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

Nora Noffke* Department of Ocean, Earth and Atmospheric Sciences, Old Dominion University, 4600 Elkhorn Avenue, Norfolk, Virginia 23529, USA
Kenneth A. Eriksson Department of Geosciences, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061, USA
Robert M. Hazen Carnegie Institution, Geophysical Laboratory, 5251 Broad Branch Road NW, Washington, DC 20015, USA
Edward L. Simpson Department of Physical Sciences, University of Pennsylvania, Kutztown, Pennsylvania 19530, USA

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 $\delta^{13}C$ 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 newly detected microbially induced sedimentary structures in sandstone support the presence of bacterial 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 by 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 (Krüner et al., 1991; Kamo and Davis, 1994), whereas the minimum age is constrained by the crosscutting Salisbury

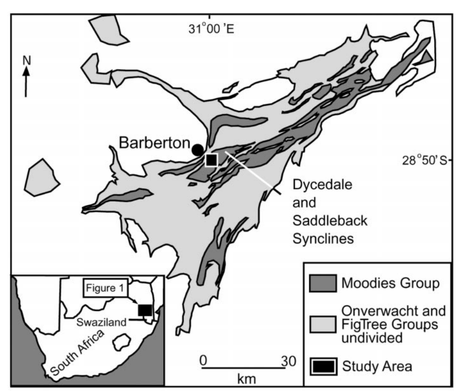

Figure 1. Study location of 3.2 Ga Moodies Group, Barberton greenstone belt, South Africa. Moodies Group contains oldest known siliciclastic tidal flat deposits in rock record.

*E-mail: nnoffke@odu.edu.

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 paleoenvironment 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., 2003a). In addition, electron microprobe analyses and isotopic measurements of $\delta^{13}C$ were determined using the methods described in Boyce et al. (2001) and Noffke et al. (2003b).

DESCRIPTION AND INTERPRETATION OF MICROBIALLY 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).

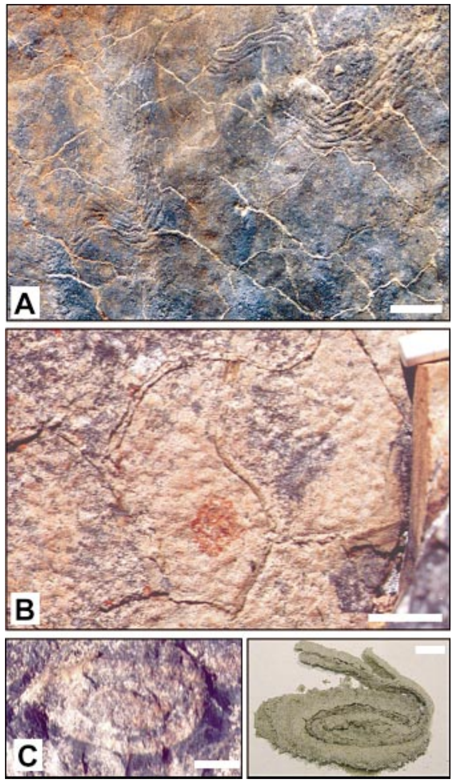

Figure 2. Microbially induced sedimentary structures (MISS), Moodies Group. A: Wrinkle structure and subsequently formed syneresis cracks on fine-grained sandstone bedding plane; scale: 10 cm. B: Wrinkle structure and desiccation cracks on sandstone bedding plane; scale: 2 cm. C: Roll-up structure; scale: 1 cm; for comparison, modern roll-up structure from tidal flats of Fishermans Island, Virginia, USA, is shown on right; scale: 1 cm.

The structure shown in Figure 2A is composed of wrinkles of 5 mm wavelength and 3 mm height, covering ~70 cm^2 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 cm^2. 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 abiotic physical 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, unlithified 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 (Gerdes 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-

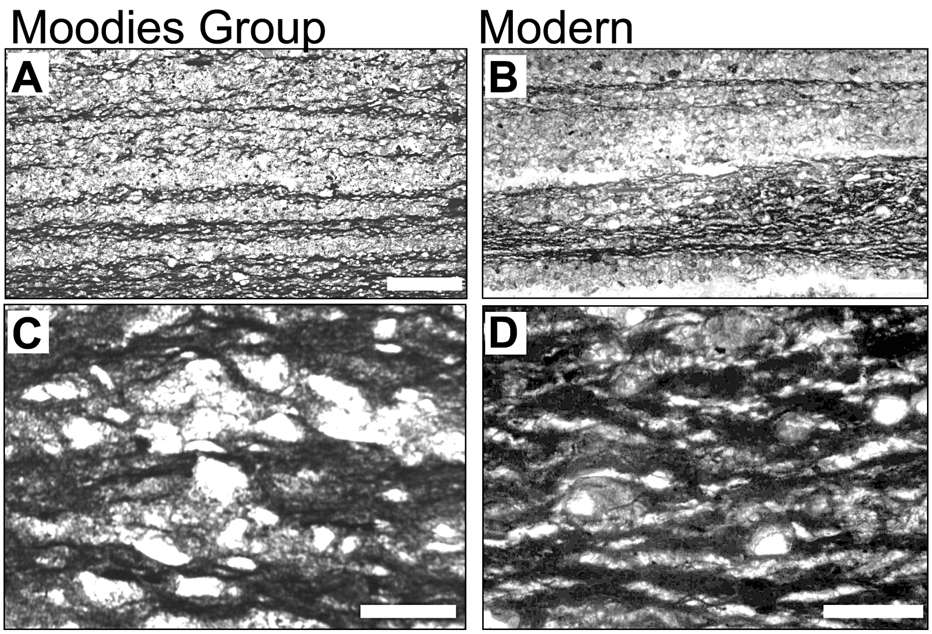

Figure 3. Comparison of textures of ancient microbial mats from Moodies Group (A, C), with modern counterparts from sandy tidal flats (Mellum Island, North Sea) (B, D). Textures are in thin sections. A: Interlayering of fine-grained quartz sandstone and carbon-containing laminae. B: Same interlaminated pattern in modern microbial mats rising from microbial mat growth episodically interrupted by deposition of fine-grained sand; scale (A, B): 1 mm. C: Filament-like textures defining network around quartz grains. D: Similar meshwork-like texture in modern microbial mat; scale (C, D): 250 μm.

tinguishing characteristic is the orientation of the long axes of the grains parallel to the microbial mat layer (Noffke et al., 1997). Such solitary quartz grains embedded in the organic mat fabrics are a common textural feature in both ancient and modern microbial mats (e.g., Noffke et al., 2002; Fig. 4B). In laboratory experiments, microbial mats first envelope single grains at the depositional surface. With increasing thickness of biofilms, the grains are lifted up and separated from each other (Noffke et al., 1997, 2001b; Fig. 4C).

Electron microprobe analyses of the opaque microstructures indicate that they consist of elemental carbon and (possibly hydrous) ferric iron oxide (hematite and/or goethite). Therefore, the laminae do not represent phyllosilicates. The bulk carbon content of the rock is relatively low (0.08 ± 0.01 wt%), but approximately 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 $-21.5‰ \pm 0.2‰$ 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 quarzites 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.

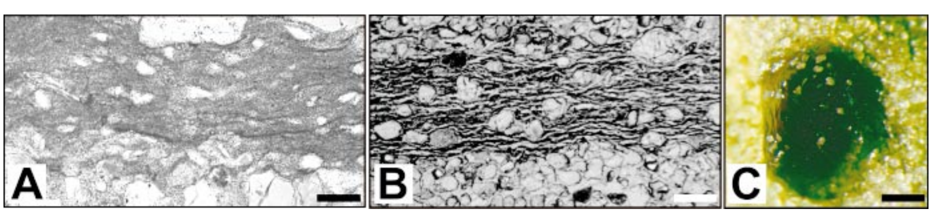

Figure 4. Comparison of textures of oriented grains typical of ancient and modern microbial mats. A: Quartz particles floating in matrix of carbon-rich laminae, Moodies Group. B: Similar texture of oriented quartz particles in modern microbial mat; scale (A, B): 250 μm. Textures are in thin sections. C: In laboratory experiment, "oriented grains" originate from substrate beneath microbial mat (dark green) and are pushed upward during mat growth (after Noffke et al., 2001b).

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 photoautotrophic. 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 photoautotrophic microbial ecosystems. The study shows that microbially induced sedimentary structures constitute an independent line of evidence for life on the Early Archean Earth.

ACKNOWLEDGMENTS

We thank Martin Brasier, Andrew H. Knoll, and Brian R. Pratt for their helpful and constructive reviews of this manuscript. Valuable technical support was provided by Chris Hadidiacos, and Marilyn Fogel, Carnegie Institution of Washington D.C., and Dina Bower and Robert Kidd, Old Dominion University. This study is funded to Noffke by the National Science Foundation (Geology and Paleontology Program; EAR-0345149).

REFERENCES CITED

Bottjer, D., 2005, Geobiology and the fossil record: Eukaryotes, microbes, and their interactions, *in*

Noffke, N., ed., Geobiology: Objectives, concepts, perspectives: Amsterdam, Elsevier, p. 5–22.

Boyce, C.K., Hazen, R.M., and Knoll, A.H., 2001, Nondestructive, in situ, cellular-scale mapping of elemental abundances including organic carbon in permineralized fossils: Proceedings of the National Academy of Sciences of the United States of America, v. 98, p. 5970–5974, doi: 10.1073/pnas.101130598.

Brasier, M.D., Green, O.R., Jephcoat, A.P., Kleppe, A.K., Van Kranendonk, M.J., Lindsay, J.F., Steele, A., and Grasslmeau, M.V., 2002, Questioning the evidence for Earth's oldest fossils: Nature, v. 416, p. 76–91, doi: 10.1038/416076a.

Brasier, M.D., Green, O.R., Lindsay, J.F., McLaughlin, N., Steele, A., and Stoakes, C., 2005, Critical testing of Earth's oldest putative fossil assemblage from the ~3.5 Ga Apex chert, Chinaman Creek, Western Australia: Precambrian Research, v. 140, p. 55–102, doi: 10.1016/j.precamres.2005.06.008.

Eriksson, K.A., 1977, Tidal deposits from the Archaean Moodies Group, Barberton Mountain Land, South Africa: Sedimentary Geology, v. 18, p. 257–281, doi: 10.1016/0037-0738(77)90015-X.

Eriksson, K.A., 1979, Marginal marine depositional processes from the Archean Moodies Group, Barberton Mountain Land, South Africa: Evidence and significance: Precambrian Research, v. 8, p. 153–182, doi: 10.1016/0301-9268(79)90027-5.

Eriksson, K.A., Simpson, E.L., and Mueller, W., 2006, Depositional and geotectonic setting of fluviotidal facies in the ~3.2 Ga Moodies Group, South Africa: Sedimentary Geology (in press).

Faure, G., and Mensing, T.A., 2004, Isotopes: Principles and applications (3rd edition): New York, John Wiley, 897 p.

Ferris, F.G., Fyfe, W.S., and Beveridge, T.J., 1987, Bacteria as nucleation sites for authigenic minerals in a metal-contaminated lake sediment: Chemical Geology, v. 63, p. 225–232, doi: 10.1016/0009-2541(87)90165-3.

Gehling, J.G., 1999, Microbial mats in terminal Proterozoic siliciclastics: Ediacaran death masks, *in* Hagadorn, J.W., Pflueger, F., and Bottjer, D.J., eds., Unexplored microbial worlds: Palaios, v. 14, p. 40–57.

Gehling, J.G., 2000, Environmental interpretation and a sequence stratigraphic framework for the terminal Proterozoic Ediacara member within the Rawnsley Quarzite, South Australia: Precambrian Research, v. 100, p. 65–95, doi: 10.1016/S0301-9268(99)00069-8.

Gerdes, G., Krumbein, W.E., and Reineck, H.E., 1991, Biolaminations—Ecological versus depositional dynamics, *in* Einsele, G., Ricken, W., and Seilacher, A., eds., Cycles and events in stratigraphy: Berlin, Springer-Verlag, p. 592–607.

Grotzinger, J.P., and Knoll, A.H., 1999, Stromatolites in Precambrian carbonates: Evolutionary mileposts or environmental dipsticks?: Annual Review of Earth and Planetary Science, v. 27, p. 313–358, doi: 10.1146/annurev.earth.27.1.313.

Hagadorn, J.W., and Bottjer, D.J., 1997, Wrinkle structures: Microbially mediated sedimentary structures in siliciclastic settings at the Proterozoic-Phanerozoic transition: Geology, v. 25, p. 1047–1050, doi: 10.1130/0091-7613(1997)025<1047:WSMMSS>2.3.CO;2.

Hagadorn, J.W., and Bottjer, D.J., 1999, Restriction of a Late Neoproterozoic biotope: Suspect-microbial structures and trace fossils at the Vendian-Cambrian transition, *in* Hagadorn, J.W., Pflueger, F., and Bottjer, D.J., eds., Unexplored microbial worlds: Palaios, v. 14, p. 73–85.

Heubeck, C., and Lowe, D.R., 1999, Sedimentary petrography and provenance of the Archean Moodies Group, Barberton greenstone belt, *in* Lowe, D.R., and Byerly, G.R., eds., Geological evolution of the Barberton greenstone belt, South Africa: Geological Society of America Special Paper 329, p. 259–286.

Heubeck, C., Wendt, J.I., Toulkerides, T., Krüner, A., and Lowe, D.R., 1993, Timing of deformation of the Archean greenstone belt, South Africa: Constraints from zircon dating of the Salisbury Kop pluton: South African Journal of Geology, v. 96, p. 1–8.

Hofmann, H.J., Grey, K., Hickman, A.H., and Thorpe, R.I., 1999, Origin of 3.45 Ga coniform stromatolites in the Warawoona Group, Western Australia: Geological Society of America Bulletin, v. 111, p. 1256–1262, doi: 10.1130/0016-7606(1999)111<1256:OOGCSI>2.3.CO;2.

Kamo, S.L., and Davis, D.W., 1994, Reassessment of Archean crustal development in the Barberton Mountain Land, South Africa, based on U-Pb dating: Tectonics, v. 13, p. 167–192, doi: 10.1029/93TC02254.

Kasting, J.F., 2001, Earth History: The rise of atmospheric oxygen: Science, v. 293, p. 819–820, doi: 10.1126/science.1063811.

Knoll, A.H., 1999, A new molecular window: Science, v. 285, p. 1025–1026, doi: 10.1126/science.285.5430.1025.

Knoll, A.H., 2003, Life on a young planet: Princeton, Princeton University Press, 378 p.

Knoll, A.H., Strother, P., and Rossi, S., 1988, Distribution and diagenesis of silicified microfossils from the Lower Proterozoic Duck Creek Formation, Western Australia: Precambrian Research, v. 38, p. 257–279, doi: 10.1016/0301-9268(88)90005-8.

Konhauser, K.O., Schulze-Lam, S., Ferris, F.G., Fyfe, W.S., Longstaffe, F.J., and Beveridge, T.J., 1994, Mineral precipitation by epilithic biofilms in the Speed River, Ontario: Canadian Applied Environmental Microbiology, v. 2, p. 549–553.

Krüner, A., Byerly, G., and Lowe, D.R., 1991, Chronology of Early Archean granite-greenstone evolution in the Barberton Mountain Land, South Africa, based on precise dating by single zircon evaporation: Earth and Planetary Science Letters, v. 103, p. 41–54, doi: 10.1016/0012-821X(91)90148-B.

Nisbet, E.G., and Sleep, N.H., 2001, The habitat and nature of early life: Nature, v. 409, p. 1083–1091, doi: 10.1038/35059210.

Noffke, N., 1998, Multidirected ripple marks rising from biological and sedimentological processes in modern lower supratidal deposits (Mellum Island, southern North Sea): Geology, v. 26, p. 879–883, doi: 10.1130/0091-7613(1998)026<0879:MRMRFB>2.3.CO;2.

Noffke, N., 2000, Extensive microbial mats and their influences on the erosional and depositional dynamics of a siliciclastic cold water environment (lower Arenigian, Montagne Noire, France): Sedimentary Geology, v. 136, p. 207–215, doi: 10.1016/S0037-0738(00)00098-1.

Noffke, N., 2003, Microbially induced sedimentary structures: Formation and application to sedimentology, *in* Middleton, C., ed., Encyclopedia of sediments and sedimentary rocks: Dordrecht, Kluwer, p. 439–441.

Noffke, N., and Krumbein, W.E., 1999, A quantitative approach to sedimentary surface structures contoured by the interplay of microbial colonization and physical dynamics: Sedimentology, v. 46, p. 417–426, doi: 10.1046/j.1365-3091.1999.00218.x.

Noffke, N., Gerdes, G., Klenke, Th., and Krumbein, W.E., 1996, Microbially induced sedimentary structures—Examples from modern sediments of siliciclastic tidal flats: Zentralblatt für Geologie und Paläontologie, v. 1995, p. 307–316.

Noffke, N., Gerdes, G., Klenke, Th., and Krumbein, W.E., 1997, A microscopic sedimentary succession indicating the presence of microbial mats in siliciclastic tidal flats: Sedimentary Geology, v. 110, p. 1–6, doi: 10.1016/S0037-0738(97)00039-0.

Noffke, N., Gerdes, G., Klenke, Th., and Krumbein, W.E., 2001a, Microbially induced sedimentary structures indicating climatological, hydrological and depositional conditions within Recent and Pleistocene coastal facies zones (southern Tunisia): Facies, v. 44, p. 23–30.

Noffke, N., Gerdes, G., Klenke, Th., and Krumbein, W.E., 2001b, Microbially induced sedimentary structures—A new category within the classification of primary sedimentary structures: Journal of Sedimentary Research, v. 71, p. 649–656.

Noffke, N., Knoll, A.H., and Grotzinger, J., 2002, Sedimentary controls on the formation and preservation of microbial mats in siliciclastic deposits: A case study from the upper Neoproterozoic Nama Group, Namibia: Palaios, v. 17, p. 1–14.

Noffke, N., Gerdes, G., and Klenke, Th., 2003a, Benthic cyanobacteria and their influence on the sedimentary dynamics of peritidal depositional systems (siliciclastic, evaporitic salty and evaporitic carbonatic): Earth-Science Reviews, v. 12, p. 1–14.

Noffke, N., Hazen, R., and Nhleko, N., 2003b, Earth's earliest microbial mats in a siliciclastic marine environment (Mozaan Group, 2.9 Ga, South Africa): Geology, v. 31, no. 8, p. 673–676, doi: 10.1130/G19704.1.

Ohmoto, H., 2004, The Archaean atmosphere, hydrosphere and biosphere, *in* Eriksson, P.G., et al., eds., The Precambrian Earth: Tempos and events: Developments in Precambrian geology: Amsterdam, Elsevier, p. 361–388.

Paterson, D., 1994, Siliciclastic intertidal microbial sediments, *in* Stal, L.J., and Caumette, P., eds., Microbial mats: Berlin, Springer, p. 97–109.

Pavlov, A.A., Brown, L.L., and Kasting, J.F., 2001, UV shielding of NH_3 and O_2 by organic hazes in the Archean atmosphere: Journal of Geophysical Research, v. 106, no. 23, p. 267.

Schidlowski, M., Hayes, J.M., and Kaplin, I.R., 1983, Isotopic inferences of ancient biochemistries: Carbon, sulfur, hydrogen and nitrogen, *in* Schopf, J.W., ed., Earth's earliest biosphere: Its origin and evolution: Princeton, New Jersey, Princeton University Press, p. 149–186.

Schieber, J., 1999, Microbial mats in terrigenous clastics: The challenge of identification in the rock record, *in* Hagadorn, J.W., Pflueger, F., and Bottjer, D.J., eds., Unexplored microbial worlds: Palaios, v. 14, p. 3–12.

Schieber, J., 2004, Microbial mats in the siliciclastic rock record: A summary of diagnostic features, *in* Eriksson, P.G., Altermann, D.R., Nelson, D.R., Mueller, W.E., Catuneanu, O., eds., The Precambrian Earth: Tempos and events: Amsterdam, Elsevier, p. 663–673.

Schopf, J.W., Kudryvtsev, A.B., Agrestl, D.E., Wdowlak, Th.J., and Czaja, A.D., 2002, Laser-Raman imagery of Earth's earliest fossils: Nature, v. 416, p. 73–76, doi: 10.1038/416073a.

Schultze-Lam, S., Fortin, D., Davis, B.S., and Beveridge, T.J., 1996, Mineralization of bacterial surfaces: Chemical Geology, v. 132, p. 171–181, doi: 10.1016/S0009-2541(96)00053-8.

Simonson, B.M., and Carney, K.E., 1999, Roll-up structures: Evidence of in situ microbial mats in Late Archean deep shelf environments, *in* Hagadorn, J.W., Pflueger, F., and Bottjer, D.J., eds., Unexplored microbial worlds: Palaios, v. 14, p. 13–24.

Tice, M.M., and Lowe, D.R., 2004, Photosynthetic microbial mats in the 3.5 Ga old ocean: Nature, v. 431, p. 549–550, doi: 10.1038/nature02888.

Manuscript received 26 September 2005
Revised manuscript received 30 November 2005
Manuscript accepted 5 December 2005

Printed in USA