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Notes

An early ecosystem of Archean tidal microbial mats (Moodies Group, South Africa, ca. 3.2 Ga)

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ABSTRACT

Abundant microbial mats from the Mesoproterozoic Moodies Group (Barberton Greenstone Belt, South Africa, ca. 3.2 Ga) are densely interbedded with coarse-grained and gravelly sandstones in a nearly mud-free setting. They apparently grew in marginal marine and possibly subaerial coastal and tidal environments. Characteristic sedimentary structures include anastomosing bedding, gas or fluid escape structures, sand volcanoes, biomat doming, patchy silicified microstromatolites, and microbial sand-chip conglomerates. They indicate rapid growth of mechanically tough microbial mats, possibly aided by early seafloor silicification, in a high-energy, high-sedimentation-rate environment.

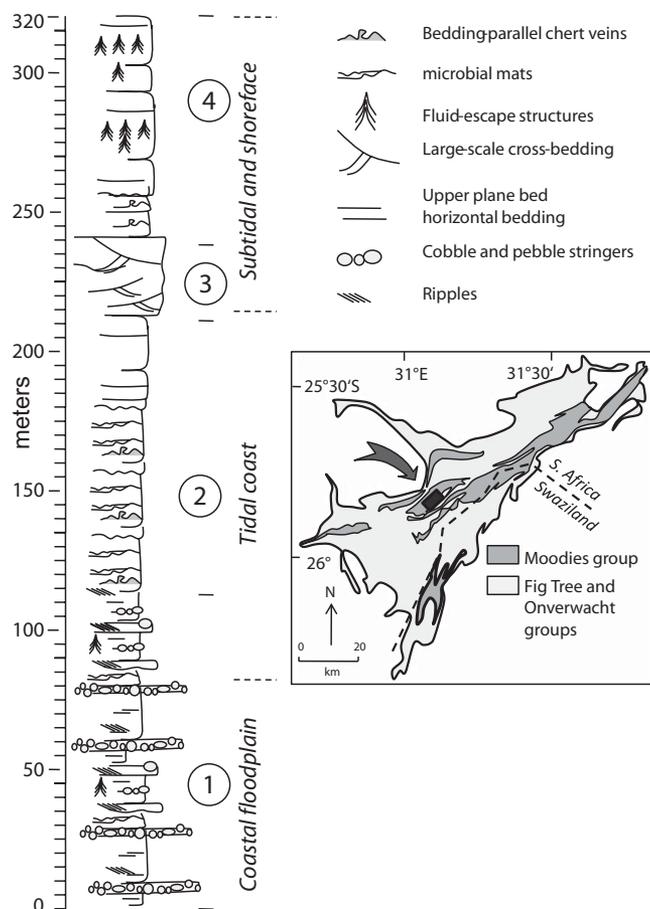
The observations expand the knowledge of the habitat of Archean microbial mats and life on early Earth. If tidal environments were more widespread in the Archean than today, biomats in extensive intertidal settings may have contributed to immobilize large volumes of sand.

INTRODUCTION AND REGIONAL SETTING

Because only few locations have escaped regional metamorphism and deformation, the environment in which early life on Earth formed and its interaction with the geosphere, hydrosphere, and atmosphere is as yet incompletely understood. One of the contentious aspects is the extent, nature, and ecologic role of microbial mats (Hagadorn et al., 1999; Noffke et al., 2001; Brasier et al., 2004; Schieber et al., 2007). Archean microbial mats in shallow-water siliclastic environments have been reported from a number of locations, mostly from South Africa and Australia (Noffke et al., 2006; see Altermann, 2001, for a review).

This study reports on the depositional setting of abundant macroscopic microbial mats and associated structures in the Moodies Group (ca. 3.2 Ga), the world's oldest, relatively unmetamorphosed quartz-dominated sedimentary sequence forming the uppermost unit of the Barberton Greenstone Belt of the Kaapvaal craton (Fig. 1). The Moodies Group dominantly consists of sandstone and subordinate conglomerate and shale deposited in alluvial to shallow-marine depositional settings (Anhaeusser, 1976; Eriksson, 1977,

Figure 1. Stratigraphic measured section (meters) showing lithologies and sedimentary structures across Oosterbeek Firebreak Ridge (25°50'29.45"S, 31°4'34.36"E). Inset map shows location of study area in Saddleback syncline of central Barberton Greenstone Belt. Stratigraphic units (circled): 1—coarse-grained, parallel-stratified, and thinly bedded sandstones interbedded with thin conglomerates, indicating sediment deposition under supercritical flow conditions, likely at shallow flow depths; 2—parallel-stratified and cross-bedded sandstones showing abundant crinkled laminae and some microbial chip conglomerate, probably representing tidal environment; 3—large-scale low-angle cross-bedded sandstones with preserved foresets as much as 2 m in height, indicating strong currents at several m water depths; 4—parallel-stratified sandstones with crinkled laminae and common flame structures.



1978, 1979; Heubeck and Lowe, 1994, 1999). Even though the greenstone belt has undergone extensive deformation and metasomatic alteration, the Moodies Group in the interior of the belt is thought to have undergone maximum temperatures of <220 °C (de Ronde et al., 1997; Toulkeridis et al., 1998). Penetrative strain is notably absent on the thick limbs of the synclines, preserving sedimentary structures in exquisite detail.

FIELD RELATIONSHIPS

An ~3.5-km-thick section of Moodies Group strata dips steeply to subvertically on the overturned limb of the Saddleback syncline in the central Barberton Greenstone Belt (Fig. 1). There, feldspathic and quartzose sandstones with subordinate conglomerates reach several hundred meters in thickness. Part of this sequence (unit MdQ1 of Anhaeusser, 1976), ~300 m thick, is largely silica cemented, forms

resistant outcrops, and lends itself to detailed investigation over several kilometers along strike. The stratigraphic section (Fig. 1) represents a deepening-upward sequence from a coastal high-energy braidplain through a shoreline into foreshore facies. Silt, shale, or sedimentary structures related to suspension settling or desiccation and indicative of a low-energy environment (Eriksson, 1978, 1979; Eriksson et al., 2006; Noffke et al., 2006) are notably lacking.

In the following description we emphasize four particular sedimentary structures relevant to the habitat of biomat growth in the studied section, suggest hydraulic consequences of the depositional environment, and discuss environmental implications.

Laminae

Ubiquitous green anastomosing branching and wavy laminations, <1 mm thick and spaced

millimeters to centimeters apart, separate individual sandstone sets in the intertidal and subtidal facies along bedding planes and laterally accreted foresets (Fig. 2A). In cross section, they form pinnacles, tufts, convex-upward domes, or anvil-shaped protrusions ~1–2 cm across and ~0.5–1 cm in height. Sandstone beds separated by laminae show a pronounced difference in grain size, suggesting variable flow velocities and local grain immobilization by microbial mats (Fig. 2B). Laminae thicknesses are unsystematic; they are observed to thicken in depressions as well on elevated locations. In plan view, laminated bedding planes show a mottled pattern of coin- to palm-sized, well-rounded nodular or biscuit-shaped patches. A biogenic origin of these kerogen-rich laminae of negative $\delta^{13}\text{C}$ composition, interpreted as

microbial mats, was established by Noffke et al. (2006) for similar but shaly and low-energy laminated beds containing wrinkle structures and a single roll-up structure in the nearby Dycedale and Saddleback synclines. Laminae are occasionally reworked and incorporated in cross-bedded medium- and coarse-grained sandstones as millimeter-thick, ~4–8-cm-long, microbial sand chips of apparently high rigidity (Fig. 2C; Pflüger and Gresse, 1996).

Conglomerates

Laminated sandstones are interbedded with nonerosive chert pebble and cobble conglomerates and gravelly sandstones that reach 10–20 cm in individual bed thickness and are laterally continuous. They form minor components of a sandy, possibly subaerial facies near

the base of the measured section. There, wavy anastomosing laminae overlie, underlie, coat, and onlap conglomerate clasts (Fig. 2D). Small sand waves form in the lee of clast accumulations, attesting to a high bedload.

Fluid and/or Gas Escape Structures

Numerous decimeter- to meter-high subvertical structures defined by upward-curved microbial mats, symmetrically arranged on either side of a central channel (Fig. 2E), commonly occur in the upper part of the measured profile in strata interpreted as subtidal facies. These structures are particularly common in gravel-clast-free, densely biomat-laminated, medium-grained, thin-bedded sandstone. They may occur on a spacing of a few meters and appear clustered. In shape and size, these structures correspond to classical flame structures; in contrast to those, however, they are not associated with mud but with biolaminae. They typically reach 10–20 cm but can attain 210 cm in height. Smaller structures tend to be inclined and to deform ductilely, whereas larger structures tend to be vertical, show internal homogenization, and include signs of brittle breakage of laminae. The central channel concentrates black carbonaceous matter. These structures are most readily interpreted as fluid or gas escape structures.

Fluid escape structures lower in the section, interbedded with coarse-grained and gravelly sandstones, are less common. There, gravel strings terminate laterally against at least one structure and may indicate potential subaerial exposure.

Microstromatolites

Sandstones containing crinkled laminae are commonly interspersed with bedding-plane-parallel black chert bands (Fig. 2F). These reach 1–3 mm thick, are ~10–30 cm long, and taper at both ends. They are concentrated in an ~20-m-thick section near the middle of the measured section. Bidirectional foreset sets and the position of this unit in the deepening-upward facies succession suggest a shallow subtidal environment. In cross section, chert bands show smoothly curved upper margins and commonly form small, upward-bulging structures; their contact to the underlying bed is typically uneven.

In thin section, the bands consist of fine-grained equigranular chert. This fill is internally structured by numerous opaque, uneven, bedding-plane-subparallel wavy laminae (Figs. 3A–3C). Laminae clearly overgrow individual grains, but solitary grains may also float in the cherty matrix. Segments of chert bands also occur as cloudy balls of irregular shape between sand grains and as wavy elongate rafts showing various degrees of ductile deformation. Laterally, they grade into the thin kerogen-rich laminae described above.

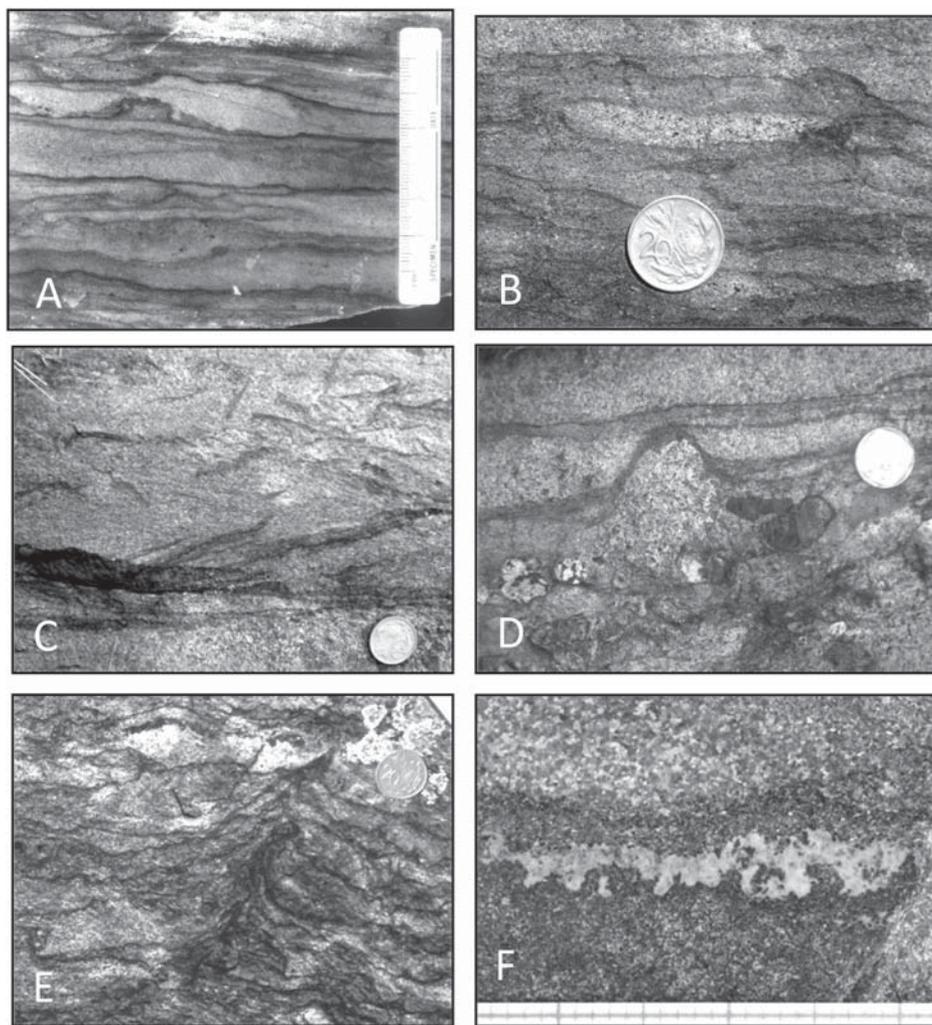


Figure 2. Sedimentary structures associated with biolaminae. A: Slabbed surface of sandstone showing crinkled, domed, and anastomosing coatings covering bedding planes and low-angle foresets. **B:** Channel of coarse-grained sand between domal protrusions, indicating subaerial relief. **C:** Outcrop photograph of microbial-chip conglomerate, suggesting reworking under high-energy conditions. **D:** Microbial mats onlap and overgrow cobble. **E:** Dewatering pipe penetrating layered microbial mats. **F:** Slabbed sandstone showing black chert band interpreted as patchy silicified microstromatolite. Coin in B, C, D is 20 mm; coin in E is 22 mm in diameter. Scale in F is in millimeters.

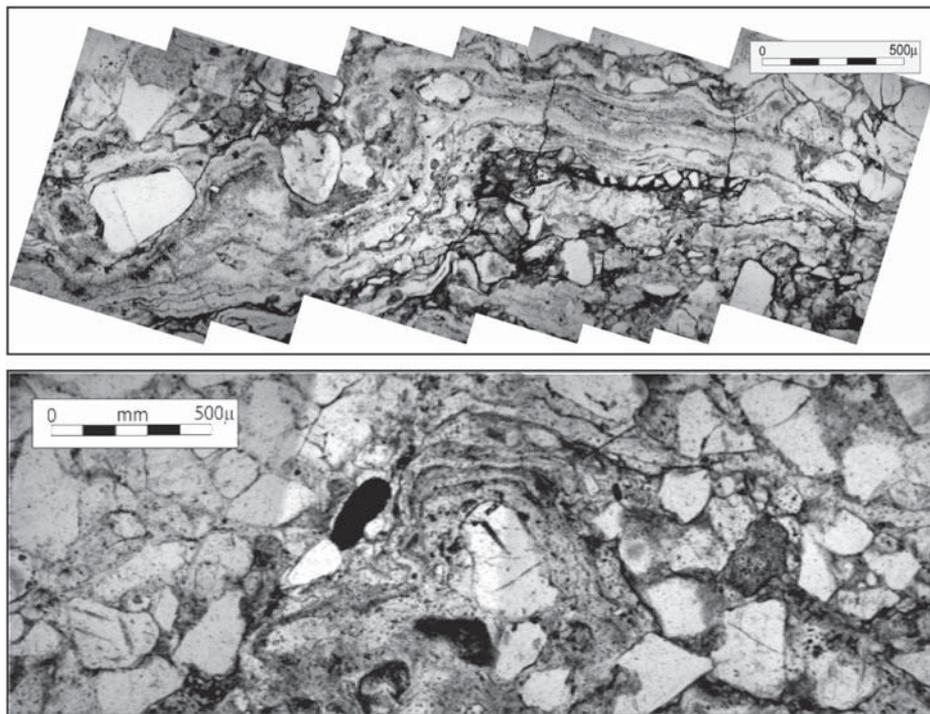


Figure 3. Photomicrographs of thin chert bands defining abundant laminations in sandstones of facies 2 of Figure 1. They show approximately parallel wavy laminations defined by elementary carbon and iron oxides, wrap-around grains, and solitary detrital quartz grains. Laminae suggest little, if any, deformation by compaction and imply early lithification.

DISCUSSION

Habitat of Biomats

The observations of the texture and geometry of the wavy laminae suggest that these represent thin cohesive epibenthic microbial mats at the sediment-water or sediment-atmosphere interface. Alternatively, they may have formed cryptoendolithic communities growing within ~1 cm from the surface, similar to those documented for Chilean hot spring fields (Phoenix et al., 2006). At least some of the laminae apparently formed a small-scale relief, thereby channelizing coarse granular sediment. The tuft-like shapes and ubiquitous bulbous domes on the wavy and crinkly surfaces (Gerdes, 2007) suggest photosynthetic activity.

The common conical fluid escape structures penetrating the laminae resemble flame structures in shape and size, but are apparently not related to the process of higher density sand sinking into lower density shale. The structures are best explained as dewatering or degassing pipes. Their number, dense spacing, and, in particular, size, however, suggest that the volume of expelled fluids and/or gases was not only related to mat decay (Dornbos et al., 2007), but that significant volumes of fluid had been retained within the framework-supported, microbially laminated sand. These interwoven mucilaginous mats compartmentalized fluids,

reduced vertical permeability, and retarded dewatering. Triggers for the mobilization of fluids are speculative; however, once a small overpressured, biomat-surrounded pressure cell was ruptured at depth, the increasing vertical connectivity of the pressurized fluid and its growing volume made the rapid vertical growth of the fluid or gas escape pathway a self-strengthening process. The geometrical relationships between biolaminae and the dewatering structures indicate that dewatering occurred prior to, during, and after microbial mat growth. Because gravely sandstone beds wedge out laterally against at least one dewatering structure, it is likely that these occasionally reached the sediment-water or sediment-atmosphere interface and formed cones or ridges as high as several centimeters. The particular significance of the fluid escape structures is in their unusual size, several meters of continuous vertical extent. This, in turn, requires biomats that yield to loading pressure only at depth, and makes them distinctive from similar structures described in the literature (e.g., Dornbos et al., 2007).

The bedding-parallel bands of black chert can be best interpreted as epibenthic microstromatolites or thick mucilaginous mats that likely grew on the sandy substrate. If the mats used sunlight for photosynthesis, they may have been covered by a thin sandy cover (modeled by Phoenix et al., 2006, to be 4–7 mm thick)

that offered them an optimum balance between ambient light and ultraviolet light (UV) protection. The internal domal, carbon-rich laminae, their occurrence in various stages of deformation, and the lateral grading into laminae indicate that black chert bands and wavy laminae both represent biomats of various thickness and of various degrees of compaction.

A striking feature of the section is the absence of any silty or shaly material. Rather, the geometry, small-scale features, and occurrence of the crinkled laminae in medium- and coarse-grained sandstones, and their association with gravel sheets, indicate that biomats grew in high-energy environments that were frequently capable of moving gravel. Mat growth was fast enough to coat individual foresets, albeit likely at times of temporarily reduced current velocity.

The several-hundred-meter-thick biomat-related stratigraphic section under study coincides with the highest detrital feldspar content in Moodies Group sandstones, constituting subarkoses with a mean of 15% and as much as 20% detrital feldspar grains ($n = 6$; Heubeck and Lowe, 1999). At present, the significance of this relationship is unknown. One could hypothesize that fluid flow was slowed by the biomat compartments sufficiently to allow silica saturation in the interstitial fluids to reach high levels, thus preventing early diagenetic feldspar dissolution.

Overall, the field evidence indicates that the microbial mats formed abundantly and rhythmically in periods of temporarily reduced flow energy and sediment movement, stabilized the sedimentary structures by overgrowing grains, and became buried with subsequent flow events.

Seafloor Silicification

The common occurrence of uncompacted silicified bands of biomats, microbial wraps around floating grains, and fluid escape structures indicates that the biomat fabric was cohesive enough to retard sediment compaction, dewatering, and possibly also degassing. Evidence for very early diagenetic silicification in sedimentary units of the Barberton Greenstone Belt is abundant (Lowe, 1999); textural or mineralogical indications of replaced carbonate, however, were not observed. An early seafloor silicification of microbial mats, initially likely as opaline crusts on a millimeter scale, would have been highly effective in compartmentalizing fluids and in retarding dewatering. An early stiffening of biomats is also suggested by the thin, brittle slabs of biomats forming the microbial sand-chip conglomerates.

The possibility of very early seafloor silica precipitation and resulting partial surface sealing and stiffening by biomats is consistent with a higher silica concentration in the Archean as a result of higher water temperature prior to 3.2 Ga, possibly $\sim 60 \pm 13$ °C (Knauth and

Lowe, 2003; Lowe and Tice, 2007), and facilitated by the absence of biogenic sinks for dissolved silica (Siever, 1992). SiO₂ solubility and silicification rates at elevated temperatures may have been many times higher than at present. Indeed, experiments and analog studies at hot springs have shown that Gram-positive bacteria silicify readily (Westall, 1997), that filamentous cyanobacteria may produce quickly mechanically resistant stacked laminae of alternating upright and prone layers (Konhauser et al., 2004), and that precipitated coatings of hydrous amorphous silica protect cyanobacteria from harmful UV radiation and from desiccation in an environment marked by intermittent submergence and exposure (Phoenix et al., 2006).

If Archean tidal ranges were generally higher, as suggested from astronomical calculations and supported by geological evidence (Hobday and Von Brunn, 1976; Eriksson et al., 2006), and if Precambrian shelves were wider and shallower than today (Eriksson et al., 1998), megatidal environments may have provided extensive regions for biotam habitats. Granular sediment in large quantities in nearshore environments would have been temporarily fixated by intertidal mats and created sharp near-surface chemoclines.

CONCLUSIONS

The high-energy siliciclastic setting of the biotams, their widespread and pervasive occurrence in medium-grained to gravelly sandstone of Mesoarchean age, and their apparently high cohesiveness and rapid growth rates constitute collectively an extension of Archean biotam habitats. Rapid seafloor silicification by mucilaginous organic substances and resulting sediment fixation aided in biostabilization and retarded dewatering rates, and may have contributed to a distinctive petrographic composition. These characteristics suggest self-stabilization of a small ecosystem against rapid change (Phoenix and Konhauser, 2008) and are consistent with the existence of anoxygenic photosynthetic thermophiles.

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