

CHAPTER ONE

PROLOGUE: AN INTRODUCTION TO MICROBIAL MATS

Paracelsus (approx. 1519) is on record as having been among the first to have taken note of the substrate-altering and rock-generating properties of biofilms (Krumbein, 1994). Yet, he simply was so far ahead of his time that his perfectly modern sounding descriptions were soon forgotten. Subsequently, scientists have discovered, forgotten, and re-invented the significance of biofilms and microbial mats many times (Krumbein, 1994). Today, the importance of microbial life and microbial mats for multiple aspects of Earth processes is undisputed, and a 3.5 billion year fossil record affirms that these oldest known ecosystems are also crucial for understanding Earth history (Margulis and Dolan, 2002). Photosynthetic microbial mats figure prominently because sunlight has long powered the bulk of global primary productivity, and, through interaction with the hydrosphere and non-photosynthetic microbial ecosystems, has profoundly influenced the evolution of the Earth's atmosphere-ocean system (e.g., Lovelock, 1988). Microbial life, geochemical processes, and the sedimentary rock record are intimately and complexly entangled. Reading the rock record for its presence and its influences is not without peril, but there is no alternative if we are to make progress in understanding Earth history.

It was a simpler world half a century ago, when Francis Pettijohn's classic text "Sedimentary Rocks" (1957) was the standard reference for the majority of sedimentary geologists. Pettijohn's text was firmly grounded in physics and chemistry, and the main role of organisms appeared to be the production of useful particles for carbonate rocks and complicating the observation of primary sedimentary structures. A tremendous amount of research into the processes that control the formation of sedimentary rocks was conducted in the following decades. Especially trace fossil studies (Seilacher, 1964; Bromley, 1990) and dissemination of the idea that carbonate stromatolites were the constructs of microbial mats (Black, 1933; Logan et al., 1964), made clear that biological influences on sedimentation were profound. Today, rather than simply being tombs for the creatures that palaeontologists enjoy studying, sedimentary rocks are the place where physics, chemistry, and biology meet and are the most closely intertwined in the rock record.

Yet, whereas major biological influences in the formation of carbonate rocks are by now largely taken for granted, many still consider terrigenous clastic sediments a product primarily of physics and chemistry. For example, none of three relatively recent and influential textbooks in sedimentary geology (Füchtbauer, 1988; Blatt, 1992; Boggs, 1995) list the terms 'microbial' or 'microbial mat' in their indexes. That the latter may actually occur in terrigenous clastics is at best noted as an aside among more weighty matters. In the widely referenced book "Sedimentary Environments", edited by H.G. Reading, the term microbial mat finally shows up in the third edition (Reading, 1996), but in a general discussion animals and plants are still considered to

have the most important impact on sedimentary and diagenetic processes (Reading and Levell, 1996).

Nonetheless, microbial mat deposits in sandstones and mudstones were first identified several decades ago (e.g., Davis, 1968; Schieber, 1986). Growing interest in microbial mats in siliciclastic sediments was stoked by a rising awareness that microbes play a vital role in their accretion and diagenesis (Krumbein et al., 1994; Hagadorn et al., 1999; Riding and Awramik, 2000), and by the importance of the microbial biomass for biogeochemical cycles throughout Earth history (Madigan and Martinko, 2006). Our new atlas illustrates the presence of a wide range of mat-induced sedimentary structures in the siliciclastic rock record, and the progress in this new field of sedimentological studies is gathering momentum and gradually entering the mainstream of geological debate. Our main purpose with this project was to provide a basic visual reference for both students and professionals, in order to more broadly disseminate our current understanding on how microbial mats in terrigenous clastics might be recognized, and to stimulate further research into the ways by which microbial mats influence physical, chemical and biotic characteristics of sandstones and shales.

Chapter 2 of this atlas details structures attributed to living/modern microbial mats in their host clastic sediments. It describes the path from initial biofilm (clusters of micro-organisms attached to a surface and commonly embedded in extracellular polymeric substances – EPS) to microbial mat, and outlines how cyanobacteria, due to their wide inventory of adaptive responses and capacity for biostabilization of illuminated clastic surfaces, became the most successful group of mat builders. Experimental work stresses the temporal component of mat evolution. For example, laboratory cultivations indicate that the transition from a thin and fragile biofilm to the durable fibrillar meshworks of a mat requires several weeks of non-burial (Gerdes and Klenke, 2003). This is a valuable piece of information to keep in mind for sedimentary facies-modelling. Cyanobacteria and other micro-organisms leave subtle traces and hints of their former presence in clastic (as well as other) sediments, with the chance thus of preservation in the rock record, particularly that of the Precambrian era. Modern examples of the continuum from biofilms to microbial mats are found most commonly within marine shallow water and tidal environments, right through to supratidal and sabkha settings. Yet, mat-forming cyanobacteria are not restricted to peritidal settings, and also occur in lake, river and other deposits (see Table 2-1 and Chapter 9(a)). They may also thrive in mixed clastic-chemical sediments, such as for example in hypersaline lagoons. This general trend of wide palaeoenvironmental adaptation is largely mirrored in the rock record (e.g., Chapter 7), with examples known even from Earth's oldest deserts (Eriksson et al., 2000). Thus, in a generic sense, microbial mat features are non-facies-specific. Only a careful evaluation of mat-produced features with regard to underlying processes (such as desiccation, erosion, gas development, etc.) allows the determination of environmental parameters. With these limitations in mind, microbial mat features can provide yet another perspective for the analysis of sedimentary facies, complementing information derived from other sedimentary structures.

Terminology and classification can be (and often is) a contentious issue irrespective of the subject matter. The evolution of sandstone classifications, from Krynine (1948) to Dickinson (1970), can serve as an example of the process, and illustrates how a prevailing philosophy of classification becomes established (Pettijohn et al., 1987). This also holds true for the relatively

young discipline of ‘microbial mat sedimentology’. Issues of terminology are addressed in both Chapter 2 and Chapter 6(a) and (c). The photographic material that makes up the bulk of this book was organised within the framework of a process-response organizational scheme devised by Schieber (2004). Main subdivisions are by lithology (sandstone or mudstone; Chapters 4 and 5 respectively), and secondary subdivisions are by the process that is predominantly responsible for a given feature (growth, metabolism, physical destruction, decay, and diagenetic overprint). While this scheme forms the organizational backbone of this book, it was adopted because it is visually appealing and has a consistent internal logic (Chapter 3; Figs. 3-1 and 3-2), not because we believe it will be the final word in this regard. The discussion of alternative schemes in Chapter 3 makes clear that we are still in the process of defining what the salient features of microbial mats in terrigenous clastics might be, and that any attempt at classification is necessarily a work in progress. By the same token, there will most likely always be problematic features that elude ready categorization.

In terrigenous clastic sedimentary rocks, features directly attributable to the constructing organisms are either rare or very localized. Proxy structures, however, resulting from interaction with the sediment, such as mat-induced sediment binding, grain agglutination, and chemical compartmentalization of the sediment, are common in shallow marine sandstones and offshore shales, especially those of Precambrian affinity. To a large degree these proxy structures owe their formation to extracellular polymer substances (EPS) secreted by cyanobacteria and other micro-organisms (Decho, 1990, 2000). Binding by EPS and microbial filaments makes sand and watery mud cohesive, and enables trapping and binding of particles. Originally granular and non-cohesive, sand will then respond differently to stress, often behaving more like mud, and forming a host of features generally not expected in sands/sandstones, such as desiccation cracks, sand-curls, and pebble-sized, flat or rolled-up fragments upon erosion (Chapter 4). Microbially colonized mud surfaces analogously exhibit a range of features incompatible with the expected behaviour of a watery mixture of clay minerals and silt grains. In addition to unexpected cohesiveness, such 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 (Schieber, 2004; Chapter 5).

More than 50 individual mat-related features are detailed within Chapters 4 (sandstone-hosted) and 5 (mudstone-hosted). Features preserved within muddy siliciclastics tend to be more subtle, and often require microscopic or even electron microscopic observations, whereas those preserved in sandstones are more readily observed in outcrop and hand specimen. Yet even there, certain features, such as diagenetic cements related to mat metabolism and decay, require microscopic examination. Chapter 2 complements Chapters 4 and 5, by providing large numbers of illustrations of modern and laboratory-cultivated microbial mat features in clastic environments. Although it is comparatively easy to understand genetic processes in observations of modern mats, when working on the rock record this exercise becomes rather involved. Quite a few of the microbial mat-related features illustrated and discussed in this book can have multiple origins, not all of them microbial. For example, microbial mat features in sandstones can be recognised with a good deal of confidence as long as we are looking at amalgamated, well-sorted sandstone beds, where evidence for cohesiveness would be unexpected. The presence of mudstone interbeds tends to complicate matters, because then cohesion-indicative features in a sandstone bed may actually be due to the cohesive behaviour of an overlying mudstone bed.

Rather than basing a microbial mat interpretation solely on outcrop studies, it is generally good practice to also examine suspected mat features in thin section. In that way the details of the contact relationship of successive sediment layers can be used to confirm (or refute) a microbial mat origin.

Microbial mat-related structures in sandstones and mudstones that range in age from Archaean to Tertiary are illustrated in Chapter 7. The oldest example is from the Moodies Group (c. 3.2 Ga) of the Barberton greenstone belt in South Africa, and the majority of examples are from Proterozoic strata. Among the latter, the Mesoproterozoic Belt Basin of North America and the Palaeo- to Neoproterozoic Vindhyan basin of India provide classic examples of sandstone- and mudstone-hosted mat features that occur in a wide range of depositional palaeoenvironments. The youngest example is from the Eocene Green River Formation in the USA and underscores the continuity of mat-induced features within the siliciclastic rock record. Although the advent of metazoan grazers in the Phanerozoic has changed the natural niches occupied by microbial mats, and despite their decreased importance compared to the Precambrian sedimentary record, the range of features that occur in lithified sands and muds remains essentially unchanged. Microbial mats thus exemplify the general applicability of uniformitarianism to the Precambrian sedimentary record (cf. Donaldson et al., 2002a).

In Chapter 8 of this volume, emerging new research is discussed, with subjects as diverse as bacterial mats produced by iron bacteria (which has important connotations for models of Precambrian BIF evolution), seismic disruption of mat-bound sands, hydraulic influences on mats within tidal flats and coastal sabkhas, to flume experiments with living and 'dead' mat fragments. As more geologists become familiar with the spectrum of structures that may result from the interaction of microbial mats with terrigenous clastic sediments, the study of microbial mat features is rapidly becoming indispensable for modern sedimentological studies. It is the purpose of this book to ease the transition for the broader geologic community. Continued expansion of the knowledge base will bring to light structures that are still unknown, as well as generating better comprehension of microbial mat influence on physical, chemical and biotic characteristics of siliciclastic depositional environments and deposits.

The Editors, November 2006:

Juergen Schieber
Pradip K. Bose
Patrick G. Eriksson
Santanu Banerjee
Subir Sarkar
Wladyslaw Altermann
Octavian Catuneanu

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