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Spatial and temporal distribution of microbially induced sedimentary structures: A case study from siliciclastic storm deposits of the 2.9 Ga Witwatersrand Supergroup, South Africa

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Abstract

Microbially induced sedimentary structures (MISS) arise from the interaction of microbial mats with the physical sedimentary dynamics of shallow-marine settings. The structures occur in siliciclastic deposits of Paleo-Archean age to modern, where they record biostabilization and baffling, trapping and binding of photoautotrophic microbenthos. In the Brixton Formation, Witwatersrand Supergroup, South Africa, erosional remnants and pockets, wrinkle structures, and oscillation cracks include carbon- and pyrite-rich filament-like textures that resemble modern trichomes of cyanobacteria. C-isotope ratios of -22 ± 0.1‰ indicate potential photoautotrophy. The MISS occur at the turning points of regression–transgression, and are restricted to a specific sedimentary facies characterized by 2–20 cm thick fine sandstone beds predominantly composed of quartz. The sandstone beds display ripple marks, which record moderate hydraulic reworking. This spatial and temporal distribution of MISS in the Brixton Formation is consistent with occurrences of those structures in comparable environments throughout Earth history.
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1. Introduction

Microbially induced sedimentary structures (MISS) constitute the siliciclastic counterparts to stromatolites. Whereas stromatolites are formed by microbial mats mediating the precipitation of mineralic substances in hypersalinar shallow-marine milieus, MISS arise from the interaction of the benthic microbial communities with the predominant physical sedimentary dynamics of non-chemical, siliciclastic environments (Noffke et al., 2001b, 2003a).

How do MISS form? In studies in modern shallow-marine environments, erosion triggers biostabilization, that is active sediment fixation by microbial mats (definition in Paterson, 1994; Noffke et al., 2003a; quantification in Noffke and Krumbein, 1999). In the case of deposition, the microbial mats react by baffling, trapping, and binding (classical study Black, 1933, quantification in Noffke and Krumbein, 1999; Noffke et al., 2003a). Those biotic-physical interactions create a great

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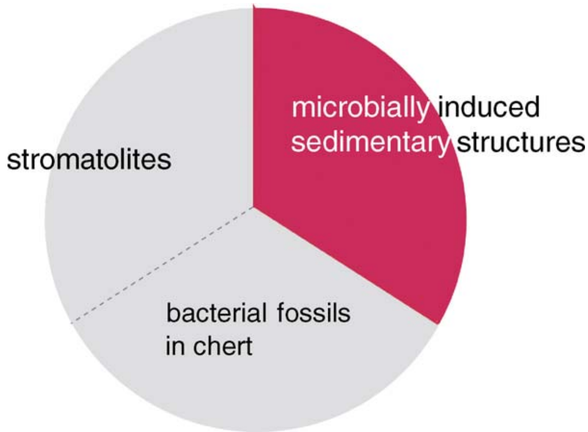

Fig. 1. Microbially induced sedimentary structures (MISS) in siliciclastic lithologies provide insight into Archean life, and form counterparts to bacterial fossils preserved in chert or as stromatolites.

variety of MISS, such as multidirected ripple marks (Noffke, 1998), oscillation mat cracks (Noffke et al., 2001a; Parizot et al., 2005), erosional remnants and pockets (Noffke, 1999), and many others. Fossil microbial mats are frequently preserved in situ as wrinkle structures (Hagadorn and Bottjer, 1997, 1999; Bottjer, 2005), or as "old elephant skin structures" (Runnegar and Fedonkin, 1992; Gehling, 1999, 2000). According to their distinct modes of formations, the MISS constitute their own category in the classification of primary sedimentary structures, *sensu* Pettijohn and Potter (1964; see also Noffke et al., 2001b, 2003a; Noffke, 2003).

MISS occur in sandstones throughout Earth history (Gehling, 1999 and references therein; Hagadorn and Bottjer, 1999; Pflüger, 1999; Noffke et al., 2003a,b, 2006; Schieber, 2004; Bottjer, 2005). In particular, the significance of MISS for the detection and interpretation of early life in the Paleo- and Meso-Archean makes them a most valuable tool for paleobiologists (Noffke et al., 2003b, 2006). Whereas the general assumption has been that Archean biogenic structures include only the robust stromatolites or the filigrane microfossils beautifully preserved in chert (for overview see e.g., Hofmann et al., 1999; Knoll, 1999; Schopf et al., 2002; Brasier et al., 2002; Altermann and Kazmierczak, 2003; Tice and Lowe, 2004; Westall, 2005), MISS opened a new window for the understanding of Earth's oldest life (Noffke et al., 2003b, 2006), Fig. 1. The structures permit insight into the evolution of bacterial groups as well as ancient life conditions.

In the siliciclastic coastal realm, microbial mats from the Paleo-Archean until today form exclusively within the photic zone of tidal and shallow shelf areas (Noffke, 2000; Noffke et al., 2002, 2003a,b, 2006). For the fossil record, a potential presence of photoautotrophic bacteria is therefore assumed. Whether those bacteria were oxygenic or non-oxygenic remains an open question (e.g., Noffke et al., 2003b, 2006; Tice and Lowe, 2004). Sulfate-reducing bacteria, which construct significant microbial mats as well, would show a distribution that was independent of the water depths (compare discussion in Noffke et al., 2003b for Meso-Archean MISS).

Aims of this paper are: (i) to describe MISS from the 2.9 Ga Witwatersrand Supergroup, South Africa and (ii) to investigate their distribution in space (sedimentary facies) and time (sea level changes).

2. Study area

The Witwatersrand Supergroup, South Africa, contains the Brixton Formation, a rock succession composed of orthoquartzite, sandstones, and sandy shale and siltstone units (Eriksson et al., 1981; Beukes, 1996). The age of the Brixton Formation is estimated to be between 2.91 Ga (Armstrong et al., 1991) and 2.98 Ga (Barton et al., 1989). Because the rocks of the Brixton Formation show only a low metamorphic grade of greenschist facies, and only minor tectonic tilting, sedimentary structures are well preserved. Therefore, the rock successions constitute ideal lithologies for the study of MISS (compare Noffke, 2000; Noffke et al., 2002, 2003b, 2006). The Brixton Formation records a shallow shelf environment that was affected by significant storms (Eriksson et al., 1981; Aigner, 1985; Brenchley, 1985; Swift et al., 1986; Arnott and Southard, 1990; Beukes, 1996). Such shallow-marine settings were preferred sites for microbial mat development through Earth history (Noffke, 2000; Noffke et al., 2002, 2003b, 2006). This favorable paleoenvironment, together with the detection of a kinneyia-like wrinkle structure by Beukes (1996), gave rise to the assumption that MISS may be widely distributed in the Brixton succession.

In order to detect MISS and to reconstruct the paleoenvironmental conditions of the ancient microbial mats, we investigated two stratigraphic sections of the Rooiport and the Blinkpoort member of the Brixton Formation (Beukes, 1996). The stratigraphic sections are located about 30 km from the city of Klerksdorp, and crop out on the farms Rooiport and Syferfontein (Fig. 2).

3. Methods

In order to investigate in which lithofacies the MISS occur, we surveyed each layer of the stratigraphic sections with respect to occurrences of MISS in the context of physical sedimentary structures, rock bed thicknesses, mineral compositions, and grades of maturity (compare field methods in Noffke, 2000; Noffke et al., 2002). In order to reveal microstructures, we employed the methods of Noffke and coworkers (Noffke, 2000; Noffke et al., 2003b, 2006). We examined 5–45 μm thick thin sections of selected MISS-samples in transmitted as well as reflected light. We employed an Olympus BX51 microscope, as well as an Olympus SZX 12 Stereoscope, both equipped with a Q-Color 3 digital camera. For electron-microprobe studies, we employed standard thin sections for semiquantitative analyses and composition maps with ±2 μm resolution. Analyses were obtained with a JEOL 8900 electron microprobe with five wavelength-dispersive spectrometers for qualitative maps of elemental composition and quantitative point chemical analyses, and an energy-dispersive spectrometer for quantitative point measurements of elemental abundance. Analyses were performed at 15 keV (Boyce et al., 2001). Isotopic measurements of δ^{13}C were performed on crushed rock in tin foil sample holders. In order to calibrate these measurements, acetate standards were run before the samples and after every 10th sample. We used a Carlo Erba elemental analyzer interfaced with a Finnigan DeltaPlusXL continuous-flow isotope-ratio mass spectrometer via the Cinflo II interface. In order to evaluate any potential contamination, we extracted rock material from the weathered surface of the MISS-samples and compared the isotope data with those data from rock material extracted from fresh portions of the MISS-samples.

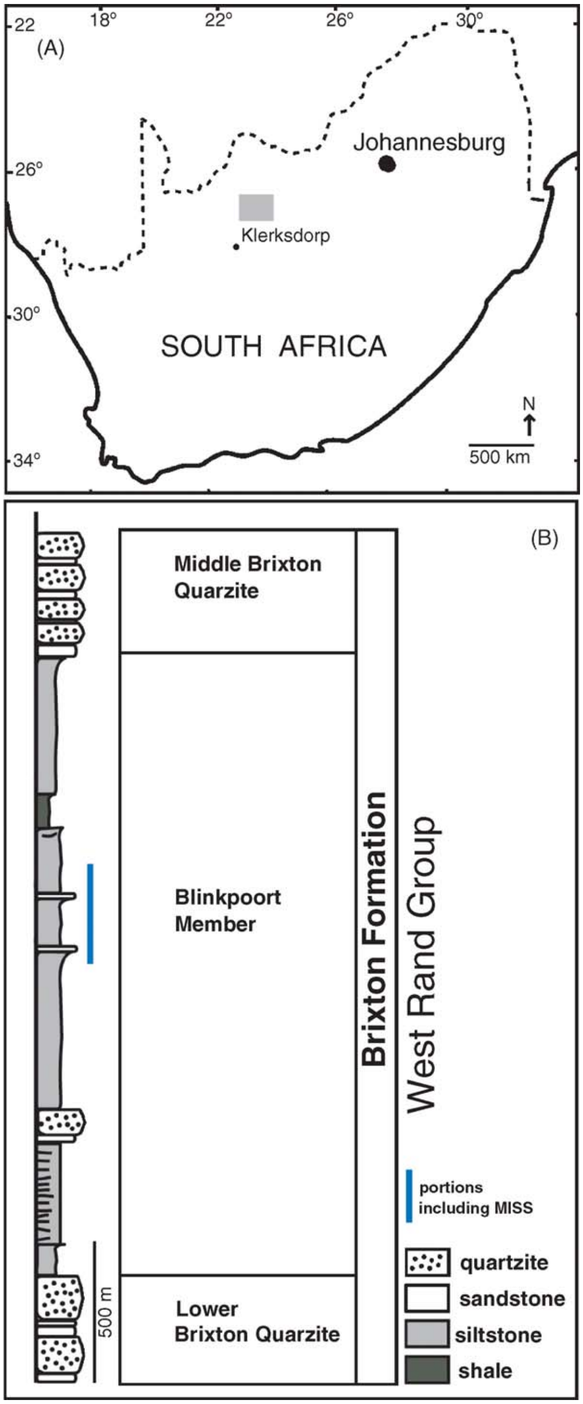

Fig. 2. Study area. (A) Location of the study area close to Klerksdorp, South Africa. (B) Studied stratigraphic succession of the Brixton Formation, Witwatersrand Supergroup (2.9 Ga old).

3.1. Description and interpretation of MISS in the Brixton Formation

Seventeen fine sandstone beds of the Brixton Formation contain MISS. We found erosional remnants and pockets (two specimen), wrinkle structures (28 specimen), and oscillation mat fractures (1 specimen) (Fig. 3).

The erosional remnants and pockets are a bed surface morphology, which is composed of flat areas and small depressions (Fig. 3A). This structure arises from partial erosion of a microbial mat-covered seafloor. Those seafloor areas that are overgrown by a microbial mat are biostabilized; that is bottom currents or wave action does not cause significant erosion. Only locally, where the microbial mat fabrics is weaker, can erosion rip off parts of the organic layer. In consequence, the sandy seafloor at those spots is eroded and depressions form (Noffke, 1999).

Wrinkle structures are crinkled bed surfaces, which record the in situ burial of ancient microbial mats (Hagadorn and Bottjer, 1997; Noffke et al., 2002),

Fig. 3B. The crinkles are of mm scale, and can display irregular or regular patterns. Two types are distinguished (Noffke, 2000): non-transparent wrinkle structures, which arise from thicker microbial mats that have covered and smoothed completely the original (physical) sedimentary surface relief; and transparent wrinkle structures, which originate from thinner microbial mats, under which earlier surface structures such as ripple marks are still clearly visible.

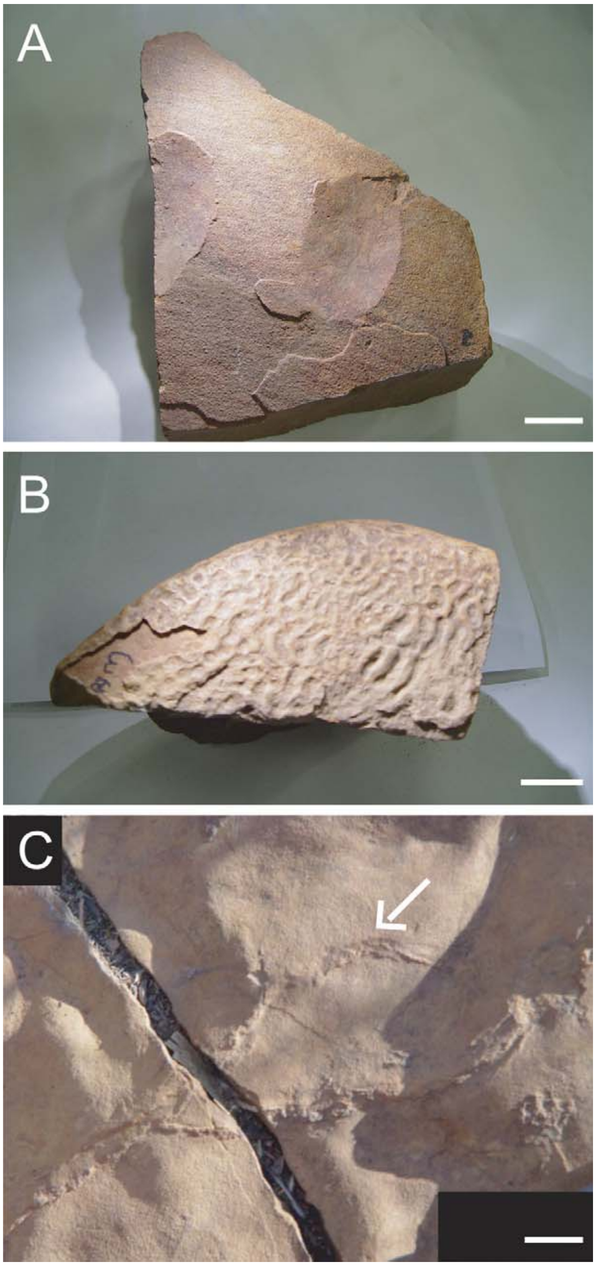

Fig. 3. Microbially induced sedimentary structures (MISS) from the Brixton Formation: (A) erosional remnants and pockets arise from partial erosion of a former microbial mat-covered and biostabilized depositional surface, scale: 5 cm. (B) Wrinkle structure originating from burial of an ancient microbial mat, scale: 2 cm. (C) Oscillation mat fracture originating from periodical subaerial exposure of a coherent microbial mat, or burial. Round-shaped fracture margins are typical, scale 2 cm.

Oscillation mat fractures (Fig. 3C), are cracks in microbial mats rising either from periodical desiccation of the organic layers during subaerial exposure of tidal flats, or from loading pressure during burial of microbial mats by heavy sediment (Noffke, 2000; Noffke et al., 2001a).

The MISS also include internal textures that support the interpretation of the structures as microbial mat-related. Thirty vertical thin-sections have been prepared from the upper bed surfaces of 25 of the MISS-samples. The thin-sections display brownish colored, opaque filament-like textures that form microbial mat fabrics (Fig. 4). This network of brownish colored filament-like textures is typical of the preservation of ancient microbial mats in sandstone lithologies (Noffke, 2000; Noffke et al., 2002, 2003b, 2006).

Widths of the filament-like textures range between 10 and 20 μm, similar to the trichomes of modern cyanobacteria (e.g., the group of *Oscillatoria*). Within some of the trichome-like microstructures, textures are visible that resemble cell compartments of modern cyanobacterial trichomes. Given the poor preservation of the filaments, this interpretation is proposed with caution.

The microbial mat-like network comprises single mineral particles that "float" in the mat matrix without any grain-to-grain contact. The long-axes of those grains are parallel to the mat surfaces. Such oriented grains are typical of the fabrics of microbial mats that occur in equivalent modern marine deposits (Noffke et al., 1997, their Fig. 3). Such grain textures result from the growth of microbial mats that drag particles from their substrate upwards. This mat texture is an important indicator for ancient microbial mats (examples shown in Noffke et al., 2002, 2003b, 2006).

Chemical analyses assist in the interpretation of microstructures. Electron microprobe analysis of the filament-like textures reveals both elemental carbon and hematite or a ferric oxide-hydroxide (probably goethite). Fresh, unweathered 1-cm thick samples that include MISS-layers have 0.05–0.07 wt.% carbon. Note that most of this carbon is associated with the opaque filaments, which may exceed 50 wt.% elemental carbon (similar values are observed by Noffke et al., 2003b, 2006). Carbon lines the walls of the trichomes, whereas the inner portions of the trichomes (including the potential cell compartments) are filled in by the iron minerals. The carbon isotopic values of the microbial mats

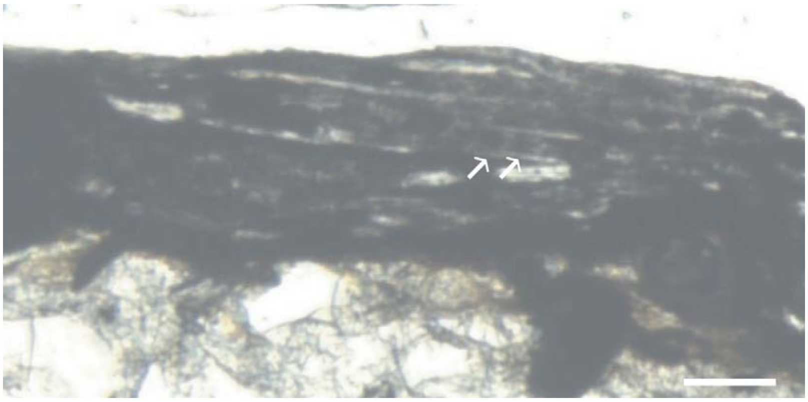

Fig. 4. Thin-section through a wrinkle structure. Fabrics of ancient microbial mat composed of filamentous bacteria, possibly cyanobacteria, scale 50 μm. Microtextures (arrows) may possibly represent cell compartments in ancient microbial trichomes.

($\delta^{13}C = -22 \pm 0.1‰$) are not only consistent with a biological origin for the carbon, but may also point to photoautotrophy of the microbial mats (Schidlowski et al., 1983). Duplicate measurements reveal that the total amount of measured carbon is proportional to the amount of fresh crushed rock used. Therefore, this value is not a contaminant from the rock surface.

In contrast, samples of weathered surfaces of the MISS-bearing fragments show approximately 0.10 wt.% carbon with $\delta^{13}C$ values ranging −16.9 to $-17.4 \pm 0.1‰$. Those values are likely the result of contamination by modern microbes, lichens, etc.

The iron oxides in the filaments probably represent weathered pyrite. Similar filament-like microstructures that form microbial mat-like fabrics preserved in siliciclastic rocks show that iron oxides (originally pyrite) at least partially replaced the original organic material of microbial filaments in equivalent siliciclastic deposits (Noffke, 2000; Noffke et al., 2002, 2003b, 2006; lab experiments by e.g., Konhauser et al., 1994; Ferris et al., 1987; Schulze-Lam et al., 1996).

3.2. Description of the stratigraphic sections, Brixton Formation

Two stratigraphic sections (I = 224 m, and II = 221 m) through the Rooiport and Blinkpoort Members were measured. The sections occur 570 m from each other. The rock successions occur in a tectonically 30–45° tilted position.

3.2.1. Stratigraphic section I

The deposits of stratigraphic section I change from sandy shales and siltstones at the base towards fine sandstone beds in the middle and top portions of the rock succession. Overall, five major thickening-upward, high-frequency sequences (HFS 1–5) can be distinguished (Fig. 5).

HFS 1 contains in its lower portion sandy shales and planar-laminated silty sandstone beds 1–5 cm thick. Within the upper third of this HFS, fine sandstone beds about 5 cm thick show hummocky-cross-stratification. The top is marked by 3–5 cm thick fine sandstone beds that display ripple marks and wrinkle structures.

The HFS 2, 3, and 4 are each characterized by a lithological change from sandy shales intercalated by 5–10 cm thick silty sandstone beds to wrinkle structure-bearing fine sandstone beds. The HFS 2 and 4 each include two minor thickening-upward sequences documented by silty sandstone beds at their bases and ripple marked fine sandstone beds at their tops. In HFS 2, two 5–10 cm-thick fine sandstone beds of the two minor thickening-upward sequences show wrinkle structures. At the top of HFS 4, two lens-shaped quartzite layers occur.

The HFS 5 at the top of the stratigraphic section I contains sandy shales at its base. In the upper portion, fine sandstone beds 7–25 cm thick intercalate more and more. One medium sand-grained orthoquarzite bed 30 cm thick occurs. At the top, very regularly bedded, 3–5 cm thick fine sandstone beds include ripple marks. One of these beds shows wrinkle structures.

3.2.2. Stratigraphic section II

The deposits of stratigraphic section II change from sandy shales and silty sandstones at the base to fine sandstone beds in the middle, and significant orthoquarzite bars up to 25 m thick in the top portions of the rock succession. Overall, four high-frequency sequences (HFS 1–4) can be distinguished (Fig. 3).

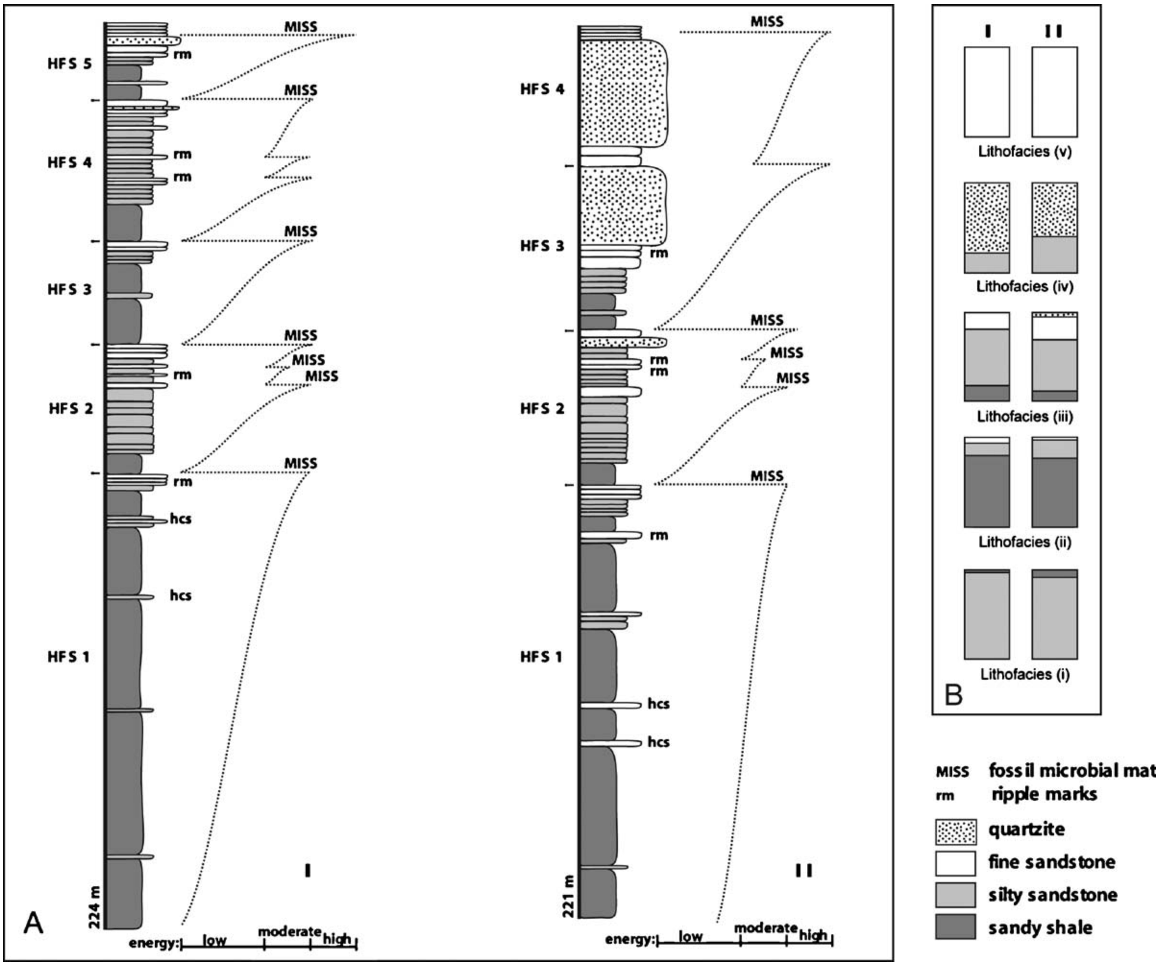

Fig. 5. Measured stratigraphic sections of the Brixton Formation. Stratigraphic section I (left) records five high-frequency sequences (HFS). Stratigraphic section II (right) records four HFS. The microbially induced sedimentary structures (MISS) correlate with turning points of regression and transgression.

HFS 1 is composed of sandy shales with intercalated silty sandstone beds. Compared to stratigraphic section I, the content of silt and sand within the shale-rich portions is greater. A few fine sandstone beds (3–10 cm thick) show hummocky cross-stratification. Towards the top of this HFS 1 the fine sandstone beds become more frequent. Some of them are covered by ripple marks. At the top, a 5 cm thick fine sandstone bed displays wrinkle structures.

HFS 2 is characterized by an increasing frequency of silty sandstone beds and fine sandstone beds 10–15 cm thick. HFS 2 includes two minor thickening-upward sequences documented by about 10–15 cm thick silty sandstones at their bases, and fine sandstone or quartzite beds in their upper portions. The fine sandstone beds show ripple marks. Three strata display different MISS, such as wrinkle structures, mat fractures, or erosional remnants and pockets at their upper bedding planes, and are 5–17 cm thick.

HFS 3 has two sandy shale units in its lower portion, up to 30 cm thick fine sandstone beds in the middle part, and an orthoquarzite bar 18 m thick at its top. The lowermost unit of HFS 4 is a stack of fine sandstone beds that shows amalgamation. The upper two thirds of this HFS is composed of a significant 25 m thick orthoquarzite bar. The orthoquarzite grain size is medium sand. On top of this bar, a few regularly bedded fine sandstone beds 3–5 cm thick follow. One of those beds shows wrinkle structures.

In comparison, both stratigraphic sections are very similar, although due to cannibalism and amalgamation, the top two HFS in stratigraphic section II are incomplete. In both stratigraphic sections, the HFS 1 and 2 (including the two minor thickening upward sequences) can be well correlated with each other. HFS 3 of the stratigraphic section II contains fine sandstone beds in its middle portion. Because those beds display ripple marks, they could correspond to the top MISS-bearing fine sandstone beds of HFS 3 of the stratigraphic section I. The top of HFS 3 of stratigraphic section II can be related to the top of HFS 4 of stratigraphic section I, because here quartzite bars are present in both successions.

3.3. Lithofacial interpretation of the stratigraphic sections, Brixton Formation

The lithology and sedimentary structures document the deposition of clastic sediment in a shelf environment, which shows a gradual transition from somewhat deeper mud- and silt-rich distal shelf portions towards sandier, shallower, proximal shelf areas (Aigner, 1985; Brenchley, 1985; Swift et al., 1986; Arnott and Southard, 1990). Over time, the sedimentary depositional area became shallower. The stratigraphic sections I and II record five different lithofacies types (i) to (v) (Fig. 5).

Lithofacies (i) records a deeper shelf dominated by fine-grained background sedimentation, which only rarely was interrupted by event deposition of sandy material. The sediments have been deposited below storm wave base. Lithofacies (i) predominates in the east of the depositional area.

Lithofacies (ii) is characterized by more frequent event deposition. Towards the west, the frequency of fine sandstone beds increases to 4%. Hummocky cross-stratification (hcs) suggests that the layers record a proximal shelf located above the storm wave base, but below the fair weather wave base.

In contrast, lithofacies (iii) defines the shoreface area well above the fair weather wave base, because sandstones comprising ripple marks show about 30% abundance. Towards the west of the depositional area, quartzite beds intercalate and account for 5.5% of the strata. The lack of hummocky cross-stratification suggests a comparatively protected site of deposition. The impressive orthoquarzite bars that are characteristic of the western margin of the sedimentary basin represent lithofacies (iv), interpreted as proximal shelf sands. The orthoquarzite shows an increased maturity and documents a very high-energy environment. Up to 30 cm thick fine sandstone beds make 21–40% in this lithofacies type.

Finally, lithofacies type (v) represents a shelf region, which has been more protected against severe hydrodynamics. Regularly bedded, fine sandstone beds predominate this lithofacies type (100%).

3.4. Interpretation of the spacial and temporal distribution of the MISS in the Brixton Formation

With respect to the spatial distribution, the MISS indicate that the ancient microbial mats were restricted to fine sand substrata predominantly composed of clear, translucent quartz grains. The physical sedimentary structures such as ripple marks that are associated with the MISS record moderate reworking energies by waves and currents. Severe storms did not affect the ancient seafloor. A similar correlation between sediment type (fine sandstone composed of 90–95% quartz), rock bed thickness (3–20 cm), and the associated physical sedimentary structures (e.g., ripple marks) recording moderate reworking is known from comparable paleoenvironments studied in rock successions of younger Earth ages (Noffke, 2000, more detailed study in Noffke et al., 2002; further locations in Noffke et al., 2003b, 2006).

With respect to the distribution in time, the microbial mats of the Brixton Formation indicate the turning point between regression and transgression. In stratigraphic section I, four MISS-bearing fine sandstone storm beds are followed by sandy shales, and two MISS-bearing fine sandstone storm beds are followed by silty sandstone beds. Only within the lithofacies (v), one MISS-bearing fine sandstone storm bed is followed by fine sandstone. In stratigraphic section II, two MISS-bearing fine sandstone storm beds are followed by sandy shales, two by silty sandstones, and one, as in stratigraphic section I, by fine sandstone beds.

This distribution of storm beds suggests that MISS are especially well developed and preserved in deposits that mark marine flooding surfaces. A similar distribution has been recognized in rock successions of Paleozoic, Proterozoic, Meso- and Paleo-Archean ages (Noffke, 2000; Noffke et al., 2002, 2003b,2006, Fig. 6. Indeed, the deposits may be regarded as distal equivalents of deltaic and coastal coal deposits (Cattaneo and Steel, 2003). The accumulation of well-developed coal seams in deltaic or marine depositional systems requires sediment starvation commonly associated with marine transgressions. A similar situation must occur for microbial mats that colonize shallow marine environments. The lower the rate of siliciclastic deposition, the greater the chance will be for mat-forming microbes to colonize a suitable shallow marine habitat successfully (Noffke et al., 2002, 2003a).

Our field studies confirm that MISS occur when the sediment input was low and few new clastics were added to the basin. Too high a rate of deposition would have led to lethal burial of the photoautotrophic microbial communities. Furthermore, the degree of stabilization of the colonized siliclastic substrate should increase as

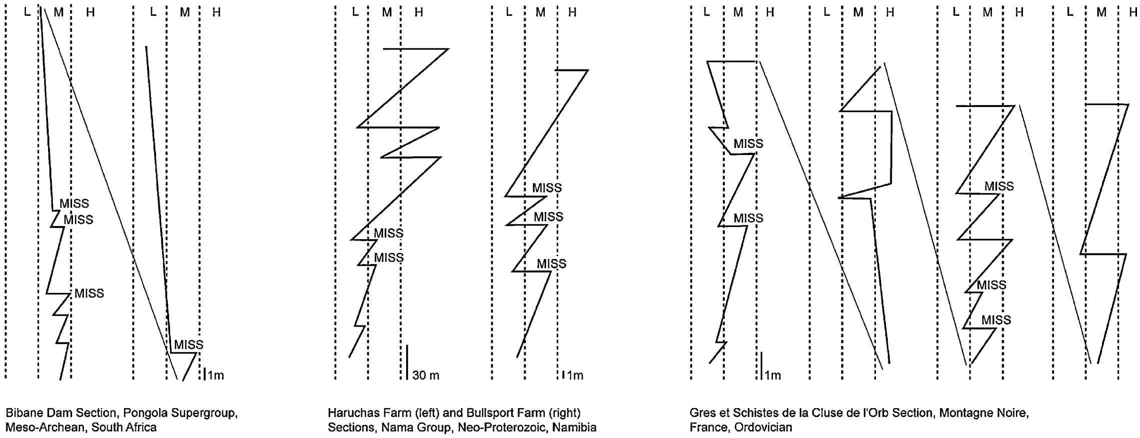

Fig. 6. Comparative rock successions from Paleozoic, Neoproterozoic and Meso-Archean ages show same relation between MISS occurrence at turning points of regression and transgression (after Noffke, 2000, Noffke et al., 2002, 2003b). The microbial mats covered large areas of the ancient sea floor, and developed at sites of moderate hydraulic reworking. Growth rate has been highest at times of low sediment input.

microbial mats thicken and cover greater areas through time. This aerial expansion, in return, increased the chances of preservation of MISS substantially (Noffke et al., 2002). The MISS show no severe destruction by erosion; that is, the ancient microbial mats must have been so significant that they prevented erosion and cannibalism of the sand deposits during subsequent storms. This biostabilizing effect of microbial mats can be observed both in ancient and modern (tidal) environments (Noffke, 2000; Noffke et al., 1997). Tool marks that are preserved at the base of many storm beds could have been caused by sand clasts bound together by microbial mats (Beukes, 1996). Those clasts (the equivalent of "microbial sand chips," Pflueger and Gresse, 1996) were dragged across the seafloor during peak storm periods.

Similar MISS have been reported from equivalent siliciclastic environments throughout Earth history, where shelves and tidal flats are overgrown by extensive microbial mats. In each case, the correlation of MISS-occurrence with shallow-water deposits pointed to the possibility of photoautotrophy of the ancient microbial mats (Noffke, 2000; Noffke et al., 2002, 2003b, 2006). From these and related studies on other Archean MISS, we conclude that microbial mats, possibly composed of photoautotrophic cyanobacteria, were widely distributed in the Meso-Archean. Our results are consistent with many other studies on similar shallow-marine, siliciclastic paleoenvironments, which have been habitats for microbial mats throughout most of Earth history (Hagadorn and Bottjer, 1999, and contributions therein). Of special note, we find that MISS in rock successions of various Earth ages serve as marker fossils for the turning points from regression to transgression. Consequently, especially in monotonous lithologies, MISS can provide mapping geologists with important evidence regarding the history of sedimentation.

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