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GR Letter

Microbially induced sedimentary structures in Archean sandstones: A new window into early life

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Abstract

Until now, the most valuable information on the early life on the Archean Earth derived from bacterial fossils and stromatolites preserved in precipitated lithologies such as chert or carbonates. Also, shales contain complex biomarker molecules, and specific isotopes constitute an important evidence for biogeneicity.

In contrast, because of their low potential of fossil preservation, sandstones have been less investigated. But recent studies revealed a variety of 'microbially induced sedimentary structures — MISS' that differ greatly from any other fossils or sedimentary structures. 'Wrinkle structures', 'multidirected ripple marks', 'biolaminites', and other macrostructures indicate the former presence of photoautotrophic microbial mats in shallow-marine to tidal paleoenvironments. The MISS form by the mechanical interaction of microbial mats with physical sediment dynamics that is the erosion and deposition by water agitation. The structures occur not only in Archean tidal flats, but in equivalent settings throughout Earth history until today.

MISS are not identified alone by their macroscopic morphologies. In thin-sections, the structures display the carpet-like fabrics of intertwined filaments of the ancient mat-constructing microorganisms. Geochemical analyses of the filaments proof their composition of iron minerals associated with organic carbon.

In conclusion, microbial mats colonize sandy tidal settings at least for 3.2 Ga years. Therefore, Archean sandstones constitute an important archive for the exploration of early life.

Keywords: Microbial mat; Archean; Tidal flats; MISS; Early life

1. Introduction

It is an intriguing task to reconstruct life in the Archean, the oldest time period of Earth recorded in rocks. One reason is that during the past 3.8–2.5 billion years and beyond, a multitude of diagenetic and tectonic processes may have altered any primary lithological features. Despite the great loss of information due to taphonomic processes, some geological windows remained that permit insight into Earth's earliest worlds.

In carbonate and cherts, rapid synsedimentary mineral precipitation and early cementation preserved tiny fossils of filigrane bacteria, or lead to the formation of sturdy, stromatolitic build-ups (e.g., Walter, 1976; Lowe, 1980; Awramik, 1984; Buick, 1992; Hofmann et al., 1999; Grotzinger and Knoll, 1999; Schopf et al., 2002; Brasier et al., 2002; Tice and Lowe, 2004; Allwood et al., 2006). In black shales, complex biomolecules are finely distributed, where they have been protected against degradation by heterotrophic microorganisms or by oxygenation (e.g., Brocks et al., 1999). Isotope signals support the evidence of ancient organic matter in the Archean material (e.g., Shen et al., 2001; Knoll, 2003; Strauss, 2003; Faure and Mensing, 2004).

In contrast to precipitated or fine-grained lithologies, siliciclastic deposits are rarely sites of good fossil preservation. Therefore, the expectation to find fossils of tiny bacteria in siliciclastic rock successions especially of very old ages has been low, and such deposits have been far less examined. Now, studies detected biosignatures of Archean ages in sandy deposits as well (Noffke et al., 2003b, 2006a,b). The studies document biogene sedimentary structures that strongly suggest the occurrence of photoautotrophic microbial mats in tidal

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habitats from the Archean to today. Therefore, also sandstones provide a valuable window for the understanding of early life on Earth.

This review gives a brief summary about the biogene sedimentary structures in siliciclastic deposits, and discusses their significance for the reconstruction of the Archean Earth.

2. Microbially induced sedimentary structures — MISS

In contrast to cherts, carbonates and shales, sandstones display biogenic sedimentary structures that resemble neither body fossils, nor stromatolites. Those unusual sedimentary structures in sandy deposits show a great variety of geometries and morphologies, and size ranges of meter to millimeter scales. Characteristic examples include 'petees' (Gehling, 1982), 'Arumberia' (Bland, 1984), 'old elephant skin structures' (e.g., Runnegar and Fedonkin, 1992; Gehling, 1999, 2000), 'sand chips' (Pflueger and Gresse, 1996); 'wrinkle structures' (Hagadorn and Bottjer, 1997); 'multidirected ripple marks' (Noffke, 1998), 'erosional remnants and pockets' (Noffke, 1999); 'roll-up structures' (Schieber, 1999; Simonson and Carney, 1999), 'mat cracks' (Parizot et al., 2005), compare also the overviews in Noffke et al., 2001b, 2003a, or Schieber, 2004. Those 'microbially induced sedimentary structures — MISS' do not arise from chemical processes, but from the biotic-physical interaction of microbial mats with the sedimentary dynamics of aquatic environments (overview in Noffke et al., 2003a). Because of their unique biotic-physical modes of formations and their so different appearances, MISS were placed as own category in the Classification of Primary Sedimentary Structures *sensu* Pettijohn and Potter 1964 (Noffke et al., 2001b, 2003a).

Especially valuable are MISS for the analyses of early Archean (and extraterrestrial) deposits (Noffke et al., 2003b; 2006a,b). The reason is that whereas the chemical conditions of marine and atmospheric environments might have changed in course of the past billions of years, the physical laws of nature must have remained the same. Therefore, actualistic studies on the biotic-physical interactions of microbial mats with the sediment dynamics are key also for the understanding of the strange Archean (or extraterrestrial) worlds. Oversimplified, modern microbial mats in tidal settings serve as an analogue to ancient (or extraterrestrial) micro-epibenthos.

3. Modern MISS and their formations

The first examples of MISS have been described in modern tidal flats of Mellum, an island situated at the North Sea coast of Germany (e.g., Gerdes and Krumbein, 1987; Gerdes et al., 1993; Noffke et al., 1996; Gerdes et al., 2000). Here, microbial mats composed of cyanobacteria overgrow quartz-rich sands of fine sand sizes (Stal et al., 1985; Gerdes and Krumbein, 1987; Noffke and Krumbein, 1999; Stal, 2000). The dominant microbial mat builder is *Microcoleus chthonoplastes*, which prefers to colonize the lower supratidal zone. This tidal zone is typically inundated by sea water only during the spring high tides or during strong landward winds. *M. chthonoplastes* is well adapted to the long lasting periods of subaerial exposure of the tidal surface. Its ubiquitous 'extracellular polymeric substances — EPS' protect the filaments of this cyanobacterium against desiccation or osmotic pressure. EPS are polysaccharides that, simply put, form a slimy mass which the bacterial cells are embedded (Decho, 1990). Towards the intertidal zone, another cyanobacterial species becomes abundant: *Oscillatoria limosa*. The trichomes (single filaments) of *O. limosa* are highly mobile thus being able to move quickly through the sediments. Because the intertidal zone is reworked with every flood current, this high motility is of great advantage for this cyanobacterium (Villbrandt, 1992).

A tidal flat is an extreme environment, because strong flood currents or storm waves rework the sediments significantly. The microbial mats are well adapted to those conditions. They stabilize their substrata by forming a dense and coherent network of entangled filaments that interweave the mineral grains of the depositional surface. In addition, their EPS smoothens the mat surface thus reducing the frictional forces of a current passing the sea floor. This microbial sediment fixation has been termed 'biostabilization' (Paterson, 1994). Measurements on the erosion stability of microbial mat-overgrown tidal flats document biostabilization values of 3 (*O. limosa*) –12

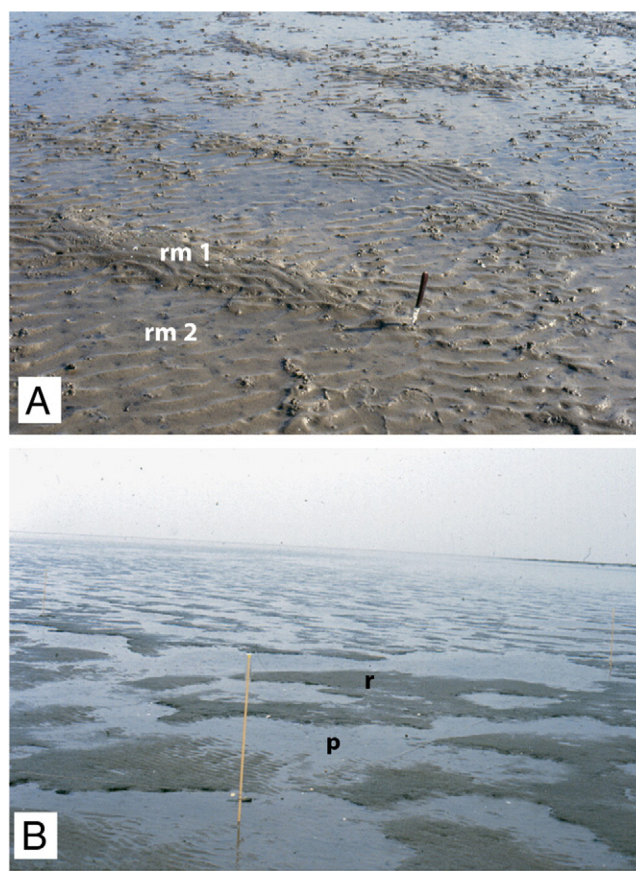

Fig. 1. Modern microbially induced sedimentary structures (MISS) from sandy tidal flats, island of Mellum, North Sea. A: Multidirected ripple marks; rm 1 indicates the first generation of ripple marks, rm 2 is the second one; scale: 20 cm (after: Noffke, 2003a); Erosional remnants and pockets; r indicates an erosional remnant, p indicates an erosional pocket; scale 1 m.