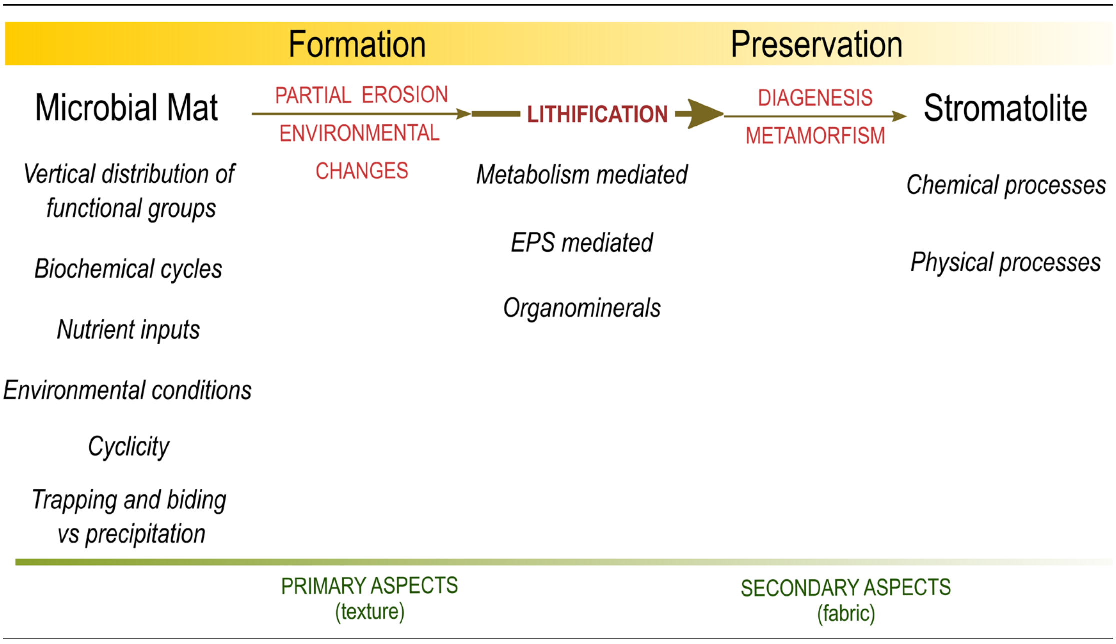


Figure 2. Stages encompassed in the development and preservation of stromatolites.

appeared at least one time were considered in the construction of the bibliographic maps.

ESTABLISHING KEY TERMS FOR THE MICROSCOPIC ANALYSIS OF FOSSIL STROMATOLITES

Analysis of the specialized literature and terminology concerning the microscopic description of stromatolites shows how complex these structures are, as they represent the product of distinct sedimentary, biological, and diagenetic/taphonomic processes. While much of the paleontological material deals with past beings and their modes of preservation, researchers who study stromatolites still need to consider one more factor in this equation: sedimentation. All these components (sediment, biological, and diagenetic) are easily identified at all scales of analysis of a stromatolite; however, it is at the microscopic scale that the complex interaction between environment and microbial mat and the subsequent biostratinomic and diagenetic overprinting become evident and can be understood. Therefore, it is important to delimit the primary components, which will have a fundamental role in understanding the stromatolite as a sedimentary product.

The reviewed articles and books show that the authors agree that the primary components that act in the formation of stromatolites are grains, precipitated minerals, and organic matter. Associated with the analysis of primary components, the authors also noticed relationships among these components, the architecture resulting from these relationships, and the cyclicity in these relationships throughout stromatolite formation. These parameters naturally arise during the analysis of the fundamental factors in stromatolite development and therefore consistently appear in descriptions of primary aspects.

If, on the one hand, the term *stromatolite* is consensual among researchers, the nomenclature and degree of detail used to describe them differ greatly (Table 2). Terms such as fabric, texture, microstructure, microfacies, laminae/lamination, ultrastructure, and variations of these terms (i.e., biofabric) were identified. They occur repeatedly in the literature independent of the temporal or regional context of the study. However, there are cases in which one term was applied throughout the entire work, while other texts used different terms to refer to the same meaning or used a single term to encompass various aspects.

While some authors clearly distinguish primary and secondary components by applying different terms to name the components, others describe all components together under the same terminology. For example, there are cases where the term *microstructure* referred to the primary minerals associated with the microfossiliferous assemblage, their diagenetic alteration, and their architectural morphology (laminar profile) and the alternation between light and dark lamination, while other work used the same term "microstructure" to refer to the microfossiliferous assemblage and their diagenetic aspects. This behavior is also not time restricted nor applied by specific research groups. It is a common, although confusing, practice.

Concerning secondary aspects, few cases used a specific term to refer to them. Most articles group them together with the primary mineral description, where they are described in different degrees of detail. Some works also propose categories of microscopic aspects, but with no intention to create a general classification (e.g., Raaben 1969, Hubbard 1972, Bertrand-Sarfati 1972, 1976, Riding 2011a, 2008, Mata *et al.* 2012, Grey and Awramik 2020). These categories, based on the combination of primary and diagenetic features, are occurrence restricted and were applied because they best described

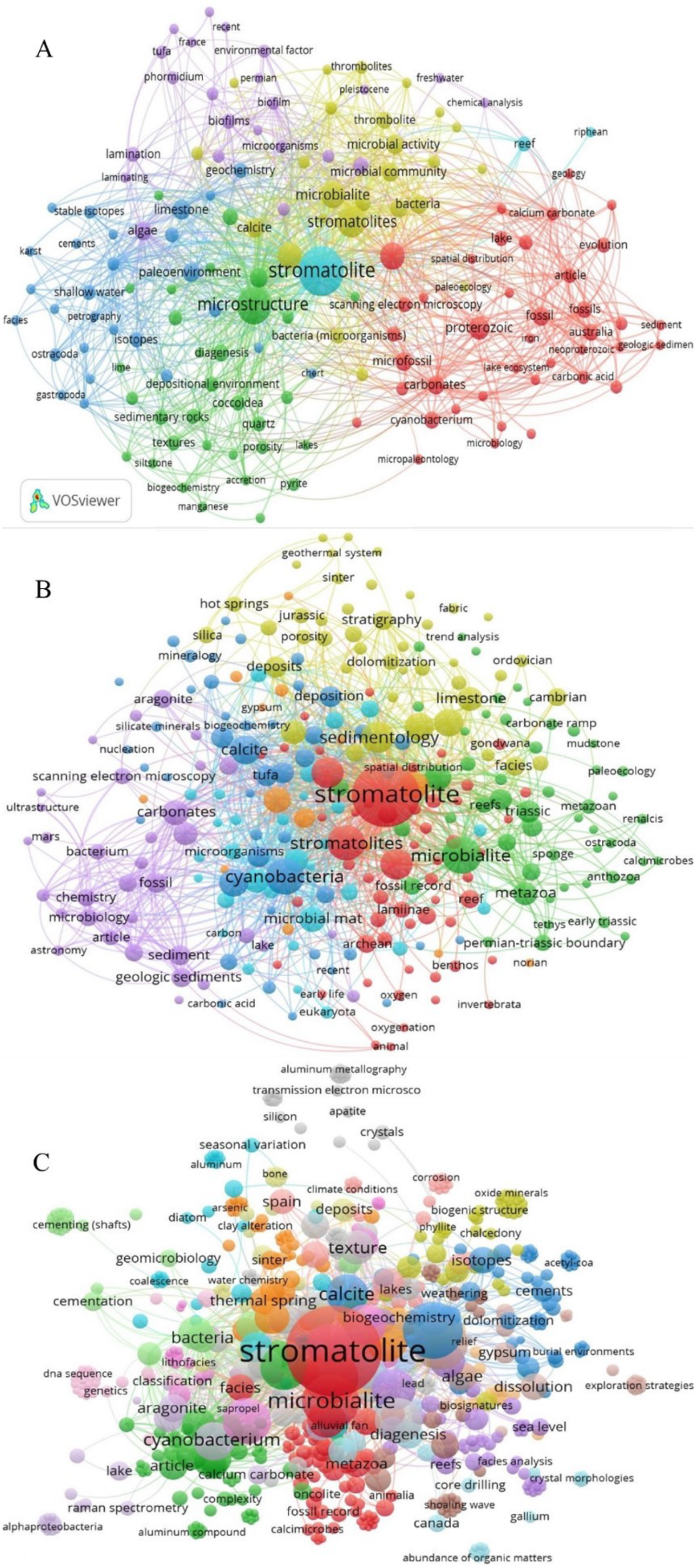


Figure 3. Bibliometric maps of the terms *stromatolites*, *microstructure*, *fabric*, and *texture*, showing the relationship between (A) stromatolite and microstructural terms, (B) stromatolite and fabric terms, and (C) stromatolite and textural terms. Size of circles reflects the frequency of the term *appearance* in the analyzed data; colors represent closest connections, creating different classes; and lines represent how close a term appears to others. Note the proximity of the term *microstructure* to the term *stromatolite* as compared to the terms *fabric* and *texture*.

complex material and provided interpretations to the description stage of the study.

The Scopus database and the following maps (Fig. 3) indicate that microstructure, fabric, and texture are the most widely used terms to describe stromatolites. Microfabrics and microtexture, also used as synonyms of fabric and texture, are less preferred among the analyzed data, whereas factory and microfacies apply to different definitions, commonly referring to palaeoenvironmental conditions and specific stratigraphic levels, respectively.

The term *microstructure* is the one that fits better the meaning it presents in the literature (Fig. 3A). The term directly connects with the term *stromatolite*, as well to sedimentary, mineralogical, and biological terms, as well as the term *texture*, representing the wide application of this term in the literature. Table 2 shows that the term *microstructure* was already attributed to all aspects and components of a stromatolite, ranging from grains and minerals, organic matter (amorphous or microfossils), diagenetic features, lamination architecture (laminar profile), the alternation of thin layers with minerals, as well as the periodic growth of a microbial mat. Its broad meaning, however, may be a problem for the standardization of stromatolite descriptions and comparisons.

On the other hand, the terms *fabric* and *texture* (Figs. 3B and 3C) exhibit the same low frequency, which is located at the margin of the respective diagrams. They presented similar connections, mainly with mineral phases and relative terms, such as sinter, silicon, limestone, apatite, and dolomitization. This scenario follows the literature, where their meanings are commonly equal. However, they do not connect to *microfossils* or similar terms, even though they are represented. In this study, it is argued that the absence of a direct connection between the terms *microfossils*, *texture,* and *fabric* may be due to the subjective meaning of the last ones. This fact is recognizable in the literature, as can be observed in Table 2. Texture and fabric have been referred as grains and minerals, organic matter (amorphous or microfossils), diagenetic features, lamination architecture (laminar profile), the alternation of thin layers with minerals, as well as the periodic growth of a microbial mat, or a combination of these parameters. However, a clearer connection to organic matter or microfossils added to their vague definitions transports the biological aspects to the background, to the point that bibliometric analysis does not trace their connections.

To standardize descriptive practices, we propose the application of a specific nomenclature for primary original components of stromatolitic laminae separated from diagenetic processes. Terminology should be different to avoid misconceptions and confusion. We apply the term *texture* (or *textural*) for primary components, a term inherited from classical sedimentology (i.e., Tucker 1991; revision at Flügel 2010). In this study, we include all the information deriving from the mat growth and development of the microbial mat (as shown in Fig. 1), including the biological components, allochemical components, the organominerals, and the quality of their preservation, as presented in Table 3. For diagenetic components and processes (see topics 4 and 5 of Table 3), we use the term *fabric*, a term first used in stromatolites by Knoll and Golubic (1979), to encompass primary and diagenetic aspects, but highlighting the latter. Fabric should include all diagenetic events and features after the mineralization of organominerals and new recrystallized or substituted minerals, following the mat burial. The general overview of textural and fabric aspects, when used together, may be referred to as *microstructure*, as proposed by Grey and Awramik (2020), and as *laminations* or *laminae* when referred to the physical unit (product) formed from the combination of different processes in a given time span, marked by surfaces and different from the previous and the following laminae.

A PRELIMINARY DESCRIPTION GUIDE FOR FOSSIL STROMATOLITE AT THE MICROSCOPIC SCALE

In this study, a description guide for microscopic analysis of fossil stromatolites is proposed (Table 3) and examples are shown (Fig. 4). It encompasses textural (primary) aspects and fabric (secondary) features, bringing together concepts and proposals from previous works on rock description, carbonate description, and stromatolitic fossils. It may be applied to different stromatolitic lithologies, mainly carbonate and silicified stromatolites.

Following the description of laminae components, two aspects must be addressed, namely, cyclicity and the lateral continuity and thickness of each lamina. Those pieces of information are necessary to understand eventual synecological variations and allow a detailed understanding of biotic and abiotic factors over time and, thus, the general development of the stromatolite.

The textural, or primary, features comprise the fossilized remains of the microbial mat's original components up to the lithification stage, including the organominerals. Microfossils, amorphous organic matter, and the primary mineral assemblage are encompassed, where qualitative and quantitative features can be addressed.

The degree of diagenetic information depends on the diagenetic history of the sample, varying between occurrences and even between samples from the same outcrop. In this sense, if possible, this description key should be applied backward in fossil samples, beginning with the fabric aspects and passing to the textural description. Thus, researchers will be allowed, at first, to understand the general aspects of the final product they are analyzing, the stromatolitic laminae, then understand and clean up the diagenetic imprints for, finally, reaching the primary aspects of the stromatolitic building up with more fidelity and accuracy. On the other way, analyzing from the primary than the diagenetic components may facilitate wrong interpretations or waste of time, once diagenetic chemical processes may result in self-organizing structures that mimetize microfossils, for example (Brasier *et al.* 2006). Also, distinguishing primary minerals and organominerals from diagenetic neomorphs may pose a challenge. It is important to highlight that stromatolite diagenesis, as diagenesis in carbonate in general, may homogenize the minerals through

Table 3. Proposed description guide for microscopic analysis of fossil stromatolites. For parameters that demands concerning number or percentage of microscopic field of view information, it is important to define and indicate the ocular and objective magnification and the area in square microns.

<table>
<tr><th colspan="5">TEXTURE</th></tr>
<tr><td rowspan="8">1. Biogenic components</td><td colspan="4">1a. Microfossils</td></tr>
<tr><td>1a.1. Morphological diversity (taxonomy, if possible)</td><td colspan="2">1a.2. Relative abundance: number of specimens in field of view</td><td>1a.3. Mode of occurrence: dispersed or concentrated in clusters or laminae</td></tr>
<tr><td colspan="4">1b. Amorphous organic matter</td></tr>
<tr><td>1b.1. Mode of occurrence: dispersed in crystalline net; as irregular masses; as short filaments or elongated corpuscles; between grains or crystals</td><td>1b.2. Relative abundance: number of clusters, filaments, or corpuscles in each microscopic field</td><td>1b.3. Color</td><td>1b.4. Transparency: transparent, translucid, opaque</td></tr>
<tr><td colspan="4">1c. Allochemical biogenic components</td></tr>
<tr><td>1c.1. Type: (e.g., shells and bones)</td><td colspan="3">1c.2. Relative abundance: number of components and % of area in field of view</td></tr>
<tr><td>1c.3. Roundness</td><td colspan="2" rowspan="2">1c.5. Relative abundance: number of grains in field of view</td><td rowspan="2">1c.6. Mode of occurrence: dispersed; in lens; as patches, encompassing the biological components</td></tr>
<tr><td>1c.4. Sorting</td></tr>
<tr><td rowspan="16">2. Mineral components</td><td colspan="4">2a. Trapped, bounded, or agglutinated mineral components</td></tr>
<tr><td>2a.1. Mineralogy</td><td colspan="2" rowspan="5">2a.6. Relative abundance: number of grains in field of view</td><td rowspan="5">2a.7. Mode of occurrence: dispersed; in lens; as patches, encompassing the biological components</td></tr>
<tr><td>2a.2. Grain size</td></tr>
<tr><td>2a.3. Morphology</td></tr>
<tr><td>2a.4. Roundness</td></tr>
<tr><td>2a.5. Sorting</td></tr>
<tr><td colspan="4">2b. Precipitated mineral components</td></tr>
<tr><td>2b.1. Mineralogy</td><td>2b.2. Authigenic crystal mosaic: hypidiotopic; xenotopic; idiotopic; poikilotopic; porphyrotopic</td><td colspan="2">2b.3. Mode of occurrence: dispersed; as laminae; in clusters; encompassing the biological components; as relic or palimpsestic</td></tr>
<tr><td colspan="4">2c. Accessory minerals</td></tr>
<tr><td>2c.1. Mineralogy</td><td colspan="2" rowspan="3">2c.4. Relative abundance: number of minerals per field of view or % of area in field of view</td><td rowspan="3">2c.4. Mode of occurrence: dispersed; clustered; associated with another textural component</td></tr>
<tr><td>2c.2. Dimensions</td></tr>
<tr><td>2c.3. Morphology</td></tr>
<tr><td colspan="4">2d. Allochemical components</td></tr>
<tr><td colspan="2">2d.1. Type: (e.g., ooids)</td><td colspan="2">2d.2. Relative abundance: number of components and % of area in field of view</td></tr>
<tr><td colspan="4">2e. Primary porosity (fenestrae)</td></tr>
<tr><td>2e.1. Dimension</td><td>2e.2. Pore shape and borders: irregular, elongate, equidimensional; rounded, sharped, angular to irregular</td><td>2e.3. Orientation relative to lamination: concordant, discordant (perpendicular, oblique)</td><td>2e.4. Relative abundance: number = % porosity in field of view</td></tr>
<tr><td>3. Quality of preservation of organic components</td><td colspan="2">3a. Relative to chemical degradation of walls, sheaths and amorphous organic matter varying from smooth and continuous, with original thickness minimally altered (excellent) to grainy, discontinuous, degraded (poor).</td><td colspan="2">3b. Relative to structural integrity of individual cells and sheaths and internal mat structure, varying from undeformed, amply represented and distributed (excellent) to deformed, irregularly preserved and patchily distributed (poor) to vestigial and faintly evident (palimpsestic).</td></tr>
</table>

Continue...

Table 3. Continuation.

<table>
<tr><th colspan="6">FABRIC</th></tr>
<tr><td rowspan="16">4. Features related to chemical processes</td><td colspan="5">4a. Dissolution surfaces</td></tr>
<tr><td>4a.1. Orientation relative to lamination: concordant (parallel) or discordant (perpendicular, oblique)</td><td colspan="3">4a.2. Relative abundance: abundant (observable in all fields of view), common (observable in most fields of view), rare</td><td>4a.3. Extent: localized or widespread</td></tr>
<tr><td>4a.4. Effect upon fossil assemblage: great, moderate, little</td><td colspan="3">4a.5. Effect upon amorphous organic matter</td><td>4a.6. Effects upon mineral assemblage</td></tr>
<tr><td colspan="5">4b. Stylolite (diagenesis involving pressure and dissolution)</td></tr>
<tr><td>4b.1. Type or style: columnar, irregular, high or low amplitude, hummocky, smooth</td><td>4b.2. Nature of stylolite sets: parallel, irregular, anastomosed, conjugated</td><td colspan="2">4b.3. Orientation relative to lamination: concordant (parallel) or discordant (perpendicular, oblique)</td><td>4b.4. Mode of occurrence: limited to laminae; at laminar contacts; widespread or localized</td></tr>
<tr><td colspan="5">4c. Dissolution of components</td></tr>
<tr><td>4c.1. Origin related to recrystallization, substitution, stylolitization, indeterminate</td><td>4c.2. Mode of occurrence
- totally
- partially</td><td>4c.3. Relationship with laminae components
- affects only the biological components
- affects only primary minerals
- affects only accessory minerals
- affects only secondary minerals
- affects all laminae components</td><td>4c.4. Secondary porosity dissolution
- intraparticular
- interparticular
- moldic
- intracrystalline
- intercrystalline
- vug porosity
- cavern porosity
- fenestrae porosity</td><td>4c.5. Fenestrae-forming dissolution
- elongated fenestrae
- rounded, irregular shaped fenestrae
- sharped, irregular shaped fenestrae
- tubular fenestrae</td></tr>
<tr><td colspan="5">4d. Cement</td></tr>
<tr><td>4d.1. Mineralogy</td><td colspan="2">4d.2. Morphology: poikilotopic, fibrous, lamellar, botryoidal, acicular, irregular</td><td colspan="2">4d.3. Mode of occurrence: primary or secondary; filling intergranular or intraparticular porosity</td></tr>
<tr><td colspan="5">4e. Recrystallization</td></tr>
<tr><td>4e.1. Degree: total, partial</td><td rowspan="2">4e.3. Micrite > micro- or pseudospar</td><td rowspan="2">4e.4. Micro- or pseudospar > micrite</td><td rowspan="2">4e.5. Dolomitization</td><td rowspan="2">4e.6. Chalcedony > microquartz > megaquartz</td></tr>
<tr><td>4e.2. Recrystallized crystal mosaic: hypidiotopic; xenotopic; idiotopic; poikilotopic; porphyrotopic</td></tr>
<tr><td colspan="5">4f. Substitution</td></tr>
<tr><td>4f.1. Mineralogy (e.g., silica, ferruginous, pyrite)</td><td>4f.2. Timing: early diagenetic, late diagenetic</td><td colspan="2">4f.3. Degree: total, partial (localized, preferential), pseudomorphic</td><td>4f.4. Substituted crystal mosaic: hypidiotopic, xenotopic, idiotopic, poikilotopic, porphyrotopic</td></tr>
<tr><td colspan="5">4g. Nodules</td></tr>
<tr><td>4g.1. Mineralogy</td><td>4g.2. Size and morphology</td><td colspan="2">4g.3. Abundance: number of nodules per field of view or % of area in field of view</td><td>4g.4. Mode of occurrence: dispersed, clustered, associated with another fabric component</td></tr>
</table>

Continue...

Table 3. Continuation.

<table>
<tr><td rowspan="9">5. Features related to physical processes</td><td colspan="4">5a. Compaction</td></tr>
<tr><td>5a.1. Type: compaction or fold</td><td colspan="2">5a.2. Orientation relative to lamination: parallel, perpendicular, oblique</td><td>5a.3. Laminar components affected: all (entire lamination) or only biological components, primary minerals, accessory minerals, or secondary minerals</td></tr>
<tr><td colspan="4">5b. Faults</td></tr>
<tr><td>5b.1. Type: normal, reverse, transcurrent</td><td>5b.2. Relative abundance: number of faults in field of view</td><td colspan="2">5b.3. Orientation relative to laminae: parallel, perpendicular, oblique</td></tr>
<tr><td colspan="4">5c. Fractures</td></tr>
<tr><td>5c.1. Type: joint, crack, fissure</td><td>5c.2. Relative abundance: number of fractures per field of view</td><td>5c.3. Orientation relative to lamination: concordant (parallel) or discordant (perpendicular, oblique)</td><td>5c.4. Mineralogy of fracture fill</td></tr>
<tr><td colspan="4">5d. Erosional features</td></tr>
<tr><td colspan="5">OTHER FEATURES</td></tr>
<tr><td>6. Recurrence of texture and/or fabric</td><td>6a. Repetitive
A-A-A-A-...</td><td>6b. Alternating
A-B-A-B-A-...</td><td>6c. Regular (complete) cycle
A-B-C-A-B-C-...</td><td>6d. Irregular (incomplete) cycle
A-B-C-A-B-A-C…</td></tr>
<tr><td>7. Lateral continuity and uniformity of lamina thickness (includes thickness in μm or other scale)</td><td>7a. Continuous and uniform</td><td colspan="2">7b. Lamina is laterally continuous, but the thickness can vary. Indicate the reason:
- because of factors intrinsic to the microbial mat (e.g., desiccation and osmotic pressure)
- because of extrinsic (e.g., erosion and wave action)</td><td>7c. Laterally discontinuous</td></tr>
</table>

entire structure, and thus, comparison between nearby laminae sets is important to identify new crystals originated by recrystallization. These crystals also occur in pores or present overgrowth behavior, in contrast to organominerals (Flügel 2010). Protocols and parameters to define neomorphism may be found in Folk (1965), Bathurst (1975), and Flügel (2010).

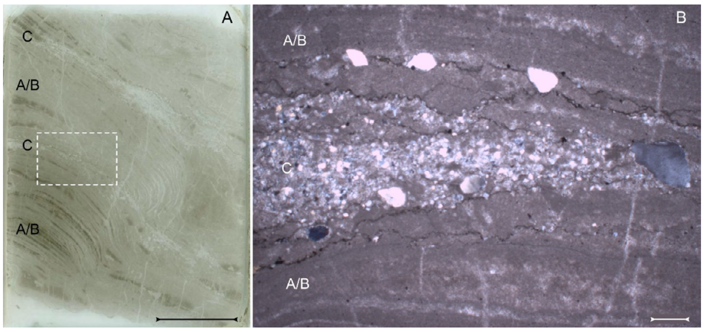
FINAL REMARKS

Stromatolites have a well-defined role as a paleoenvironmental and paleoecological tool for interpretations of the Earth's evolution. However, due to the lack of a standardized guide for microscopic description, their potential for paleobiological and sine-, demo- and autoecological discussions is not fully explored and may undermine their paleontological value, mainly for the understanding of long-term variations in stromatolite abundance, diversity, Precambrian reef-building forms, and evolution of microbial mat components.

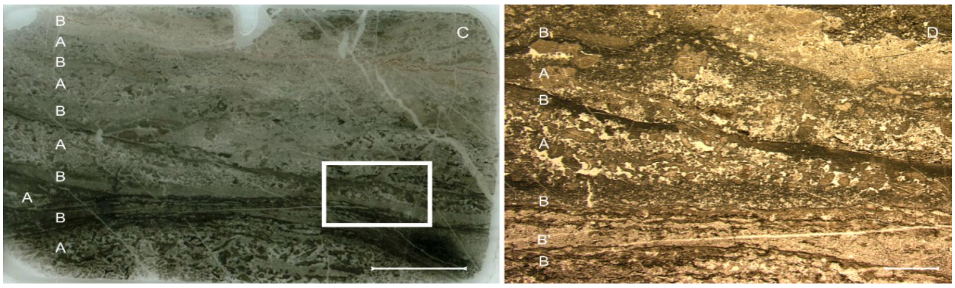
In this study, a microscopic description guide is proposed to complete the previous meso- and macroscopical description keys and to contribute to filling some of the above-listed gaps in paleontological knowledge concerning fossil stromatolites. To date, a microscopic description pattern is a neglected field that strongly contributes to the limitation of stromatolite application beyond paleoenvironmental interpretations. The present guide gathers previous statements and description schemes scattered in the literature, after a wide analysis of articles focused on stromatolite description. Although it does not exhaust all possibilities, it is an attempt to standardize the petrographic descriptions through a quantitative description for some aspects, which, soon, can add a statistical comparison to the stromatolitic research and possibly to thrombolites as well. This guide may be also helpful when coupled with other techniques, mainly isotopes and chemical mapping analysis.

This guide may provide a straightforward approach and a common ground for research targeting stromatolites since their study comprises different Biological and Earth Sciences professionals. Such approaches have the perspective to futurely bring a new perspective to the stromatolite analysis once it allows statistical comparisons.

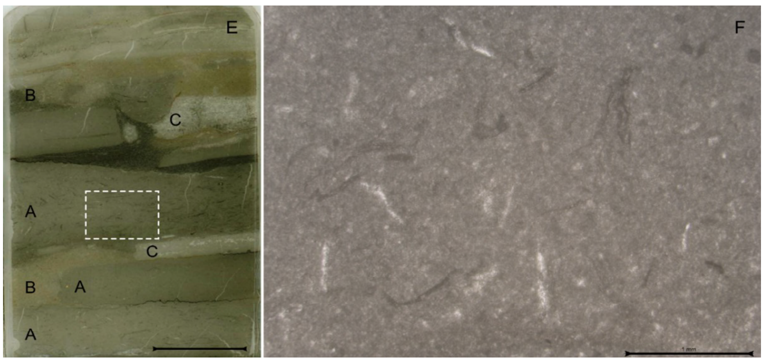
In addition, a standardized microscopic description of stromatolites is not only important for understanding terrestrial geological samples but also given the possibility of finding stromatolite analogs on the Martian surface.



Description:
Texture: Occurrence of amorphous organic matter dispersed in the crystalline net (1b.1), brown color (1b.3) and translucid (1b.4). Amorphous organic matter may concentrate more in some laminae than in others, resulting in the alternating light and dark lamination (represented by letters A and B). Precipitated minerals originally comprising micrite (2b.1) with xenotopic aspect (2b.2) and forming the laminae sets along amorphous organic matter. Occurrence of multisized quartz grains (accessory minerals, 2a.1), subrounded (2a.4), forming thin layers between the laminae sets (represented by letter C, 2a.7). No porosities were observed.
Fabric: Occurrence of irregular parallel stylolites (4b.1 and 4b.2), parallel to the stromatolitic lamination (4b.3) and widespread through the entire sample (4b.4).
Recurrence: Regular cycle (6c)
Lateral continuity: Lamination is laterally continuous, but the thickness of laminae varies due to the mat growth dynamic (7b). Lamination thickness varies between 20 and 300 μm.



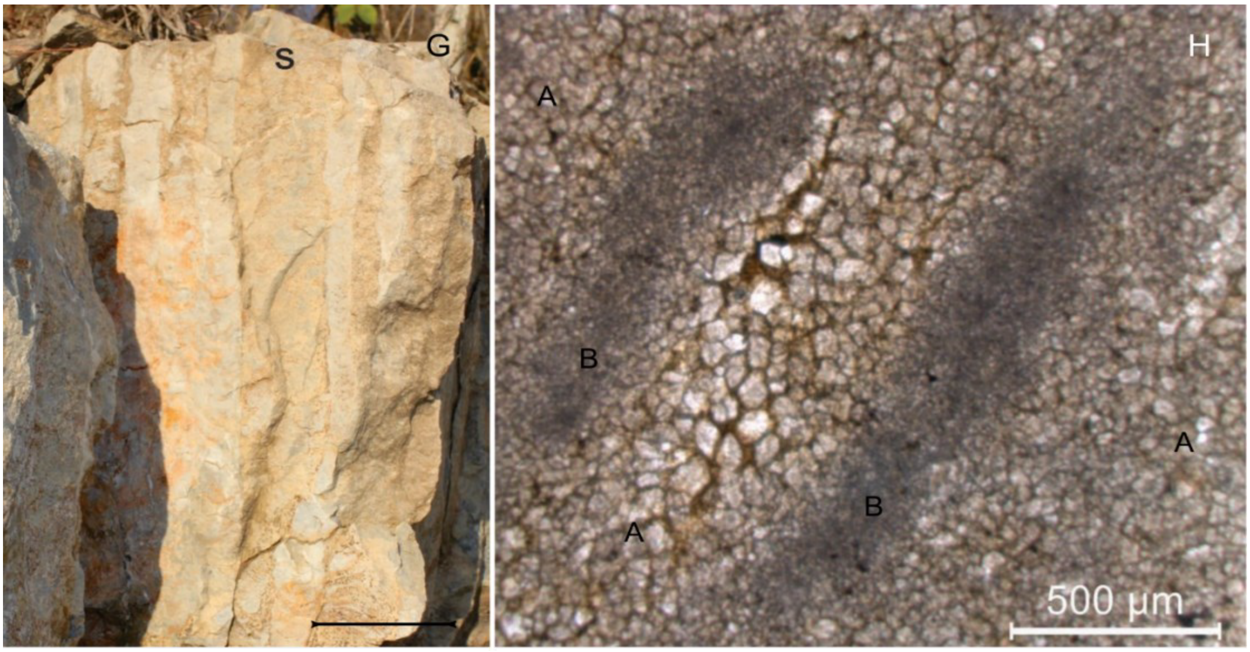
Description:
Texture: Occurrence of amorphous organic matter dispersed in the crystalline net (1b.1), brown color (1b.3), and translucid (1b.4). Amorphous organic matter may concentrate more in some laminae than in others, resulting in the alternating light (organomineral micrite-rich) and dark (organic matter-rich) lamination, represented by letters B and B'. Micrite (2b.1) from the lighter laminae (B') presents xenotopic aspect (2b.2). This set of laminae alternates with peloid laminae-rich (packstone - 2d.1), mostly composed of grains and few matrix, represented by letter A (2d.2.). No porosities were observed.
Fabric: Occurrence of a single fracture, fissure type (5c.1), oblique to the lamination (5c.2) and filled by micrite (5c.4).
Recurrence: Alternating (6b)
Lateral continuity: Lamination is laterally continuous, but the thickness of laminae varies due to the hydrodynamic flux (7b). Lamination thickness varies between 20 μm (B and B' laminae) and 3 mm (peloid-rich laminae).



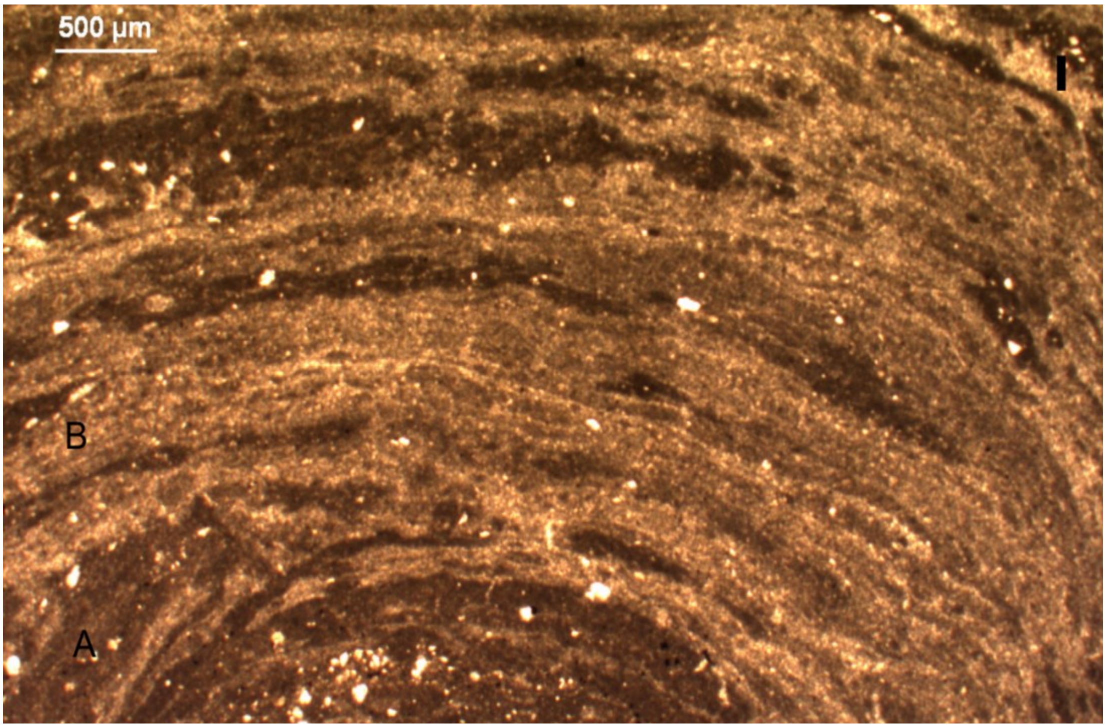
Description:
Recurrence: Irregular cycle (6d)
Lateral continuity: Most lamination is laterally discontinuous with one exception. Thickness of laminae varies due to the erosion and possibly physical disruption (7b). Lamination thickness varies between 1 and 1.5 cm.
Example of fabric (image F) composed by totally recrystallized micrite, of xenotopic aspect, where it is still possible to observe dispersed relics of short dark opaque filaments of amorphous organic matter.

Continues...

Figure 4. Examples of application of the proposed guide from Table 3 to Brazilian stromatolite samples. (A-B) Sample FZA-59, a domal stromatolite from Piumhí region, Sete Lagoas Formation, Ediacaran age. (C-D) Sample FZA-76, a stratiform stromatolite also from Piumhí region, Sete Lagoas Formation, Ediacaran age. (E-F) Sample PAI, a stratiform stromatolite also from the Pains region, Sete Lagoas Formation, Ediacaran age. (G-H) Cylindrical columnar stromatolite from Porto Morrinhos area, Bocaina Formation, Late Ediacaran. (I) *Conophyton* stromatolite from the Paracatu region, Lagamar Formation, Late Stenian to Early Tonian age. Scales: 1 cm in A, C, and E; 1 mm in F. Rectangles in A, C, and E represent the area of B, D, and F, respectively. For codes inside parentheses, refer to Table 3.



Description (S – stromatolite):
Texture: Mostly not observable due to strong recrystallization event. Relic micrite occurs as laminae.
Fabric: Alternating laminae composed by relic micrite and hipidiotopic (4e.2) dolomite crystals (4e.1) after the full (4e.1) dolomitization event (4e.5).
Recurrence: Alternating (6d)
Lateral continuity: Lamination is laterally continuous. Thickness of laminae varies due the recrystallization process (7b). Lamination thickness varies between 250 μm and 1.5 mm.



Description:
Texture: Occurrence of amorphous organic matter dispersed in the crystalline net (1b.1), brown color (1b.3), and opaque (1b.4). Amorphous organic matter may concentrate more in some laminae than in others, resulting in the alternating light and dark lamination (represented by letters A and B). Precipitated minerals originally comprising micrite (2b.1) with xenotopic aspect (2b.2) and forming the laminae sets along amorphous organic matter. Occurrence of multisized quartz grains (accessory minerals), subrounded, dispersed the laminae sets. No porosities were observed.
Fabric: Dolomitization process (4e.5) with xenotopic aspect (4e.2) of the entire material (4e.1).
Recurrence: Regular cycle (6c)
Lateral continuity: Dolomite-rich lamination is laterally continuous (B laminae) and alternates with lateral discontinuous organic matter-rich laminae (A laminae). Thickness of laminae varies due to the mat growth dynamic (7b). Lamination thickness varies between 100 μm for organic matter-rich laminae and 2 mm for dolomite-rich lamination.

Figure 4. Continuation.

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