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The criteria for the biogeneicity of microbially induced sedimentary structures (MISS) in Archean and younger, sandy deposits

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ABSTRACT

The identification of fossils or biogenic sedimentary structures in rocks of Archean age is difficult, because similar lithological features could rise from purely physical or chemical processes alone. Therefore it is important to define criteria that serve the secure definition of a fossil or structure in question as of biological origin. Such criteria have been established for stromatolites and microfossils.

This contribution discusses the 6 criteria of biogeneicity of 'microbially induced sedimentary structures' (MISS). Those structures are found in sandy deposits of early Archean age to the present, and rise from the interaction of benthic microbiota with physical sediment dynamics. The six criteria for their biogeneicity are: (i) MISS occur in rocks of not more than lower greenschist facies; (ii) in stratigraphic sections, MISS correlate with turning points of regression–trangressions; (iii), MISS correlate with a characteristic depositional facies that enhances the development and the preservation of microbial mats; (iv), the distribution of MISS correlates with the ancient average hydraulic pattern; (v), the geometries and dimensions of fossil MISS correspond to that of the modern ones; (vi), the MISS include at least one of 9 specific microtextures.

1. Introduction

The detection of life in Earth's oldest era preserved in the rock record – the Archean time period – poses a great challenge (Lowe & Tice, 2007). Archean rocks are rare, and have experienced many alterations by tectonic overprint, intensive thermodynamic recrystallization, and deep weathering. However, signs of ancient life do exist, and the robust, reef-like stromatolites, and tiny fossils of bacteria beautifully preserved in glasslike chert constitute the fundaments of research on Earth's earliest organisms (Walter & Schopf, 2007). Whereas rapid precipitation of minerals in carbonate and silica-rich lithologies enhances the preservation of biogenic structures and fossils (e.g., Sumner, 2000; Bishop & Sumner, 2006), microbial traces have been detected recently in other types of rocks such as ophiolites (Furnes et al., 2004, 2007) and sandstones (Noffke et al., 2003b, 2006b, 2008) as well.

For a long time siliciclastic lithologies have been overlooked, because paleontologists do not expect many fossils preserved in such highly porous rocks. Freshly deposited sand is well aerated, and already during early diagenesis, circulating water contributes to the quick decay of any organic material. However, even if body fossils can rarely be found, sandstones are most important host rocks for trace fossils (Bromley, 1990; Seilacher, 2007). Traces and trace fossils are not the only result of the activity of burrowing or grazing macroorganisms, but also of microbes that interact with the sediment. For at least 3 billion years, benthic microbiota colonize sandy substrata in shallow-marine settings. Here, they form biofilms or microbial mats (e.g., Stal, 2000). Aquatic deposits are constantly reworked by water motion, and therefore all benthic organisms must be able to tolerate the physical sediment dynamics caused by waves and currents. Indeed, the photoautotrophic cyanobacteria, and many other microbial mat-forming bacterial groups are highly mobile organisms, and can move actively through the sediment (e.g., Golubic & Knoll, 1999). In response to erosive forces, filamentous microorganisms stabilize the sediment by entangling the mineral particles like an organic meshwork, and the adhesive mucilages (extracellular polymeric substances, EPS, Decho, 1990) glue the mineral particles together. This twofold microbial sediment fixation is termed biostabilization (Paterson, 1994). If sedimentary particles are deposited on the sea floor, the microorganisms move upward to keep up with the rising sedimentary surface, simultaneously accumulating sediment by baffling and trapping. However, during periods of calm hydraulic conditions, the microbial cells assemble in the sedimentary surface layer to form the organic meshwork of a carpet-like microbial mat (binding). Those activities of benthic prokaryotes in response to the sediment dynamics form characteristic 'microbially induced sedimentary structures (MISS)' (Noffke et al., 1996; 2001a, b, 2003a,b). The formation of those structures has been studied and quantified in modern tidal flats, where benthic cyanobacteria are most abundant (Noffke et al., 1997a; Noffke 1998, 1999; Noffke & Krumbein, 1999). Seventeen main types of MISS have been distinguished. Those structures are traces with a high preservation potential, and indeed

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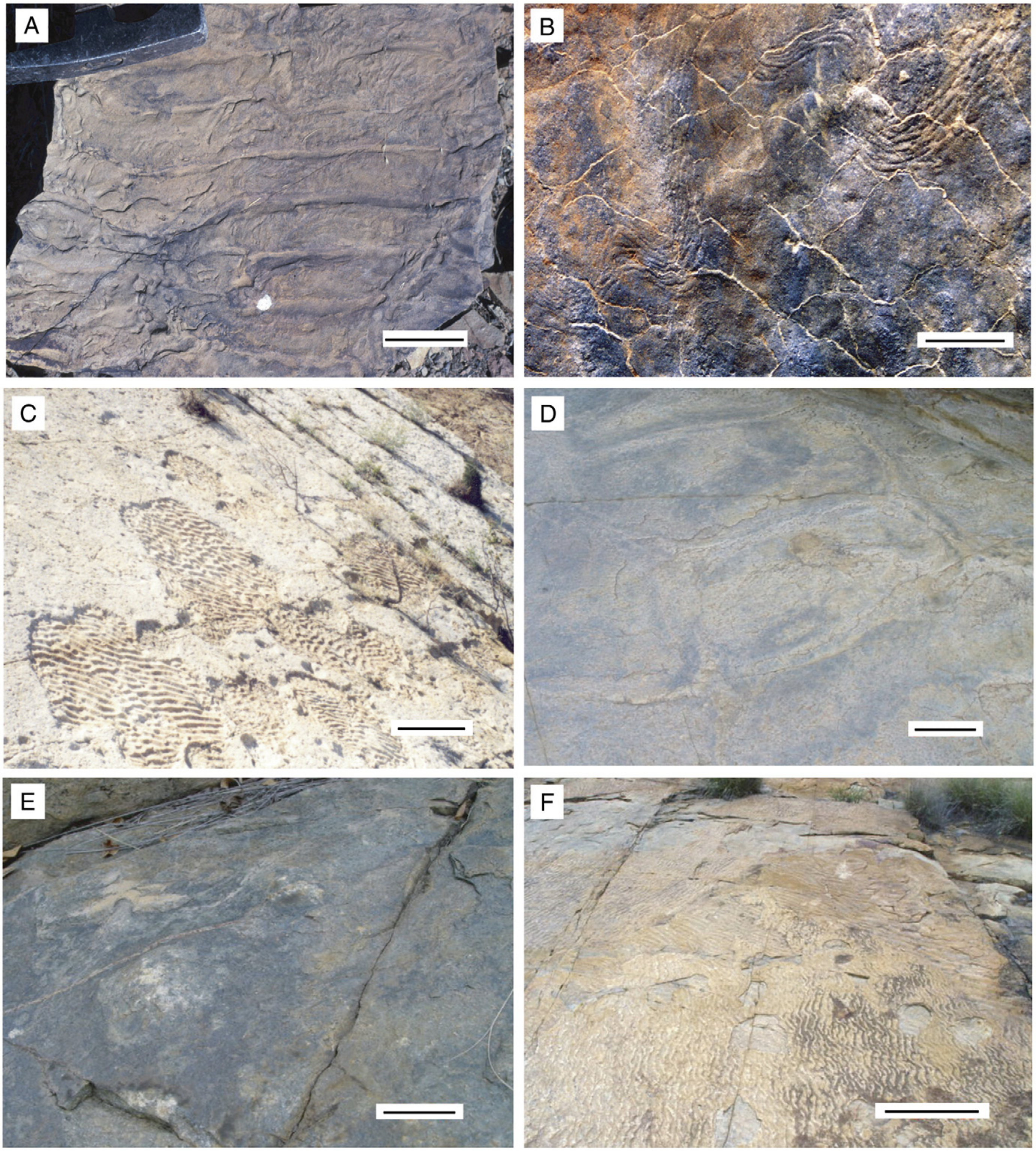

Fig. 1. Microbially induced sedimentary structures (macroscopic): A: Transparent wrinkle structure, Neoproterozoic Nama Group, Namibia; scale: 5 cm. Such wrinkle structures are *in situ* preserved, thin microbial mats. B: Non-transparent wrinkle structure, Paleoarchean Moodies Group, Barberton Greenstone Belt, South Africa; scale: 10 cm. Such wrinkle structures are *in situ* lithified, thick microbial mats. C: Erosional remnants and pockets, Cretaceous Dakota Sandstone, Colorado, USA; scale: 1 m; such a tidal flat morphology rises from partial erosion of a mat-stabilized sedimentary surface. Note the flat-topped planar elevations, which are ancient microbial mats, and the ripple marked depressions, where erosion took place. D: Polygonal oscillation cracks; Mesoarchean Pongola Supergroup, South Africa; scale: 10 cm; such a polygonal pattern of cracks rises from alternating degrees of meterological humidity in a semi-arid climate. The cracks are formed in microbial mats, here preserved *in situ*. E: Gas domes, Mesoarchean Pongola Supergroup, South Africa; scale: 2.5 cm; gas domes are elevations that rise from gases accumulating underneath a microbial mat. The increasing gas pressure lifts the microbial mat up. F: Multidirected ripple marks, Mesoarchean Pongola Supergroup, South Africa; scale: 1.5 m. Such a chaotic-like pattern of ripple marks is formed by a set of storms that interrupt the growth of a microbial mat layer in course of a year. Each storm leaves a ripple mark generation of different orientation.

occur in shallow-marine sandstones throughout Earth history (Gehling, 1982; 1999; 2000; Bland, 1984; Runnegar & Fedonkin 1992; Hagadorn & Bottjer 1997, 1999; Pflueger & Gresse, 1996; Pflueger, 1999; Schieber, 1998, 1999; Simonson & Carney, 1999; Eriksson et al., 2000; Prave, 2002; Sarkar et al., 2005; Draganits & Noffke, 2004). During the past decade, a systematic study investigated equivalent siliciclastic rock successions starting from most recent sandy deposits towards increasingly older stratigraphic sections including the early Archean period, and revealed that from the early Archean on, extensive microbial mats widely overgrew large areas of the ancient seafloors, forming organic carpets in shallow-marine environments (Noffke 2000; Noffke et al., 2002, 2003b, 2006a,b, 2008). This study on Phanerozoic, Neoproterozoic, Meso- and Paleoarchean sandstone successions used the steps for the identification of MISS as of biological origin as presented here, and therefore constitute the data base for this contribution. In the following, I would like to give a brief overview.

The Ordovician stratigraphic section exposed along the river Orb in the Montagne Noire, France, includes transparent and non-transparent wrinkle structures recording endobenthic and epibenthic microbial mats in various tidal, lagoonal, and shelf environments (Noffke, 2000), Fig. 1A and B. Overfold textures and microsequences indicate that the sandy substrate has been biostabilized by the cohesive, ubiquitous EPS of extensive microbial mats. The symmetry of the rock beds indicates that biostabilization, baffling, trapping and binding of the extensive microbial mats significantly influenced the ancient sedimentary processes on the shelf, and contributed to a much thicker accumulation of sediments than we could expect without the presence of microbial mats.

The Nama Group, Namibia, is of Neoproterozoic age. Wrinkle structures again are the most abundant MISS, and detailed sequence stratigraphic analyses of mm scale reconstruct the formation of wrinkle structures as consequence of deformation and dewatering processes that take place in course of the burial and compression of water rich microbial mats (Noffke et al., 2002).

The oldest MISS have been found in the 2.9 Ga old Mesoarchean Pongola and Witwatersrand Supergroup, as well as the 3.2 Ga old Moodies Group, South Africa (Noffke et al., 2003b, 2006a,b). Those stratigraphic sections include roll-up structures, erosional remnants and pockets, as well as polygonal oscillation cracks, and a multitude of wrinkle structures (Fig. 1C and D). However, the recently detected, spectacular outcrop in the Sinqueni Formation of the Pongola Supergroup contains about 600 individual structures, representing the whole spectrum of MISS as we find them today (Noffke et al., 2008). For example, this outcrop displays beautiful polygonal oscillation cracks, gas domes, and multidirected ripple marks (Fig. 1E and F). Of importance are not only such macroscopic MISS, but also the microtextures commonly associated with microbial mats such as tufts, oriented grains, sinoidal structures and many more (Fig. 2).

Despite all those findings, the fossil record for the Archean era is spotty, and recent debates on stromatolites and microscopic fossils of bacteria especially of early Archean time underline that 'biogene' structures and 'bacterial' textures could also be result of syndepositional, diagenetic, or metamorphic processes (Grotzinger & Rothman, 1996; Schopf et al., 2002; Brasier et al., 2002; 2005; 2006; Schopf et al., 2007). Therefore, it is important to establish firm criteria for the biogeneicity of potential biogenic features. Such criteria have been defined for stromatolites and microfossils in several detailed contributions (Buick et al., 1981; 1990, Brasier et al., 2006, and references on this topic therein).

Because a large volume of Archean rocks are sandstones, the MISS constitute a major and still to be explored archive for the exploration and the understanding of Earth's dawn of life. Therefore, a catalogue of criteria must be set into place to assist the diagnosis of MISS in ancient marine habitats. In correspondence to the criteria used for determining the biogeneicity of stromatolites, I here like to establish the criteria for the evaluation of potential 'microbially induced sedimentary structures — MISS' in sandstone. As indicated above, my set of criteria is result of our systematic studies conducted on fossil MISS of Phanerozoic (Ordovician), Neoproterozoic, Meso- and Paleoarchean ages (Noffke, 2000; Noffke et al., 2002; 2003b; 2006a, b; 2008).

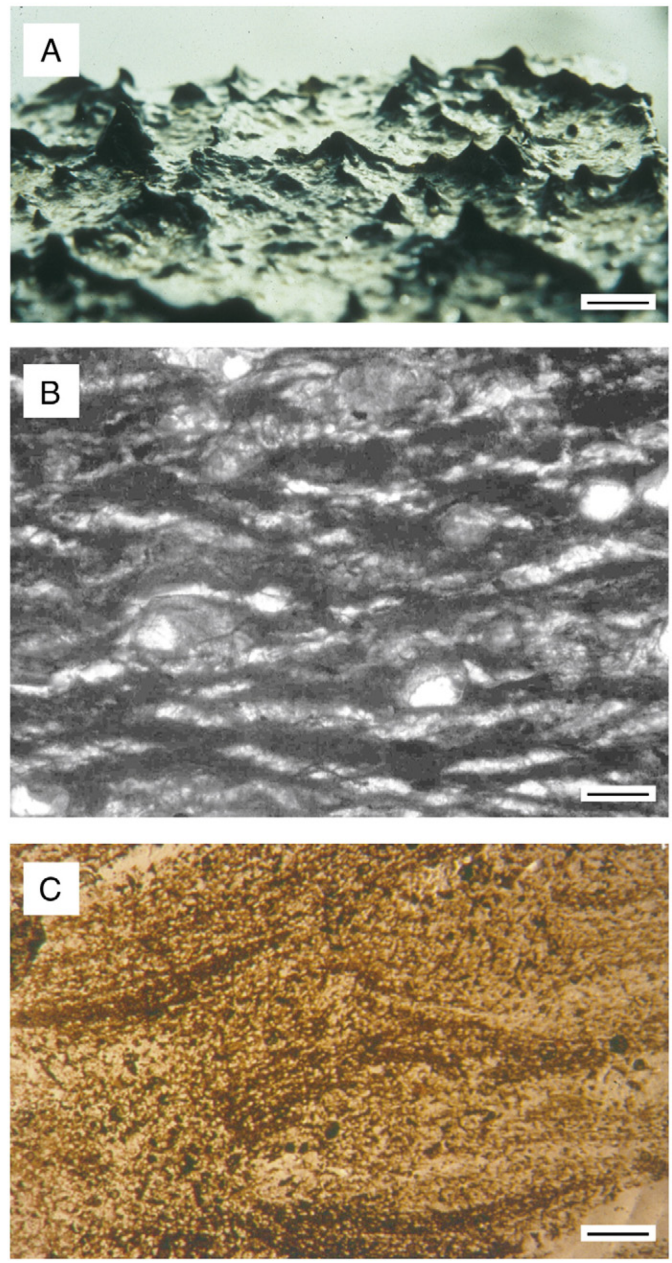

Fig. 2. Microbially induced sedimentary structures (microscopic): A: Tufts, modern microbial mats from southern Tunisia; scale: 0.5 cm. Tufts are bundles of perpendicularly oriented cyanobacterial filaments. B: Oriented grains in a microbial mat fabrics, Paleoarchean Moodies Group, South Africa; scale: 0.02 mm. Oriented grains are particles that originally derive from the sandy substrate underneath the microbial mat. Here, the microbial mat is constructed by horizontal (?cyano)bacterial filaments. The grains were dragged upward during the growth of the microbial mat and they rotated until their longaxes were parallel to the bedding planes. C: Sinoidal structures in a core from modern tidal sediments, Mellum Island, Germany; scale: 1 mm. Sinoidal structures line the tops of ripple marks and are *in situ* preserved biofilms.

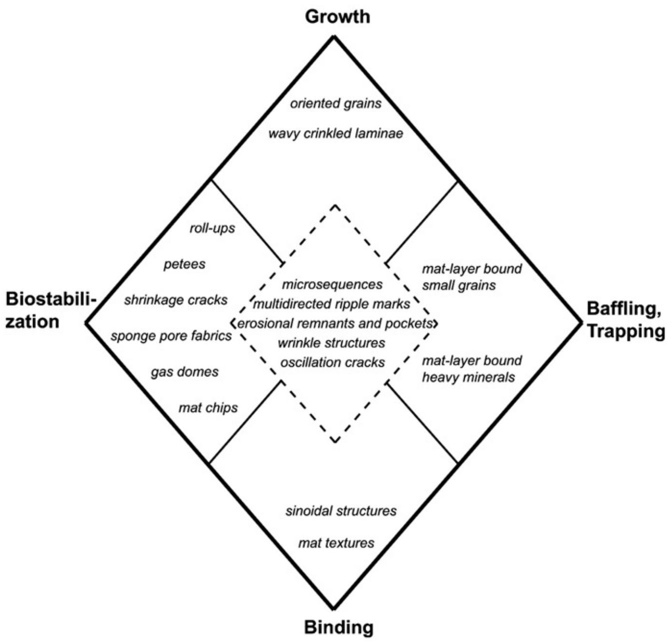

Fig. 3. Microbially induced sedimentary structures — classification and genetic relationships. MISS look different than stromatolites. Their 17 main types are grouped in accordance to their modes of formations. We distinguish structures induced by growth, biostabilization, baffling, trapping, and binding, and by the interference of all biotic–physical interactions.

2. Stromatolites and MISS

I would like to start first with a brief discussion on the relationship between stromatolites and MISS, following for this article the most suitable contribution by Buick et al. (1981): Buick et al. describe that the term stromatolite means 'layered rock' (Kalkowsky, 1908), and was introduced first for structures of specific morphology and of specific microbial origin (mainly the biologically induced precipitation of carbonate minerals). Later contributions, so Buick et al., either reduced the term for the description of any updomed sedimentary structure with a layered internal texture equally what origin this structure has; or the term is used exclusively for laminated structures of definitively biological origin (organo-sedimentary structures). Buick et al. term sedimentary structures definitively caused by biological activity 'stromatolites', those of possible biogene origin as 'stromatoloids'. The biological influence is mostly understood as microbial baffling, trapping and binding of sedimentary particles plus the *in situ* precipitation of mineralic substance.

In the first description of MISS in siliciclastic settings, Noffke et al. (1996) distinguished sedimentary structures that differ greatly in morphologies from stromatolites (and stromatoloids). Whereas stromatolites include planar to updomed features, MISS constitute a group of sedimentary structures of 17 individual morphologies, from meter to millimeter scale (Fig. 3).

Because MISS do not resemble stromatolites at all, we separate MISS from those, and regard MISS as specific type of Buick et al.'s stromatolites and stromatoloids. We distinguish 5 genetic categories of MISS: structures induced by growth, by biostabilization, by baffling, trapping and binding, as well as structures that are induced by the interference of all those parameters (Fig. 3).

3. Definition of MISS

The definition of MISS is: "MISS are primary sedimentary structures that rise syndepositionally from the physical interaction of biofilms and microbial mats with the sediment dynamic caused by hydraulic parameters in siliciclastic aquatic environments. Biostabilization counteracts erosion, baffling and trapping responds to deposition of sediment, and binding and growth take place during latencies (the time periods of no or low sediment reworking). Mostly, all biotic–physical interactions overlap in the formation of MISS, which is quantified with modern examples. Whereas primary mineral precipitation does not play any role in the formation of the MISS, secondary mineral accretion induced by the decay of the biofilm or mat constructing microorganisms and their EPS assists in the preservation of those structures. In thin-section, the MISS must include microtextures that are related to, have been caused by, or represent ancient biofilms or microbial mats. MISS occur from the early Archean to the present."

4. Criteria of biogeneicity for MISS, and rationale

The studies by Noffke (2000), Noffke et al. (2002, 2003b, 2006a, b, 2008) each follow the same principle of identification of MISS in fossil settings. In the following, I would like to list our steps we used for the secure definition of MISS as our criteria, and finally I would like to discuss our findings with the catalogue for stromatolites by Buick et al. (1981).

4.1. The MISS occur in sedimentary rocks that experienced not more than low grades of metamorphosis (greenschist facies)

We can identify fossils and sedimentary structures only in rocks that have not been overprint by too intensive tectonic pressure and high temperatures. At all our fossil study sites, we chose locations of in maximum lower greenschist metamorphosis to ensure the best lithological frame for a good trace fossil record.

4.2. In stratigraphic sections, the MISS correlate with regression–transgression turning points

Today, wide tidal flats and shallow shelves are formed along the passive continental margins in consequence of the sea level rise of the Holocene transgression. Because our present tidal flat and shelves are so extensive, microbial mats thrive. This recent correlation of extensive microbial mats in shallow-marine environments is reflected in the fossil record very well. In all our fossil stratigraphic sections, MISS exclusively correlate with transgressive portions of the rock successions.

4.3. The MISS occur in the 'microbial mat depositional facies' that enhances development and preservation of photoautotrophic microbiota

In summary, all our studies show that mats developed only at specific depositional sites, and that only a succession of distinct sedimentary events enhances their preservation. Noffke et al. (2002), differed into the ecological window of microbial mat development, and the taphonomic window of microbial mat preservation (Fig. 4).

In this context, we conclude in our reports on fossil MISS that the MISS-causing microorganisms most likely have been photoautotrophic. The presence of cyanobacteria (or similar large-sized, mobile and photoautotrophic prokaryotes) is assumed for our material 2.9 Ga and younger. However if those microbiota were oxygenic or non-oxygenic is unresolved. I would like to underline that I do not insist on the presence of cyanobacteria in the Archean study sites, but that other prokaryotes of similar morphology and behaviour may well have caused MISS too.

Our conclusions on ancient photoautotrophy are based on the observations on the development of modern MISS-forming microbial mats in sandy tidal flats that we can compare with our fossil MISS (ecological window), Fig. 4. Both modern and fossil microbial mats preferently develop on fine sand. For our ancient microbial mats this could be a hint on the presence of cyanobacteria (or other photoautotophic, mobile microbes). Cyanobacteria are relative large microbes and they are able to move actively through the sediment. Because very fine grained substrata such as mud have strong adhesive

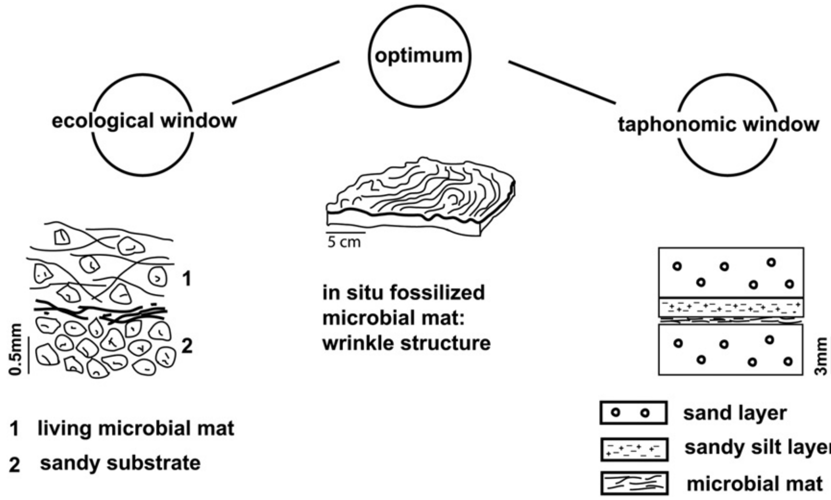

Fig. 4. The optimal depositional facies. The depositional facies (optimum) consists of an ecological window (sediments that enhance the development of microbial mats), and a taphonomic window (a taphonomic path that leads to the fossilization of a microbial mat). Ecological window: Microbial mats develop especially well in sediments composed of 'clear' (translucent) quartz minerals of fine sand grain sizes at sites, where the hydraulic reworking is moderate. Taphonomic window: Only, if the sequence of subsequent sedimentary events that lead to the formation of a microbial mat is complete, wrinkle structures (or other MISS) are preserved (after: Noffke et al., 2002, modified). Ia: a layer of fine sand is deposited; IIa: a microbial mat establishes; IIb: the microbial mat accumulates finer grained particles by baffling, trapping, and binding; III: a layer of sediment buries the mat, however the mat biostabilizes its substrate. Therefore during the placement of layer III no cannibalism of the former deposits takes place, and in consequence the surface and the surface structures are preserved.

forces that would keep cyanobacterial cells from roaming easily through the sediment, typically the microbes avoid those deposits. If the grain sizes of the substrates are large, and exceed medium sand diameters, cyanobacteria cannot build up their characteristic microbial mat fabrics, and only biofilms form.

Not only the grain sizes play a role in the establishment of photoautotrophic microbenthos. Important is also the mineralic composition of the fine sands. Modern and ancient microbial mats preferently develop on sand that consist at least 95% of clear (translucent) quartz grains. Similar like lenses or glass fiber cables, the quartz grains serve to conduct light into deeper portions of the microbial mat, which in consequence becomes much thicker. In vertical section, the close-up on a microbial mat shows the many quartz grains firmly interwoven by the microbial filaments, of which in modern samples even the microorganisms in several mm deep sediment layers are still photosynthetic active.

In a given area of a depositional environment, fine sand composed of quartz is accumulated by waves and currents that are strong enough to prohibit the fall-out of fines ('mud'). Indeed, a drape of mud that would cover the photosensitive microbial mats would block the essential sun light — a lethal consequence for the microorganisms. It appears from our actualistic investigations and from our findings at the fossil sites, that the average 10–25 cm/s average current velocity constitutes a dynamic window most suitable for the establishment of a photoautotrophic microbial mat. Indeed, small scale ripple marks of about 3–8 cm frequently are associated with MISS, both in the present and in the past, and record bottom current velocities of this range.

The waves and currents that prohibit the deposition of mud at the sites of microbial colonization however are not strong enough to erode the microbial mats once they are established. In our modern study sites epibenthic microbial mats withstand episodic top velocities of currents of up to 160 cm/s and endobenthic microbial mats of up to 60 cm/s. Areas of highly intensive currents or waves are void of microbial mats.

In the fossil sandstone successions, the mild hydraulic effect of moderate waves and currents is reflected by 2–20 cm thick rock beds. Interestingly, the rock beds show no cannibalism that is the bedding planes are well preserved. The reason is that because at the time of the deposition of the sands, microbial mats and biofilms protected the surfaces against erosion. This leads me to another aspect, which is that microbial mats do not only develop in this sedimentary facies, but that their preservation is enhanced as well (the taphonomic window), Fig. 4.

The taphonomic path of microbial mats is very complex, and is composed of (i) deposition of fine sand, (ii) establishment of a microbial mat, which accumulates finer grained sediment particles by baffling and trapping, and (iii) placement of a subsequent sediment layer, which buries the microbial mat. However, because of biostabilization, the microbial mat itself is not destroyed. The fines that have been trapped and bound during the life time of the microbial mat now serve to separate two sedimentary beds, and assist the preservation of any surface structure.

In summary, microbial mats develop and become preserved under specific hydraulic and depositional conditions — the overlap of the ecological and the taphonomic window, manifested by the characteristic microbial mat depositional facies (Fig. 4). This facies includes fine grained sand composed of quartz particles accumulated by moderate physical dynamic forces forming small scale ripple marks.

4.4. The distribution of MISS is not at random, but reflects the average hydraulic pattern in a defined area

Our detailed surveys show that the fossil MISS are restricted to tidal, lagoonal and shallow shelf paleoenvironments, and that the distribution of the different types of MISS reflects the long-term, average hydraulic (and sometimes climatic pattern) governing those depositional areas.

The fair weather and storm waves that dominate the ancient shelves caused transparent wrinkle structures (fossil endobenthic microbial mats in regularly reworked settings), and non-transparent wrinkle structures (fossil epibenthic microbial mats in mainly quiet zones).

Stratigraphic sections that record lagoons are composed of the typical thinly bedded, 'clean' fine sandstones, separated by a fine siltstone layer. Each sandstone bed is covered by a wrinkle structure (= an *in situ* fossilized microbial mat). Depending on the former length of calm periods, either transparent or non-transparent wrinkle structures formed.

The more complex hydraulic system that governs tidal flats creates a lateral succession of different biofilms and microbial mats along a transect from the low to the high water line. Such a lateral succession is termed 'biofilm-catena'. Each type of biofilm or microbial mat of this catena causes a characteristic MISS. One example is the biofim-catena recorded in the 2.9 Ga Nhlazatse Section, Pongola Supergroup, South Africa. This stratigraphic section includes an ancient, sandy tidal flat. Like today, endobenthic microbial mats developed in the upper intertidal zone, and epibenthic microbial mats in the lower supratidal zone. Like today, the corresponding MISS include multidirected ripple marks, flat-topped erosional remnants and pockets, and mat chips in the upper intertidal zone, and polygonal oscillation cracks, petees, gas domes, steep erosional remnants and pockets, and many more in the lower supratidal zone (Fig. 1). Other examples for biofilm-catenae include Pleistocene–modern successions from south Tunisia (Noffke et al., 2001a), or sequences of the Devonian Muth Formation in the Himalaya (Draganits & Noffke, 2004).

4.5. The geometries and dimensions of the fossil MISS correspond to that of the modern ones

Conveniently, we can measure the geometries and dimensions of MISS in modern tidal settings, and monitor the change of their morphologies in course of a year (e.g., Noffke 1998; 1999; Noffke & Krumbein, 1999). The same morphologies must be shown by fossil MISS.

One example is 'erosional remnants and pockets'. Their geometry is expressed by the 'MOD-I, the modification index' (Noffke & Krumbein, 1999). This is a dimensionless number that indicates the degree of microbial influence in the formation of the erosional remnants and pockets. The MOD-I is composed of three subindices expressing (i) the extension of a mat-covered surface portion in a given area, (ii) the degree of the angle of slope of the erosional remnants, and (iii), the degree of leveling of ripple marks (thickness of a microbial mat in ripple valleys). Different types of microbial mats such as endobenthic or epibenthic microbial mats and their seasonal variations give rise to different values of MOD-I (ranging between 0 for no microbial influence, and 1 for maximum microbial influence). The same MOD-I can be established for ancient erosional remnants and pockets, indicating the position of the MISS on the ancient tidal flat, the seasonality of the paleoclimate, and the possible mat type (a good example in Noffke et al., 2008).

Of course, compaction and dewatering processes during the lithification of the sand to sandstone, and the fossilization of the microbial traces could have affected the shapes of MISS. However, because sand composed mainly of quartz is very resistant to any pressure and temperature, a metamorphosis of greenschist grade does not alter a sandstone much, and MISS in general are 1:1 preserved. Exceptions are silica-rich sandstones that have been formed in evaporitic settings. Here, the slight compaction of the silica cement may have caused stylolites that now are visible in thin-sections. However, this minor, only microscopic compaction does not affect the macroscopic morphology of the MISS.

Another point to consider is one fundamental difference between Phanerozoic and Precambrian microbial worlds: with the appearance of metazoa about 540 Ga ago, new ecological niches have been defined, and the macroorganisms began to interact with the microbenthos (Marenco & Bottjer, 2007). In consequence, traces and trace fossils, as well as body fossils are often associated with MISS of younger Earth ages. However, those trace and body fossils just reflect that the microorganisms now have to share their space with the 'newcomers', the macroorganisms. The geometries and dimensions of the MISS are not affected.

4.6. The MISS include microtextures that either represent, or have been caused by, or are related to ancient biofilms or microbial mats

In thin-section, the MISS must include microtextures that are either related to, or have been caused by, or represent ancient biofilms or microbial mats (Fig. 2). In my investigations of modern tidal sediments interwoven by microbial mats, or sealed by EPS-rich biofilms, I distinguished 9 main types of microtextures (Fig. 3). All those microtextures we found in fossil MISS as well.

Microtextures representing ancient biofilms or microbial mats, and caused by growth: Wavy crinkled laminae represent the ancient microbial mat layers. Often the laminae show great inheritance, recording piles of microbial mats of up to 2 cm thickness. Also tufts occur (Fig. 2A). In higher magnification, those wavy crinkled laminae are composed of elongated textures that resemble microbial filaments. I interpreted the filament-like textures as relics of ancient bacterial filaments, even if they are not as well preserved like the famous microfossils in chert. The diffusion of biomolecules and chemical compounds in course of the lithification process of sand is very strong, and therefore appear bacterial cells in highest magnification as accumulations of mineralic substance with an indistinct, diffuse outline (such as clouds). Because of the poor preservation of the siliciclastic material (compared to chert fossils), I prefer to use the term filament-like, not filament. Caution must be used not to interpret stylolites as possible filamentous remains. Characteristically, the filament-like textures are composed by iron sulfides or -oxides, in general weathered to iron hydroxides. The mineralic substance is intimately related to organic carbon. Silica (chert) could be mineralized EPS. Oriented grains are frequent too (Fig. 2B).

Microtextures caused by the activity of biofilms and microbial mats: Baffling and trapping by the microorganisms accumulated mineral particles of smaller grain sizes compared to the grain sizes of the host sediment. Often heavy minerals and mica line the mat layers trapped by the sticky EPS.

Microtextures related to binding of biofilms and microbial mats: In lower magnification we gain an overview on the microbial mat fabrics itself, a network of entangled filament-like textures that interweave quartz grains. Those grains have been bound during the formation of the mat fabrics, and are especially characteristic for endobenthic microbial mat types. Sinoidal structures are former, organic coatings of ripple marks (Fig. 2C).

Microtextures related to biostabilization of biofilms and microbial mats: Sponge pore fabrics are a high porosity that resulted syndepositionally from intrasedimentary gases accumulating underneath a sealing, EPS-rich microbial mat layer. The 'fenestrae fabrics' are the correspondent feature in carbonate rocks.

Microtextures caused by the interference of all microbial activities: Microsequences are cm-scale upward fining sand layers that are topped by a microbial mat. Typically the microbial mat is not destroyed by the former erosion during the placement of the subsequent layer on top of the mat surface, even if this subsequent, high dynamic layer includes large grains at its base (Noffke et al., 1997a for a modern example).

5. Discussion of the criteria for biogeneicity for MISS in the context of those for stromatolites and stromatoloids

Although there are many good discussions available on the aspect of biogeneicity of stromatolites, I chose for this paper on MISS the contribution by Buick et al. (1981) as the most suitable one.

In their essay on stromatolites, Buick et al. include both criteria related to the paleoenvironmental setting of the structure in question, and the morphologies and textures of this structure. The above criteria for the biogeneicity of MISS are separated into those two categories as well. I list 4 criteria related to the environmental parameter that control the development and preservation of biofilms and microbial mats, and 2 criteria that describe and quantify the morphologies and internal microstructures of MISS.

Buick et al. require the identification of a host rock of a stromatolite as indeed of sedimentary origin, and that the stromatolite in question

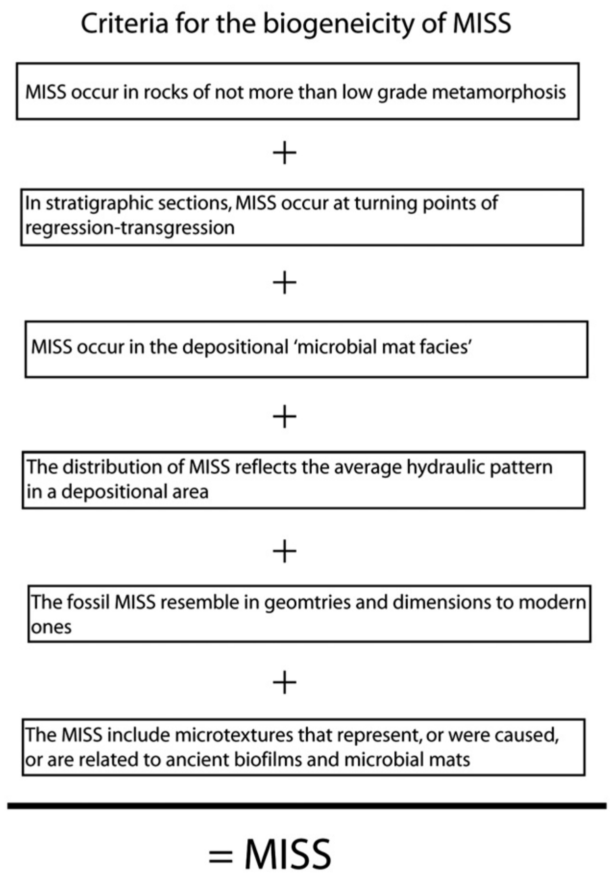

Fig. 5. The criteria for the biogeneicity of MISS. Only, if all six criteria are fulfilled, a fossil sedimentary structure in question can be defined as MISS.

must have formed syndepositionally. Even though the morphologies of the MISS are very distinctive, and in general cannot be mimicked by physical sedimentary processes, I too underline the importance of a solid geological field survey to analyze the exact position of a MISS feature in its paleoenvironmental context. The MISS are clearly a result of both biological activities and physical processes. Therefore, the structures impossibly can be studied without considering their environmental surroundings.

For stromatolites, Buick et al. recognize the significance of actualistic comparison of Archean (and younger) with modern structures, and prefer the occurrence of a fossil stromatolite in an ancient shallow-marine and photic setting. However, this is difficult for the simple, cone-shaped stromatolites of the early Archean that cannot necessarily be compared with their modern relatives. Because of this problem, the biogeneicity of the famous stromatolites (or stromatoloids) of the 3.5 Ga old Strelley Pool chert in Australia has been controversially debated (e.g., Lowe, 1994; Buick et al., 1981; Grotzinger & Knoll, 1999; Brasier et al., 2006; Allwood et al., 2007). Because MISS and their habitats seem to not have changed for at least 3.2 Ga years, they are recorded in sandy deposits throughout the younger Earth history with no apparent differences. Therefore, the actualistic comparison of ancient MISS with modern ones is not only possible, but essential, and is listed as requirement for all my criteria except the first one.

Buick et al.'s criterion 3, the preponderance of convex-upward structures for stromatolites and stromatoloids does not exclude other morphologies. Therefore, I would like to add the 17 morphologies of MISS into this category. However, please note that gas domes have a convex-upward morphology as well, and therefore microtextures including intrasedimentary pores have to confirm their biogeneicity to differ them from stromatoloids.

Buick et al. differ stromatolites that include fossil microbial filaments or 'tussocks' forming a typical microbial mat texture, from stromatoloids that lack this definitive evidence of presence of microorganisms. This is different to MISS. All MISS do and must include microtextures (criterion 6). In contrast to stromatolites, MISS must not display fossil mat fabrics or filament-like textures that represent fossilized biofilms or microbial mats to be considered as biogenic. Often, the microbiota are gone, but their past activities such as baffling and trapping, or leveling has created typical textures that differ from the fabrics formerly caused by the physical background dynamics in the host rock. A good example is oriented grains.

Because of the many characteristics of MISS, their criteria for biogeneicity are firm, and features that look like MISS, but cannot necessarily be related to a biological origin must not be considered. Very often I receive from interested colleagues images of wrinkle structures with the question, if those are made by microbial mats. Of course, wrinkle structures can be related to abiotic processes such as water motion in sand, desiccation, or tectonic overprint (Noffke, 2000). However, all discussions on the biogeneicity of a wrinkle structure in question are unnecessary, if the paleohabitual setting is considered, and the petrological investigations of thin-sections as presented in all our papers on fossil MISS are followed, Fig. 5.

This contrasts to the question of biogeneicity of stromatolites. In precipitated lithologies, stromatolithic build-ups can be manifestations of purely chemical processes, and therefore caution is used in defining stromatolites. For this good reason, Buick et al. term sedimentological features that resemble stromatolites, but are of questionable origin as stromatoloids.

6. Summary

The MISS occur in siliciclastic, shallow-marine settings throughout the geological record, and constitute a specific group of stromatolites. The six criteria for biogeneicity of MISS are firm and – if applied in concert! – allow the exact distinction of MISS from abiotic structures.

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