MICROBIAL MATS IN TERRIGENOUS CLASTICS: THE CHALLENGE OF IDENTIFICATION IN THE ROCK RECORD

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ABSTRACT

Increasingly, microbial communities are recognized for playing a potentially important role in defining and modifying surface sediment characteristics in various settings, ranging from terrestrial, through marginal marine, to continental margins. Whereas microbial mat presence can be established with comparative ease in modern terrigenous clastics, in sedimentary rocks this poses a big challenge.

Terrigenous clastics of the Belt Supergroup (Mid-Proterozoic) show a number of features that can serve as microbial mat indicators: (A) domal buildups; (B) cohesive behavior; (C) wavy-crinkly character of laminae; (D) irregular wrinkled bed surfaces; (E) ripple patches; (F) laminae with mica enrichment; (G) irregular, curved-wrinkled impressions on bedding planes; and (H) lamina specific distribution of early diagenetic minerals (dolomite, ferroan carbonate, pyrite). Positive identification of a fossil microbial mat requires one to find microbial filaments in life position. This is a difficult task even in the case of very favorable preservation of organic matter, and impossible to accomplish in many instances where fossil microbial mats are suspected. Nonetheless, the above features (especially when found in combination) are highly suggestive of microbial mats, and can serve as guides to sediments that may have accumulated under the influence of microbial mats.

Whereas the Belt Basin examples are all from shallow water environments, microbial mats may also have played an important role in deeper water oxygen-deprived settings - the realm of black shale formation. In areas of modern oxygen minimum zones, microbial mats have been found to thrive at the seafloor, profoundly influencing the chemistry of the sediment/water interface and sediment stability. Possible ancient analogs occur in a variety of black shale deposits (e.g. Jet Rock, Monterey Formation, Green River Formation), with wavy to crinkly kerogen-rich laminae being the main indication of possible microbial mat origins. More evidence is clearly desirable. Although microbial mats clearly have the ability to thrive in black shale environments, it will require more research to firmly establish whether, and how extensively, they occupied this niche in the geologic past.

INTRODUCTION

Microbes are all around us. In terms of numbers they rule the earth, and they manage to live under extreme conditions, such as in hot springs, in polar ice, at depth in rock formations, and in any conceivable environment in between (e.g. Edwards, 1990; Vincent, 1988). Of interest for this paper are microbes that colonize, stabilize, and modify the surfaces of sandy and muddy sediments. Microbial mat deposits in carbonates are excluded, although the vast majority of published examples is found in that rock type (e.g. Awramik, 1984; Walter et al., 1992).

Modern microbial mats on sandy sediment surfaces are well documented (Bauld et al., 1992; Gerdes and Krumbein, 1987; Gerdes et al., 1985; Gunatilaka; 1975; Schwarz et al., 1975; Witkowski, 1990). The microbial colonization of muddy surfaces, although less known, can be readily observed in modern puddles a few days after a rainstorm. Essentially, for any sedimentary surface there is likely a microbial community that is equipped to thrive there if sedimentation rates are sufficiently small. Some can even prosper in absence of sunlight (Gallardo, 1977), or in the harsh and dry conditions of deserts (Krinsley and Dorn, 1991; Taylor-George et al., 1983).

Considering how many times the "present has been the key to the past", it stands to reason that numerous ancient sand and mud surfaces were colonized by microbial communities. Thus, we may assume that sandstone and mudstone deposits of the geologic record should abound with microbial mat deposits

It is at this point that an old geologic truth asserts itself once again: "just because something should have existed does not mean that it has been preserved". Positively proving the former presence of microbial mats in sedimentary rocks of any kind is actually quite a formidable task. Even in modern microbial mat systems, all remnants of the constructing microbiota may be destroyed within the first few hundred years of burial (Park, 1976; Krumbein and Cohen, 1977). Furthermore, if one applies strict criteria of biogenicity, such as preserved filaments in live position (e.g. Buick et al., 1981; Krumbein, 1983; Grotzinger and Rothman, 1996) to published examples of fossil microbial mats (or stromatolites), only a very small portion can actually be shown to have a clearly demonstrable organosedimentary origin.

So, what is a sedimentologist to do? Simply play it safe and assume that a given laminated sediment is not of microbial origin because proof positive is missing? Maybe we should look at the question from a different angle. In trace fossils, for example, the animal that produced the fossil is typically not preserved in association with the burrow. There is no dispute, however, that the traces were produced by a variety of animals, and that traces can be considered "fossilized behavior" (Bromley, 1990). As these animals were searching for food or seeking shelter, they invariably modified the sediment and produced trace fossils that record the interaction of the animal with the sediment. Likewise, laminated sediments produced by microbial mats can be considered the "trace" that reflects the interaction of the mat community with the environment.

Unfortunately, laminated sediments can just as well be produced by purely physical sedimentation processes. Thus, there is a need to develop criteria for the identification of microbial mat laminae. The best place to start looking for microbial mat deposits in sandstones and mudstones is the Proterozoic. Its biosphere was dominated by microorganisms (Schopf and Klein, 1992) and the bulk of all published microbial mat deposits (stromatolites), albeit in carbonates, come from that time period. . In the Phanerozoic, of course, bioturbation and grazing had a negative impact on the preserved biomat record (Garrett, 1970).

Thus, for the first part of this paper I will give an overview of suspected microbial mat features in sandstones and shales of the Proterozoic Belt basin of Montana, Idaho, and British Columbia. These occurrences have been described and discussed in detail by Schieber (1986, 1998). In this paper I will summarize these observations and focus on criteria for microbial mat recognition that can be applied to terrigenous clastics in general. These criteria will then be

applied to suspected microbial mat deposits in the Monterey Shale (Miocene), the Jet Rock (Jurassic), and the Green River Formation (Eocene).
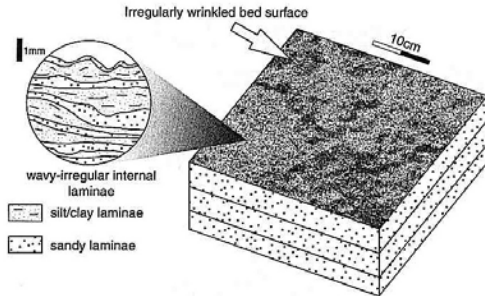

Figure 1: Irregularly wrinkled bed surface as observed in sandstones from the Belt Supergroup (Schieber, 1998). The larger surface features may for example be interference ripples, but this rippled surface has a superimposed finely wrinkled surface morphology (see detail view) that may be of microbial mat origin.

Figure 2: Wavy-crinkly carbonaceous laminae in carbonaceous silty shale beds of the Newland Formation that were interpreted as subtidal microbial mat deposits by Schieber (1986). The thick shale drapes in the upper part of the photo that contain silt lenses at the base were interpreted as event deposits due to minor storms or floods. Scale bar is 0.5 mm long.

MICROBIAL MAT FEATURES IN SHALES AND SANDSTONES OF THE BELT SUPERGROUP

In the Belt Supergroup, various shallow water to periodically emergent sedimentary units contain indications of microbial activity (Schieber, 1998). Indicative features include wavy-crinkly laminae; cohesive behavior during erosion, transport, and deposition; ripple patches; domal structures; impressions of mat fragments; mica enrichment and random micas; and carbonate-rich laminae (Schieber, 1998).

Wavy-Crinkly Laminae and Irregularly Wrinkled Bed Surfaces

These features are observed in both sandstones (Fig. 1) and mudstones (Fig. 2). In mudstones, wavy crinkly laminae are in many instances associated with carbonaceous layers (Fig. 2; Schieber, 1986). Similarity to modern and sub-recent carbonaceous microbial mat laminae (e.g. Horodyski et al., 1977; Krumbein and Cohen, 1977) suggests a mat origin, as does the fact that laminae in non-mat carbonaceous shales are typically quite even and parallel (Schieber, 1986). Although not a certain indicator of microbial mats, the presence of wavy-crinkly laminae alerts us to the possibility, especially when an origin via soft sediment deformation can be ruled out. As shown below in a discussion of wavy laminae in the Jet Rock, caution has to be exercised to make sure that wavy laminae are not an artifact of differential compaction around microconcretions, fecal pellets, silt lenses, etc.

Cohesive Behavior

Cohesive behavior during erosion, transport, and deposition is observed in both sandstones and mudstones, and can be a very useful indicator of microbial mat colonization (Gill, 1977; Simonson and Carney, this volume). In soft sediment, cohesive behavior is indicated by thin sediment layers that were rolled up and about during transport (Figs. 3, 4b), through stretching and overfolding of thin microbially bound layers (Figs. 3, 5), and through stark differences in behavior between alternate layers of sediment (Figs. 3, 5). Modern examples were reported by Reineck (1979). Observations that indicate flexible behavior during transport, such as folded over or rolled up fragments, also help to distinguish cohesion due to microbial binding from cohesion caused by synsedimentary cementation. In sediments that underwent drying, cohesion due to microbial binding is more difficult to rationalize. For example, the curved chips of a dried out and cracked mud layer will behave as single entities during transport and deposition, regardless if they were initially bound by microbial mats or not. If on the other hand a curved, chip-like feature consists essentially of sand grains (Fig. 4d), some binding agent that curls up due to drying and holds the grains together during transport is called for (see
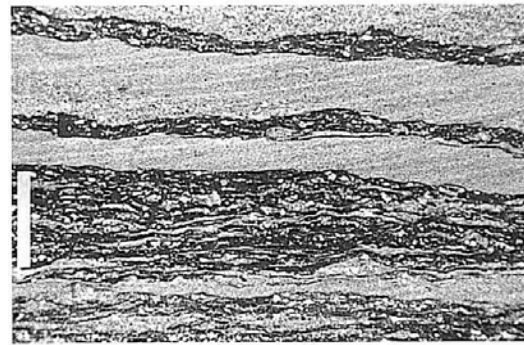
aslo Pflüger and Gresse, 1996). Microbial mats are a reasonable choice.

Carbonaceous Laminae

In shales, such cohesive layers may be more carbonaceous (carbonaceous laminae) than surrounding sediments due to the organic content of microbial mats (Figs. 3, 6). The small permeabilities of muds and mudstones restrict access by oxygen and sulfate, resulting in reduced microbial metabolization of mat material during early burial and enhanced preservation of organic matter (Bauld, 1981; Gerdes and Krumbein, 1987). Carbonaceous laminae as such have little diagnostic value, however, because they primarily reflect reducing conditions in the sediment. Yet, when coinciding with wavy-crinkly morphology (Fig. 2) and cohesive behavior (Fig. 3) they can serve as a supporting argument for a microbial mat origin.

Mat-Decay Mineralization as a Relict Feature

In sandstones, in contrast, we have comparatively high permeability. As a result, organic matter is readily metabolized by microbes during early burial. Later migration of formation waters is likely to remove most of the organic material left in pore spaces. Yet, the fact that microbial mats constitute a sharply defined geochemical boundary (Bauld, 1981) may provide clues for their former presence in sandstones. Due to anaerobic decay of mat material, chemical conditions beneath modern mats in sandy sediments tend to be strongly reducing (Bauld, 1981, Gerdes et al., 1985). This may lead to formation of "anoxic" minerals beneath the mat (e.g. pyrite, siderite, ferroan dolomite), although the mat surface itself is in contact with oxygen bearing waters (Gerdes et al., 1985). The cementation of sand grains by these minerals can be considered a "mat-decay mineralization". Observing well defined, thin, stratiform horizons of these minerals (Fig. 4a) in a shallow water sandstone may well be a "tip-off" for the former presence of microbial mats (Gerdes et al., 1985; Garlick, 1988). Pieces of redeposited mat, be it as rigid fragments of dried out mats (Fig. 4), or as deformed pieces of soft, wet mat (Fig. 4), may upon decay also lead to "mat-decay mineralization" cement that marks and preserves their former outline (Fig. 4b, 4d) and hints of original cohesive behavior.

Ripple Patches

On modern coastal sandflats, microbial mats greatly reduce the erodability of sand (Neumann et al., 1970; Reineck, 1979) and sand movement. During storms these sandflats can undergo partial erosion. Eroded material may be swept together as convoluted fragments and buried as discussed above (Fig. 4b). Because the binding force of the mat is missing in eroded areas, wave and current ripples form (Fig. 4c) in the unstabilized sand (Reineck, 1979; Gerdes et
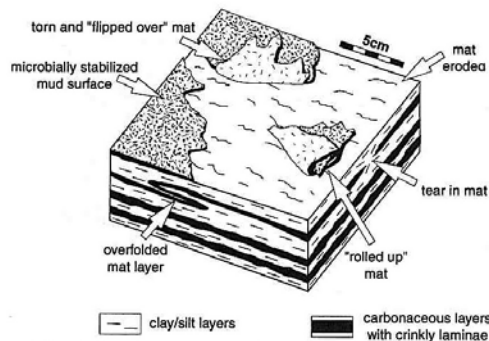
Figure 3: Summary diagram that shows sedimentary features that reflect cohesive behavior of carbonaceous layers that are of suspected microbial mat origin. Where overfolded mat layers occur, the less cohesive inter-mat sediment is squeezed out of the folds. Where tears in the mat occur it shows stretching and inter-mat sediment flowed into the gap. Mat fragments can get rolled up as they are transported by currents. Partially eroded mats can be turned over at the edges. These features are described in detail by Schieber (1986) from the Newland Formation of the Belt Supergroup.

al., 1985). Ancient examples of this feature have been reported from the Cretaceous Dakota Sandstone (Reineck, 1979) and from various units in the Belt Supergroup (Schieber, 1998).

Features resembling ripple patches due to microbial mat erosion can be produced when a sandstone layer overlying a layer of rippled sandstone is partially broken out during outcrop weathering. Basically, erosion produces "windows" that reveal a lower rippled layer. In that case, however, there will be a sharp break between the rippled layer and the remaining cover (Fig. 7b). In contrast, when we have ripple patches due to partial microbial mat erosion, the transition between the rippled area and the originally mat covered surface is typically smooth (Fig. 7a).

One of the reviewers pointed out that elevated portions of a shallow water sand surface might be selectively reworked, thus leading to a patchy occurrence of ripples. In the case of microbial mats, however, ripple patches form in shallow depressions, rather than on elevated spots.

Domal Structures
Domal Structures in Sandstones

In carbonate rocks, microbial mats produce a variety of three dimensional, dome-like buildups (Walter, 1976). In contrast, comparable buildups in terrigenous clastics are rare. A few reported occurrences in sandstones are from the Ordovician of Minnesota (Davis; 1968), the Proterozoic of Zambia (Garlick, 1981), and the Proterozoic of Montana (Garlick, 1988; Schieber, 1998). Load structures, a common feature at the bases of sandstone beds, resemble "upside down" domes. Thus, it has to be established in outcrop that domal features are indeed "convex up" at the upper surface of sandstone beds. Laminae at the margin of sandy domal features that are steeper than the angle of repose also suggest binding by microbial mats. In the Revett Formation of the Belt Supergroup, systematic thickening of laminae on one side of domal features (Fig. 8) is suggestive of upcurrent sediment trapping by sticky microbial mats (Gerdes and Krumbein, 1987). Although features shown in Figure 8 may superficially resemble migrating and accreting bedforms, they are more random and irregular than hummocky and climbing ripple beds in the same sediment package, and may also show buildups without directional preference. Garlick (1988) also reports domal and columnar structures in Revett sandstones that suggest competition for height and light by microbial mats.
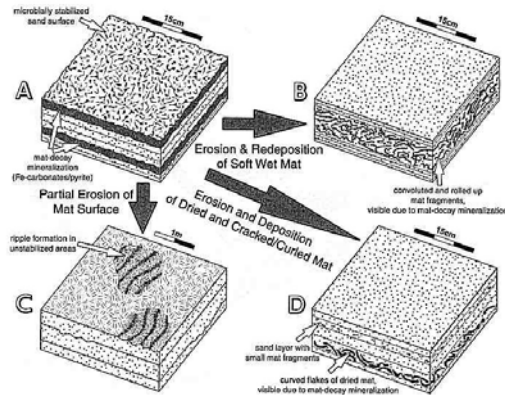

Figure 4: Summary diagram that shows features that may develop where sandy substrates are colonized by microbial mats. (A) Decay of buried mat material produces a reducing microenvironment beneath the mat and leads to precipitation of early diagenetic "mat-decay mineralization", for example pyrite, dolomite, ferroan dolomite, and siderite. Modern analogs are probably the versicolored sand flats of Mellum (Gerdes et al., 1986). (B) Redeposited mat fragments may upon burial and decay also give rise to "mat-decay mineralization". The latter marks the former location of such fragments in the consolidated sediment. (C) When mat stabilized sand surfaces are partially eroded, those areas that lack a stabilizing mat can become rippled by waves and/or currents. Modern examples can be found on tidal sand flats of the North Sea (Reineck, 1979). (D) If a mat dries out it can crack and peel off the surface. When these sandy algal curls and chips are redeposited and buried, the rotting of the organic binding material can again lead to "mat-decay mineralization" that marks the former location of these particles in the consolidated sediment. Sandstones with these features were observed in various units of the Belt Supergroup (Schieber, 1998).

Figure 5: Hand specimen photograph that shows features summarized in Figure 3. Sample is from the Mid-Proterozoic Newland Formation in Montana and consists of interbedded carbonaceous shale (dark) and dolomitic clay-rich shale (light). The carbonaceous layers are interpreted as microbial mat deposits (Schieber, 1986). The small arrows point out an overfolded but otherwise intact mat layer. Most of the dolomitic shale has been squeezed out of fold noses and limbs. This indicates that beds of carbonaceous shale were considerably more cohesive than dolomitic clayey beds, and that the latter behaved like a highly viscous fluid during penecontemporaneous deformation. The large arrows point out torn and ruptured mat layers. The thickening of the upper ruptured layer is probably due to a piece of "flipped over" mat (Fig. 3). Scale bar is 1 mm long. The faint diagonal lines are saw marks.
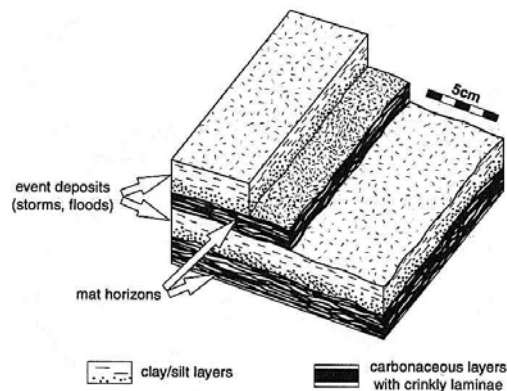
Figure 6: Diagram shows interbedding of carbonaceous shale layers with wavy-crinkly lamination, and non-carbonaceous clay/silt layers. The carbonaceous shale layers show evidence of considerable internal cohesion (Figs. 3, 5), and are thought to be microbial mat deposits. Slow accumulation of carbonaceous mat deposits was infrequently interrupted by event deposits due to storms or floods. Event deposits smother the underlying mat, but cycanobacterial filaments are motile, move upwards through the fresh sediment layer, and establish a new mat (Schieber, 1986).

Domal Features in Shales, Dolomitic Laminae, and Random Micas

In mudstones and shales of the Belt Supergroup, suspected microbial buildups can take the appearance of low-amplitude hummocks or domes as shown in Figure 9, or of small hemispherical features (Fig. 10). Mudstone intervals that contain such buildups typically show fine, even laminae of silt, clay, and silt/clay mixtures, and are interbedded with dolomite horizons that show domal stromatolites (Schieber, 1998). Buildups as shown in Figures 9 and 10 occur in thin horizons that differ from mudstones above and below in that they contain dolomitic laminae. The latter consist of a mixture of dolomite, clay, silt, and randomly oriented micas, and alternate with clay/silt laminae wherein the micas are aligned parallel to bedding (Figs. 9, 10). Dolomitic laminae show mica enrichment by up to a factor of 4 relative to clay/silt laminae. The lamina texture of horizons with buildups (Figs. 9, 10) is very similar to that found in associated dolomitic stromatolite horizons. The latter show alternating dolomitic and clastic/dolomitic laminae, and random micas in dolomitic laminae. The overall dolomite content of dolomitic stromatolite horizons, however, is significantly higher.

Chafetz and Buczynski (1992) showed that bacterial decay of cyanobacterial filaments beneath a microbial mat strongly enhances carbonate precipitation. Gebelein and Hoffman (1973) observed that mat laminae in stromatolites are preferentially dolomitic, due to Mg uptake in the mucilaginous sheaths of filamentous cyanobacteria. These observations support a microbial mat interpretation of the dolomitic laminae described above (Figs. 9, 10).

Domal features (Fig. 10), oversteepened laminae (Fig. 10), and textural and compositional parallels to actual stromatolite horizons, are all suggestive of a microbial mat origin for the features shown in Figures 9 and 10. Mat building organisms often produce sticky excretions (Gerdes and Krumbein, 1987) that are able to trap sedimentary particles traveling across the mat (a "flypaper" effect). Abundant micas in dolomitic laminae of buildups in mudstone/shale intervals (Figs. 9, 10) may indicate currents over these mats that were strong enough to transport mica flakes, but insufficient to carry large quantities of detrital quartz. The "flypaper" effect of mat surfaces led to mica enrichment. The random orientation of mica flakes in
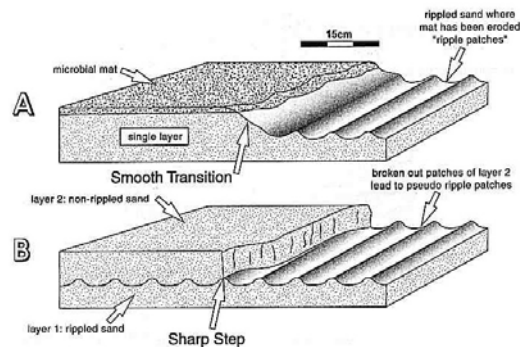

Figure 7: The difference between "smooth transitions" and "sharp steps". (A) shows the smooth, sloping, margin of a ripple patch produced by partial erosion of microbial mat that stabilizes sand surface. This is the type of margin observed in modern and ancient examples (e.g. Reineck, 1979). After burial and lithification we will have a single, unrippled layer of sand with slight depressions that are rippled. (B) shows the significance of sharp steps. They are produced when patches of an overlying (non-rippled) bed are removed (break out) during outcrop weathering. Because we have two layers, partial removal of the upper layer can produce pseudo ripple patches that typically have sharp stepped edges as shown.

dolomitic laminae probably reflects early cementation that prevented alignment during subsequent burial. Garlick (1981) also noted mica enrichment in suspected microbial mats deposits from sandstones of the Zambian Copperbelt.

Mat Fragment Impressions on Bedding Planes

Some mudstone intervals in the Belt Supergroup show irregular curved impressions on bedding surfaces (Fig. 11b). This feature was first described by Horodyski (1982), and attributed to dried-out fragments of thin microbial mats. Microbial mats on episodically exposed modern mudflats dry out, crack, curl up, and can then be transported by wind or flowing water (Fig. 11a). Once the rigid mat fragments are covered up by sediment, they resist immediate compaction and leave their mark in the under- and overlying sediments (Fig. 11b). Comparable bedding plane markings also occur in the Middle Proterozoic Troy Quartzite of Arizona (Horodyski, 1993). Although these impressions and their geological significance have been known for some time (Trusheim, 1936; Clarke and Teichert, 1946), they are very subtle features and require excellently preserved bedding planes to be recognizable.

MICROBIAL MAT FEATURES IN SOME PHANEROZOIC SHALES

Reports of microbial mat deposits in Phanerozoic terrigenous clastics are even more rare than those from the Proterozoic (Gehling, this volume; Hagadorn and Bottjer, this volume). Examples are indications of flat microbial mats in the Cretaceous Dakota Sandstone of Colorado (MacKenzie, 1972), and sandy stromatolites from the Ordovician of Minnesota (Davis, 1968). Whereas these and the Belt Basin examples are all from shallow water environments and thus were probably composed of filamentous photosynthetic cyanobacteria (e.g. Horodyski, 1980), filamentous microbial mats can also develop in deep water, aphotic settings.

Modern deep-water microbial mats are dominated by nonphotosynthetic sulfur-oxidizing bacteria (Williams and Reimers, 1983). They have been reported from the Santa Barbara Basin (Soutar and Crill, 1977) and from upwelling regions along the South American continental margin (Gallardo, 1977), and consist of filamentous sulfur-oxidizing
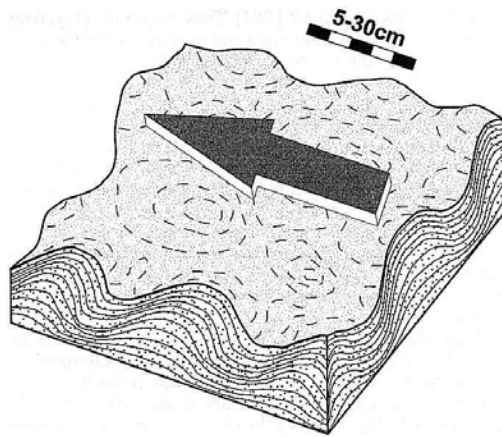
5-30cm

Figure 8: Envisioned formation of domal stromatolites in sandstones. Competition for light promotes upward growth of mats. Sediment is moved over the mat surface by currents and is trapped by sticky mucilaginous mat surface. This causes preferred growth of stromatolite laminae in upcurrent direction (described by Garlick, 1988). Domes of this type were observed in the Revett Formation of the Belt Supergroup (Schieber, 1998).

low amplitude
hummocks/domes

5cm

dolomitic laminae with random micas

clay/silt laminae with aligned micas

irregular laminated mudstone with dolomitic laminae

Figure 9: Diagram showing low amplitude hummocks/domes in mudstone/shale. Lamina style copied over from actual cut rock surfaces. This irregular lamina style is characterized by alternating dolomitic and clay/silt laminae (see detail drawing). Micas are aligned in terrigenous laminae, and random in dolomitic laminae. The latter are supposed to be fossil microbial laminae (Schieber, 1998).

bacteria belonging to the family Beggiatoaceae. Because the mucilaginous sheaths of these bacteria trap and bind other sedimentary particles, their mats constitute "potential stromatolites" (Krumbein, 1983). These mats develop best in low-oxygen environments, because higher oxygen levels would promote burrowing and grazing by benthos (Williams, 1984). They may have played an important role in ancient deep-water oxygen-deprived settings, typically the realm of black shale formation.

Microbial Mat Indications in the Monterey Shale
Williams and Reimer (1983) and Williams (1984) examined organic-rich laminae in the Miocene Monterey Formation, and concluded that the laminae were due to bacterial mats that covered these deep-water sediments. Their conclusion was based on the presence of wavy lamination and the recognition of a spongy texture that was considered analogous to spongy textures in modern bacterial mat deposits (Williams and Reimer, 1983; Williams, 1984).

While these features are intriguing, they constitute no more than a suggestion of microbial surface colonization. The Monterey Formation has a complex history of early diagenetic silica deposition (Isaacs et al., 1983), and it is quite possible that some of the observed waviness of laminae may be due to compaction around early diagenetic silica spherules. As far as the recognition of spongy mat texture is concerned (Williams, 1984), the resemblance between ancient and modern textures is limited.

Although the Monterey Formation was probably deposited in a deep-water low oxygen environment that today seems to favor formation of bacterial mats, it would be highly desirable to base such a determination on more than wavy laminae and vague textural resemblance. If such a determination is to be made, additional evidence needs to be found. Considering that there will be no competition for light in this kind of mat, domal structures are highly unlikely. Although sediment trapping from bottom currents might still produce buildups of the type shown for example in Figure 9, modern deep water mats have a comparatively loose and fuzzy consistency (Gallardo, 1977). At current velocities typical for shallow water environments of the Belt Basin (Schieber, 1990), this type of mat would probably be destroyed. All mats are cohesive, however, and features suggestive of that property (Fig. 3) may well be uncovered
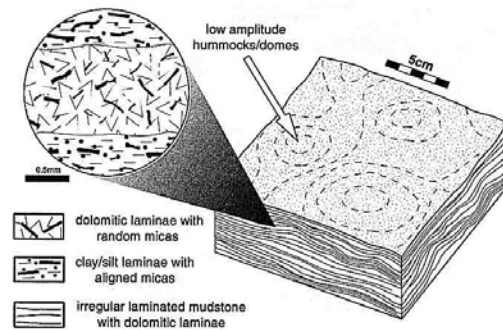
through diligent searching.

Microbial Mat Indications from the Jet Rock
In a recent study of the classical black shale succession of the Jet Rock (Jurassic) of Britain, O'Brien (1990) noticed an unusual, wavy lamina style. Wavy laminated black shales occur in an intermediate position between finely laminated and thickly laminated carbonaceous shales (O'Brien, 1990). The finely laminated shales were interpreted as deposited in anoxic waters beneath a pycnocline, whereas the more silty thickly laminated shales were perceived to reflect more energetic nearshore conditions. For the wavy laminated shales, O'Brien (1990) suggests that the seafloor was colonized by microbial mats that were able to tolerate an oxygen-restricted environment (above pycnocline). Clayey sediment was deposited on top of the sticky, gelatinous mat surface. Alternation of mat growth and fine-grained sedimentation produced the observed wavy lamination (O'Brien, 1990).

The general appearance of the wavy laminated shales is shown in Figure 12. There is a definite resemblance to wavy-crinkly laminae in suspected carbonaceous microbial mat deposits from the Belt Supergroup (Fig. 2). Closer examination, however, shows that the wavy nature of the lamination may not necessarily be due to the irregular surface relief of a microbial mat. Small concretionary bodies (Fig. 13) and tiny lenses of calcareous detritus (Fig. 14) are often found in the non-organic laminae that separate the supposed organic mat laminae. Differential compaction around these lenses, as well as ribbed thin shells of ammonites and flat clams (Fig. 14), may upon compaction impart a wavy texture to these shales.
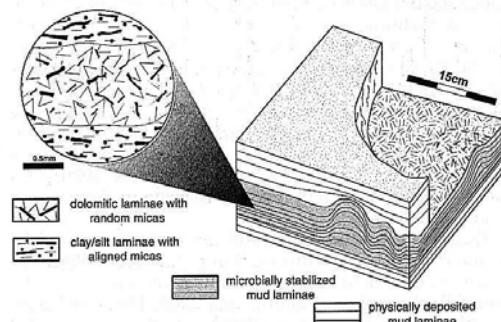

15cm

dolomitic laminae with random micas

clay/silt laminae with aligned micas

microbially stabilized mud laminae

physically deposited mud laminae

Figure 10: Diagram showing small domal buildups in mudstone/shale. Note oversteepended laminae at edge of buildups. Those intervals that show domal buildups are characterized by the same style of alternating dolomitic and clay/silt laminae (see detail drawing) as found in shales/mudstones with low amplitude hummocks/domes (Fig. 9). The dolomitic laminae are supposed to be fossil microbial laminae (Schieber, 1998). The shale draping over these small domes consists only of clay and silt laminae, dolomitic laminae are absent.
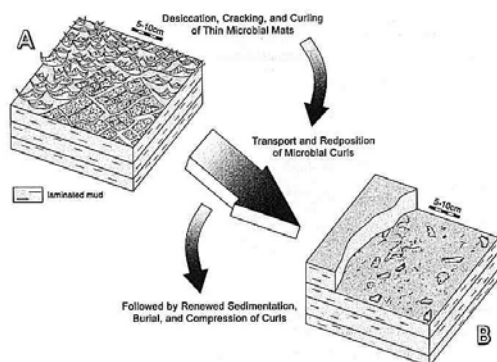
Figure 11: Diagram that illustrates the origin of mat fragment impressions on mudstone bedding planes. Thin microbial mats dry out, crack, and curl up (A). After transport, redeposition, and burial, their rigidity resists initial compaction and leads to curved, irregular impressions on bedding planes (B).

Nonetheless, there are also samples (Fig. 15) where wavy lamination is visible in the absence of detrital lenses, concretionary bodies, etc., suggesting that the waviness is indeed primary. In view of their position within the basin and perceived low oxygen conditions (O'Brien, 1990), a bacterial mat interpretation is very tempting because conditions should have been optimal for growth of deep-water bacterial mats (Williams and Reimer, 1983). Further study of these rocks may well reveal other indications for microbial mats, such as cohesive behavior during sediment erosion and transport (Fig. 3), or mineralogical features interpretable as mat-decay mineralization.

Microbial Mat Indications in the Green River Formation

The Eocene Green River Formation consists of a succession of lake deposits that were deposited under varying climate conditions and has been studied intensively (e.g. Bradley, 1964; Roehler, 1990; Surdam and Stanley, 1979). Extensive horizons of carbonaceous shale with high contents of organic matter and kerogen make it one of the largest oil shale deposits of the world (Tuttle, 1991). The organic matter in these oil shales is usually thought to reflect accumulation of plankton on a lakebed (Bradley, 1964). Because at least some of the Green River lakes were quite shallow (Surdam and Wolfbauer, 1975), it is possible that photosynthetic as well as non-photosynthetic microbial mats may at times have colonized portions of the lake bed.

Smoot (1983) briefly mentioned a possible microbial mat origin for Green River oil shales. Erosion and transport of oil shale intraclasts and the lack of soft sediment deformation beneath silt ripples overlying oil shale beds suggested a cohesive nature and a possible microbial mat origin. Unfortunately, Smoot (1983) only devoted half a paragraph to this issue and did not provide any illustrations. I have therefore chosen to present some key observations from my own examination of the Wilkins Peak Member (Bradley, 1964) of the Green River Formation.

Organic-rich oil shale beds in the Wilkins Peak Member are from less than a mm to several cm thick, and show gently wavy to wrinkled internal laminae (Fig. 16). Clay-rich interbeds (Fig. 16) can contain fragments of organic-rich layers that range in size from less than a mm to several cm (Fig. 17). Deformation and overfolding (Fig. 17) suggests that these fragments were soft and watery at the time of transport, and indicates cohesive behavior during erosion and transport. The edges of these fragments have a frayed appearance (Figs. 17, 18), suggesting that something that had strength in the horizontal direction was being torn apart. Above observations suggest that the organic-rich layer behaved like a tough leathery membrane during erosion and transport. This is the kind of behavior we would expect from a microbial mat, but not from a passively accumulated organic muck.

Carbonaceous and/or kerogen-rich beds with wavy-crinkly laminae have also been reported from several other lacustrine successions, and were interpreted as microbial mat deposits (e.g. Goth, 1990; Goth and Schiller, 1994; Wuttke and Radtke, 1993). Gibling et al. (1985a, 1985b) reports on laminated oil shale deposits from intermontane basins of Thailand, where the organic laminae seem at least in part due to benthic algae (Hutton et al., 1980).

Clay-rich layers in the Wilkins Peak member also contain curious clusters of sand and silt grains (Fig. 19) that may be up to several mm across. Hydrodynamically, these clusters are incompatible with the much finer material that surrounds them (Fig. 19), and may be testament to microbial mats that grew along the lake margins. Fagerstrom (1967) pointed out that mat-bound coarser sediment from lake margins may float up and be rafted to deeper portions of lakes that typically receive only fine sediment. Examples of such algally rafted material ("algal dropstones") have been reported from Triassic lake sediments by Olsen et al. (1978). Sand/silt clusters in Green River shales may be of the same origin.

CONCLUSION

Sediments from the Proterozoic Belt Supergroup and several Phanerozoic successions contain sedimentary features that indicate the former presence of microbial mats in shales and sandstones. Features that may alert us to the possibility of microbial deposits are wavy laminae, wrinkled bed surfaces, and carbonaceous laminae. In the absence of preserved remains of mat building organisms, the changes in sediment behavior that were caused by microbial mats provide the best indications of microbial surface colonization. Ripple patches, for example are due to mat-induced changes in erodability and mobility of surface sediment (Fig. 4c). The cohesive nature of microbial mats leads to overfolding, contorted, and rolled up fragments (Figs. 3, 4, 5), as well as supporting oversteepened laminae and domal buildups (Figs. 8, 10). Compression of dried out algal crusts, whether transported or in situ, may lead to subtle bedding plane markings (Fig. 11). Mat decay may lead to early diagenetic mineralization of dolomite, ferroan dolomite, pyrite and siderite. When this mineralization follows individual laminae/layers of sediment, or if it is clearly associated with deformed, contorted, or curved features (Fig. 4) in rocks that otherwise lack these minerals, microbial mats should be suspected.

These indicators provide circumstantial evidence for microbial mats, they do not constitute proof. Yet, just like a trace fossil, they can be considered a reflection of mat-sediment interaction. The larger the number of different microbial mat indicators that are found in a given sediment horizon, the better the chance that the sediment was indeed microbially colonized.

Our survey indicates that there are probably many more microbial mat deposits hidden in the sedimentary record. Although the search may be tedious, it is a worthwhile endeavor because we might be rewarded with radically altered perceptions of sedimentary environments and conditions. The observation of microbial mat indicators in black shales and oil shales indicates two things: (1) it will require more research to more firmly establish a microbial mat origin for this type of occurrence; and (2) that there is still a lot to be learned about the potential role of benthic microbial communities in the formation of hydrocarbon source rocks.

Biomarkers in sediments derive from a multitude of materials, and their structures can retain evidence of their biological source (Brassell, 1992). Study of biomarkers from various mat building organisms and mat communities may show distinctions from passively accumulated detrital organic matter, and may in the future allow detection and even differentiation of various types of microbial mats in the geologic record.
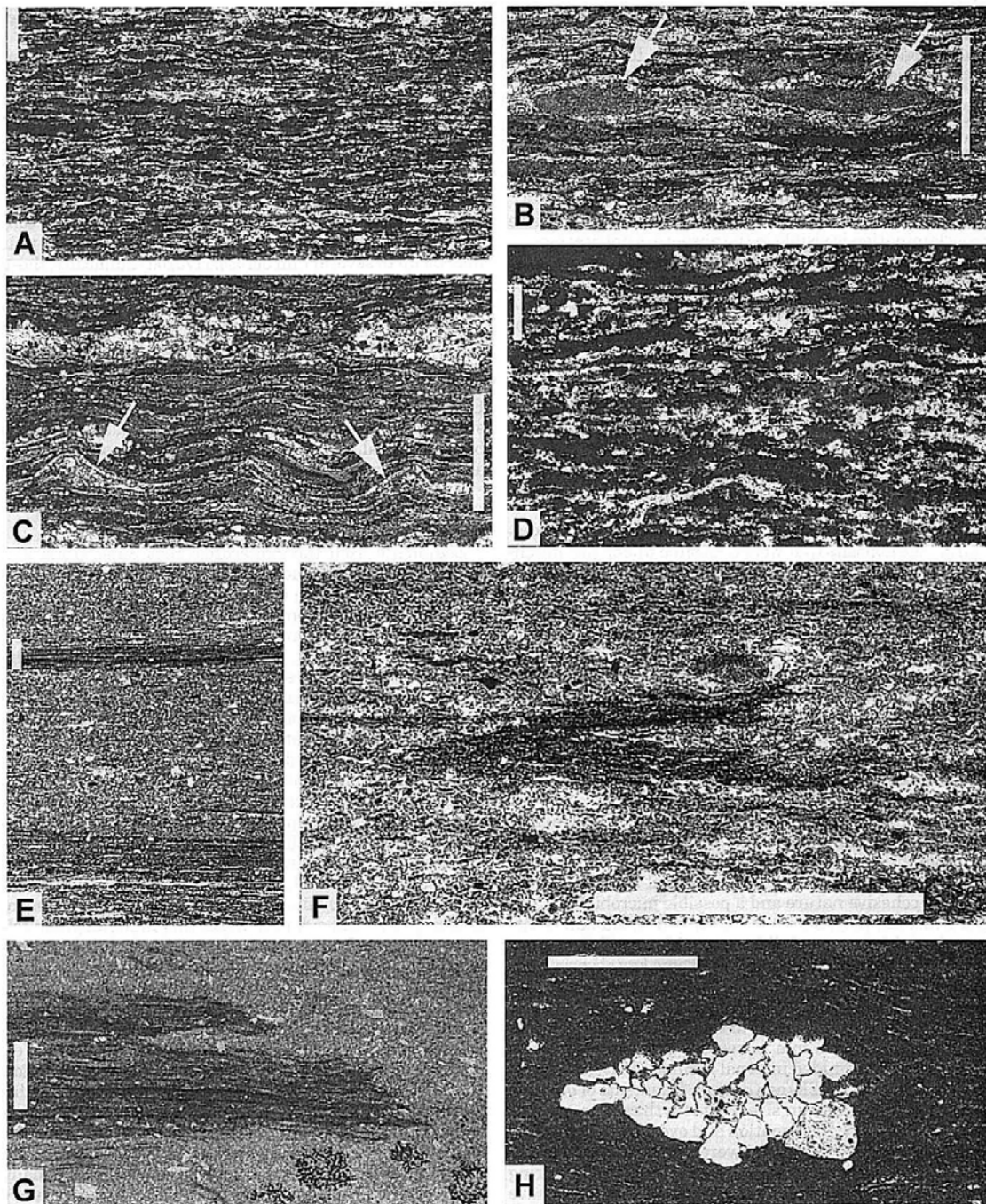
Figure 12 A: Photomicrograph of wavy laminae in the Jet Rock. Dark laminae are rich in organic matter, light laminae contain mainly recrystallized calcareous debris, silt, and clay. Scale bar is 0.5 mm long. See also O'Brien (1990).

Figure 12 B: Photomicrograph of wavy laminated Jet Rock at higher magnification than Fig. 12. Shows fine-crystalline calcareous microconcretions (arrows) that may be the cause for wavy laminae. These microconcretions may also represent fecal pellets, but regardless of their origin they will impart a wavy texture after compaction. Scale bar is 0.5mm long.

Figure 12 C: Photomicrograph of wavy laminated Jet Rock where wavy lamination was caused by rigidity of ribbed fossil shell (arrows). Also note how differential compaction around tiny lenses of calcareous detritus (light color) in the upper half of the photo produces wavy lamination. Scale bar is 0.5mm long.

Figure 12 D: Photomicrograph close-up of wavy laminated Jet Rock where wavy laminae seem not to be caused by microconcretions or ribbed fossil shells. Dark laminae are rich in organic matter, light laminae contain mainly recrystallized calcareous debris, silt, and clay. These wrinkly laminae could possibly be microbial laminae. Scale bar is 0.1 mm long.

Figure 12 E: Photomicrograph close-up of interbedded carbonaceous shale (oil shale, dark layers) and clay beds (light layers) in the Wilkins Peak Member of the Green River Formation. Carbonaceous layers (arrows) show slightly wavy laminae. Scale bar is 0.5 mm long.

Figure 12 F: Photomicrograph close-up of carbonaceous shale fragment (arrow) in clay bed (Wilkins Peak Member of the Green River Formation). The fragment was deformed and folded over during transport, and shows frayed edges. These features suggest cohesive behavior and erosion from a cohesive substrate. Scale bar is 0.5 mm long.

Figure 12 G: Photomicrograph close-up of edge of larger carbonaceous shale fragment in clay bed (Wilkins Peak Member of the Green River Formation). The fragment edges are frayed like a torn piece of fabric. This is suggestive of erosion from a cohesive substrate. Scale bar is 0.5 mm long.

Figure 12 H: Photomicrograph of cluster of sand and silt grains in clay bed of Wilkins Peak Member of the Green River Formation. These grain clusters may have been "rafted in" from the lake margins, bound to microbial mat fragments. Scale bar is 0.5 mm long.

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