

9(a) Paleogeography of Microbial Mats in Terrigenous Clastics – Environmental Distribution of Associated Sedimentary Features and the Role of Geologic Time

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Introduction

In classical studies of the relationships between organisms and environments, the environment or palaeoenvironment is defined by a range of physical and chemical parameters (water depth, energy regime, temperature, salinity, etc.). Whether or not an organism can live in a given environment depends on its ability to tolerate or adapt to the given conditions, and whether suitable food sources are available. For elephants for example, the environment needs to be situated in tropical latitudes and must support sufficient plant growth, and as a consequence elephants only occur in tropical Africa and Asia. Other organisms, such as rats, are known for their ability to extract sustenance from a great range of environments and are found across the globe. Thus, in general terms one should expect that environmental parameters do have an impact on what types of organisms will thrive in a given locale.

Yet, biofilms and microbial mats have been reported from such a wide range of environments that one might think that environmental parameters exert little influence. Once a moist substrate and an energy source are provided, microbial mats will enter the scene quickly as long as grazers are kept at bay. Most of us can probably recall multiple examples of ‘opportunistic’ mats (Figure 9(a)-1) from visits to construction sites and other areas affected by human impact. Microbial mats are found in the deep oceans surrounding hot spring vents (Figure 9(a)-2A), and even deeper, coating fracture surfaces within ocean floor basalts (Cregg et al., 1992; Reysenbach and Cady, 2001). They occur near methane seeps at various depths, on the ocean floor, the continental slope, and even the continental shelf (Joye et al., 2004; Reitner et al., 2005). We also find them in areas where oxygen concentrations are below the threshold of metazoan grazers (Schulz et al., 1996; Bernhard et al., 2000), regardless of actual water depth (Figure 9(a)-2B). Because of comparatively easy access, the study of tidally influenced sedimentary environments has generated the largest number of published records on modern microbial mats (e.g., Gerdes et al., 2000a; see Chapter 2 for images). Yet, modern microbial mats do not stop at the ocean’s edge. We find them in fluvial settings, such as in rivers and streams with a low sediment load (Figures 9(a)-2C, -2D), in lakes (Figure 9(a)-3A) and hot spring pools (Figure 9(a)-3B) (Ward et al., 1998; Last and Ginn, 2005), in deserts as cryptobiotic soil crusts (Figure 9(a)-3C) (Belnap and Gardner, 1993; Eldridge and Green, 1994), and in the frozen expanses of Antarctica beneath the permanent ice cover of lakes (Figure 9(a)-3D) (Hawes and Schwarz, 1999; Sabbe et al., 2004).

Once the above examples (Figures 9(a)-2 and -3) are examined in detail it becomes clear, however, that each given environment presents unique challenges, and that in each case different consortia of bacteria are involved in mat formation. Biofilms and microbial mats are ubiquitous in a multitude of environments not because they are some highly adaptable organism, but rather because mat formation appears to represent a very effective strategy for optimising microbial survival in a wide range of environments. It is a strategy that apparently is employed with great success by a large variety of microbial communities (Figures 9(a)-2 and -3).

Common to many mats is that they enhance sediment cohesion and resistance to erosion, as well as stabilizing vertical chemical gradients within the sediment. Thus, their mechanical interactions with the sediment, such as for example the formation of fold-overs, rip-ups, roll-ups, ripple patches, domal buildups, etc. (see [Chapter 3](#)), may be qualitatively similar for mats that were produced by distinctively different microbial consortia. In the rock record, therefore, we may find that sedimentary features left behind by photosynthetic cyanobacterial mats that thrived in the photic zone ([Figure 9\(a\)-1B](#) and [Chapter 2](#)), may be quite similar to those found in much more distal and deeper water settings that may actually testify to the former presence of chemosynthetic microbial mats ([Figure 9\(a\)-2B](#) and [Chapter 7\(e\)](#)). Yet, although features due to mechanical interactions can not help us to make that distinction, the associated diagenetic minerals, as well as geochemical fingerprints, may point us in the right direction (Logan et al., 1999a).

Chronology of microbial mats

At the very beginning of the history of life on Earth, primitive life forms may well have tested multiple approaches to optimise microbial survival. By the time of the Apex Chert microbiota (Schopf, 1993), however, at ~3.5 Ga, microbial fossils are already so similar to modern counterparts that they must represent considerable evolution from the earliest microorganisms. At this point in time as well, microbial mats and stromatolites already show the structural and textural features that they maintain for the remainder of Earth history (Hofmann et al., 1999). We must conclude then that at least as far back in time as 3.5 Ga, microbial mats comparable to modern counterparts were already a common presence in marine and marginal marine environments. Evidence for microbial mats in terrestrial environments, such as rivers and lakes, goes back as far as 2.7 Ga (Buck, 1980; Buick, 1992), and geochemical considerations suggest that as early as 2.6 Ga microbial mats had become a factor in soil formation (Watanabe et al., 2000). It is therefore reasonable to assume that by Late Archaean times at the latest, microbial mats most likely flourished in all environmental settings that we find them in today. In essence, from that point forward we can expect to find them in any conceivable environment that meets their moisture, nutritional, and energy needs.

Microbial mats and (palaeo-)environmental settings

As indicated above, because of the ubiquity of microbial mats across a broad range of environments, the mere presence of mats in a given rock unit has limited value for the assessment of palaeoenvironment. In Precambrian sediments, however, this shortcoming is partially mitigated by the lack of bioturbation that allows much better preservation of all types of sedimentary features, including those that are related to mat-sediment interaction. In addition, specific features of microbial mat deposits, such as for example elongated domal buildups, ‘soft’ microbial sand chips, and rigid curved sand chips (Garlick, 1981, 1988; Schieber, 1998a; Pflüger and Gresse, 1996; Bouougri and Porada, 2002; Sarkar et al., 2006), can give information about environmental energy levels, episodes of desiccation and reworking, etc., and thus allow narrowing of the number of feasible environments.

The published literature gives the impression that microbial mat features are most common, in the rock record, from deposits formed within high energy shallow marine settings. This, however, is most likely a perception skewed by fortuitous availability of exposures (sandstones make better exposures than mudstone-dominated successions) and because their identification is easier due to an abundance of modern analogues (see [Chapter 2](#)). Scattered reports of, for example, subtidal, distal deep basin, fluvial, and lacustrine environments (e.g., Schieber, 1986; Eriksson et al., 2000; Yeo et al., 2002; Prave, 2002; Sur et al., 2006) indicate that future systematic study of all terrigenous clastic rock types is likely to erase this bias.

Having indications of terrestrial and potentially pedogenic microbial mats as early as the Late Archaean (Watanabe et al., 2000) also speaks to another conundrum, the common occurrence of extremely pure quartz arenites in Proterozoic and lower Palaeozoic strata. While long thought of as a result of multicycling and aeolian abrasion, we do have evidence for first-cycle quartz arenites in the Proterozoic that formed in the absence of the efficient chemical weathering that we associate with vascular land vegetation (Dott, 2003). This suggests that microbial crusts like the one illustrated in [Figure 9\(a\)-3](#) already occupied Precambrian land surfaces, promoted intense weathering and destruction of chemically labile components, and left behind a quartzose residue that was then reworked into quartz arenites (Dott, 2003).

Many of the classic occurrences of microbial mat features in terrigenous clastics are found within epeiric marine coastal settings, such as for example the Mid-Proterozoic Belt basin of North America and the Palaeo- to Neo-proterozoic Vindhyan basin of India. The sandy nearshore facies of these basins has much in common with the famous tidal flats of Mellum Island in the North Sea, where much of the research on sandy microbial mats has been undertaken (see [Chapter 2](#)). Because most large basins preserved on cratons tend to be marine and are affected by relative sea level movements of both global and local origin throughout their history, widespread coastal marine facies will tend to dominate their rock record. Apart from anything else, the arenitic rocks formed within most coastline settings will resist weathering and erosion more easily, and be topographically more prominent in forming accessible outcrops than central-basinal argillaceous rocks. Disputed ophiolites apart, very little of the Precambrian seafloor has been preserved in the record, once again enhancing the apparent importance of coastal arenitic settings. However, in the succeeding section of this chapter, Catuneanu discusses the fact that certain mat-related features may have been preferentially preserved in Precambrian subtidal shelf settings rather than the higher energy coastal palaeoenvironments. He attributes this feature to enhanced wind regimes (and thus concomitantly, enhanced wave energy) that affect the preservation potential of mat related structures within coastal facies.

Phanerozoic microbial mats

While today we still find microbial mats in all the ecological niches and environments that they presumably occupied in the Precambrian ([Figures 9\(a\)-2 and -3](#)), the advent of metazoans in the Cambrian effectively ended 3 billion years of mat-dominated surface environments (Garrett, 1970). Yet, while metazoans might have laid waste to surficial mats, they did not eliminate their constituent microbes. The latter point is easily demonstrated by stratified and mat-forming

microbial assemblages in Winogradsky columns (microbiological enrichment columns; Sagan and Margulis, 1988) prepared from random soil and sediment samples (Figure 9(a)-4). In essence, the microbes that potentially form mats are ever-present in the environment, they just need a chance to thrive (Figure 9(a)-4). Thus, just like in areas disturbed by human activity (Figure 9(a)-1) where microbial mats are early colonisers, they probably did the same in Phanerozoic environments when the prior ecosystem had been disrupted by ‘catastrophes’, such as storms, volcanic eruptions, impacts, etc. If these disruptions were short-lived, the mats probably were soon after eaten and/or destroyed by returning metazoans, making for negligible preservation potential. If, on the other hand, disruptions resulted in environmental change that adversely affected metazoans, such as high salinity, lack of oxygen, etc., thick mats with a potential to be preserved in the rock record could form. Thus, although the evolution of metazoans in the Cambrian caused a major shift in mat preservation, mats could still develop given an opportunity.

The Proterozoic–Phanerozoic transition not only witnessed a major reduction of three-dimensional mat proliferation, but also a shift to abundant development of thin biofilms around discrete particles (Seilacher and Pflüger, 1994). Fragmentation of sandy or muddy mat surfaces by metazoans, in tandem with current and wave reworking, probably was a major factor in the formation of features like ‘algal biscuits’, oncoids, and generally coated grains. These mobile ‘granular mats’, such as microbially formed oncoidal pyrite grains in the Ordovician Winnipeg Formation of Saskatchewan, Canada (Schieber and Riciputi, 2005), might have been of less interest to metazoans because they did not offer a contiguous food supply, and as loose grains were more difficult to graze on. Regardless of these changes, however, we still find evidence of mat colonisation in Phanerozoic terrigenous clastics (see Chapter 7), and a growing awareness on how they might be identified will probably lead to recognition in many additional places, even when partially obscured by grazing and bioturbation.

Conclusions

As pointed out above, although in times past microbial mats may have been as widespread environmentally and geographically as today, not all locales may have offered the same preservation potential. While processes of mat erosion and deformation may well be similar between environments occupied by photosynthetic mats versus those covered by chemosynthetic mats, the mats might have offered different levels of ‘resistance’ under otherwise identical conditions of flow. Because photosynthetic cyanobacteria are very adept at mat generation (Chapter 2), lighting conditions are most likely an important factor for the growth of many structured mats in the rock record.

Our current knowledge base about modern mats constructed by chemoautotrophs is much smaller than that for photosynthetic microbes. More work needs to be done on modern chemosynthetic mats if we, for example, want to evaluate whether coccoidal bacteria-rich mats from the Triassic deep sea (Mastandrea et al., 2006) could indeed form a sustainable mat.

If one sees microbial mat-related structures as part of the larger continuum of physically-formed sedimentary structures, such as suggested by Noffke et al. (2001a) in an adaptation of the well-known Pettijohn and Potter (1964) classification, then mat-induced features may not be any more facies-specific than their physically-formed counterparts.

Noffke and co-workers (e.g., Noffke et al., 2001a, 2006a, 2006b) instead suggest that microbially-induced sedimentary structures (MISS) are very facies-specific. They also relate them to regression–transgression turning points, and thus imbue them with very specific sequence stratigraphic meaning as well. As can be seen in Section 9(b) of this chapter, this is to be disputed. Those who work in modern mat-bound clastic sedimentary settings, such as the famous Mellum Island in the North Sea, or the tidal flats and sabkhas of the Tunisian coast, will obviously find it easy to establish direct relationships between mat-related structures and well-defined depositional environments (e.g., Gerdes et al., 1985b, 1985c; Noffke et al., 2001b). The same applies, however, to most investigations of modern sedimentary settings and their component physically-formed sedimentary structures. Elucidation of palaeoenvironments from the rock record is almost always a much greater challenge with a less certain result.

The relatively limited reports on the occurrence of ancient mat-related structures and the observed distribution of their modern counterparts can be integrated to predict the palaeoenvironmental distribution of the various mat-related features. Because the palaeoenvironmental relationships of mat features is seldom very specific, they are presented here within a broad framework: coastal, shallow sea/lake, deep sea/lake, fluvial and aeolian settings. The first includes beach, intertidal–supratidal, delta plain, coastal swamp, etc. above mean sea level, while the second includes the generally agitated shallow water environments like the shoreface and the shelf beneath mean sea level.

The third covers the quiet deep-water environments, which may only occasionally be agitated. Table 9(a)-1 shows features in sandstone, and Table 9(a)-2 their equivalents in shale, in their respective palaeoenvironmental context (bar thickness stands for relative abundance, as reported or projected).

In summary we can say that probably since the Late Archaean, microbial mats and the microbial communities that form them have occupied every conceivable ecological niche on the planet, much as they do today (Figures 9(a)-1, -2 and -3). Many published examples of microbial mats in terrigenous clastics are from marginal marine sandy deposits, both in the Precambrian and the Phanerozoic. This bias, however, will probably gradually disappear as we learn how to more reliably identify microbial mat deposits in other facies and lithologies. A major shift in mat preservation occurred with the evolution of metazoan grazers in the Cambrian. Mats still grew whenever given a chance, but typically were ‘eaten’ or destroyed almost as fast as they formed. Thus, extensive sediment colonisation with a potential for preservation in the rock record was severely curtailed. Nonetheless, we do find evidence of mat colonisation in Phanerozoic terrigenous clastics (see Chapter 7), and a growing awareness on how they might be identified will probably lead to recognition in many other places, even when partially obscured by grazing and bioturbation. Integration of textural studies that focus on sediment rheology as influenced by microbial binding, with mineralogical/geochemical studies should help our ability to identify which microbial ‘lifestyle’ (e.g., photosynthesis versus chemosynthesis) dominated a given mat community.

Table 9-1: Features in Sandstones (see Chapter 3)

Palaeoenvironment							
		+	Shallow Sea/lake	Deep Sea/lake	Fluvial	Aeolian	Remarks
Mat-related features	Multi-directed, Palimpsest Ripples						Very shallow water to fair weather wave base. Most likely preserved in coastal to shallow sea/lake settings.
	Surface Ornamentation, Wrinkle Structures, "Elephant Skin" etc.						Judging from modern analogs these should be most common in coastal to shallow sea/lake settings. Potentially also associated with shallow water bodies on floodplains and coastal plains.
	Domal, Convex-Up Features						Current energy required for accretion, thus more likely in shallow water settings. In high energy coastal settings poorer development due to erosion? May occur locally in fluvial channels with strongly episodic sediment transport.
	Petees & Ridges						Modern analogs suggest need for at least one of the following: strong shear forces, desiccation, or gas expansion. Thus, coastal and other very shallow water environments most likely.
	Cements & Floating Grains						It helps if surface sediment maintains similar pore space chemistry for extended time periods (small sedimentation rates). Coastal to shallow/deep sea/lake should be most common environments.
	Sand Cracks, Manchuriophycus etc.						Requires desiccation, thus mainly expected in coastal and fluvial environments. Also possible in intermittently moist interdune depressions.
	Ripple Patches						Within fair weather wave base, need for powerful erosive events. Coastal setting most likely. Minor occurrences shallow offshore?
	Flip-Overs, Roll-Ups, Sand Chips						Strong currents/wave action needed. Most likely to form in coastal environments. Petering out into deeper water. Potentially also in moist terrestrial settings.
	Curved Sand Chips						Desiccation and strong currents required. Most likely in terrestrial and coastal environments..
	Gas Domes & Kinneyia						Shallow water favors formation of larger gas buildups. Likely environments are coastal and possibly shallow ponds on floodplains.

	Mat Decay Mineralization	—	—	—	- - - -	<p>Permanently water-logged pores enhance preservation potential. Thus, preservation more likely in shallow-deep sea/lake settings. In terrestrial environments only if sediment is continuously water-logged for long periods of time.</p>
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Table 9-2: Features in Shales (see Chapter 3)							
Mat-related Features	Palaeoenvironment						
		Coastal	Shallow Sea/lake	Deep Sea/lake	Fluvial	Aeolian	Remarks
	Wavy-Crinkly	—	■	■	—	—	Probably best preserved below storm wave base. Preservation unlikely in environments with ready oxygen access (oxidation of organic matter), such as terrestrial and supratidal. Exception for areas with permanent water cover (lakes, swamps, lagoons). Potential for preservation also in wet interdune depressions with clay-rich sediment.
	Bed-Smoothing	—	■				Because the surface of coarser layers (granule to pebble size particles) is to be smoothed, more likely observed in coastal and shallow sea/lake settings.
	Domal Build-up	—	■		—		Current energy probably required for accretion, thus more likely in shallow water settings. In high energy coastal settings poorer development due to erosion?.
	Striped Shale	—	■	—			Requires episodic sedimentation to cover mats, thus not too distal is better. Coastal unlikely because of reworking. Shelf below storm wave base most likely. In deeper water only when influx of storm and flood reworked sediment possible.
	False X-laminae	—	■	—			Best developed where there are abundant small sediment pulses during mat growth. Should be best developed in shallow sea/lake environments below storm wave base.
	Lamina-specific Grain selection	■	■	—	■	—	Requires across-mat sediment transport by currents, thus effect seen more likely in higher energy settings.
	Random Mica Flakes	■	—		---		Requires across-mat sediment transport by strong currents, thus effect seen more likely in higher energy settings. Also need for early cement formation. Thus not as likely in terrestrial environments.
Rafted Grain Cluster	—	■	■	---		Could occur everywhere, but best recognized in the most fine grained facies.	

In: *Atlas of microbial mat features preserved within the clastic rock record*, Schieber, J., Bose, P.K., Eriksson, P.G., Banerjee, S., Sarkar, S., Altermann, W., and Catuneau, O., (Eds.), Elsevier, p. 267-275. (2007)

	Irregular Impressions	—			—	—	Requires surfaces of still somewhat moist, stiff mud. Microbial flakes derived from dried out mats on mud surfaces. Impossible in permanently water covered areas. Most likely to occur in coastal supratidal settings, alluvial floodplains, and interdune depressions.
	Roll-Ups, & Flip-Overs,	—	■	■	- - - -	- - - -	Related to erosion/transport, thus should be more typical for higher energy settings. Offshore transport has to be considered. Roll-ups of thin organic “skins” may also be found in current affected deeper water environments. Not as likely in environments affected by desiccation (rigidity factor), but desiccated-curl mat fragments may look very similar.
	Mat Decay Mineralization	—	■	■	- - - -	- - - -	Permanently water-logged pores enhance preservation potential. Thus, preservation more likely in shallow-deep sea/lake settings.

Figures

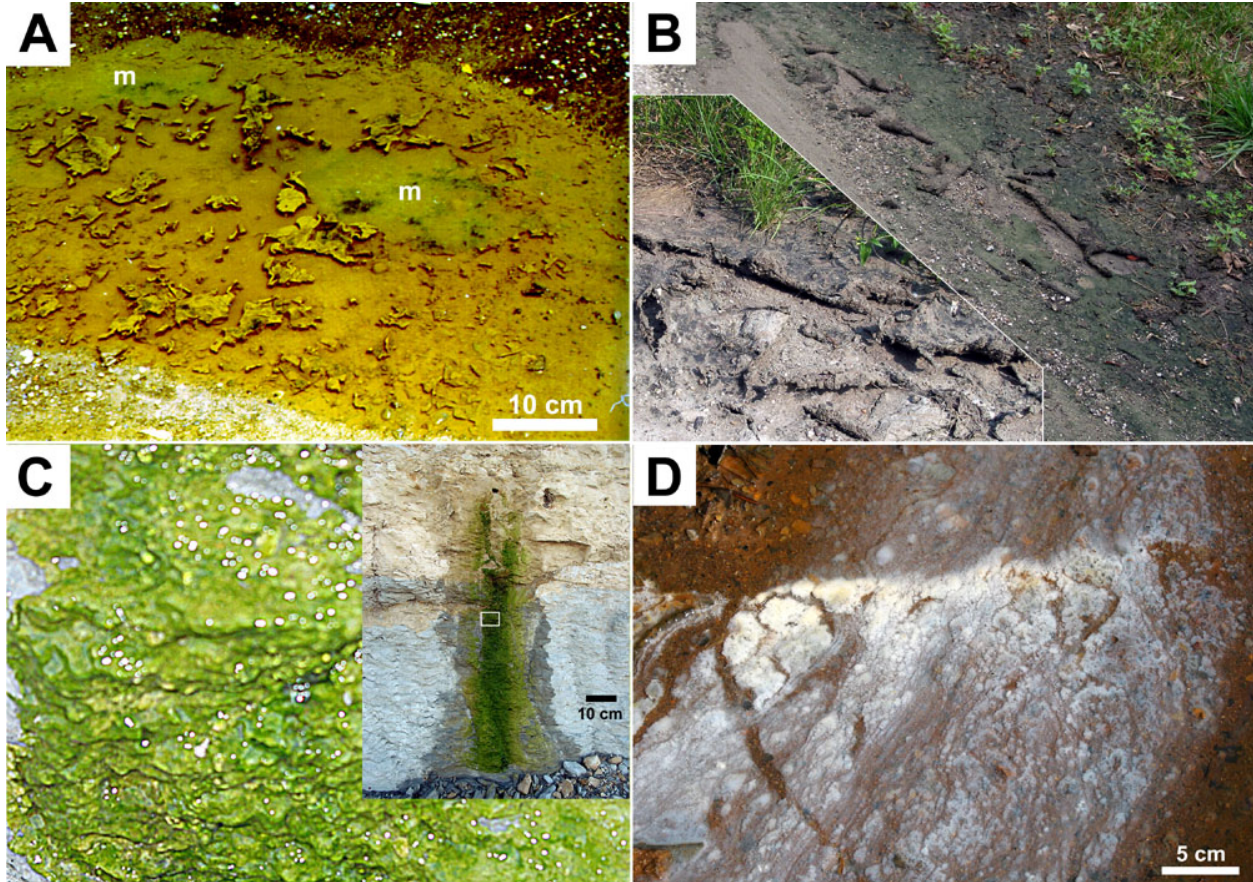


Figure 9(a)-1: ‘Opportunistic’ mats in modern settings. (A) A modern puddle with benthic cyanobacterial mat on mud substrate (marked ‘m’). Portions of the mat have floated up because of attached oxygen bubbles. Photo by J. Schieber. (B) Modern cyanobacterial mat in a roadside ditch on a sandy substrate. Fast currents during rainstorms have caused the mat to be partially eroded and/or ‘flipped over’ at the edges. Inset shows dried-out, cracked and curled mat from same locality. Vegetation for scale. Photo by J. Schieber. (C) ‘Vertical’ microbial mat on the wall of a construction pit (inset). Water flow from a spring provides continuous moisture. Photo by J. Schieber. (D) Whitish mat of acidophile bacteria that thrive in low pH runoff from a weathering exposure of pyrite-bearing black shale. Pyrite oxidation is the cause for low pH values. Photo by J. Schieber.

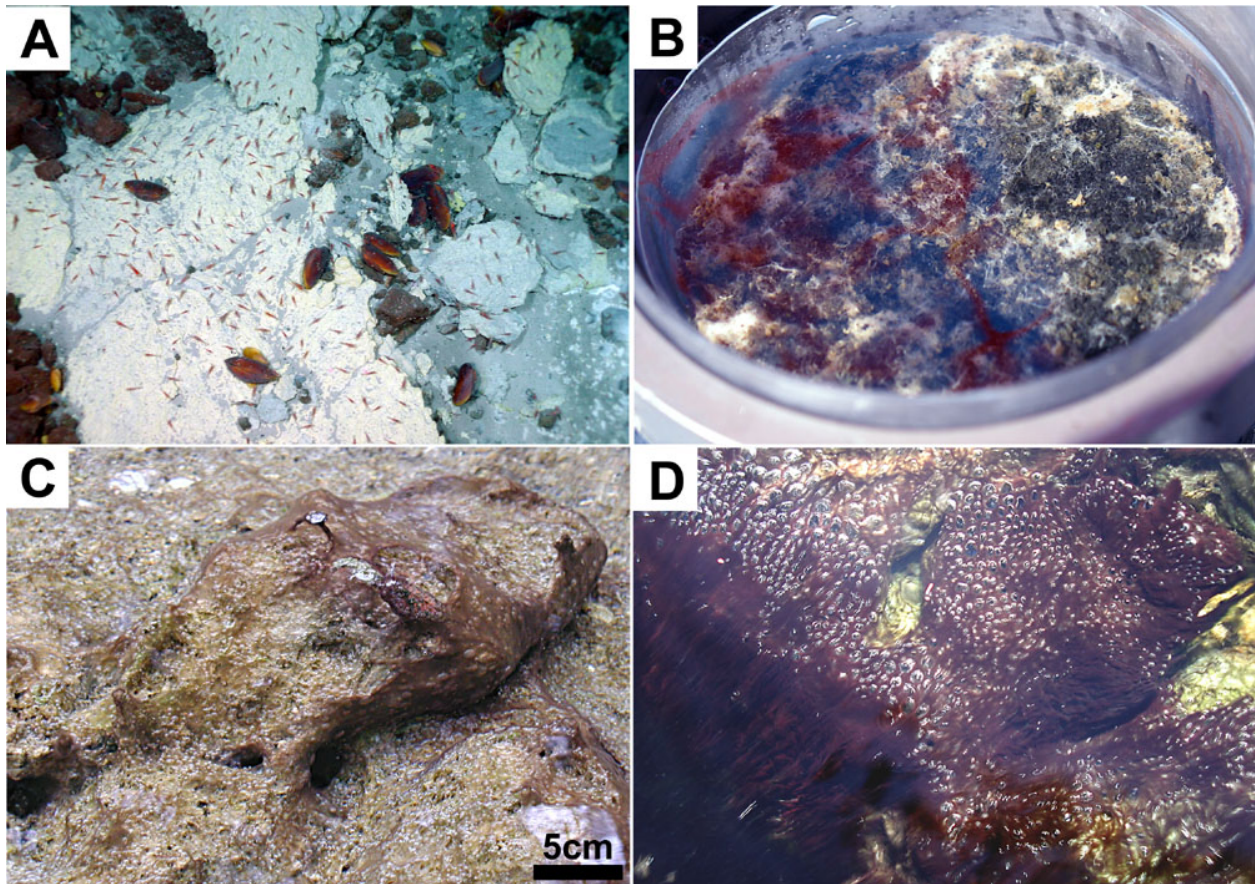


Figure 9(a)-2: (A) Thick, fragile mat of whitish sulphide oxidizing bacteria near a white smoker vent. The mat biomass constitutes the base of the food chain in this area and is utilized by small vent shrimp and larger mussels. Photo from NOAA Explorer web site, <http://www.oceanexplorer.noaa.gov/explorations/04fire/logs/april12/>. (B) Top of sediment core from Santa Barbara Basin, offshore California. The whitish clumps and filaments are formed by the sulphide oxidizing bacterium *Beggiatoa*. This is a *Beggiatoa* mat in its early stages and will eventually cover the sediment surface with a solid layer of entangled filaments. Diameter of core barrel is 10 cm. Photo by J. Schieber. (C) Mat consisting of cyanobacteria and diatoms coating the bottom of a shallow creek near Sulfur, Oklahoma. The Creek normally has a very low sediment load because it is spring-fed. Photo by J. Schieber. (D) Same Creek as before, mat with abundant trapped oxygen bubbles (2-5 mm in size). Flow is from the upper right to the lower left. Photo by J. Schieber.

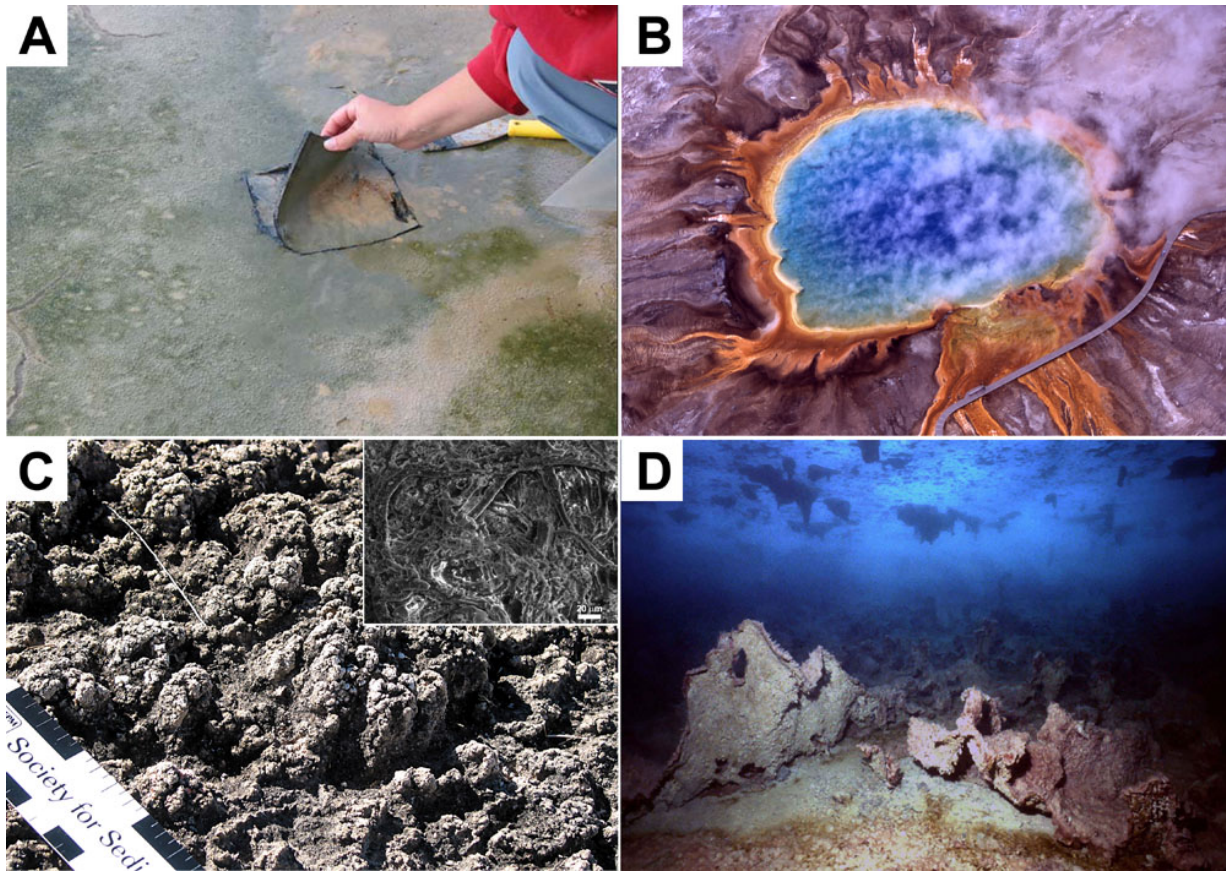


Figure 9(a)-3: (A) Example of living microbial mat near a saline spring, Lake Winnipegosis region, Manitoba, Canada. These mats can reach several centimetres in thickness and are often laminated (image courtesy of Last and Ginn, 2005). (B) Aerial view of the Grand Prismatic hot spring in the Midway Geyser Basin, Yellowstone National Park, USA. Steam is rising from the hot and sterile central portion (deep blue water). The orange colored periphery constitutes the much shallower overflow areas where the water cools rapidly as it moves away from the spring. The orange colour is due to microbial mats, and the concentric zonation marks microbial consortia with different temperature preferences. The spring is approximately 115 meters in diameter, and over 40 metres deep. Image courtesy of US National Park Service. (C) Rugged surface expression of cryptobiotic crust on desert soil from White Sands National Monument, New Mexico. Scale has long black bars of 1 inch length, and short black bars of 1 cm length. Inset shows scanning electron micrograph of crust surface with entangled microbial filaments and minerals grains. Both photos by J. Schieber. (D) microbial mats at the bottom of permanently ice covered Lake Bonney in Antarctica (depth ~ 5-6 m). These mats are photosynthetic in spite of low light intensities and can float up because of attached oxygen bubbles. Photo courtesy of Dale T. Andersen (© All Rights Reserved).

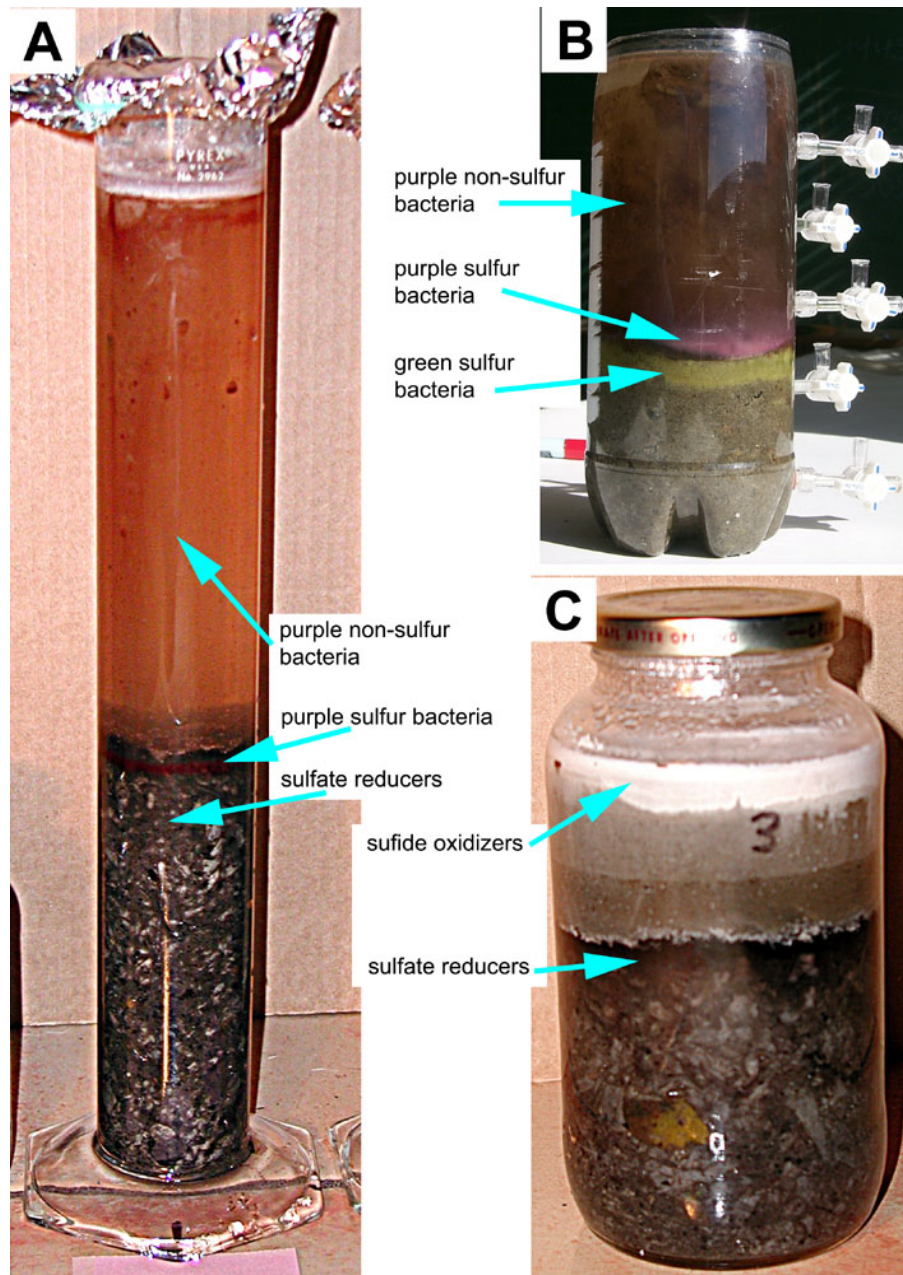


Figure 9(a)-4: Microbial stratification of Winogradsky columns prepared from lake mud. (A) Shows darkening by sulphate reducing bacteria in the bottom portion, a horizon with purple sulphur bacteria (anaerobic photosynthetic) just below the sediment/water interface, and purple non-sulphur bacteria (photoheterotroph, low H_2S tolerance) in most of the rest of the water column. Photo by J. Schieber. (B) Column has well developed zones of green and purple sulphur bacteria (just like in microbial mats from sandy tidal flats), overlain by water with purple non-sulphur bacteria. Image courtesy of Dr. Joe Vallino, Semester in Environmental Science, Marine Biological Laboratory, Woods Hole, MA 02543. (C) A column with restricted oxygen access. Shows well-developed darkened lower layer with sulphate reducing bacteria, and an upper layer (microbial mat) that consists of sulphide oxidizing bacteria. Photo by J. Schieber.

References

Altermann, W., 2004. Evolution of life and Precambrian bio-geology. In: Eriksson, P.G., Altermann, W., Nelson, D.R., Mueller, W.U., Catuneanu, O. (Eds.), *The Precambrian Earth: Tempos and Events. Developments in Precambrian Geology 12*, Elsevier, Amsterdam, pp. 587-591.

Banerjee, S., Jeevankumar, S., 2005. Microbially originated wrinkle structures on sandstones and their stratigraphic context: Paleoproterozoic Koldaha Shale, central India. *Sediment. Geol.* 176: 211-224.

Belnap, J., Gardner, J.S., 1993. Soils microstructure in soils of the Colorado Plateau: the role of the cyanobacterium *Microcoleus vaginatus*. *Great Basin Naturalist* 53: 40-47.

Bernhard, J.M., Buck, K.R., Farmer, M.A., Bowser, S.S., 2000. The Santa Barbara basin is a symbiosis oasis. *Nature* 403: 77-80.

Bouougri, E., Porada, H., 2002. Mat-related sedimentary structures in Neoproterozoic peritidal passive margin deposits of the West African Craton (Anti-Atlas, Morocco). *Sediment. Geol.* 153: 85-106.

Brown, L.F., Jr., Fisher, W.L., 1977. Seismic stratigraphic interpretation of depositional systems: examples from Brazilian rift and pull apart basins. In: Payton, C.E. (Ed.), *Seismic Stratigraphy - Applications to Hydrocarbon Exploration*. American Assoc. Petrol. Geol. Mem. 26, Tulsa, Oklahoma, pp. 213-248.

Buck, S.G., 1980. Stromatolite and ooid deposits within the fluvial and lacustrine sediments of the Precambrian Ventersdorp Supergroup of South Africa. *Precambrian Res.* 12: 311-330.

Buick R., 1992. The antiquity of oxygenic photosynthesis: evidence from stromatolites in sulphate-deficient Archaean lakes. *Science* 255: 74-77.

Catuneanu, O., 2006. *Principles of Sequence Stratigraphy*, 1st edn. Elsevier, Amsterdam, 375 pp.

Catuneanu, O., Eriksson, P.G., 1999. The sequence stratigraphic concept and the Precambrian rock record: an example from the 2.7-2.1 Ga Transvaal Supergroup, Kaapvaal craton. *Precambrian Res.* 97: 215-251.

Coe, A.L. (Ed.), 2003. *The Sedimentary Record of Sea-Level Change*. Cambridge University Press, New York, 287 pp.

Cregg, B.A., Harvey, S.M., Fry, J.C., Herbert, R.A., Parks, R.J., 1992. Bacterial biomass and activity in deep sediment layers of the Japan Sea, Hole 798 B. *Proc. Scientific results, ODP, Legs 127/128, Japan Sea*, pp. 761-776.

In: *Atlas of microbial mat features preserved within the clastic rock record*, Schieber, J., Bose, P.K., Eriksson, P.G., Banerjee, S., Sarkar, S., Altermann, W., and Catuneanu, O., (Eds.), Elsevier, p. 267-275. (2007)

Cross, T.A., Lessenger, M.A., 1998. Sediment volume partitioning: rationale for stratigraphic model evaluation and high-resolution stratigraphic correlation. In: Gradstein, F.M., Sandvik, K.O., Milton, N.J. (Eds.), *Sequence Stratigraphy - Concepts and Applications*. Norwegian Petroleum Society (NPF) Spec. Publ. 8, Elsevier, Amsterdam, pp. 171-195.

Davies, S.J., Gibling, M.R., 2003. Architecture of coastal and alluvial deposits in an extensional basin: the Carboniferous Joggins Formation of eastern Canada. *Sedimentology* 50: 415-439

Demarest, J.M., Kraft, J.C., 1987. Stratigraphic record of Quaternary sea levels: implications for more ancient strata. In: Nummedal, D., Pilkey, O.H., Howard, J.D. (Eds.), *Sea Level Fluctuation and Coastal Evolution*. Soc. Econ. Paleontol. Mineral. Spec. Publ. 41, Tulsa, Oklahoma, pp. 223-239.

Diessel, C., Boyd, R., Wadsworth, J., 2000. On balanced and unbalanced accommodation/peat accumulation ratios in the Cretaceous coals from the Gates Formation, Western Canada, and their sequence-stratigraphic significance. *Int. J. Coal Geol.* 43: 143-186.

Dott, R.H., 2003. The importance of eolian abrasion in supermature quartz sandstones and the paradox of weathering on vegetation free landscapes. *The J. Geol.* 111: 387-405.

Eldridge, D.J., Green, R.S.B., 1994. Microbiotic soil crusts - a review of their roles in soil and ecological processes in the rangelands of Australia. *Australian J. Soil Res.* 32: 389-415.

Emery, D., Myers, K.J., 1996. *Sequence Stratigraphy*. Blackwell Science, Oxford, 297 pp.

Eriksson, K.A., Simpson, E.L., 2000. Quantifying the oldest tidal record: The 3.2 Ga Moodies Group, Barberton Greenstone Belt, South Africa. *Geology* 28: 831-834.

Eriksson, P.G., Simpson, E.L., Eriksson, K.A., Bumby, A.J., Steyn, G.L., Sarkar, S., 2000. Muddy roll-up structures in siliciclastic interdune beds of the c. 1.8 Ga Waterberg Group, South Africa. *Palaios* 15:177-183.

Eriksson, P.G., Altermann, W., Nelson, D.R., Mueller, W.U., Catuneanu, O. (Eds.), 2004. *The Precambrian Earth: Tempos and Events*. *Developments in Precambrian Geology* 12, Elsevier, Amsterdam, 941 pp.

Galloway, W.E., Hobday, D.K., 1996. *Terrigenous Clastic Depositional Systems*, 2nd edn. Springer-Verlag, Berlin, 489 pp.

Garlick, W.G., 1981. Sabkhas, slumping, and compaction at Mufulira, Zambia. *Econ. Geol.* 76: 1817-1847.

Garlick, W.G., 1988. Algal mats, load structures, and syngenetic sulfides in Revett Quartzites of Montana and Idaho. *Econ. Geol.* 83: 1259-1278.

In: *Atlas of microbial mat features preserved within the clastic rock record*, Schieber, J., Bose, P.K., Eriksson, P.G., Banerjee, S., Sarkar, S., Altermann, W., and Catuneanu, O., (Eds.), Elsevier, p. 267-275. (2007)

Garrett, P., 1970. Phanerozoic stromatolites: noncompetitive ecologic restriction by grazing and burrowing animals. *Science* 169: 171-173.

Gerdes, G., Krumbein, W.E., Reineck, H.-E., 1985b. The depositional record of sandy, versicolored tidal flats (Mellum Island, southern North Sea). *J. Sediment. Petrol.* 55: 265-278.

Gerdes, G., Krumbein, W.E., Reineck, H.-E., 1985c. Verbreitung und aktuogeologische Bedeutung mariner mikrobieller matten im Gezeitenbereich der Nordsee. *Facies* 12: 75-96.

Gerdes, G., Klenke, T., Noffke, N., 2000a. Microbial signatures in peritidal siliciclastic sediments: a catalogue. *Sedimentology* 47: 279-308.

Gradstein, F.M., Sandvik, K.O., Milton, N.J. (Eds.), 1998. *Sequence Stratigraphy - Concepts and Applications*. Norwegian Petroleum Society (NPF) Special Publication 8, Elsevier, Amsterdam, pp. 171-195.

Grotzinger, J.P., 1990. Geochemical model for Proterozoic stromatolite decline. *American J. Sci.* 290A: 80-103.

Hawes, I., Schwarz, A.-M., 1999. Photosynthesis in an extreme shade environment: benthic microbial mats from Lake Hoare: a permanently ice-covered Antarctic lake. *J. Phycol.* 35: 448-459.

Hofmann, H.J., Grey, K., Hickman, A.H., Thorpe, R.I., 1999. Origin of 3.45 Ga-old stromatolites in Warrawoona Group, Western Australia. *Geol. Soc. America Bull.* 111: 1256-1262.

Jervey, M.T., 1988. Quantitative geological modeling of siliciclastic rock sequences and their seismic expression. In: Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A., Van Wagoner, J.C. (Eds.), *Sea Level Changes - An Integrated Approach*. Soc. Econ. Paleontol. Mineral. Spec. Publ. 42, Tulsa, Oklahoma, pp. 47-69.

Joye, S.B., Boetius, A., Orcutt, B.N., Montoya, J.P., Schulz, H.N., Erickson, M.J., Lugo, S.K., 2004. The anaerobic oxidation of methane and sulfate reduction in sediments from Gulf of Mexico cold seeps. *Chem. Geol.* 205: 219-238.

Last, W.M., Ginn, F.M., 2005. Saline systems of the Great Plains of western Canada: an overview of the limnogeology and paleolimnology. *Saline Systems* 1: 1-38.

Leckie, D.A., 1994. Canterbury Plains, New Zealand - implications for sequence stratigraphic models. *American Assoc. Petrol. Geol. Bull.* 78: 1240-1256.

Logan, G.A., Calver, C.R., Gorjan, P., Summons, R.E., Hayes, J.M., Walter, M.R., 1999a. Terminal Proterozoic mid-shelf benthic microbial mats in the Centralian Superbasin and their environmental significance. *Geochim. et Cosmochim. Acta* 63: 1345-1358.

Mastandrea, A., Perri, E., Russo, F., Spadafora, A., Tucker, M. 2006. Microbial primary dolomite from a Norian carbonate platform: northern Calabria, Southern Italy. *Sedimentology* 53: 465-480.

Miall, A.D., 1997. *The Geology of Stratigraphic Sequences*. Springer-Verlag, Berlin, 433 pp.

Mitchum, R.M., Jr., 1977. Seismic stratigraphy and global changes of sea level, part 11: glossary of terms used in seismic stratigraphy. In: Payton, C.E. (Ed.), *Seismic Stratigraphy - Applications to Hydrocarbon Exploration*. American Assoc. Petrol. Geol. Mem. 26, Tulsa, Oklahoma, pp. 205-212.

Noffke, N., 1998a. Multidirected ripple marks rising from biological and sedimentological processes in modern lower supratidal deposits (Mellum Island, southern North Sea). *Geology* 26: 879-882.

Noffke, N., Gerdes, G., Klenke, T., Krumbein, W.E., 2001a. Microbially induced sedimentary structures - a new category within the classification of primary sedimentary structures. *J. Sediment. Res.* A71: 649-656.

Noffke, N., Gerdes, G., Klenke, T., Krumbein, W.E., 2001b. Microbially induced sedimentary structures indicating climatological, hydrological and depositional conditions within Recent and Pleistocene coastal facies zones (Southern Tunisia). *Facies* 44: 23-30.

Noffke, N., Hazen, R., Nhleko, N., 2003a. Earth's earliest microbial mats in a siliciclastic marine environment (2.9 Ga Mozaan Group, South Africa). *Geology* 31: 673-676.

Noffke, N., Beukes, N., Hazen, R., 2006a. Spatial and temporal distribution of microbially induced sedimentary structures: a case study from siliciclastic storm deposits of the 2.9 Ga old Witwatersrand Supergroup, South Africa. *Precambrian Res.* 146: 35-44.

Noffke, N., Eriksson, K.A., Hazen, R.M., Simpson, E.L., 2006b. 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.

Payton, C.E. (Ed.), 1977. *Seismic Stratigraphy - Applications to Hydrocarbon Exploration*. American Assoc. Petroleum Geol. Mem. 26, Tulsa, Oklahoma, 516 pp.

Pettijohn, F.J., Potter, P.E., 1964. *Atlas and Glossary of Primary Sedimentary Structures*. Springer-Verlag, Berlin, 370 pp.

Pflüger, F., Gresse, P.G., 1996. Microbial sand chips- a non-actualistic sedimentary structure. *Sediment. Geol.* 102: 263-274.

Pflüger, F., Sarkar, S., 1996. Precambrian bedding planes – bound to remain. *Geological Society of America Abstracts with Program* 28, p. 491.

In: *Atlas of microbial mat features preserved within the clastic rock record*, Schieber, J., Bose, P.K., Eriksson, P.G., Banerjee, S., Sarkar, S., Altermann, W., and Catuneau, O., (Eds.), Elsevier, p. 267-275. (2007)

Posamentier, H.W., Allen, G.P., 1999. Siliciclastic Sequence Stratigraphy: Concepts and Applications. Soc. Econ. Paleontol. Mineral. Concepts in Sedimentology and Paleontology 7, Tulsa, Oklahoma, 210 pp.

Posamentier, H.W., Jervey, M.T., Vail, P.R., 1988. Eustatic controls on clastic deposition I - conceptual framework. In: Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A., Van Wagoner, J.C. (Eds.), Sea Level Changes - An Integrated Approach. Soc. Econ. Paleontol. Mineral. Spec. Publ. 42, Tulsa, Oklahoma, pp. 110-124.

Prave, A.R., 2002. Life on land in the Proterozoic: evidence from the Torrodonian rocks of northwest Scotland. *Geology* 30: 811-814.

Rautenbach, C.J.deW., 2001. A hypothetical approach to determining the effect of palaeorotational rates on Earth's Neoproterozoic palaeoclimate. *J. African Earth Sci.* 33: 463-473.

Reitner, J., Peckmann, J., Reimer, A., Schumann, G., Thiel, V., 2005. Methane-derived carbonate build-ups and associated microbial communities at cold seeps on the lower Crimean shelf (Black Sea). *Facies* 51: 66-79.

Reysenbach, A.L., Cady, S.L., 2001. Microbiology of ancient and modern hydrothermal systems. *Trends in Microbiol.* 9: 79-86.

Sabbe, K., Hodgson, D.A., Verleyen, E., Taton, A., Wilmotte, A., Vanhoutte, K., Vyverman, W., 2004. Salinity, depth and the structure and composition of microbial mats in continental Antarctic lakes. *Freshwater Biol.* 49: 296-319.

Sagan, D., Margulis, L., 1988. *Garden of Microbial Delights*. Harcourt Brace Jovanovich, Boston, 229 pp.

Sarkar, S., Banerjee, S., Eriksson, P.G., 2004. Microbial mat features in sandstones illustrated. In: Eriksson, P.G., Altermann, W., Nelson, D.R., Mueller, W.U., Catuneanu, O. (Eds.), *The Precambrian Earth: Tempos and Events*. *Developments in Precambrian Geology* 12, Elsevier, Amsterdam, pp. 673-675.

Sarkar, S., Banerjee, S., Eriksson, P.G., Catuneanu, O., 2005. Microbial mat control on siliciclastic Precambrian sequence stratigraphic architecture: examples from India. *Sediment. Geol.* 176:191-205.

Sarkar, S., Banerjee, S., Samanta, P., Jeevankumar, S., 2006. Microbial mat-induced sedimentary structures in siliciclastic sediments: examples from the 1.6 Ga Chorhat Sandstone, Vindhyan Supergroup, M.P., India. *J. Earth Sys. Sci.* 115: 49-60.

Schieber, J., 1986. The possible role of benthic microbial mats during the formation of carbonaceous shales in shallow Mid-Proterozoic basins. *Sedimentology* 33: 521-536.

In: *Atlas of microbial mat features preserved within the clastic rock record*, Schieber, J., Bose, P.K., Eriksson, P.G., Banerjee, S., Sarkar, S., Altermann, W., and Catuneanu, O., (Eds.), Elsevier, p. 267-275. (2007)

Schieber, J., 1998a. 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., 1999. Microbial mats in terrigenous clastics: the challenge of identification in the rock record. *Palaios* 14: 3-12.

Schieber, J., 2004. Microbial mats in the siliciclastic rock record: a summary of the diagnostic features. In: Eriksson, P.G., Altermann, W., Nelson, D.R., Mueller, W.U., Catuneanu, O. (Eds.), *The Precambrian Earth: Tempos and Events. Developments in Precambrian Geology* 12, Elsevier, Amsterdam, pp. 663-673.

Schieber, J., Riciputi, L., 2005. Pyrite and marcasite coated grains in the Ordovician Winnipeg Formation, Canada: An intertwined record of surface conditions, stratigraphic condensation, geochemical "reworking," and microbial activity. *J. Sediment. Res.* 75: 907-920.

Schlager, W., 2005. *Carbonate Sedimentology and Sequence Stratigraphy*. Soc. Econ. Paleontol. Mineral. Concepts in Sedimentology and Paleontology 8, Tulsa, Oklahoma, 200 pp.

Schopf, J. W., 1993. Microfossils of the Early Archean Apex Chert: new evidence of the antiquity of life. *Science* 260:640-646.

Schopf, J.W., 2004. Earth's earliest biosphere: status of the hunt. In: Eriksson, P.G., Altermann, W., Nelson, D.R., Mueller, W.U., Catuneanu, O. (Eds.), *The Precambrian Earth: Tempos and Events. Developments in Precambrian Geology* 12, Elsevier, Amsterdam, pp. 516-539.

Schulz, H.N., Jørgensen, B.B., Fossing, H.A., Ramsing, N.B., 1996. Community structure of filamentous, sheath-building sulfur bacteria, *Thioploca* spp., off the coast of Chile. *Appl. Environ. Microbiol.* 62:1855-1862.

Schumm, S.A., 1993. River response to baselevel change: implications for sequence stratigraphy. *J. Geol.* 101: 279-294.

Seilacher, A., 1999. Biomat-related lifestyles in the Precambrian. *Palaios* 14: 86-93.

Seilacher, A., Pfluger, F., 1994. From biomats to benthic agriculture: a biohistoric evolution. In: Krumbein, W.E., Paterson, D.M., Stal, L.J. (Eds.), *Biostabilization of Sediments*. Bibliotheks- und Informationssystem der Carl von Ossietzky Universität Oldenburg, (BIS)-Verlag, Oldenburg, pp. 97-105.

Shanley, K.W., McCabe, P.J. (Eds.), 1998. *Relative Role of Eustasy, Climate and Tectonism in Continental Rocks*. Soc. Econ. Paleontol. Mineral. Spec. Publ. 59, Tulsa, Oklahoma, 234 pp.

Sloss, L.L., 1962. Stratigraphic models in exploration. *American Assoc. Petrol. Geol. Bull.* 46: 1050-1057.

In: *Atlas of microbial mat features preserved within the clastic rock record*, Schieber, J., Bose, P.K., Eriksson, P.G., Banerjee, S., Sarkar, S., Altermann, W., and Catuneanu, O., (Eds.), Elsevier, p. 267-275. (2007)

Sur, S., Schieber, J., Banerjee, S., 2006. Petrographic observations suggestive of microbial mats from Rampur Shale and Bijaigarh Shale, Vindhyan basin, India. *J. Earth Sys. Sci.* 115: 61-66.

Twenhofel, W.H., 1939. *Principles of Sedimentation*. McGraw-Hill, New York, 610 pp.

Van Wagoner, J.C., Posamentier, H.W., Mitchum, R.M., Vail, P.R., Sarg, J.F., Loutit, T.S., Hardenbol, J., 1988. An overview of sequence stratigraphy and key definitions. In: Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A., Van Wagoner, J.C. (Eds.), *Sea Level Changes - An Integrated Approach*. Soc. Econ. Paleontol. Mineral. Spec. Publ. 42, Tulsa, Oklahoma, pp. 39-45.

Van Wagoner, J.C., Mitchum, R.M., Jr., Campion, K.M., Rahmanian, V.D., 1990. Siliciclastic sequence stratigraphy in well logs, core, and outcrops: concepts for high-resolution correlation of time and facies. *American Assoc. Petrol. Geol. Methods in Exploration Series 7*, Tulsa, Oklahoma, 55 pp.

Ward, D.M., Ferris, M.J., Nold, S.C., Bateson, M.M., 1998. A natural view of microbial biodiversity within hot spring Cyanobacterial mat communities. *Microbiol. Mol. Biol. Rev.* 62: 1353-1370.

Watanabe, Y., Martini, J.E.J., Ohmoto, H., 2000. Geochemical evidence for terrestrial ecosystems 2.6 billion years ago. *Nature* 408: 574-578.

Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A., Van Wagoner, J.C. (Eds.), 1988. *Sea Level Changes - An Integrated Approach*. Soc. Econ. Paleontol. Mineral. Spec. Publ. 42, Tulsa, Oklahoma, 407 pp.

Williams, G.E., 2004. Earth's Precambrian rotation and the evolving lunar orbit: implications of tidal rhythmite data for palaeogeophysics. In: Eriksson, P.G., Altermann, W., Nelson, D.R., Mueller, W.U., Catuneanu, O. (Eds.), *The Precambrian Earth: Tempos and Events*. *Developments in Precambrian Geology 12*, Elsevier, Amsterdam, pp. 473-482.

Yeo, G., Percival, J.B., Jefferson, C.W., Bernier, S., Hunt, P., 2002. Clay oncoids and crypto-microbial laminates from the late Paleoproterozoic Manitou Falls Formation, Athabasca Basin, Saskatchewan. *Summary of Investigations 2002, Volume 2*, Saskatchewan Geological Survey, Sask. Industry Resources, Misc. Rep., 2002-4.2, CD-ROM, Paper D-9, pp. 1-9.