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MICROBIAL MATS: SUMMARY AND CONCLUSIONS

Final comments

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1. General Background

This volume encompasses many aspects of microbial mats. Many of the chapters dealt with their description, their geographical distribution and their environmental properties. They presented the characteristics of the mats and of the microorganisms from which they are composed. The chapters include descriptions of microbial mats in fresh water, soils, seepages, marine settings and in hypersaline areas. Among the microorganisms encountered there are green algae, diatoms, cyanobacteria, lichens, and many others. Geographical locations included marine settings such as the Baltic Sea, the hypersaline mats of Guerrero Negro, the acidic environment of the Rio Tinto biofilms, and the cold Antarctic Dry Valleys). Some chapters discussed molecular aspects of the mats, their osmotic adaptation, biosignatures and other properties of the microbial communities. Other chapters dealt with the ancient mats (the paleoenvironment of early Earth), comparing their properties with those of modern mats. Their occurrence in extreme environments could serve as a model for similar structures which might possible exist in extraterrestrial bodies such as on Europa (satellite of Jupiter) Mars, and other celestial bodies.

2. Geological and Fossil Mats

The study of microbial mats is important not only for understanding modern environments, but also for interpreting the geological record. Microbial cells are rarely preserved in the fossil record and, as has been demonstrated by various investigators, simple microbe-like morphologies such as spheres and filaments may be formed abiologically. Other biosignatures, including fossil microbial mats, have therefore become important in investigating the abundance and the environments of life on the early Earth. Fossil mats provide a microenvironmental context for individual microbial fossils and a record of microbial activity in the absence of such structures.

Very fine microbial mat structures preserved by early silicification are present in rocks of the Kaapvaal Craton in southern Africa and the Pilbara Block in northwestern Australia. The diversity of mat types represented and their depositional association with varying, and often extreme, environmental settings suggest that early life had occupied a variety of niches on the Earth as early as 3.5 billion years ago. Examining these and other fossil mats with a combination of traditional petrographic and chemical techniques and new high resolution analyses will result in a more confident and detailed understanding of the record of life on Earth.

3. Biofilms Form, Everywhere on and within Clastic Sediments

An important concept to understand is the continuum from thin and vulnerable (in terms of preservation) biofilms through tough leathery (fibrous, filamental) microbial mats to the range of subtle features formed and preserved within clastic sedimentary environments by the interaction of mat growth, mat metabolism, mat decay, mat destruction and sedimentation processes. The concomitant time scale related to this continuum varies from several hours for biofilms, to several weeks for fully formed leathery mats to reach fruition (e.g., Gerdes and Klenke, 2007), to periods probably measurable in months to even years for the secondary structures alluded to above (e.g., Eriksson *et al.*, this volume). The continuum is interpreted from the clastic sedimentary record based on a relatively large (ca. 50) set of essentially subtle or proxy features, which result from the highly diverse interaction of evolving mats and unconsolidated sediment, varying mostly from sand grades down to mud-sized particles. Mostly, it is features indicative of sediment behavior incompatible with the normal physical and chemical controls on clastic sedimentation processes that suggest a role for microbial mats within the observed sedimentation system.

The inherent complexity resulting from the sum of the above basic observations rivals and possibly exceeds that inherent in the relationship between the physically (and to a lesser extent, chemically-) formed sedimentary structures and their genetic processes and host (paleo-)environments. However, this picture has been subject to some bias and confusion due to the number of studies carried out on modern and ancient equivalent examples from shallow marine tidal to supratidal settings as well as hypersaline lagoons (e.g., Gerdes *et al.*, 1985a, b and c; Gerdes, 2007). Consequently some diagnostic prejudice towards such specific settings has emerged in the literature (e.g., Noffke *et al.*,

2006; Noffke, 2007). This viewpoint contrasts with a more widely supported one where a non-facies specific relationship appears to be paramount for the mat-sediment interactions (e.g., Schieber *et al.*, 2007 a and c; three case studies in Eriksson *et al.*, this volume). What is remarkable and possibly even characteristic of microbial mats within clastic sedimentary settings, is their enormous environmental range, known from at least shallow marine environments through a full range of continental aqueous settings, even to deserts (Schieber, 1998; Eriksson *et al.*, 2000; Schieber *et al.*, 2007, a and c; Gerdes, 2007). However, when abundance and variety of mat-related structures (MRS) are considered, there is a measure of truth to a littoral sandy setting bias (Schieber *et al.*, 2007c). Microtopographic variability within any specific environmental setting also plays a role in determining preservation and even type of MRS, particularly within the littoral settings (e.g., Eriksson *et al.*, this volume).

It is commonly asserted that metazoan grazing below in settings younger than the Neoproterozoic-Phanerozoic boundary significantly reduced the abundance of microbial mats, effectively restricting their occurrence to stressed environmental settings (see also in this issue, papers by: Green; Oren) such as desiccating tidal flats or hypersaline lagoons; however, Schieber *et al.* (2007b) question this simple assertion, pointing out also that the broad adaptability of mats is the same either side of this boundary. This question is discussed in some detail by Krumbein in this volume.

Microbial mats and the binding properties they provide for clastic sediment particles can potentially result in differences in clastic sediment architecture and even in sequence stratigraphic stacking patterns (e.g., Sarkar *et al.*, 2005; Banerjee and Jeevankumar, 2005; Catuneanu and Eriksson, 2007), but much more work is still needed to understand this. Analogously, a large body of work is required to tie the different MRS features to specific environments and subenvironments, to make these sedimentary features equally useful in palaeoenvironmental interpretative studies as their much better known physically and chemically formed sedimentary structure equivalents.

4. Mats in Extreme Environment on Earth and Elsewhere

Microorganisms the major part of all life on Earth, and they are also organized in microbial mats and into biofilms. For this reason, this volume's main focus is the description of different aspects of microbial mats that are fundamental for our deeper understanding of a major cross-section of microbiology in general, and for astrobiology. We have discussed multiple implications of the study of microbial mats. Prominent amongst them is the understanding of the early Earth, before multicellularity evolved. Microbial mats may help us to understand the possibility of life elsewhere in our own solar system, such as on Europa, Mars, Enceladus (one of the innermost moons of Saturn) and Titan (satellite of Saturn).

Indeed, microbial mats are ubiquitous in extreme environments: at high and low temperatures; in hypersaline bodies of water such as the Dead Sea; in hot springs, where they not only survive, but thrive as exemplified by the startling colored microbial mats that live in Yellowstone National Park. Microbial mats are also present in volcanic vents on the ocean floor, called black smokers. Other environments suitable for microbial mats are deserts and, specifically the Dry Valleys of Antarctica in the MacMurdo region that is

traversed by striking glaciers. The British explorer Sir Robert Scott discovered the Dry Valleys in 1905. Some of the most interesting lakes in this region are permanently covered by ice. These extraordinary environments present us with an ideal window to glance at significant events that are relevant for ancient life, and even for paleolimnology that is suggestive of the possible perseverance of life on Mars in an earlier Eden-like epoch.

The extremophiles that are trapped in microbial mats may also be living under the Taylor Glacier in the Taylor Valley, a region that is bounded by the Ferrar Glacier and the Asgard Range. These microbes probably lived in the ocean at one time, but when the floor of the Dry Valleys rose more than a million years ago, the glacier covered seawater when it advanced and trapped the microorganisms in pockets of water. An intriguing feature, named Blood Falls, suggests the presence of microbial mats underneath the Taylor glacier. The name is due to its resemblance with a blood-red color waterfall at the glacier's extreme end. This coloring is analogous to the colored microbial mats that live in the hot springs of the Yellowstone National Park. Isotopic measurements of sulfate, water, carbonate, and ferrous iron as well as gene analyses imply that a microbial consortium facilitates a catalytic sulfur cycle that may be analogous to the metabolic events that may sustain life elsewhere in the Solar System (Mikucki *et al.*, 2009). This is especially relevant to the icy satellites of the outer Solar System, including Europa, where sulfur patches were discovered by the Galileo Mission (1995-2003). These stains on the icy surface of the Jovian satellite are suggestive of chemosynthetic products of metabolism.

From the point of view of geology and microbiology, some of the best studied frozen lakes are in the Taylor Valley, namely Lake Fryxell and Lake Hoare. Further north, in the Wright Valley, Lake Vanda is also remarkable for its biota. Amongst the microbial mats that are permanently thriving in the frozen lakes there are examples of both prokaryotes and eukaryotes. Besides, some of the most interesting geologic paleoindicators for reconstructing the history of these lakes are stromatolites. In the Dry Valleys these structures consist of various species of cyanobacteria, such as *Phormidium frigidum* Fritsch, a prokaryote that forms the matrix of most mat types (Wharton *et al.*, 1983).

Modern organisms analogous to ancient life are to be found in the Dry Valley lakes. What is most significant is that single-celled eukaryotes are amply represented in this Antarctic biota. Amongst the related paleoindicators that have been found are diatom frustules, while cyst-like structures, most likely of crysophycean origin have also been identified. These intriguing lakes contain various taxa of planktonic and benthic microorganisms. These environments are dominated by lower life forms inviting us to search for biomarkers of an earlier biota since grazing, for instance, is totally absent (Doran *et al.*, 1994). Microbial mats in lake Bonney, Chad, Fryxell, Hoare and Vanda have been thoroughly documented, especially since the 1980s. For instance, in these environments microbial mats are known to include not only the above-mentioned cyanobacteria, but also heterotrophic bacteria, eukaryotic algae (mainly diatoms) and fungi (Baublis *et al.*, 1991). There are some dinoflagellates *Gymnodinium* and *Glenodinium* in Lake Fryxell, where in addition protozoan taxa were associated with the algal mats (Cathey *et al.*, 1981).

5. References

- Banerjee, S., and Jeevankumar, S. (2005) Microbially originated wrinkle structures on sandstone and their stratigraphic context: Palaeoproterozoic Koldaha Shale, central India. *Sediment. Geol.* **176**: 211-224.
- Baublis JA, Wharton, R. A. Jr., Volz P. A. (1991) Diversity of micro-fungi in an Antarctic dry valley., *J Basic Microbiol.*, **31**(1), 3-12.
- Cathey, D. D., Parker, B. C., Simmons Jr., G. M. Yongue Jr. W. H. and Van Brunt M. R. (1981) The microfauna of algal mats and artificial substrates in Southern Victoria Land lakes of Antarctica, *Hydrobiologia*, **85**, 3–15.
- Catuneanu, O., and Eriksson, P.G. (2007) Sequence stratigraphy of the Precambrian. *Gondwana Res.* **12/4**: 560-565.
- Doran P. T., Wharton, R. A. Jr. and Lyons, W. B. (1994) Paleolimnology of the McMurdo Dry Valleys, Antarctica, *Journal of Paleolimnology*, **10**, 85-114.
- Eriksson, P.G., Simpson, E.L., Eriksson, K.A., Bumby, A.J., Steyn, G.L., and Sarkar, S. (2000) Muddy roll-up structures in siliciclastic interdune beds of the ca. 1.8 Ga Waterberg Group, South Africa. *Palaios* **15**: 177-183.
- Gerdes, G., 2007. Structures left by modern microbial mats in their host sediments. In: J. Schieber, P.K. Bose, P.G. Eriksson, S. Banerjee, S. Sarkar, W. Altermann, and O. Catuneanu (eds.), *Atlas of Microbial Mat Features Preserved within the Siliciclastic Rock Record*. Atlases in Geoscience 2, Elsevier, Amsterdam, pp. 5-38.
- Gerdes, G., and Klenke, T. (2007) States of biogenic bedding as records of the interplay of ecologic time and environment (a case study of modern siliciclastic sediments, Mellum Island, southern North Sea). *Senckenbergiana Maritima* **37/2**: 129-144.
- Gerdes, G., Krumbein, W.E., and Holtkamp, E.M. (1985a) Salinity and water activity related zonation of microbial communities and potential stromatolites of the Gavish Sabkha. In: G.M. Friedman and W.E. Krumbein (eds.), *Hypersaline Ecosystems: the Gavish Sabkha*. Springer-Verlag, Berlin, pp. 238-266.
- Gerdes, G., Krumbein, W.E., and Reineck, H.E. (1985b) The depositional record of sandy, versicoloured tidal flats (Mellum Island, southern North Sea). *J. Sediment. Petrol.* **55**: 265-278.
- Gerdes, G., Krumbein, W.E., and Reineck, H.E. (1985c) Verbreitung und aktuogeologische Bedeutung mariner mikrobieller Matten im Gezeitenbereich der Nordsee. *Facies* **12**: 75-96.
- Mikucki, J.A., Pearson, A., Johnston, D.T., Turchyn, A.V., Farquhar, J., Schrag, D. P., Anbar, A.D., Priscu, J.C. and Lee P.A. (2009) A Contemporary Microbially Maintained Subglacial Ferrous “Ocean”, *Science* **324** (5925) 397-400. DOI: 10:1126/ Science, 1167350.
- Noffke, N., Eriksson, K.A., Hazen, R.M and Simpson, E. L. (2006). A new window into Early Archean life: microbial mats in Earth’s oldest siliciclastic deposits (3.2 Ga Moodies Group, South Africa). *Geology* **34**: 253-256.
- Noffke, N. (2007) Microbially-induced sedimentary structures (MISS) of Early and Middle Archean ages – Moodies Group, Pongola Supergroup, Witwatersrand Supergroup (South Africa). In: J. Schieber, P.K. Bose, P.G. Eriksson, S. Banerjee, S. Sarkar, W. Altermann, and O. Catuneanu (eds.), *Atlas of Microbial Mat Features Preserved within the Siliciclastic Rock Record*. Atlases in Geoscience 2, Elsevier, Amsterdam, pp. 153-157.
- Sarkar, S., Banerjee, S., Eriksson, P.G., and Catuneanu, O. (2005) Microbial mat control on siliciclastic Precambrian sequence stratigraphic architecture: examples from India. *Sediment. Geol.* **176**: 195-209.
- Schieber, J. (1998) Possible indicators of microbial mat deposits in shales and sandstones: examples from the Mid-Proterozoic Belt Supergroup, Montana, USA. *Sediment. Geol.* **120**: 105-124.
- Schieber, J., Bose, P.K., Eriksson, P.G., Banerjee, S., Sarkar, S., Altermann, W., and Catuneanu, O. (2007a) Prologue: An introduction to microbial mats. In: J. Schieber, P.K. Bose, P.G. Eriksson, S. Banerjee, S. Sarkar, W. Altermann and O. Catuneanu (eds.) *Atlas of Microbial Mat Features Preserved within the Siliciclastic Rock Record*. Atlases in Geoscience 2, Elsevier, Amsterdam, pp. 1-3.
- Schieber, J., Bose, P.K., Eriksson, P.G., Banerjee, S., Sarkar, S., Altermann, W., and Catuneanu, O. (eds.), (2007b) *Atlas of Microbial Mat Features Preserved within the Siliciclastic Rock Record*, Atlases in Geoscience 2, Elsevier, Amsterdam, 311 pp.
- Schieber, J., Bose, P.K., Eriksson, P.G., and Sarkar, S. (2007c) Palaeogeography of microbial mats in terrigenous clastics – environmental distribution of associated sedimentary features and the role of geologic time. In: J. Schieber, P.K. Bose, P.G. Eriksson, S. Banerjee, S. Sarkar, W. Altermann, and O.

- Catuneanu (eds.), *Atlas of Microbial Mat Features Preserved within the Siliciclastic Rock Record*. Atlases in Geoscience 2, Elsevier, Amsterdam, pp. 267-275.
- Wharton, R. A. Jr., Parker, B. C. and Simmons G. M. Jr (1983) Distribution, species composition and morphology of algal mats in Antarctic Dry Valley lakes, *Phycologia*, **22**, 355–365.