

CHAPTER 10

CONCLUSIONS

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Life on Earth is largely microbial, both in terms of biomass and the length of its existence. Approximately eighty percent of the entire history of life on Earth is exclusively microbial, and the biosphere acts as a 'geobiological agent' that has adapted to as well as modified a constantly changing environment. When it comes to sustaining life on a geologically active planet, we can learn a great deal from the history of microbial life on Earth.

In the Precambrian, when mat-consuming metazoans were absent, microbial mats probably thrived in all environments where energy and sufficient moisture were available and where mat growth could outpace sedimentation (Schieber, 1999). Even today the global biomass is strongly influenced by the contribution from microbial life, and microbial cycling of elements significantly influences the composition of the atmosphere and hydrosphere (e.g., Fenchel and Finlay, 1995; Banfield and Nealson, 1997; Ehrlich, 1998).

As pointed out already in the introduction to this book, the first description of microbial mats and biofilms in the literature is attributed to Paracelsus (approx. 1519; Krumbein, 1994), long before the term microbial mat came into common usage. Since then various authors have written on the topic, usually from a biologic or geologic perspective (see Krumbein, 1983, 1994 for further references). The term algal mat gained considerable popularity when growth forms of blue-green algae in tropical seas were viewed as equivalent to those of Precambrian stromatolites (Darwin, 1839; Kalkowsky, 1908; Black, 1933; Cloud, 1942). When blue-green algae turned out to be cyanobacteria (Krumbein, 1979; Krumbein et al., 1979a; Rippka et al., 1979) and the mats were found to be a consortium of varied kinds of symbiotic/syntrophic organisms (Brock et al., 1994), the term microbial mat was widely adopted.

Microbial communities organize themselves in response to environmental gradients (e.g., light, moisture, nutrients) and form sheet-like structures known as microbial mats at the sediment-water interface. Within these thin (millimetre-scale) zoned communities of micro-organisms photosynthetic cyanobacteria typically (but not always) predominate over bacteria, algae, and fungi. An upper layer of aerobic phototrophs (cyanobacteria) typically passes successively downwards into anoxygenic phototrophs, and chemo-organotrophs (sulphur bacteria, sulphate-reducing bacteria and sulphide-oxidizing

bacteria) requiring neither oxygen (which is toxic to some species) nor light (Revsbech et al., 1983; Jørgensen et al., 1983; Pierson et al., 1987; Stolz, 1990, 1991, 2000; Brock et al., 1994). Mats of sulphide-oxidizing bacteria, such as *Beggiatoa*, that cover the seafloor in low oxygen settings, for example in the Santa Barbara Basin off the coast of California, are an example of non-photosynthetic mat communities (Bernhard et al., 2000). Within these multi-layered mats, the nature of the community changes rapidly downwards, and light, oxygen, and other chemical gradients are very steep.

Just like a complex food web, microbial mats are communities of micro-organisms in which each member depends and is depended on by others in the community. Within microbial mats we see an amazing array of energy harvesting strategies, and virtually every way in which energy can be extracted from the environment can be found in microbial mats, often over vertical distances of only a few millimetres. Yet, while the active mat community may extend just a few millimetres deep into the sediment, its chemical impact, via buried and decaying biomass, may influence the sediment for decimetres and even metres beneath the surface. Identification of the actual participants in a mat-forming microbial community is hardly ever possible in the terrigenous clastic rock record. As has been illustrated in the preceding chapters of this book, however, indirect evidence is potentially plentiful.

With the advent of metazoan grazers in the Cambrian, mats became restricted to settings where extreme conditions, such as high salinity (Shark Bay), elevated temperatures (Yellowstone), or strong currents (Bahamas) exclude or severely restrict access by metazoans. In areas where metazoans destroyed mats and reworked the sediment, microbial life did not disappear but simply went underground, and formed microbial coatings on grains rather than contiguous biofilms (Monty, 1972). The vanishing of the Precambrian matground (Seilacher and Pflüger, 1994) may have been responsible for the demise of many Ediacaran organisms which were no longer able to anchor themselves easily to their shallow marine substrates (Gehling, 1999). The abundance of mat-related structures in preserved Precambrian shelf sequences suggests that *in-situ* production and preservation of organic carbon was important, a factor which needs to be considered in conceptual models for sedimentary carbon burial, global carbon cycling, and source rock formation in this era.

To date, the oldest known microbial mats in siliciclastic settings have been reported from c. 3.2 Ga old rocks in South Africa (Noffke et al., 2006b). There are numerous occurrences in Proterozoic siliciclastics, probably reflective of the many epeiric seas of that era (e.g., Eriksson et al., 2005), where generally low sedimentation rates allowed microbial mats to thrive in many places. Interestingly, however, reduced erosion due to microbial mat binding of surface sediments may in fact result in increased rates of net local sedimentation (Sarkar et al., 2005). Surface stabilization by mats may also have caused bedforms to be generally smaller in the Precambrian, when compared to what physical flow modelling would predict. The implications of bedform size and sedimentation rates at the large scale, particularly in a sequence stratigraphic context, are discussed in more detail in Chapter 9(b) of this book. Terrestrial (i.e. non-marine) mat systems have been documented as far back as 1.8 Ga (Eriksson et al., 2000).

Microbial mats within siliciclastic sediments lose their characteristic forms readily in the general absence of early cements. Compaction, decomposition and consumption by other organisms generally obliterate mat-produced organic matter within siliciclastic (and other) deposits. Anoxia and low sediment permeability underneath a mat cover may make offshore shales a relatively better host of organic carbon-rich mat laminae (Schieber, 1986, 1998; Banerjee and Jeevankumar, 2005), but a high degree of sediment compaction renders biotic and textural elements hardly recognizable within them. Factors like frequent sediment reworking, rapid sedimentation and oxidation, generally hinder mat growth and make maintaining a mat cover on shallow-water sands more difficult. Notwithstanding these disadvantages, excellent preservation of microbial mats and their associated features is possible within sandstones, including beach arenites. Fragments torn away from active surface mats may also be found locally, on or beneath sandstone beds. Microbial growth in mud-depositing offshore environments may be disturbed periodically and the microbial mat cover may be destroyed partially by distal tempestites and turbidites. Pieces of torn mat fragments produced by such erosional action can be recognized and be distinguished from *in-situ* mats in shales.

After some burial, it is rarely possible to actually identify mat-building organisms in terrigenous clastics. Fortunately, the associated sediment binding, grain agglutination, and chemical effects produce proxy structures that have much better preservation potential. Microbial filaments and EPS (extracellular polymeric substances) transform the stress response of originally loose (sand) or barely cohesive (watery mud) sediment, and make it behave in ways that are atypical for such a sediment in the absence of microbial binding. For example, upon colonization by a microbial mat, an originally granular and non-cohesive sand will respond differently to physical stress. Added cohesion and EPS infusion will actually make it behave more like a layer of mud. It will form desiccation cracks upon drying, curl up due to differential shrinkage between top and bottom, and form pebble-sized flat and rolled-up fragments upon erosion. Microbially colonized mud surfaces as well show a range of features that are incompatible with the expected behaviour of a watery mixture of clay minerals and silt grains. In addition to unexpected cohesiveness and sedimentary features resulting from it, microbially stabilized mud surfaces are also characterized by lamina textures that suggest microbial growth, and are associated with authigenic minerals that reflect sub-mat decay of organic matter. Many microbially bound mud layers show wavy and crinkly lamination, are dark due to decaying organic matter, and may show lamina-specific pyrite enrichment (Schieber, 2004). It is these atypical and unexpected behaviours that most commonly guide us towards identification of microbial mats in terrigenous clastics.

Carbonate stromatolites and microbial laminites extend far below the Proterozoic-Archaean boundary (up to 3.5 Ga; Golubic and Seong-Joo, 1999), and one might expect that microbial mat features in siliciclastic rocks should show a comparable temporal extent. Yet, at present their known record extends only to about 3.2 Ga (Noffke et al., 2006b). Is this circumstance merely a sampling artifact, or does it signify something of importance for the evolution of life?

Mats possibly also played an important role in biological evolution. For example, one of the plausible explanations for the demise of many Ediacaran organisms is that their ability to anchor themselves to the substrate with holdfasts was degraded concurrent with the rapid decline in microbial mat coverage at the Proterozoic-Phanerozoic transition (Seilacher and Pflüger, 1994). With the advent of burrowers, microbial influence extended deeper beneath the sediment surface, but contiguous biofilms were more difficult to sustain. This may have shifted the balance of sedimentary biofilms towards those that form as microbial coatings around individual grains, such as oncoids and 'algal biscuits' (Monty, 1972). Abundance of mat-related structures in shelf sequences also implies *in-situ* production and preservation of organic carbon. Conceptual models for sedimentary carbon burial and source rock formation in the Precambrian have to take this significant difference to the Phanerozoic into account. There is also a growing interest in terrestrial microbial mat systems and in the freshwater microbes that produce stromatolites (Freynet and Verrecchia, 1998).

Due to the large contribution of microbial life to the global biomass, atmosphere-hydrosphere chemical cycles are strongly influenced by microbes (e.g., Fenchel and Finlay, 1995; Banfield and Nealson, 1997; Ehrlich, 1998). For example, close to the depositional site, ammonification, denitrification and sulphate reduction of microbial sediment leads to a rise in alkalinity of ambient water (Krumbein, 1979; Visscher et al., 1992; Castanier et al., 2000; Knorre and Krumbein, 2000; Riding, 2000). Microbial mats also play an important chemical role in the reductive fixing of metals like iron, manganese, gold and uranium (Milodowski et al., 1990; Watterson, 1992; Nealson and Saffarini, 1994; Ferris, 2000). Thus, the trace element geochemical signatures of sedimentary rocks may be misinterpreted if the former presence of microbial mats goes undetected.

Aside of their utility for palaeoenvironmental reconstructions, mat-induced structures can also serve as important palaeogeographic indicators and have potential for refining techniques of basin analysis in Precambrian strata. The impediment to erosion caused by prolific mat growth may be a key factor that encouraged vertical stacking of highstand systems tracts in the Precambrian. At a smaller scale, mat growth reflects a low rate and the discontinuous nature of sedimentation, and partly controls bedform evolution. Establishing an interest in microbial mat structures in siliciclastic sediment is, therefore, laden with the possibility of elucidating a wide range of geological phenomena.

Fossil microbial mats, or stromatolites, attest to the existence of water or moisture in which microbial life thrived, and constitute the oldest and most pervasive evidence of life on Earth. Therefore they also figure prominently in our attempts to identify life on other planets. NASA's Mars rovers *Spirit* and *Opportunity*, for example, have sufficient optical resolution to readily image all of the mat-related morphological features illustrated from sandstones in this book, and the Microscopic Imager on these rovers has enough resolution to image at least a portion of the features we might expect to find in fine-grained rocks. In NASA's upcoming Mars Science Lab mission (launch planned for 2009), more sophisticated imaging devices are bundled with an instrument suite (mass spectrometer, gas chromatograph, tunable laser spectrometer) for detection and analysis

of carbon compounds. Any rocks with features that would suggest the former presence of microbial mats would also be a logical target for additional geochemical analysis. Due to surface waters that were apparently of quite low pH (Squires et al., 2004) our chances of finding nicely preserved carbonate stromatolites might be negligible. However, that still leaves us with plenty of clastic rocks that can be examined for microbial mat indications. Thus, learning as much as we can about microbial mats in terrigenous clastics on Earth will benefit our efforts to detect life elsewhere in the solar system. In absence of the preserved mat-building organisms, detecting the former presence of microbial mats in terrigenous clastics necessarily depends on judicious assembly of indirect evidence. Thus, careful evaluation of non-mat processes is a must (Fig. 10-1).

Building broader awareness of what microbial mats and their proxies might look like in terrigenous clastic sediments and sedimentary rocks is the main objective of this book. Nonetheless, the sampling of microbially produced sedimentary features in terrigenous clastics provided in this atlas is far from exhaustive. The illustrations of modern and ancient mat features in sandstones and mudstones are intended as a starting point for identification of potential occurrences by others. They should not be viewed as a definitive listing of all things microbial in sandstones and mudstones. A good deal of valuable geological information will remain out of our reach unless the mat-related structures within siliciclastic sedimentary rocks receive the attention they deserve, and we are confident that increased awareness will bring forth many additional features that simply have not yet been described. If this richly illustrated compendium spurs new research into microbial mats in terrigenous clastic sediments, their temporal and spatial distribution, and their role and significance for past and present siliciclastic depositional systems, we will have accomplished our goal.

Chapter 10: Figure and Caption

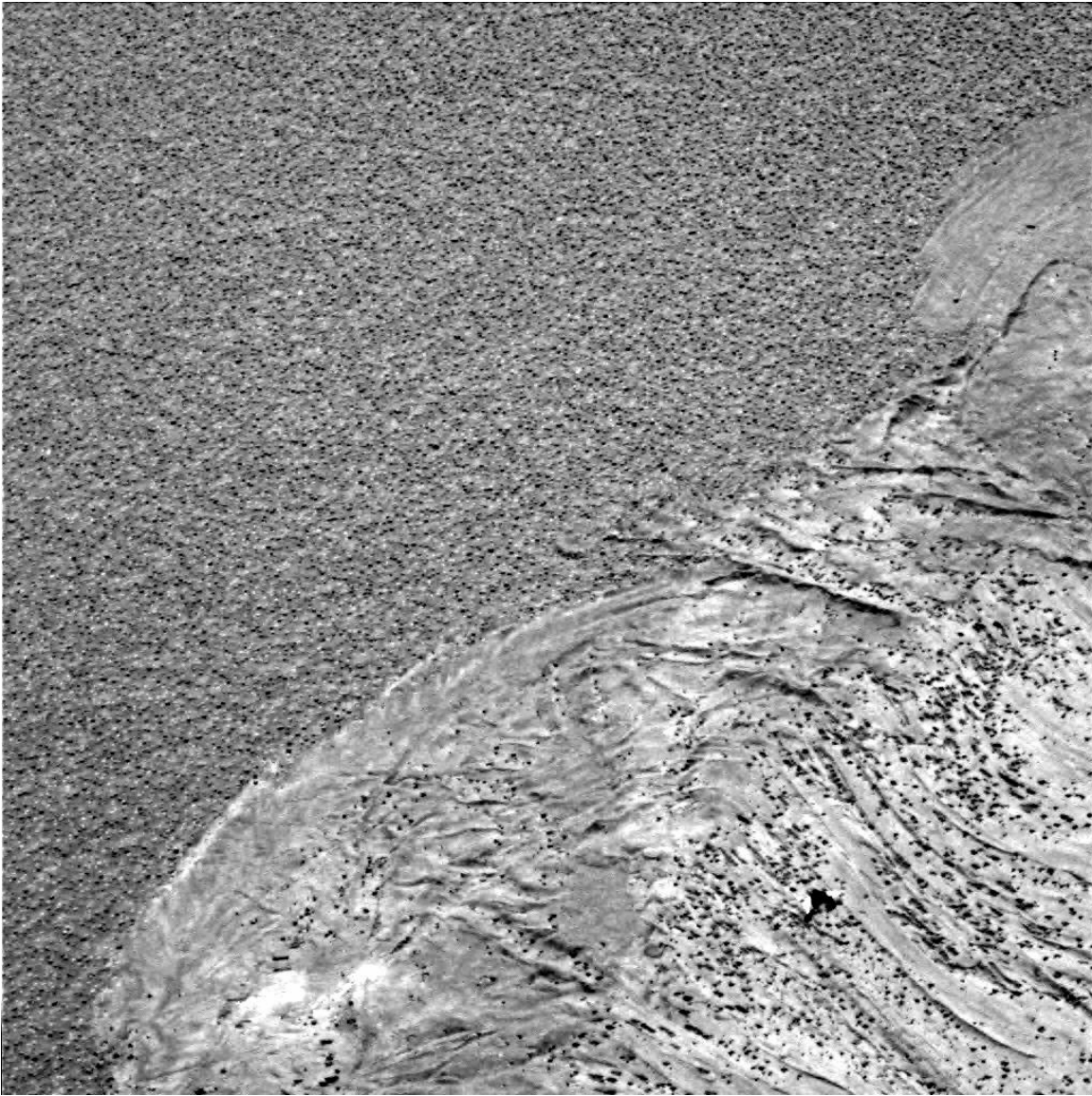


Fig. 10-1:

Wrinkle structures from the landing site of the Mars rover *Opportunity* (January 2004, image from NASA web site; image no. 1P128449562RAD0200P2213L2C1). These wrinkles were produced when the deflated airbags were pulled in towards the lander, prior to egress of *Opportunity*. They attest to a cohesive nature of the surface sediment and temporarily did get some people excited about the possibility for microbial binding and thus microbial life at the surface. Closer inspection, however, showed that the soil matrix is fine-grained in nature (detection of clays is not possible with the rover instruments) and that the cohesiveness is a physical phenomenon, comparable to the way

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in which fine powders can readily be moulded into a wide variety of three-dimensional shapes.

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