CHAPTER 5

MICROBIAL MATS ON MUDDY SUBSTRATES – EXAMPLES OF POSSIBLE SEDIMENTARY FEATURES AND UNDERLYING PROCESSES

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In modern environments where environmental parameters, such as low oxygen conditions or high salinity, restrict metazoan grazing, microbial mats tend to prosper. Examples are the Beggiatoa mats in the depths of the Santa Barbara Basin offshore of California (low oxygen), and the famous stromatolites of Sharks Bay in Western Australia (high salinity). Regardless of substrate, microbial mats can produce unique surface morphologies, display textures related to lateral expansion and grain capture, cause resistance to loading, enhance cohesion of surface layers, and upon erosion form flexible fragments with properties that contrast strongly from those of a simple sediment. Yet, whereas in carbonate rocks and sandstones the resulting sedimentary features might be recognized by their resemblance to features observed in modern environments, microbial mat features in mudstones are quite subtle and often overlooked (Schieber, 1999).

Nonetheless, the presence of microbial mats changes the rheology of the surface muds, and the organic material that they produce impacts mudstone diagenesis upon decay and burial. Whereas the organic mat texture, such as the original surface morphology (e.g. smooth, wrinkled, ridged, pinnacled) and the arrangement of filaments within the mat may largely be lost upon decay and compaction, the impact that the mat had on physical and chemical sediment properties (e.g. erodability, cohesion, redox conditions and authigenic minerals) can still be detected upon careful examination. In a sense these impacts are analogous to trace fossils in that they record the mat induced changes in the mechanical and chemical behavior of the mud substrate. An overview of these features was given by Schieber (2004) and is summarized in Chapter 3 of this book. In the following paragraphs examples from the rock record are discussed and illustrated with the accompanying figures.

Features related to mat growth

In addition to the continued growth of microbial filaments and clumps, microbial mats typically produce copious amounts of sticky extracellular polymer substances (EPS). Cumulatively, this organic production results in the trapping, agglutination, baffling, and binding of sediment particles that rain down on the mat surface or are transported across it (Gerdes et al., 2000). As is true for sandy and carbonate environments, sedimentation in muddy environments is episodic, reflecting sediment pulses due to storms, floods, dust storms, and other short lived disturbances (Schieber, 1998a). These sediment pulses will intermittently blanket microbially stabilized
muddy surfaces, and this sediment blanket will be resurfaced by microbial mats once normal conditions return. The thin clay drapes that accentuate laminae in carbonaceous shale beds of the Newland Formation (Belt Supergroup, Montana; Fig. 5-1A) are interpreted to be of such origin (Schieber, 1986), and the thicker graded silt/mud couplets of Proterozoic striped shales (Fig. 5-1D; see also Chapter 7(b) and (c)) can be viewed as simply reflecting more voluminous or more proximal sedimentation events (Schieber, 1986).

When colonizing muddy substrates, microbial mats provide a sharp geochemical interface beneath which the sediment is reducing and prone to better preservation of organic matter (Krumbein and Cohen, 1977). Thus, in mudstones the former presence of microbial mats may be indicated by laminated carbonaceous shale beds. Not all lamination in carbonaceous shales, however, is of microbial mat origin. Many non-mat carbonaceous shales are laminated as well (Figs. 5-1B, -1C). Yet, while laminae in the latter are typically even and parallel (Figs. 5-1B, -1C) in the absence of differential compaction effects, microbial mat-produced carbonaceous laminae tend to be more wavy-crinkly in nature (Fig. 5-1A).

Although wavy-crinkly anastomosing carbonaceous laminae appear to be a characteristic feature of several examples of microbial mats in the rock record (Schieber, 1986; Sur et al., 2006; Patranabis-Deb et al., Chapter 7(c)) and probably are an “afterglow” of the once wrinkled irregular surface of a microbial mat, the presence of this lamina style should not be considered as diagnostic of surface colonization by microbial mats. The reason for this cautionary note is that differential compaction around microconcretions, fecal pellets, silt lenses, etc. can produce a comparable style of lamination (Schieber, 1999). For example, mat-colonized muds of the Santa Barbara Basin (Beggiatoa mats) contain between 80 to 90 percent water (personal observations). Compaction will therefore tend to not only cause a severe reduction of original surface relief, but also produce waviness due to compaction around denser particles and sediment regions.

Presumed microbial mat laminae in Green River Formation oil shales (see Chapter 7(j)) differ from the above Middle Proterozoic examples by being smooth-wavy in appearance rather than wavy crinkly (Fig. 5-2A). The reason behind this difference is uncertain. The mat-forming communities could for example have formed a very even surface film that did not have many wrinkles to start with. Alternatively, terrigenous influx during times of optimal mat development could have been so small as not to produce thickness variations in the mat layer due to sediment trapping.

In more energetic shallow water environments, a combination of competition for light and sediment trapping by microbial mat surfaces (agglutination) tends to promote the formation of domal buildups in sandstone and carbonate environments (Schieber, 1999). Domal buildups of various amplitude and spacing have for example been observed in shallow water mudstones of the Belt Supergroup (Schieber, 1998b, 1999; see also Chapter 7(b)). These domal features (Fig. 5-2B, -2C) may have developed because better lighting conditions allowed slightly elevated areas to grow more biomass and EPS, and as a consequence were also more efficient in trapping and binding sediment that moved across the sea floor by currents and waves. Domal features of this type have so far only been reported from mudstone units in the Middle Proterozoic Belt Supergroup (Schieber, 1998b), but potentially could occur in other Proterozoic shale successions.
as well. The paucity of observations may not so much reflect their actual rarity, but equally well might indicate that these features rarely survive outcrop weathering.

As pointed out above, sudden sedimentation events (storms, floods) can “bury” a growing mat and cause an interruption of growth. If these even layers are of the thickness of millimeters to centimeters they give the shales a unique striped appearance (Fig. 5-1D), such as also illustrated in Chapter 7(b) and (c). In the case of an incomplete but expanding mat cover, occasional deposition of thin clay drapes may lead to false cross-lamination (Fig. 5-3A) as outward movement of mat margins is intermittently interrupted by deposition of clay drapes (Schieber, 1986). Depending on the regularity with which the growth-interrupting sedimentation events occur, the resulting false cross-lamination may look quite a bit more irregular than depicted in Fig. 5-3A.

When micas are transported by currents across a microbial mat they are likely to be trapped in random orientation on a surface covered by a tangle of microbial filaments and sticky EPS. For mats growing on a muddy substrate, however, an initial random mica fabric will typically be obscured by later burial compaction. Thus, although random micas can be a growth related fabric element, this feature is only preserved in cases where mineral precipitation (Fig. 5-3D) significantly reduces compaction (see below).

**Features related to physical forces acting on mat stabilized mud layers**

Generally speaking, surface muds are of low density because they contain abundant (70 to 90%) water. If covered with a layer of denser sediment, such as silt or sand, the loading of these hydroplastic mud layer results in subsidence of sand and silt in the form of lobes and to upwards movement of mud in the form of tongues. The resulting sedimentary structures are commonly known as load casts, flame structures, and ball-and-pillow structures (Reineck and Singh, 1980). In Fig. 5-2D a thin silt layer overlying a bed of gray shale is visible, with a subsided silt pillow projecting into the underlying mud. The structure implies that the underlying mud behaved like a viscous fluid. In Fig. 5-2E a silt layer of the same thickness on top of a wavy-crinkly laminated carbonaceous shale layer can be seen. Instead of sinking in and forming pillows, the silt layer only produces shallow depressions in the underlying mud. Comparing the two images suggests that the carbonaceous shale layer offered more resistance to loading than the gray shale layer. Both images are from the same Middel Proterozoic shale unit, and the carbonaceous layer has wavy-crinkly internal laminae that are suggestive of a microbial mat origin (Fig. 5-1A). If the carbonaceous layer simply had originated as an organic muck it would have behaved very similarly to a clay-water mixture and shown sunk-in pillows like those seen in Fig. 5-2E. The load resistance of the carbonaceous layer suggests internal cohesion, a property that is consistent with a surface-stabilizing microbial mat.

The shales pictured in Figs. 5-3B and -3C show soft sediment deformation of alternating layers of gray and carbonaceous shale (striped shales; see Chapter 7(b) and (c)). These shales were unconsolidated when rupturing and folding occurred, and carbonaceous shale layers behaved like cohesive sheets, whereas the interbedded gray shales flowed into gaps (Fig. 5-3B) and were squeezed out of fold hinges (Fig. 5-3C). In essence, the gray shales behaved like a thick fluid that
in viscosity probably compared well to stirred yoghurt, and the carbonaceous layers possessed internal cohesion. These observations are testament to considerable original rheological differences between gray shales and carbonaceous shales, and are consistent with a microbial mat origin for the carbonaceous beds. If the latter had originally been a simple mixture of terrigenous material and organic particles (an organic muck), a fluid-like rather than a cohesive behaviour should be expected. Thus, whenever mechanical behaviour indicates that a given mudstone layer had considerably more internal cohesion than what could be expected of a simple mixture of its components, a microbial mat interpretation should be entertained.

Although microbial mats act to bind and stabilize the surface sediment (e.g., Neumann et al., 1970; Yallop et al., 1994; Paterson et al., 1994; Paterson, 1997), once eroding currents are too strong, holes will be eroded into the mat, and we may see features like “flipped over” mat edges, overfolded mat layers, and “roll-up” structures (Fig. 5-4A). Eroded and deformed mat fragments may be several millimetres thick (Figs. 5-3B and -3C) or may just be thin films (Figs. 5-4B, -4C, -4D, -4E and -4F). In both cases, however, these fragments will exhibit high “within-lamina or layer” cohesiveness. On bedding planes of shales, carbonaceous fragments like those in Figures 5-4B, -4C, -4D, -4E and -4F will appear as irregularly shaped dark flakes that range in size from a few millimetres to centimetres.

The fragmentation of microbial mats during erosion and transport is analogous to the tearing of a fibrous fabric, and mat fragments may show frayed edges as a result. The phenomenon is also known as “blotting paper effect” from the study of modern microbial mats (Gerdes et al., 1993), and is illustrated in Fig. 5-5 with various examples from the rock record.

In carbonates, the very early diagenetic cementation of microbial mat layers can preserve remains of the mat-constructing microbes and provide a supporting argument for the microbial mat origin of ancient examples. In mudstones such preservation rarely occurs, and the postulation of a microbial mat origin based on the observation of wavy-crinkly carbonaceous laminae alone is tenuous. Observing, however, that the alleged mat layers and laminae are erosion-resistant and appear to have internal cohesiveness strongly improves the odds that one is indeed looking at microbially bound surfaces. In mudstones evidence for the cohesive behaviour of microbial mats is one of the most useful indicators of their former presence (Schieber, 1999).

The integrity of microbial mats can also be destroyed through desiccation, and personal observations of modern sediments suggest that mudracks in clay substrates do differ from those observed in mat bound muddy substrates. There is, however, to date no formal study of desiccation effects in ancient mat-bound sediments. Drying out of mat-bound surfaces can produce fragments that are able to float out into open water bodies (Fagerstrom, 1967) and which can transport detrital grains from nearshore areas to deeper and mud-dominated portions of a basin. Clusters of coarser grains (Fig. 5-6B) in a much finer mudstone matrix may be of such origin, being “rafted in” by mat fragments and then buried collectively once a mat-fragment had detached and sunk to the bottom (Olsen et al., 1978; Schieber, 1999). Benthic microbial mats may also be torn apart because some portions are so strongly buoyed by attached gas bubbles that they detach from the substrate and float to the surface (Fig. 5-6A). These could then conceivably be carried deeper into the basin and there deposit out-of-place coarse grains. Wave
agitation, however, will tend to sink dried “rafts” and will shake lose air bubbles from buoyed mat fragments. Thus, this rafting process is most likely restricted to lakes during tranquil weather periods. Ice is of course another potent rafting agent, but in that case we can probably expect to find a larger grain size range (up to pebble size) and distinct horizons with rafted material. Furthermore, for the Phanerozoic time period other factors aside of microbial mats have to be considered for grain rafting, such as floating plant debris (root attached material), animal carcasses (buoyed by decay gases), and fecal pellets.

Features related to mat metabolism

For carbonate stromatolites, microbial photosynthetic carbon assimilation is generally considered the cause of calcification, and modern cyanobacteria are known to induce precipitation of gypsum, calcite, and magnesite from alkaline lake waters (Thompson and Ferris, 1990; Thompson et al., 1997). Calcification of cyanobacterial filaments has also been proposed as a source of carbonate micrite in the Phanerozoic (Pratt, 2001), but the underlying details of calcification of microbial sheaths and EPS is still a matter of some debate (Arp et al., 2001). It has also been suggested that magnesium concentrated in microbial sheaths is released upon decomposition and leads to dolomite formation in the micro-environment of microbial mat layers (Gebelein and Hoffman, 1973).

In mudstones, conformable laminae enriched in calcite or dolomite can in principle have multiple origins. They could for example simply be due to carbonate mud that was washed off adjacent carbonate banks by storms and then settled through the water column and blanketed the pre-existing mud surface. Alternatively they might also be the deposits of lutite flows that originated from a shallow water carbonate bank. In both cases, however, we would expect these deposits to be of uniform thickness at the thin section and hand specimen scale, to possibly show a sharp base and normal grading, and also to be largely devoid of terrigenous material. Carbonate laminae in the Mt. Shields Formation of the Middle Protoerozoic Belt Basin (Chapter 7(b)), found as parts of domal buildups (Fig. 7(b)-9 and -10) and in places exhibiting fenestral texture (Fig. 7(b)-9D), have been interpreted as microbial (Schieber, 1998b). They are used here (see below) to illustrate likely differences between carbonate-rich laminae due to mechanical deposition and those that owe their origin to in situ carbonate production in a microbial mat.

Given the right water chemistry, syngenetic carbonate precipitation in microbial mat laminae is a well known phenomenon (e.g., Thompson and Ferris, 1997; Pratt, 2001) and can occur in terrigenous clastic environments just as well as in carbonate dominated settings. In mudstones, one feature that might set apart microbially produced carbonate laminae from those related to allochthonous carbonate deposition could, for example, be diffuse lower and upper boundaries of carbonate-rich laminae (Fig. 5-7A and -7B), suggesting in situ growth of carbonate grains rather than transport into a predominantly terrigenous clastic setting. The random orientation of mica flakes in such laminae (Fig. 5-3D and Fig. 5-7B) is consistent with a scenario where currents transported micas across the mat surface and that these micas then were trapped in random orientation on a surface covered by a tangle of microbial filaments and EPS. Very early (pre-burial) cementation of these laminae probably preserved original orientation of the mica flakes. Cementation later in diagenetic history would have allowed for prior compaction and partial

rotation of mica flakes into the horizontal (Fig. 5-7C). Another textural feature that is consistent with an *in situ* cemented mat lamina and is hard to explain with deposition by lateral flow (gravity driven, storm and tidal currents, etc.) or vertical settling, is the presence of terrigenous grains “floating” in a carbonate matrix, such as the already illustrated mica flakes and floating quartz grains (Fig. 5-6D). Lateral transport is unlikely because carbonate mud, mica flakes, and quartz grains differ significantly in their hydrodynamic properties and would be segregated early on in any conceivable transport process. Deposition by settling through the water column would also have produced segregation of these three components into discrete laminae. Based on the sum of these considerations, interpreting the carbonate laminae in Mt. Shields mudstones as the *in situ* product of metabolic processes within a microbial mat is considered the most suitable interpretation because it is consistent with all the observed features.

**Features related to mat decay and diagenesis**

Gas development during decay of submerged mats may produce enough buoyancy to allow portions of a decaying mat to float to the surface and become an agent of grain rafting, in the same way as described above for desiccated mat fragments and photosynthesis buoyed fragments. The result would be analogous clusters of coarser grains in a much finer matrix (Fig. 5-6B). The caveats pointed out for desiccated and photosynthesis buoyed fragments apply here as well.

Because mudstones tend to preserve organic matter, microbial mats may be preserved as beds of carbonaceous shale (see Chapter 7(b)). Formation of these beds through continued growth of microbial mats implies that earlier mat laminae become buried and undergo decay. Typically this decay occurs in an anaerobic environment and provides favourable conditions for the precipitation of “anoxic” minerals, such as pyrite, siderite, and other ferroan carbonates. In marine settings sulphate reducing bacteria thrive in the sub-mat environment, produce hydrogen sulphide, and induce pyrite formation if soluble iron is available (Berner, 1984). In the Newland Formation of the Belt Supergroup, striped shales that consist of alternating carbonaceous layers (interpreted as benthic microbial mats) and silt/clay couplets (event deposits) can in places grade into a pyritic facies variant (Schieber, 1989) where the carbonaceous microbial mat layers become increasingly pyritic (see Chapter 7(b)). Pyrite content ranges from carbonaceous laminae dusted with tiny pyrite grains (Schieber, 1989) over moderately pyritic laminae with discontinuous wavy texture (Fig. 5-6C and -6D) to strongly pyritic laminae that follow the original carbonaceous laminae and mimic their wavy anastomosing texture (Fig. 5-8A and -8B). Thus, wavy anastomosing laminae that contain abundant fine crystalline pyrite (Figs. 5-6 and 5-8) can also indicate former microbial mats in generally carbonaceous shales. They have been observed in the Newland Formation of the Belt Supergroup, in various pyritic striped shales in the Proterozoic of Australia (Schieber, 1989; see Chapter 7(b)), and also in the Middle Proterozoic Bijaygarh Shale of the Vindhyan Supergroup in India (Fig. 5-6D).

The above illustrated pyritic laminae show on the one hand deformation by load casts (Fig. 5-8B and -8C), but also evidence of early hardening through cementation by pyrite (see Chapter 7(b), Fig. 5-5C). These observations suggest that the pyritic laminae were not pyritic from the start, and that pyrite formed at very shallow depth within the sediment. Because iron is very immobile
in sediments with sulphidic pore waters (Berner, 1984), there is little chance that it could have been redistributed in the decay zone beneath the active mat. The fact that the pyrite distribution mimics the carbonaceous laminae indicates therefore that the iron distribution is a primary sedimentary feature and that an iron precursor, possibly floccules of iron hydroxide (Schieber, 1987, 1989, 1995), was initially deposited on the growing mat surface. Later diagenetic effects may include further pyrite cementation between the original fine crystalline pyrite (Fig. 5-8C), grain enlargement by overgrowth on original pyrite grains (Fig. 5-8D), and formation of coarse crystalline pyrite nodules centered on earlier beds of fine crystalline pyrite (Strauss and Schieber, 1990).

Conclusion

The mudstone hosted microbial mat features illustrated in this section do most likely not represent the full range of microbial mat features in mudstones. Mudstones comprise approximately two thirds of the sedimentary rock record, and only a small portion of them has been studied in any detail for their sedimentary features (Schieber, 1998b). Even fewer have been investigated for the potential presence of microbial mats. To make matters worse, there are few studies of modern muds where the effects of microbial mat colonization have been adequately documented. Thus, as time goes by we can expect to witness the assembly of a substantially larger array of mat-related sedimentary features in mudstones than depicted here.
Figure 1:
Comparison of microbial mat lamination with lamina styles typical in laminated Phanerozoic carbonaceous shales. (A) striped shale, Newland Formation, Belt Supergroup, Middle Proterozoic of Montana, USA. Note wavy crinkly carbonaceous laminae that are interpreted as having been produced by a benthic microbial mat (Schieber, 1986; and Chapter 7(b)). Light coloured layers are graded silt-mud couplets that are interpreted as event layers, possibly due to storms or floods. (B) Laminated black shale from Dowelltown Member of the Chattanooga Shale. The silt laminae are even and parallel and interpreted as due to seafloor reworking by storm waves (Schieber, 1998c). (C) Even parallel laminated Posidonia Shale from southwest Germany. The lighter laminae consist of tiny carbonate grains and fecal pellets. Although (A), (B), and (C) are all carbonaceous shales, the microbial mat laminae in (A) differ distinctly from the bottom current and wave produced even parallel laminae in (B) and (C). (D) Graded silt/mud couplets in Proterozoic striped shales (see also Chapter 7(b)) reflect intervals of mat growth interrupted by brief sedimentation events (Schieber, 1986). From Schieber, 1999.
Figure 2:
(A) Undulating continuous organic laminae (reddish brown) in lacustrine oil shale (Green River Formation). Laminae are not wavy crinkly like in Proterozoic carbonaceous shales of microbial mat derivation (Chapter 7(b)), but instead are gently undulating. They are interpreted as remains of a contiguous organic film that covered the lake bottom (Chapter 7(j)).
(B) Formation of positive relief buildups (small domes) in greenish gray laminated mudstones of the Mt. Shields Formation (Belt Supergroup, Middle Proterozoic of Montana, Chapter 7(b)).
(C) Low amplitude domes in reddish mudstones of the Mt. Shields Formation (Belt Supergroup, Middle Proterozoic of Montana, Chapter 7(b)). In both cases the domes contain dolomitic laminae that are interpreted as microbial (Schieber, 1998b; Chapter 7(b)). Buildups may reflect upwards growth towards sunlight. (D) and (E) Comparing loading behaviour of silt layer on non-microbial mud layer with loading behavior on microbial mat layer. In (D) the silt is able to sink into the underlying mud and forms small pillows (arrows), whereas in (E) the mat layer resists loading and the silt only forms shallow depressions. Images (D) and (E) are from shales of the Newland Formation, Belt Supergroup, Middle Proterozoic of Montana (see Chapter 7(b)).
Figure 3:
(A) “False cross-lamination” at the base of a carbonaceous silty shale bed from striped shale in the Newland Formation (Belt Supergroup, Middle Proterozoic of Montana). Internal drapes of clay (red arrows) range from 0.01 to 0.1 mm in thickness. The clearly visible thicker shale drapes form an angle of about 5 degrees with the base of the carbonaceous silty shale bed and continue into the underlying bed of clayey shale. The feature is interpreted as the result of the step-wise lateral expansion of a pioneer mat that was interrupted by deposition of clay drapes (Schieber, 1986). Stratigraphic “up” is to the left. (B) Ruptured bed (red arrows) of carbonaceous silty shale in striped shales of the Newland Formation. The left part of this bed has been overfolded and thickened during early soft sediment deformation. The outer hinge of the overfolded portion is marked with a yellow arrow.

Note that the intervening clay layer has been squeezed out of the hinges. These observations indicate that the clay layers were of a semi-liquid or yoghourt-like consistency, whereas the carbonaceous layers behaved like a cohesive, leathery membrane (see also C). (C) Overfolded (red arrow) but intact bed of carbonaceous silty shale (dark) interbedded with clayey shale (light). Most of the light clay-rich material has been squeezed out of the fold noses and limbs. This indicates that the dark beds were considerably more cohesive than beds of clayey shale, and that the latter behaved more like a highly viscous fluid during soft sediment deformation (Newland Formation, Belt Supergroup, Middle Proterozoic of Montana). (D) Photomicrograph of dolomitic lamina attributed to microbial mat growth (marked at right with yellow bar). The latter are common in domal features observed in the Mt. Shields Formation of the Belt Supergroup (see Chapter 7(b)). Characteristic for these laminae is a random orientation of mica flakes (muscovite). Some large mica flakes are pointed out by yellow arrows.

Figure 4:
(A) Examples of the erosion, transport, and deformation of microbial mat stabilized muds. From Schieber, 1999. (B) Eroded and transported microbial mat fragment from the Newland Formation, Belt Supergroup, Middle Proterozoic of Montana (see also Chapter 7(b)). The fragment is now a thin carbonaceous film (arrows) that originally was approximately 10 mm in diameter. It has been rolled up by transport over the sediment surface. (C) Another microbial mat fragment (arrows) in shales of the Newland Formation. It has attached silt grains and appears to be overfolded with fold hinge at right. (D) Folded-over carbonaceous flake of probable microbial mat origin (Newland Formation, Belt Supergroup, Middle Proterozoic of Montana). (E) Carbonaceous flake with attached silt grains from the Rampur Shale, Vindhyan Supergroup, Middle Proterozoic of India. (F) Folded-over carbonaceous fragment in Green River Formation oil shale (Eocene of Wyoming).
Figure 5: Torn and frayed edges of microbial mat fragments:
(A) Edge of carbonaceous fragment in oil shale of Green River Formation (Eocene of Wyoming). (B) Carbonaceous fragment with internal laminae and attached silt grains from Middle Proterozoic Somanpalli Group, India (see Chapter 7(c)). Frayed edge pointed out by arrow. (C) Carbonaceous fragment with internal laminae and frayed edge (arrows). Newland Formation of Belt Supergroup (Middle Proterozoic). (D) Carbonaceous fragment with attached silt grains and frayed edge (arrows). Rampur Shale of Middle Proterozoic Vindhyan Supergroup, India.

Figure 6:

(A) Modern puddle with benthic cyanobacterial mat on mud substrate (marked m). Portions of the mat have floated up (arrows) because of attached oxygen bubbles. These fragments can float and transport attached detrital grains. (B) Isolated cluster (marked by arrows) of sand to silt sized grains in a much finer mudstone matrix. Green River Formation, Eocene of Wyoming. (C) Wavy laminae of fine crystalline pyrite (red arrows) in carbonaceous beds of striped shale facies in the Newland Formation (Belt Supergroup, Middle Proterozoic of Montana). The pyrite enrichment coincides with carbonaceous laminae in wavy-crinkly laminated carbonaceous shale beds (Schieber, 1989). (D) Comparable pyritic laminae (red arrows) in carbonaceous shales from the Middle Proterozoic of India (Sur et al., 2006; Bijaygarh Shale, Vindhyan Supergroup).
Figure 7: Dolomitic laminae of probable microbial mat origin in mudstones and siltstones of the Mt. Shields Formation (Middle Proterozoic Belt Supergroup, Montana, see Chapter 7(b)):

(A) Laminae of fine crystalline dolomite with randomly oriented micas (marked with black bars) alternate with laminae that are dominated by clay and silt. (B) Close-up of dolomitic lamina (black bar) showing randomly oriented mica flakes. (C) Close-up of silt and clay dominated lamina. The mica flakes show preferred orientation parallel to bedding due to compaction of mud layer. (D) Floating grains of quartz (marked Q) and mica (flakes) in a fine crystalline matrix of dolomite.
Figure 8: Images from pyritic striped shales in the Newland Formation, Belt Supergroup, Middle Proterozoic of Montana (see Chapter 7(b)):

(A) Wavy anastomosing laminae of fine crystalline pyrite in pyrite enriched bed. The pyritic laminae are also rich in organic matter. The texture is virtually identical to that observed in “normal” carbonaceous shale beds of this facies that have been interpreted as benthic microbial mat deposits (Schieber, 1986). (B) An example of a wavy laminated pyritic bed that is overlain by a silt layer (event deposit). Note loading at the base of the silt layer. Deeper loading, such as pillow formation, was prevented by the cohesiveness of the mat-bound surface. (C) Another example of a wavy laminated pyritic bed with individual laminae that are more strongly pyritic. They contain a higher concentration of the same tiny pyrite grains that are found in laminae of (A) and (B). Thickened portions of laminae (red arrows) show secondary pyrite cement between primary pyrite grains and thus resisted compaction. (D) Close-up of (C). Shows typical lamina with tiny and probably primary micron-sized pyrite grains (yellow arrows) next to thickened lamina where impinging pyrite grains (red arrows) and grain enlargement by secondary overgrowth can be seen.
References


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