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Microbial Mats in the Siliciclastic Rock Record:

A Summary of Diagnostic Features

by

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INTRODUCTION

Although in many instances quite subtle and often overlooked, microbial communities are nonetheless a ubiquitous component in many modern siliciclastic depositional environments. In modern environments the overall impact of microbial communities on sedimentation processes is somewhat diminished as a consequence of metazoan grazing. In the Precambrian, in contrast, they probably colonized most surfaces where their moisture, light, and nutrient requirements were met (e.g. Hagadorn et al. 1999; Schieber 1999).

Typically, the organic components of these communities are degraded upon burial, and what remains is mainly the impact they had on physical and chemical sediment properties (e.g. erodability, cohesion, redox conditions, authigenic minerals). These indirect indicators are in a way analogous to trace fossils, in that the absence of a preserved trace-maker does not preclude the preservation of a record of animal-sediment interactions.

As far as studies of modern examples of microbial mats in siliciclastics are concerned, most progress has been made with regard to mats in shallow marine and tidal settings, primarily because of ease of access (e.g. Gerdes at al., 2000). While still lagging behind research on microbial mat recognition in carbonate rocks, work on microbial mats in siliciclastics has accelerated substantially in the past few years (e.g. Hagadorn et al., 1999; Schieber, 1999; Pflüger, 1999; Gehling, 1999). As a result, we have now a much larger array of sedimentary features to draw upon when we search for microbial mats in the siliciclastic rock record.

In order to make best use of the limited space for this contribution, I have chosen to provide a schematic summary of sedimentary features attributed to microbial mats in mudstones and sandstones in two figures. The accompanying short narrative provides the necessary leads to the in-depth literature on the subject.

Generally speaking, microbial mats influence the depositional fabrics of sedimentary rocks across a broad spectrum of physical, biological, and chemical processes. Their imprints have long been neglected in sedimentological research, in part because knowledge of modern analogs was lacking, and in part because of their cryptic nature. The most telling features that attest to former presence of mats are usually those that indicate uncharacteristic sediment cohesiveness (e.g. for a layer of sand), impermeability (e.g. to gas), tensile strength, erosion resistance, and geochemical behavior during early diagenesis. I hope that the following overview, although quite brief, stimulates further research and leads to the recognition of more fossil occurrences of microbial mats in siliciclastics.

MICROBIAL MAT FEATURES IN SANDSTONES

Figure 1 provides an overview of features we might find in sandstones where microbial mats flourished in the past. The processes behind these features are arranged clockwise, along a continuum from active mat growth to final destruction during diagenesis.

Mat Growth

Binding, trapping, and baffling are typical processes associated with mat development (Gerdes et al., 2000). Depending on the amount of time available for unhindered mat growth and the overall rate of sediment supply, mats may develop (1) as layers of intermingled microbial filaments and extracellular polymers with little mineral content (up to several cm thick), or (2) as thin biofilms of intermingled filaments and sand grains. The latter tend to stabilize sediment surfaces after episodes of physical reworking. Microbial binding "freezes" surface morphology and can in that way lead to (1) surfaces with palimpsest ripples (Fig. 1A) when new sediment is brought in (Pflüger, 1999) and to (2) surfaces with multidirectional ripple marks (Noffke, 1998). With sufficient energy partial erosion of ripple crests may occur, revealing an erosion-resistant top veneer as narrow ridges (Fig. 1B; Pflüger, 1999).

Aside of surface features, sediment binding and trapping can also produce characteristic lamina features. For example, in Fig. 1C graded laminae record brief depositional events, whereas laminae with horizontal mineral grains record episodes of mat formation (Noffke et al., 1997). In these latter laminae sand grains were either embedded horizontally, or rotated into a horizontal orientation as the mat decomposed and compacted. Although potentially useful, this feature has not yet been reported from the rock record, and may be difficult to differentiate from other compaction-related features. Biolamination can also be caused by lamina specific grain selection, such as enrichment with heavy minerals (Fig. 1D; Gerdes et al., 2000) or micas (Garlick, 1981, 1988). The energy level of the environment is another factor in microbial mat development. Under conditions of high current or wave activity three dimensional forms such as domes (Fig. 1E) may develop (favored by rapid synsedimentary lithification), whereas at low energy levels planar forms are prevalent (Hoffmann, 1976; Sami and James, 1993). Domal structures in sandstones have been reported from various Proterozoic and Phanerozoic occurrences (Davis, 1968; Garlick, 1981, 1988; Schieber, 1998).

Interaction between the different members of microbial mat communities, filament abundance, water depth and flooding history (Horodyski, 1977; Horodyski et al, 1977; Gerdes et al., 2000) can lead to a wide range of surface morphologies, including tufts, pinnacles, and pustules (Fig. 1F), bulges and reticulate ornamentation that has been described as "elephant skin" (Gehling, 1999; Fig. 1G), and a variety of wrinkle structures (Hagadorn and Bottjer, 1997, 1999; Schieber, 1998, 1999; Fig. 1H). Although of lesser preservation potential than comparable structures in carbonate producing environments, there is a growing number of reports on these features from Proterozoic sandstones worldwide.

Winds, currents, and gas development, as well as intermittent drying, can lead to intermittent disturbance of mat growth and produce buckling, doming, and rupturing of microbially bound surface layers. Modern examples of such antiform structures in microbial mats have been described as petees (Reineck et al., 1990; Gerdes et al. 1993), and ancient examples have been identified by Gehling (1999). Depending on the intensity of disruption we may see simple polygonal networks of petee ridges (Fig. 1I), or complex sinuous ridges with rupturing of microbial surfaces (Fig. 1J).

Metabolic Effects

Study of modern mats indicates that metabolic process, such as photosythesis, can shift carbonate solubility within mats sufficiently to lead to carbonate precipitation between and along the filaments of growing mats (Krumbein, 1974, 1986; Gerdes and Krumbein, 1987; Chafetz and Buczynski, 1992; Chafetz, 1994). Visible effects in the rock record may be the formation of irregular ooids (Gerdes and Krumbein, 1987), disseminated carbonate grains (e.g. Kropp et al., 1997), micritic cement between terrigenous grains, and highly lamina-specific carbonate cementation of otherwise terrigenous laminae. The presence of high Mg concentrations in sheaths of filamentous cyanobacteria may also favor the formation of very early diagenetic dolomite (Gebelein and Hoffman, 1973). In sandstones, due to their inherent high permeability, it is very likely that these essentially syngenetic signatures are overprinted by subsequent diagenetic processes. Certain textural features, however, such as terrigenous grains'‘floating’in a carbonate matrix, would be suggestive of precompactional and possibly syngenetic carbonate formation (Garlick, 1988; Schieber, 1998). In addition, highly lamina-conformable distribution of pyrite may be reflective of the activity of sulfate reducing bacteria beneath the photosynthetic surface layer (Schieber, 1989).

Physical Mat Destruction

Drying out of mat-bound sand layers can either lead to polygonal or incomplete crack networks that are themselves filled with sand (Fig. 1K), as well as complexly superimposed sets of spindle-shaped cracks (Bouougri and Porada, 2002; Banerjee pers. comm. 2001; not pictured). The critical observation in that case is that the cracks be in a sand layer. In a non-mat sand layer, the inherent grain support makes shrinkage impossible, thus a shrunken sand layer must have had an additional component that could shrink during dehydration. In absence of clays, which could produce similar features during dewatering, a water-rich microbial substrate is the most likely candidate. A special case of this type of sand-based cracks are sinuous-circular cracks known as *Manchuriophycus* (Fig. 1L), probably forming in ripple troughs with thicker mat development (Pflüger, 1999; Gehling, 2000).

Microbial mats may also maintain some of their initial cohesiveness for some time after burial. Thus, during deformation, microbially bound sand layers may show contrasting behavior to over- and underlying layers of loose sand. Non-penetrative microfaults (Fig. 1M) in sand have been interpreted as indicative of microbial mats by Pflüger (1999) and Gehling (1999).

Although microbial mats render a sand surface substantially more resistant to erosion (Neumann, et al., 1970), erosion and reworking will commence once currents are sufficiently strong. The binding of the sand surface, however, leads upon erosion to sedimentary features that are distinctively different from we would expect from erosion of a loose grain substrate. For example, local erosion of mats can expose underlying sand to wave and current action, leading to rippled patches in an otherwise smooth surface (Fig. 1N). This feature has been observed on modern tidal flats (Reineck, 1979; Gerdes et al., 1985), as well as in the rock record (MacKenzie, 1972; Reineck, 1979; Schieber, 1998). The cohesiveness of mat-bound sand surfaces also leads to formation of flipped over edges (Fig. 1O) of partially eroded mat surfaces, as well as redeposition of deformed and rolled up mat fragments (Fig. 1P & 1W). Reports on modern examples are for example by Reineck (1979) and Gerdes et al. (2000), and on ancient examples by Schieber (1998, 1999), Garlick (1981, 1988), Simonson and Carney (1999), and Eriksson et al. (2000).

Microbial sand chips (Pflüger and Gresse, 1996; Bouougri and Porada, 2002) are a variation on this theme (Fig. 1Q). They are typically smaller (a few cm at most) than the irregular and rolled up mat fragments pictured in Fig. 1P, of similar size in a given occurrence, plastically deformed, and often current aligned (Pflüger and Gresse, 1996) and even imbricated (Bouougri and Porada, 2002). These observations suggest that microbial sand chips are a sub-class of eroded mat fragments, abraded and sorted due to a longer transport history. Dried out microbially bound sand surfaces typically yield rigid curved chips (several cm across; Fig. 1V) that can be transported and form intraclasts in high energy sand deposits. Fossil examples are reported by Garlick (1988) and Schieber (1998). In the absence of textural differences (grain size, lamination) between sand chips and their sand matrix, diagenetic effects (mat decay mineralization) related to the organic content of the former (Garlick, 1988; Schieber, 1999) may be the only clue to their recognition (see below).

Mat Decay and Diagenetic Effects:

Gas development from decaying portions of microbial mats can lead to physical disturbance of the sediment and disruption of surface mats. Observed features are gas domes and convoluted internal lamination (Fig. 1R), produced by gas buildup beneath mats (Gerdes et al., 2000; Bouougri and Porada, 2002), as well as ruptured gas domes termed“Astropolithon”(Pflüger, 1999; Fig. 1S). In the latter, the substrate cohesiveness that is implicit in the radial ruptures of the dome (Fig. 1S) is again a good indication of the former presence of a mat. Gas development also contributes to the formation of the more severely disturbed and ruptured petee structures (Fig. 1J).

Kinneyia style ripples (Fig. 1T) show considerable similarity to wrinkled mat surfaces (Fig. 1G & 1H). On account of the steep slopes of their troughs and their flat tops, however, they were interpreted by Pflüger (1999) to reflect gas trapping beneath flat mats. Whereas those described by Pflüger (1999) really seem to represent gas trapping beneath mats, many *Kinneyia* described in the literature show more resemblance to the round crested microbial wrinkle marks described by Hagadorn and Bottjer (1999). Thus, care to detail is clearly needed to properly interpret wrinkled surface features.

Due to the permeability of sand, organic matter is readily metabolized by microbes during early burial, making it unlikely that organic matter will survive as a microbial mat indicator. Fortunately, microbial mats also constitute sharply defined geochemical boundaries (Bauld, 1981), and anaerobic decay beneath mats favors formation of "anoxic" minerals such as pyrite, siderite, and ferroan dolomite. Cementation of sand grains by these minerals constitutes "mat-decay mineralization" (Schieber, 1998). Ghosts of filaments may be preserved in these cements.

Observing thin, stratiform horizons of these minerals (Fig. 1U) in a shallow water sandstone (above wave base) is suggestive of the former presence of microbial mats

(Gerdes et al., 1985; Garlick, 1988). Depending on water chemistry (e.g. marine vs. freshwater) different minerals will be favored (e.g. pyrite vs. siderite). Burial of rigid (Fig. 1V) or soft fragments (Fig. 1Q & W) of resedimented mat can upon decay give rise to comparable cementation that preserves the former outline of transported mat fragments (Garlick, 1988; Pflüger and Gresse, 1996; Schieber, 1998).

MICROBIAL MAT FEATURES IN SHALES

Figure 2 provides an overview of microbial mat features we might find in ancient mudstones. As in Figure 1, causative processes are arranged clockwise, and their effects illustrated with drawings and photos.

Mat Growth

Although binding, trapping, and baffling are equally well associated with microbial mats on muddy substrates, preservation of surface relief is of a more subtle nature, due the intrinsically high degree of compaction. Nontheless, the initial surface relief leads to wavy-crinkly laminae (Fig. 2A) that are distinctively different from the parallel laminae that form in mudstones as a result of physical sedimentation processes (Schieber, 1986; Fairchild and Herrington, 1989; O'Brien, 1990; Goth, 1990; Goth and Schiller, 1994; Wuttke and Radtke, 1993).

There are also examples where mat colonization of an irregular surface (e.g. an intraclast conglomerate) had a smoothing effect (Fig. 2B). In non-mat mudstones, compactional effects over comparable relief tend to be visible for a greater distance upward from the underlying surface irregularities.

Surface stabilization by mat cover can also be deduced from differences in loading behavior (Schieber, 1986). For example, in mudstone units where silt layers were deposited on mat-bound surfaces as well as on non-mat muds, comparable silt layers produce miniature ball and pillow structures on the latter (Fig. 2C), and only minor load features on the former (Fig. 2D).

Whereas above wavy-crinkly carbonaceous laminae have mainly been reported from inferred subtidal and shelf deposits (Schieber, 1986; Fairchild and Herrington, 1989; Logan et al., 1999), domal buildups of various amplitude and spacing have been observed in nearshore mudstones (Fig. 2E & F; Schieber, 1998). It is quite likely that the inherent rapid weathering of mudstones has thus far concealed a variety of other occurrences in the rock record from scrutiny.

By burying a growing mat under a sudden influx of sediment, event sedimentation (storms, floods) can cause interruption of mat growth. Intermittent event sedimentation in an area of mat growth can lead to "striped shales" with alternating mat and event layers (Fig. 2G; Schieber, 1986; Logan et al., 1999). Occasional deposition of thin clay drapes in areas of incomplete but expanding mat cover may lead to false cross-lamination (Fig. 2H) at the edge of expanding mat patches. In this situation mats re-establish themselves (vertical movement of filaments) on top of recently deposited clay drapes and expand laterally (Schieber, 1986). In many instances, the resulting false cross-lamination probably will probably look quite a bit more irregular than depicted in Fig. 2H.

The processes leading to petee structures are not dependent on a particular substrate (e.g. Reineck at al., 1990; Gerdes et al., 2000), and analogous structures (but at a smaller scale) occur in modern mud puddles. It is probably only a matter of time before fossil analogs will be recognized in the rock record.

Enrichment of mat laminae with mica flakes (Fig. 2I) is one type of lamina specific grain selection that has been observed in mud-based microbial mats (Schieber, 1998). Just as for sandy microbial mats, the underlying causes for this type of grain enrichment are not well understood (Gerdes et al., 2000).

Metabolic Effects

Just as in sandy microbial mats, we can expect to see syngenetic carbonate precipitation associated with mats growing on a muddy substrate. Observation of randomly oriented (instead of subhorizontal) mica flakes in conformable carbonate-rich laminae can for example be a suggestion of syngenetic carbonate deposition (Schieber, 1998). Cementation later in burial history would most likely be accompanied by partial rotation of mica flakes into the horizontal. Terrigenous grains floating in a carbonate matrix would similarly suggest essentially syngenetic carbonate precipitation. Although pyrite formation also happens quite early, because it results from mat decay under anaerobic conditions it is considered with diagenetic effects (see below).

In cases where bituminous substances can still be extracted from suspected fossil mat deposits, carbon isotopes and biomarkers, in conjunction with determination of carbon and sulfur isotopes, can be used to deduce the likely metabolic pathways operating at the time of deposition (Brassell, 1992; Logan et al., 1999). These biomarkers may help to determine whether a mat system was dominated by cyanobacteria (oxygenic photosynthesis), photosynthetic sulfur bacteria (anaerobic photosynthesis), or sulfide oxidising bacteria (chemoautotrophy; Gallardo, 1977; Williams and Reimers, 1983). Because of the implications for the global cycling of carbon and sulfur, the differentiation of photosynthetic mats from non-photosynthetic and sulfide oxidizing types, as well as the magnitude of microbial mat involvement in black shale formation, is of considerable interest.

Physical Mat Destruction

Sedimentary features produced by erosion of mat-bound mud surfaces are broadly similar to those observed in the erosion of sandy microbial mats (Fig. 1N, O, P). Flipped over mat edges (Fig. 2J), overfolded mat layers (Fig. 2K), and "roll-up" structures of various size have all been observed in ancient examples (Schieber, 1986, 1998, 1999). Mat layers distinguish themselves from other mud layers by their display of "within layer" cohesiveness upon erosion and transport (Fig. 2L), as well as by rheological differences between mat layers (firm-doughy, less compactable) and normal mud (soft-fluid, yogurt-like; Fig. 2K; Schieber, 1986).

Because the tearing of a mat is analogous to the tearing of a fibrous fabric, torn mats tend to display frayed edges (Fig. 2M). This phenomenon has been termed "blotting paper effect" in studies of modern mats (Gerdes et al., 1993), and has also been described from fossil examples (Schieber, 1999).

Although, desiccation of muddy microbial mats will produce cracks and dried out mat chips, recognition in the rock record is not a trivial task. While in the case of sandy surfaces, shrinkage features (Fig. 1K) and coherent transport (Fig. 1Q) are highly suggestive of a binding material with high water content (such as a mat), muds are already watery and coherent in the absence of mats. Thus, even without a mat they will crack and produce chips when dried. Though modern mats on muddy substrate tend to modify crack morphology and crack edges (Gerdes at al., 1993), to date I am unaware of any systematic documentation of desiccation effects in ancient mat-bound muddy sediments.

One example of desiccation in mats on a muddy substrate concerns the drying out of thin mats (biofilms) covering mudflat surfaces. As these microbial films dry out they crack and curl up, and can then be transported by wind (Trusheim, 1936) and water (Fagerstrom, 1967). Because these fragments resist compaction upon redeposition, they leave irregular impressions on mudstone bedding planes (Fig. 2N), that on occasion are reported from the rock record (Horodyski, 1982, 1993).

Dried-out mat fragments can also float out into open water bodies (Fagerstrom, 1967), and thus transport detrital grains from nearshore regions to deeper portions of a water body. Clusters of coarser grains (Fig. 2O) that occur in otherwise "pure" mudstones may thus be explained as material that was "rafted in" by mat fragments from nearshore areas, and buried collectively once a fragment had sunk to the bottom (Olsen et al., 1978; Schieber, 1999). In Phanerozoic sediments care has to be taken to positively eliminate alternative mechanisms, such as rafting in with plant debris and animal carcasses (buoyed by decomposition gases), as well as fecal pellets.

Mat Decay and Diagenetic Effects

An effect similar to that produced by grain rafting via dried-out mat fragments, may also occur when gas formation in submerged mats, either due to photosynthesis or to decay processes, induces portions of the mat to detach from the substrate and to float upward (Fagerstrom, 1967). Attached coarser grains may then be rafted offshore and give rise to clusters of coarse grains within a much finer matrix (Fig. 2O).

Anaerobic decay of organic matter beneath a growing mat is a favorable environment for precipitation of "anoxic" minerals, such as pyrite, siderite, and ferroan dolomite. In marine settings, this sub-mat decay typically leads to production of hydrogen sulfide and to pyrite formation (Berner, 1984). Depending on the availability of iron, manifestations in the rock record can range from carbonaceous laminae dusted with tiny pyrite grains (Schieber, 1989), to strongly pyritic laminae (Fig. 2P) that closely follow the original organic laminae and mimic the wavy-crinkly mat lamination (Fig. 2A; Schieber, 1989).

Later diagenetic effects may include pyrite overgrowth and cementation of the fine grained original pyrite (Strauss and Schieber, 1990), as well as recrystallization and enlargement of carbonate minerals in layers with syngenetic carbonate accumulations (Fig. 2Q). Maturation of organic matter upon further burial leads to reduction of organic content (hydrocarbon formation), as well as gradual destruction of biomarkers and kerogens. In contrast to sandstones, however, the low permeability of mudstones thwarts complete organic matter destruction and leads to preservation of anastomosing carbonaceous laminae (Fig. 2R).

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FIGURE CAPTIONS

Figure 1: Overview of features we might find in sandstones where microbial mats flourished in the past. Processes that produce these features are arranged clockwise, along a continuum from active mat growth to final destruction during diagenesis.

Figure 2: Overview of microbial mat features we might find in ancient mudstones. Processes that produce these features are arranged clockwise, along a continuum from active mat growth to final destruction during diagenesis.

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Figure 1

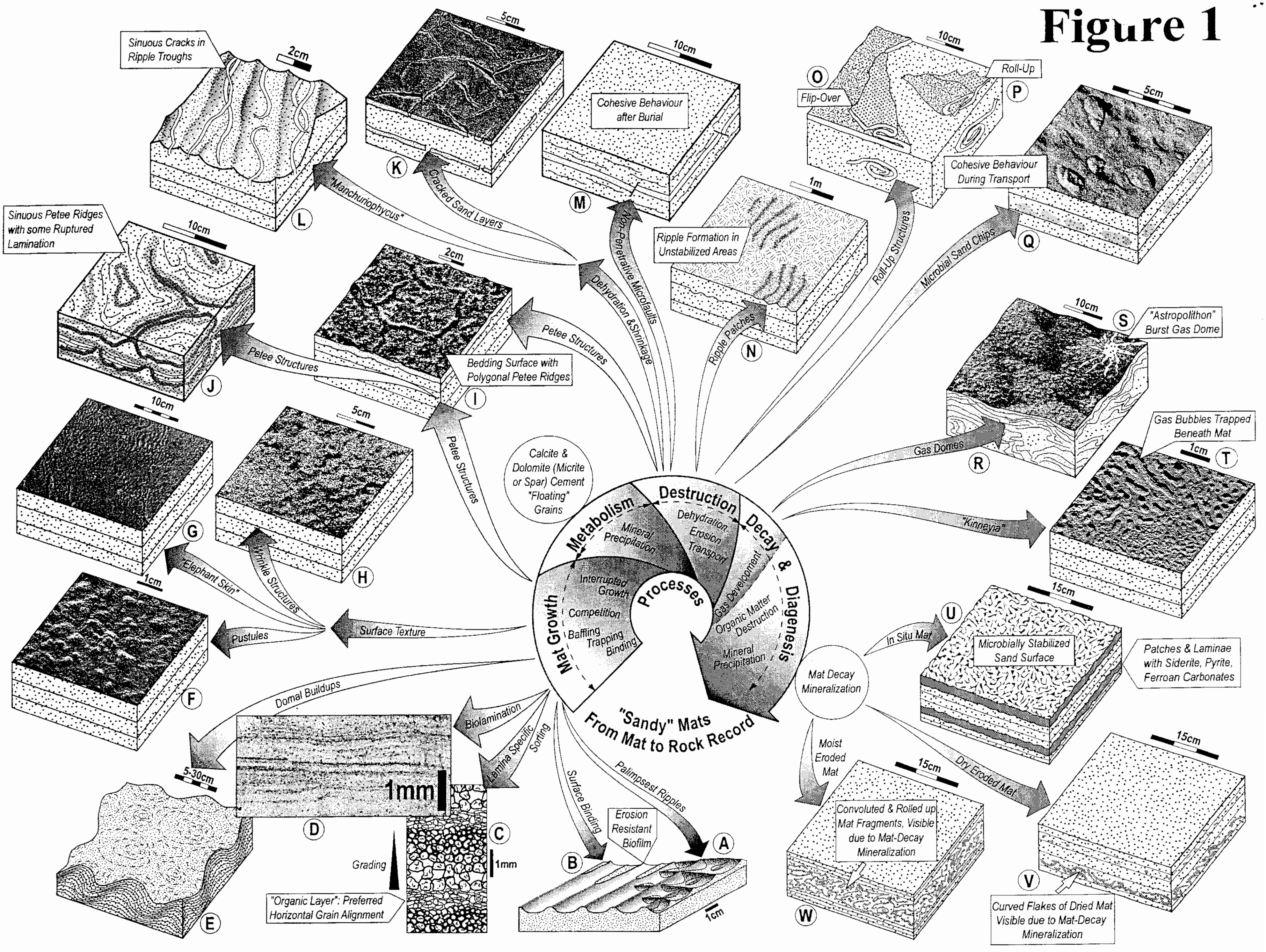
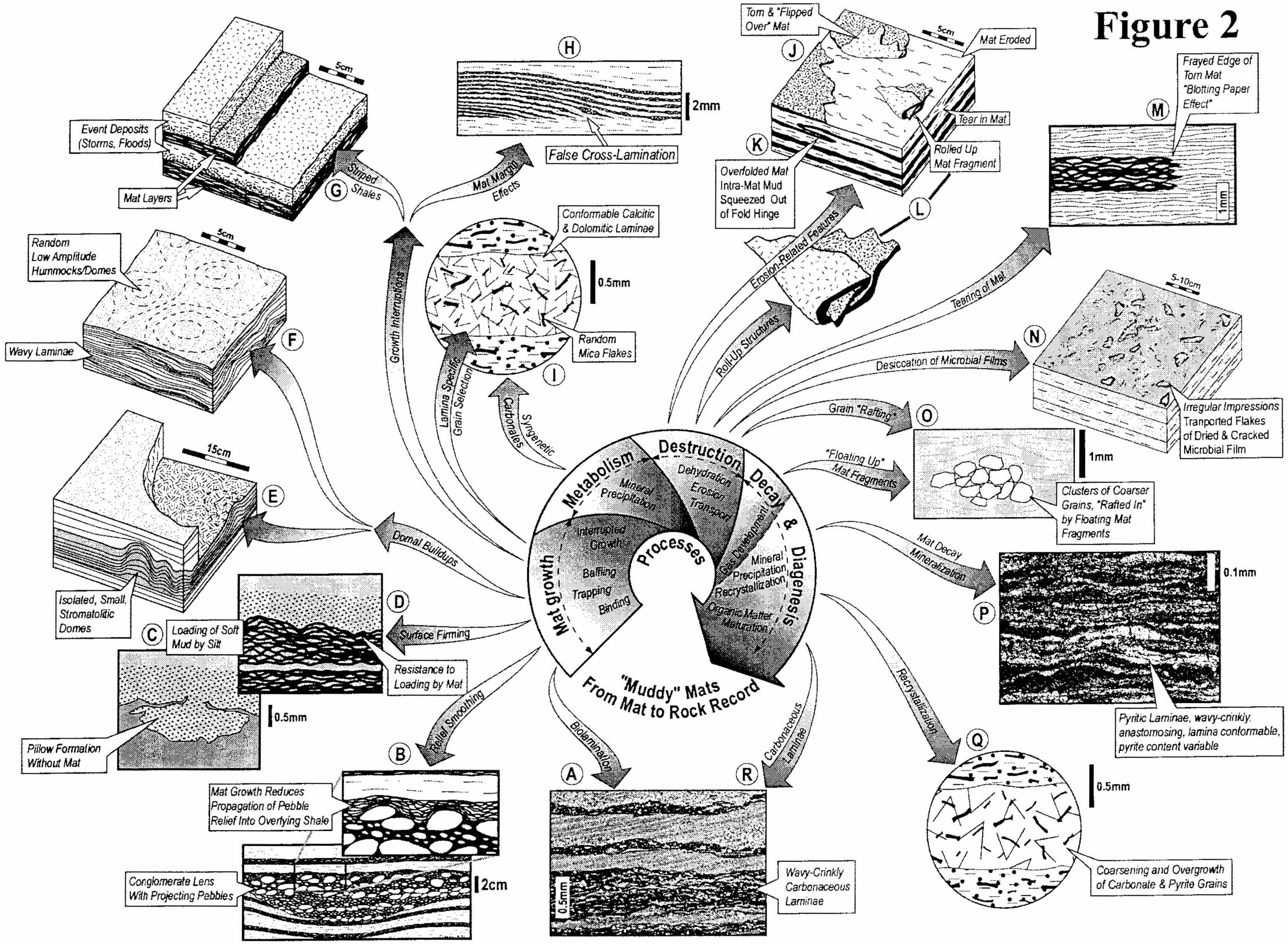

"Sandy" Mats
From Mat to Rock Record
Processes
Mat Growth
Interrupted Growth
Competition
Baffling
Trapping
Binding
Metabolism
Mineral Precipitation
Destruction
Dehydration
Erosion
Transport
Decay & Diagenesis
Gas Development
Organic Matter Destruction
Mineral Precipitation
Calcite & Dolomite (Micrite or Spar) Cement "Floating" Grains
Palimpsest Ripples
Surface Binding
Erosion Resistant Biofilm
A
B
1cm
Lamina Specific Sorting
Biolamination
C
1mm
D
1mm
Grading
"Organic Layer": Preferred Horizontal Grain Alignment
Domal Buildups
5-30cm
E
Surface Texture
Pustules
F
1cm
"Elephant Skin"
G
10cm
Wrinkle Structures
H
5cm
Petee Structures
I
2cm
Bedding Surface with Polygonal Petee Ridges
Petee Structures
J
10cm
Sinuous Petee Ridges with some Ruptured Lamination
Petee Structures
Dehydration &Shrinkage
"Manchuriophycus"
L
2cm
Sinuous Cracks in Ripple Troughs
Cracked Sand Layers
K
5cm
Non-Penetrative Microfaults
M
10cm
Cohesive Behaviour after Burial
Ripple Patches
N
1m
Ripple Formation in Unstabilized Areas
Roll-Up Structures
O
Flip-Over
P
Roll-Up
10cm
Microbial Sand Chips
Q
5cm
Cohesive Behaviour During Transport
Gas Domes
R
S
10cm
"Astropolithon" Burst Gas Dome
"Kinneyia"
T
1cm
Gas Bubbles Trapped Beneath Mat
Mat Decay Mineralization
In Situ Mat
U
15cm
Microbially Stabilized Sand Surface
Patches & Laminae with Siderite, Pyrite, Ferroan Carbonates
Moist Eroded Mat
W
15cm
Convoluted & Rolled up Mat Fragments, Visible due to Mat-Decay Mineralization
Dry Eroded Mat
V
15cm
Curved Flakes of Dried Mat Visible due to Mat-Decay Mineralization

Figure 2


Processes
Mat growth
Interrupted Growth
Baffling
Trapping
Binding
Metabolism
Mineral Precipitation
Destruction
Dehydration
Erosion
Transport
Decay
Gas Development
& Diagenesis
Mineral Precipitation
Recrystallization
Organic Matter Maturation
"Muddy" Mats
From Mat to Rock Record
Event Deposits (Storms, Floods)
Mat Layers
5cm
G
Striped Shales
H
2mm
False Cross-Lamination
Mat Margin Effects
Growth Interruptions
Conformable Calcitic & Dolomitic Laminae
0.5mm
Random Mica Flakes
I
Lamina Specific Grain Selection
Syngenetic Carbonates
Torn & "Flipped Over" Mat
J
5cm
Mat Eroded
Tear in Mat
Rolled Up Mat Fragment
K
Overfolded Mat Intra-Mat Mud Squeezed Out of Fold Hinge
L
Erosion-Related Features
Roll-Up Structures
Figure 2
Frayed Edge of Torn Mat "Blotting Paper Effect"
M
1mm
Tearing of Mat
Random Low Amplitude Hummocks/Domes
5cm
Wavy Laminae
F
5-10cm
N
Desiccation of Microbial Films
Irregular Impressions Tranported Flakes of Dried & Cracked Microbial Film
Grain "Rafting"
O
1mm
"Floating Up" Mat Fragments
Clusters of Coarser Grains, "Rafted In" by Floating Mat Fragments
15cm
E
Domal Buildups
Isolated, Small, Stromatolitic Domes
D
Surface Firming
Loading of Soft Mud by Silt
C
Resistance to Loading by Mat
0.5mm
Pillow Formation Without Mat
Mat Decay Mineralization
0.1mm
P
Pyritic Laminae, wavy-crinkly, anastomosing, lamina conformable, pyrite content variable
B
Relief Smoothing
Mat Growth Reduces Propagation of Pebble Relief Into Overlying Shale
Conglomerate Lens With Projecting Pebbles
2cm
Biolamination
A
0.5mm
R
Carbonaceous Laminae
Wavy-Crinkly Carbonaceous Laminae
Recrystallization
Q
0.5mm
Coarsening and Overgrowth of Carbonate & Pyrite Grains