A new window into Early Archean life: Microbial mats in Earth's oldest siliciclastic tidal deposits (3.2 Ga Moodies Group, South Africa)

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ABSTRACT

Newly discovered sedimentary structures produced by ancient microbial mats in Early Archean sandstones of the 3.2 Ga Moodies Group, South Africa, differ fundamentally in appearance and genesis from Early Archean stromatolites and bacterial cell fossils preserved in chert. Wrinkle structures, desiccation cracks, and roll-up structures record the previous existence of microbial mats that effectively stabilized sediment on the earliest known siliciclastic tidal flats. In thin-section, the sedimentary structures reveal carpet-like, laminated fabrics characteristic of microbial mats. Negative δ13C isotope ratios of −20.1 to −21.5 ± 0.2‰ are consistent with a biological origin for the carbon preserved in laminae. The biogenicity of the sedimentary structures in the Moodies Group is substantiated by comparative studies on identical mat-related features from similar tidal habitats throughout Earth history, including the present day. This study suggests that siliciclastic tidal-flat settings have been the habitat of thriving microbial ecosystems for at least 3.2 billion years. Independently of controversial silicified microfossils and stromatolites, the tidal-flat settings have been the habitat of thriving microbial ecosystems for at least 3.2 billion years. Independently of controversial silicified microfossils and stromatolites, the newly detected microbially induced sedimentary structures in sandstone support the presence of microbial life in the Early Archean.

Keywords: microbially induced sedimentary structures, microbial mats, Moodies Group, Early Archean, siliciclastic tidal flats.

INTRODUCTION

Until now, early life on Earth has been recognized primarily from the geological record of marine paleoenvironments, where chemical precipitation led to the preservation of bacterial cells in secondary chert, or to the formation of stromatolites (e.g., Nisbet and Sleep, 2001). At present, several lines of evidence suggest that life existed in Early Archean oceans, although biogenicity is controversial: (1) stromatolites (e.g., Hofmann et al., 1999; but see Grotzinger and Knoll, 1999); (2) bacterial microfossils (e.g., Schopf et al., 2002; but see Brasier et al., 2002; 2005; (3) roll-up structures (Tice and Lowe, 2004); (4) C- and S-isotopes (Schidlowski et al., 1983; Knoll, 2003; Faure and Mensing, 2004); and (5) fossil biomolecules (e.g., Knoll, 1999).

In contrast to earlier studies conducted on chert or carbonate lithologies, no paleontological investigation has recognized microbial influences in sandstones older than 3.0 Ga, although these rocks make up a significant proportion of the Early Archean sedimentary record. Whereas microbial structures in carbonates and cherts are predominantly formed by mineral precipitation, equivalent structures in siliciclastic lithologies originate by the physical interaction of benthic microbiota with the tidal dynamics (Noffke et al., 2001b, 2003a). In these settings, microbial mats respond to erosion by biostabilization or react to deposition of sediment by baffling, trapping, and binding (Paterson, 1994; Noffke, 1998; Noffke and Krumbein, 1999; Noffke et al., 2003a). This distinctive biotic-physical interaction creates a variety of characteristic sedimentary structures that, due to their unique mode of formation, have been categorized as their own group termed ‘microbially induced sedimentary structures’ (Noffke et al., 1996, 2001b, 2003a; Noffke, 2003b).

Numerous studies of siliciclastic deposits have described these structures from tidal and shallow-shelf environments of Middle Archean to Holocene age (e.g., Simonson and Carney, 1999; Hagadorn and Bottjer, 1999; Gehling, 1999; 2000; Noffke, 2000; Noffke et al., 2002, 2003a, 2003b; Schieber, 1999, 2004; Bottjer, 2005). These studies have shown that microbially induced sedimentary structures contribute to our understanding of the evolution of ancient microbiota.

The significance of microbially induced sedimentary structures for the interpretation of Earth’s earliest lithological record lies in the fact that these structures, in contrast to other fossil evidence, cannot be mimicked by purely physical processes, but arise exclusively from the biotic-physical origins described herein. Based on our latest findings of microbially induced sedimentary structures in the Middle Archean (2.9 Ga) Pongola Supergroup, South Africa (Noffke et al., 2003b), we continued our exploration for Archean microbial mat-related structures in the even older, 3.2 Ga Moodies Group, Barberton greenstone belt, South Africa.

STUDY AREA

The Moodies Group is the uppermost of three stratigraphic units that comprise the Swaziland Supergroup in the Barberton greenstone belt, South Africa (Fig. 1). The Moodies Group consists of 3.7 km of alluvial to shallow-marine sandstone with subordinate conglomerate and mudstone, as well as volcanic rocks (Eriksson, 1979). The maximum age of the Moodies Group is constrained by ages of ignimbrites (3226 ± 1 Ma), porphyries (3222 ±10/−4 Ma), and dacitic clasts in conglomerates (3225 ± 3 Ma) at the top of the Fig Tree Group (Kriener et al., 1991; Kamo and Davis, 1994), whereas the minimum age is constrained by the crosscutting Salisbury...
Kop pluton (3079 ± 6 Ma) in the eastern part of the greenstone belt (Heubeck et al., 1993). Despite the old age of the rocks, they are relatively undeformed and of low metamorphic grade (lower greenschist). Consequently, as in the case of the sandstones of younger age (Noffke, 2000; Noffke et al., 2002, 2003b), primary sedimentary structures are well preserved. In order to detect microbially induced sedimentary structures, we conducted a survey on the lower part of the Moodies Group in the Dycedale and Saddleback synclines (Fig. 1). Both rock successions preserve evidence of periodic transgressive drowning of wide, emergent tidal flats (Eriksson, 1979; Heubeck and Lowe, 1999). Evidence of a tidal-flat palaeoenvironment for the studied intervals includes mudstone-draped cross-bed foresets, and sandstone-siltstone/mudstone couplets, which record evidence of twice-daily tides and spring-neap tidal rhythms (Eriksson, 1977; Eriksson et al., 2006). Desiccation cracks indicate subaerial exposure at low tide.

METHODS

Microbially induced sedimentary structures, such as wrinkle structures, roll-up structures, and laminated textures composed of carbon and iron oxide, have previously been described from analog tidal environments from the Middle Archean (2.9 Ga) Pongola Supergroup (Noffke et al., 2003b), the 0.650 Ga Nama Group, Namibia (Noffke et al., 2002), and the Lower Arenigian (Ordovician) of the Montagne Noire, France (Noffke, 2000). Like the Moodies material, all microbially induced sedimentary structures are from undeformed or moderately deformed rocks of up to lower greenschist-facies metamorphic grade. Similar field work and microscopy techniques to those used in the previous investigations were employed in this study. Microbially induced sedimentary structures from the Moodies Group were compared with thin sections of modern microbial mats that were collected from the siliciclastic tidal flats on Mellum Island, North Sea (for location, see Noffke et al., 2001a). In addition, electron microprobe analyses and isotopic measurements of δ13C were determined using the methods described in Boyce et al. (2001) and Noffke et al. (2003b).

DESCRIPTION AND INTERPRETATION OF MICROBIALY INDUCED SEDIMENTARY STRUCTURES

In the following, we describe a variety of microbially induced sedimentary structures from the fine-grained sandstones from the Moodies Group, and present an interpretation for each example. In the Saddleback Syncline, wrinkle structures are preserved on bedding planes of fine-grained sandstone (Fig. 2A–B).

The structure shown in Figure 2A is composed of wrinkles of 5 mm wavelength and 3 mm height, covering ~70 cm² of the bedding surface as a 5–10-cm-wide sinuous belt. The structure in Figure 2B shows wrinkles of similar dimensions covering an area of ~30 cm². Superficially, these wrinkle structures may resemble compacted phyllosilicates produced by pressure solution. However, the Moodies facies in question is devoid of phyllosilicates, and the wrinkle structures occur as impressions in well-sorted, fine-grained, quartz-rich sandstones. No known abiogenic or chemical process produces such structures in this lithology, especially at lowest metamorphic grade. Wrinkle structures record ductile deformation of a microbial mat-bound sandy surface during burial by freshly deposited sediment (Hagadorn and Bottjer, 1997; Gehling, 2000; Noffke et al., 2002, 2003b). The wrinkle structures in the Moodies Group are covered by a pattern of cracks, which indicates that the loose grains of the ancient sandy surface must have been bound together by a cohesive medium before subaerial exposure resulted in cracking (Noffke, 2000; Noffke et al., 2001a).

A roll-up structure is preserved in a 2–3-cm-thick, fine-grained sandstone bed in the Dycedale Syncline. This structure is lens shaped with dimensions of ~3 × 2.5 cm (Fig. 2C, left) and is composed of alternating millimeter-thick sandstone and sub-millimeter-thick carbon-rich laminae. Such roll-up microbial mats are not uncommon on modern tidal flats (Noffke et al., 2001a; Fig. 2C, right). They are produced by bottom currents that overfold microbial mats. Similar fossil structures with the same dimensions have been described in many studies, e.g., from tidal and shelf sandstones of Lower Arenigian ages (Noffke, 2000), from shelf quartz sandstones of the 2.5 Ga Hamersley Basin, Australia (Simonson and Carney, 1999), and in 3.4 Ga chert of the Barberton greenstone belt, South Africa (Tice and Lowe, 2004).

In thin section, the microbially induced sedimentary structure samples reveal a wavy-crinkly pattern of dark, opaque laminae characteristic of ancient microbial mats in sandstones (Noffke, 2000; Noffke et al., 2002, 2003b). The dark, opaque laminae are between 50 and 500 µm thick and alternate with millimeter-thick quartz sand layers (Fig. 3A). The fine-grained sand layers between the dark laminae are composed of 98% quartz grains with subangular shapes. In modern, un lithified tidal sand deposits, this laminated pattern arises from microbial mat growth, forming the dark laminae, episodically interrupted by deposition of fine sand by tidal currents (Geres et al., 1991; Noffke et al., 2003a; Fig. 3B). In close-up, the dark laminae are brownish colored and have diffuse borders (Fig. 3C). The laminae are interwoven like the network of a carpet. This network resembles, in size and shape, the fabrics evident in thin sections of modern (Fig. 3D) as well as ancient microbial mat samples from equivalent tidal settings (Noffke, 2000; Noffke et al., 2002, 2003b). By comparison with modern analogs, such networks probably are produced by bacterial (or cyanobacterial) filaments. The diffuse appearance of the laminae under high magnification could be the result of postmortem diffusion of the original organic matter of bacterial cells, a phenomenon well described for Precambrian fossils (Knoll et al., 1988). In addition to diffusion, collapse of the ancient microbial mats, coupled with postburial compaction, may have added to dissolution and destruction of tiny bacterial cells.

Strong evidence for ancient microbial mat textures includes solitary quartz grains that float without grain-to-grain contact in a dark, laminated matrix (Fig. 4A). The quartz grains have identical grain sizes to the particles of the substrate beneath the microbial mat. A dis-
Evidently half of the opaque laminae is composed of elemental carbon. Thus, most of the rock carbon is concentrated in these laminated textures. Negative $\delta^{13}C$ isotope values are necessary to support the biogenicity of ancient organic matter (Schidlowski et al., 1983; Faure and Mensing, 2004; Knoll, 2003). The $\delta^{13}C$ isotope ratio of $-21.5\pm0.2\%$ from the Moodies samples is consistent with a biological origin for these laminated microstructures. Most probably, those iron oxides are weathered products of pyrite. In studies of similar types of preservation, iron sulfide replaces the original organic material of microbial filaments in siliciclastic deposits (Noffke, 2000; Noffke et al., 2002, 2003b; experiments by Konhauser et al., 1994; Ferris et al., 1987; Schulze-Lam et al., 1996).

A final argument for the biogenicity of the microbially induced sedimentary structures in the Moodies Group is that the structures occur exclusively at the tops of decimeter-scale, upward-fining cycles. This stratigraphic position appears to be characteristic of ancient microbial mats in quartz sand marine settings in more recent times (Noffke, 2000; Noffke et al., 2002, 2003b). It is also noteworthy that mudstones and quartzites in the Moodies Group, as well as in the comparative rock successions of the younger Earth, do not contain microbially induced sedimentary structures. This finding, along with previous studies, shows that microbially induced sedimentary structures are restricted to specific fine-grained quartz sandstone lithologies.

**DISCUSSION**

Based on this distinct distribution of microbially induced sedimentary structures in shallow-water deposits, the microbial mats in the 3.2 Ga shallow-marine environment could have been photosynthetic. Microbially induced sedimentary structures in the 2.9 Ga Pongola Supergroup, South Africa, suggest the former presence of cyanobacteria, but the evidence remains equivocal (Noffke et al., 2003b). The oxygen content of the atmosphere prior to 3.0 Ga is unresolved (cf. Kasting, 2001; Ohmoto, 2004). Photosynthesis of the ancient microbial mats inferred in this study may have been nonoxygenic, but if microbial communities of this type were oxygenic (Pavlov et al., 2001), then for hundreds of millions of years, such photosynthetic systems may have provided a steady, yet rapidly consumed source of oxygen—a source that would gradually come to dominate the atmospheric chemistry of Earth.

In conclusion, microbially induced sedimentary structures provide biological signatures that are not mimicked by physical processes. Therefore, the microbially induced sedimentary structures in the 3.2 Ga Moodies Group permit insight into the antiquity of life on early Earth. Together with microbially induced sedimentary structures detected in comparable sandstone lithologies from younger times, the distinctive structures point to an environment that, since earliest Earth history, has been a habitat for thriving photosynthetic microbial ecosystems. The study shows that microbially induced sedimentary structures constitute an independent line of evidence for life on the Early Archean Earth.

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