Possible indicators of microbial mat deposits in shales and sandstones: examples from the Mid-Proterozoic Belt Supergroup, Montana, U.S.A.

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Abstract

It has been suspected for some time that microbial mats probably colonized sediment surfaces in many terrigenous clastic sedimentary environments during the Proterozoic. However, domination of mat morphology by depositional processes, post-depositional compaction, and poor potential for cellular preservation of mat-building organisms make their positive identification a formidable challenge. Within terrigenous clastics of the Mid-Proterozoic Belt Supergroup, a variety of sedimentary structures and textural features have been observed that can be interpreted as the result of microbial colonization of sediment surfaces. Among these are: (a) domal buildups resembling stromatolites in carbonates; (b) cohesive behaviour of laminae during soft-sediment deformation, erosion, and transport; (c) wavy–crinkly character of laminae; (d) bed surfaces with pustular–wrinkled appearance; (e) rippled patches on otherwise smooth surfaces; (f) laminae with mica enrichment and/or randomly oriented micas; (g) irregular, curved–wrinkled impressions on bedding planes; (h) uparched laminae near mud-cracks resembling growth ridges of polygonal stromatolites; and (i) lamina-specific distribution of certain early diagenetic minerals (dolomite, ferran carbonates, pyrite). Although in none of the described examples can it irrefutably be proven that they are microbial mat deposits, the observed features are consistent with such an interpretation and should be considered indicators of possible microbial mat presence in other Proterozoic sequences. © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

The Proterozoic biosphere was dominated by microorganisms (Schopf and Klein, 1992) and the published record of their fossil remains is strongly dominated by stromatolites — finely laminated organosedimentary structures due to the sediment binding and/or carbonate precipitating activities of microbial communities. Whereas microbial mats, their modern analog, today only figure prominently in re-

stricted settings that reduce or eliminate competition and grazing by other organisms (Garrett, 1970), the microbial communities that produced Precambrian stromatolites very likely colonized any conceivable environment where their light and nutrient requirements were met. Practically all reports of stromatolites in Proterozoic basins, however, are from carbonate environments (Awramik, 1984; Walter et al., 1992), whereas reports from terrigenous clastic environments are extremely rare (Schieber, 1986). This is in contrast to observations on a variety of modern sedimentary environments where microbial mats are

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found on siliciclastic sandy (e.g. Gunatilaka, 1975; Schwarz et al., 1975; Gerdes et al., 1985; Gerdes and Krumbein, 1987; Witkowski, 1990) as well as on fine-grained siliciclastic substrates (e.g. Miller, 1975). Just casually observing the microbial colonization of the bottom of an ephemeral puddle in a clay pit or a construction site should demonstrate convincingly that microbial communities can thrive quite well on all kinds of terrigenous clastic substrates.

Considering that microbial mat colonization of siliciclastic sediment surfaces is not uncommon in modern environments, one has to wonder about the paucity of recorded stromatolite occurrences in Proterozoic terrigenous clastic sequences. That such colonization did not occur is unlikely, considering the inevitable dominance of microbial communities in the Proterozoic. Thus one must conclude that the problem lies in recognizing microbial mat deposits in terrigenous rocks.

Most geologists will probably feel reasonably comfortable to refer to laminated carbonate rocks with a three-dimensional domal or columnar structure as stromatolites because an extensive literature has been published on them (e.g. Logan et al., 1964; Walter, 1976) and because their morphological features are readily identified in the field. However, already with regard to the more abundant flat laminated carbonate rocks of microbial origin (e.g. Wilson, 1975) that were for example described as cryptalgalaminites or planar stromatolites by Aitken (1967), recognition is not as straightforward. Rather than being based on morphology, it relies in that case on textural characteristics such as lamina structure, fenestrae, microfossils and other features.

Recognizing microbial mats in ancient terrigenous sediments is a difficult task. The likelihood that, just as their modern analogs (e.g. Gunatilaka, 1975; Bauld, 1981; Gerdes and Krumbein, 1987; Witkowski, 1990), microbial mats in ancient terrigenous deposits were most probably of the flat laminated type, is a major obstacle to their identification. Even if such mats had some original surface relief, it would inevitably be reduced or obscured due to burial compaction (e.g. Park, 1976; Krumbein and Cohen, 1977). Also, in contrast to carbonate microbial mat deposits where early diagenetic cementation may preserve domal morphology, lamina textures, and even filament structures (e.g. Horodyski, 1975),

decomposition of organic matter and subsequent fabric collapse in terrigenous mats may lead to complete obliteration of definitive microbial mat features. To make matters worse, proving that a given domal, columnar, or planar laminar sedimentary feature is indeed of biogenic origin is far from trivial. 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 criteria of biogenicity (e.g. Buick et al., 1981; Krumbein, 1983; Grotzinger and Rothman, 1996) to published examples of stromatolites (almost all in carbonates), only a very small proportion of these actually qualify as having a clearly demonstrable organosedimentary origin. Considering these obstacles, one might think it a fairly hopeless proposition to prove biogenic origin of suspected microbial mat deposits in Proterozoic terrigenous clastics.

Compared with carbonate rocks, there clearly is a paucity of possible microbial mat deposits reported from Precambrian terrigenous clastics. To have any chance to conclusively prove the existence of organosedimentary structures in such rocks, one will first have to identify localities where such a quest has a chance to succeed. Furthermore, it needs to be established which sedimentological and textural features may indicate the presence of microbial mat deposits. It is the purpose of this paper to show on examples from the Belt Supergroup what kind of features could be useful to that end. It is hoped that they will alert others to the possible presence of microbial mat deposits in Proterozoic terrigenous clastics elsewhere. Eventually one should be able to identify at least some occurrences with exceptional preservation (e.g. with early diagenetic silicification) where positive proof of organosedimentary origin can be established. This would in turn help to tighten sedimentological and textural criteria for mat recognition.

In the Belt Supergroup, microbial mats in terrigenous sediments have been suspected in three stratigraphic units, the Revett Formation (Garlick, 1988), the Wallace Formation (Grotzinger, 1981), and the Newland Formation (Schieber, 1986). However, only in the latter case has a detailed investigation of possibly mat-related sedimentary features been undertaken. The question arises whether a plausible case for microbial mats in the former two formations

can also be made, and whether other terrigenous formations of the Belt Supergroup might also contain possible microbial mat deposits.

2. Geologic setting

The Belt Supergroup and its Canadian equivalent, the Purcell Supergroup, constitute a thick, primarily terrigenous clastic sequence (Fig. 1) that was deposited between 1450 and 850 m.y. ago (Harrison, 1972). Whether the Belt basin was connected to the Proterozoic world ocean (Price, 1964; Harrison, 1972), or whether it was an inland body of water (Stewart, 1976; Sears and Price, 1978), has been an ongoing debate for almost a century. Recently a lacustrine interpretation of the Belt basin has been promoted by Winston (1986), based on a comparison of sedimentary features with lacustrine sediments elsewhere. Cressman (1989) on the other

hand, based on a Proterozoic plate reconstruction by Piper (1982), palinspastic restorations, tectonic subsidence analysis, and a stratigraphic study of the Prichard Formation, came to the conclusion that, even though the Belt basin is located on continental crust, it formed a narrow gulf that was connected to the Proterozoic ocean. According to Cressman (1989) the initial Belt basin was fairly deep during most of Prichard deposition, shallowed toward the end of Prichard deposition, and was filled with shallow water to subaerial deposits for the remainder of Belt sedimentation. Recently an interpretation of the Belt Supergroup as the fill of a remnant ocean basin (episutural basin model) has been suggested by Hoffman (1988).

Winston's (1986) lacustrine interpretation is based primarily on a comparison of facies and sedimentary cycles in the Missoula Group (Fig. 1) with those of the lacustrine Green River Formation (Eocene).
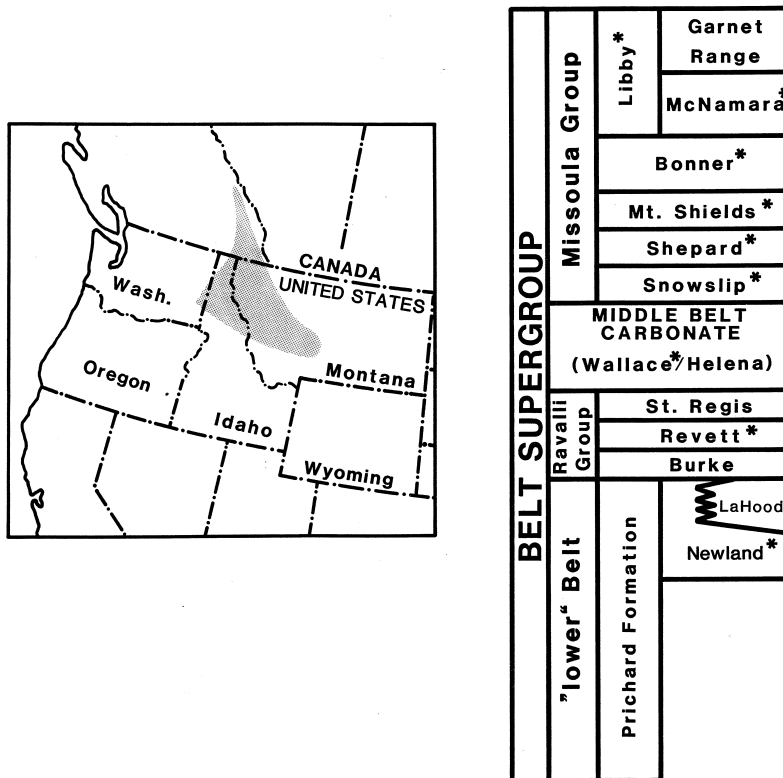

Fig. 1. Location of study area. Present-day outline of Belt basin outlined with stipple pattern. Overview of Belt Supergroup nomenclature largely after Harrison (1972). Relationships of Libby, McNamara, and Garnet Range Formations after Kidder (1987), and of LaHood and Newland Formation after Schieber (1992). Star symbols indicate formations where microbial mat indicators were found.

However, if as Cressman suggests the Belt basin was a shallow gulf during Missoula time, tidal influence was probably strongly attenuated (Shaw, 1964), and the distinction between shallow marine and lacustrine facies cannot be made on sedimentologic criteria alone. Geochemical considerations, such as the question of the source for the large quantities of calcium and magnesium in the dolomites of the 'Middle Belt Carbonate' (Grotzinger, 1986), as well as sulphur isotope studies of sedimentary pyrites (Strauss and Schieber, 1990), suggest that, even though an epicratonic setting is indicated, the Belt basin was nonetheless connected to the Proterozoic ocean (Schieber, 1998). Furthermore, because of the large environmental tolerance of microbial mat communities (Krumbein, 1983), indications of their former presence should be detectable in shallow water terrigenous clastics of the Belt Series regardless of a marine or lacustrine setting.

3. Observations

Well exposed outcrops of sandstones and shales in various formations in the Belt Supergroup were examined for indications of microbial activity. Prior studies of the examined formations (e.g. Winston, 1986; Schieber, 1989) suggest that the examined sediments were deposited in shallow water to episodically emergent environments (Table 1). Most observations suggesting former presence of microbial mats were made on the Newland, Revett, Mt. Shields, and McNamara Formations. Additional observations suggest probable microbial mat deposits in terrigenous rocks of the Snowslip, Shepard, Bonner, and Libby Formations. Table 1 lists the various features that are thought to be related to microbial mat deposition, the formations in which they have been observed, and gives a generalized assessment of depositional setting. Sedimentary features of possible microbial mats in shales of the Newland Formation have been described in detail in an earlier publication (Schieber, 1986), and several of these features were also found in other formations of the Belt Supergroup. The various features in Table 1 are described in the following section.

Sediments of the Belt Supergroup have in all but the easternmost localities undergone various degrees of greenschist-grade metamorphism. In the examined outcrops, however, metamorphic features are so minor that not even cleavage development is obvious in thin section, and all of the details of primary sedimentary structures are faithfully preserved. Therefore, terrigenous clastics will be described as sandstones and shales regardless of metamorphic overprint.

3.1. Wavy–crinkly laminae

Wavy–crinkly laminae are a textural feature that has been observed in most of the suspected microbial mat occurrences (Table 1). This feature is best observed in thin section, but also may give rise to irregularly wrinkled and pustular–crinkled surface relief on otherwise 'smooth' bedding planes (see also below). Bed surfaces from the Mt. Shields and McNamara Formations (Figs. 2 and 3), as well as thin sections from the Newland Formation (Fig. 4) display this feature.

In the Mt. Shields Formation these laminae are petrographically characterized by abundant finely crystalline dolomite and randomly oriented detrital micas (Fig. 5). These laminae are themselves interlaminated with physically deposited laminae of silt and clay that show size grading and lamina-parallel alignment of micas (Fig. 6). Detrital mica flakes are proportionally more abundant in the wavy–crinkly dolomitic laminae than in the 'normal' terrigenous laminae.

Alternating silt and clay laminae of wavy–crinkly appearance in the McNamara Formation (Fig. 3) were found overlying cross-laminated sand. In cross-section (Fig. 7) these laminae resemble those of microcolumnar buildups or microbial tufts observed in modern mats (Gerdes and Krumbein, 1987).

In the Newland Formation wavy–crinkly laminae are found in beds of carbonaceous silty shale, consisting of alternating carbonaceous laminae, drapes of dolomitic clayey shale, and tiny lenses of silt (Fig. 4). The carbonaceous shale beds can be entirely dolomite-free, or may contain up to 30 or 40% finely crystalline dolomite.

3.2. Carbonaceous microlaminae

Carbonaceous shales similar in appearance to those of the Newland Formation (Fig. 4) were described by Kidder (1987) from the Libby Formation

Table 1
Summation of possible microbial mat features with regard to various formations in the Belt Supergroup, and generalized depositional settings

Observations	Newland	Revett	Wallace	Snowslip	Shepard	Mt. Shields	Bonner	McNamara	Libby
wavy-crinkly laminae	■			■	■	■	■	■	■
carbonaceous microlaminae	■		■	■	■	■		■	■
cohesive behaviour	■	■	■						
ripple patches						■		■	
domal structures		■	■			■			
uparching of laminae						■			
possible mat fragment impressions			■						
dolomitic laminae and ferroan carbonates	■	■				■			
mica enrichment and random micas		■		■	■				
smooth and irregularly wrinkled to pustular-crinkled bedding planes				■		■	■	■	

Depositional settings (left to right): calm-offshore, sea-marginal sandflats, shallow nearshore lagoons, shallow nearshore, calm-offshore

as 'microlamina sediment type'. The latter occurs in other units of the Belt Series as well (Winston, 1986), and examples from the Wallace Formation were thought to be of microbial origin by Grotzinger (1981).

Upon close inspection, carbonaceous microlaminae in the Newland Formation (Schieber, 1986) are characterized by wavy–crinkly texture, cohesive behaviour during erosion, transport, and deformation, patterns of selective sediment trapping, and growth in response to pulses of episodic sediment input (Schieber, 1986). Examples of carbonaceous microlaminae from the Wallace and Libby Formations were examined in similar detail. The majority of laminae from these two formations, however, show interspersed tiny silt lenses and laminae, and size grading with carbonaceous particles on top. Most laminae are even to only slightly crinkled when compared to laminae in the Newland Formation.

3.3. 'Smooth' bedding planes

Interbedded siltstones, sandstones, and shales of shallow water origin in the Belt Supergroup are characterized by sedimentary features such as wave ripples, current ripples, desiccation cracks, and salt casts on sediment surfaces (Winston, 1986). Although sediment surfaces that reflect processes of current flow, wave reworking, desiccation, and evaporation are the most common ones, in several formations that were examined for this study there are also bed surfaces that are comparatively smooth, show irregularly wrinkled (Fig. 2), or pustular–crinkled surface relief (Figs. 3 and 7), and display wavy–crinkly laminae in
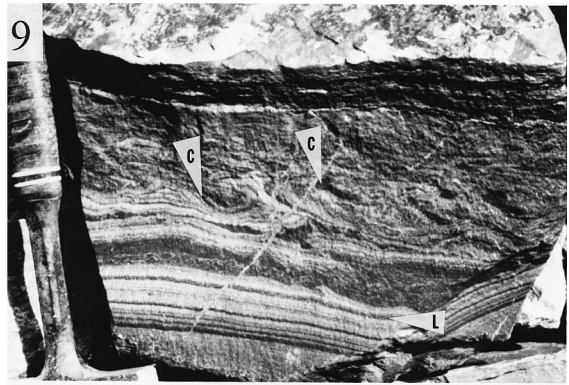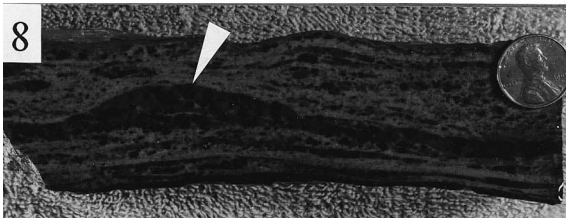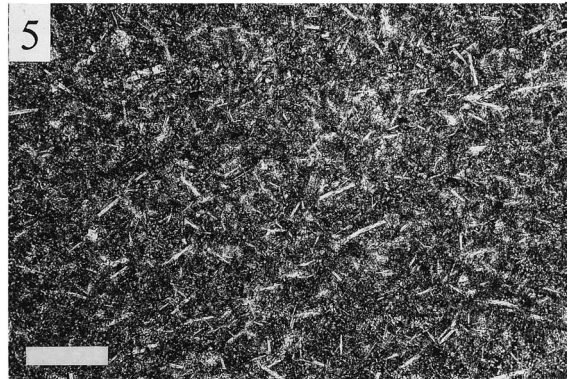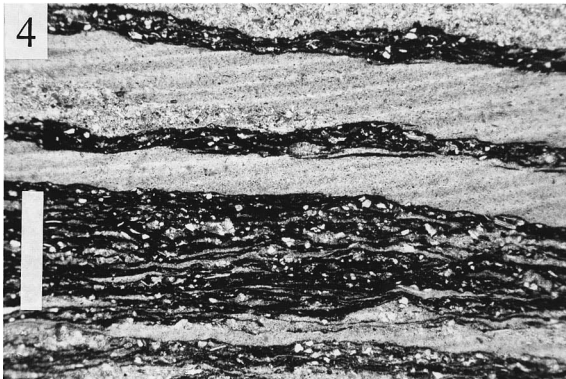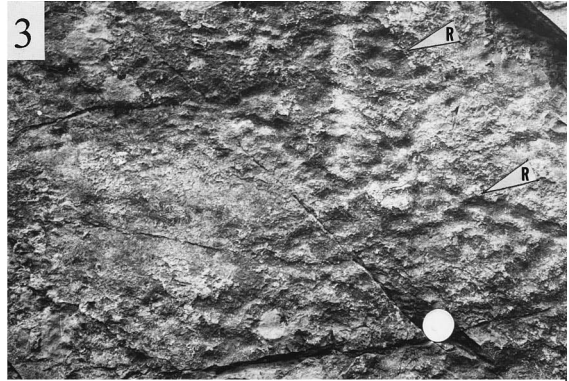
thin section. None of the processes (wave, current, desiccation, evaporation) that shaped the other beds left a recognizable record, and what shaped these surfaces is not immediately apparent. In places these surfaces contain ripple patches as described below.

3.4. Possible mat fragment impressions

Irregular, generally curved impressions on bedding planes of the Snowslip Formation were interpreted by Horodyski (1982) as impressions of microbial mat fragments via comparison with modern analogs. These features are subtle and difficult to photograph, and the pictures by Horodyski (1982) are the best that are available. These impressions are similar in appearance to the irregularly wrinkled sediment surfaces mentioned above.

3.5. Cohesive behaviour

Examination of suspected microbial mat deposits in the Newland Formation suggests that their carbonaceous laminae possessed considerable internal cohesiveness during penecontemporaneous soft-sediment deformation and erosion (figs. 11, 12 and 16 in Schieber, 1986), whereas intervening sediment layers seem to have had a yogurt-like consistency. Similar appearing deformation of carbonaceous mi-

crolaminae has also been reported from the Wallace Formation (Grotzinger, 1981; Winston, 1986).

In the Revett Formation, Garlick (1988) interpreted conformable Fe-stained layers and laminae in sandstone (Fig. 8) as the remnants of microbial mats. These layers may show soft-sediment deformation and convolute bedding, and disturbed intervals are over and underlain by sandstone with horizontal Fe-stained laminae (Fig. 9). Where breakup and fragmentation of laminae occurs during deformation, the lamina fragments remain intact during further deformation (Fig. 9). These fragments are found in a matrix of unstained (no Fe-carbonate cement) structureless sandstone. In some places scoured depressions contain what appears to be curved fragments of Fe-stained laminae (Fig. 10).

3.6. Ripple patches

On 'smooth' or irregularly wrinkled sandy sediment surfaces wave- or current-rippled spots of irregular outline (Figs. 11 and 12), ranging in diameter from approximately 30 to 150 cm, were observed in several formations (Table 1). The inverse feature, meaning 'smooth' or irregularly wrinkled patches on wave-rippled surfaces, was also observed. Transitions between rippled surfaces and non-rippled surrounding areas are smooth (Fig. 13).

Fig. 2. Irregular wrinkled bedding plane in Mt. Shields Formation. The observable surface features might be imprints of wrinkled, rolled up, and/or redeposited fragments of desiccated mat. Hammer head is 180 mm long.

Fig. 3. Pustular–crinkled bedding plane surface in McNamara Formation. Surface features pointed out by arrows *R* possibly represent rippled (interference ripples?) surfaces. However, there is a pustular–crinkled surface morphology superimposed on these presumed ripples. Coin is 24 mm in diameter.

Fig. 4. 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 contain silt lenses at the base and were interpreted as event deposits due to minor storms. Scale bar is 0.5 mm long.

Fig. 5. Closeup of dolomitic lamina. Shows randomly oriented mica flakes in a finely crystalline dolomitic matrix. Scale bar is 0.2 mm long.

Fig. 6. Physically deposited laminae in reddish shale with mica (arrows) alignment parallel or subparallel to lamination. Note contrast to Fig. 5. Scale bar is 0.1 mm long.

Fig. 7. Thin section cut perpendicular to surface shown in Fig. 3. Note the microcolumnar buildups on bedding plane surface (arrow), and the wavy–crinkly laminae below the surface. Scale bar is 1.0 mm long.

Fig. 8. Cut specimen of Revett sandstone with limonitic (Fe-stained) wavy–undulose laminae (dark). Arrow points out lamina with domal thickening, possibly an incipient stromatolitic dome. Coin is 19 mm in diameter.

Fig. 9. Interval of soft-sediment deformation in Revett Formation, over and underlain by sandstone with horizontal limonitic laminae (dark laminae, arrow *L*). Note fragments of contorted limonitic laminae (arrows *C*). Hammer handle is 30 mm wide at the base.
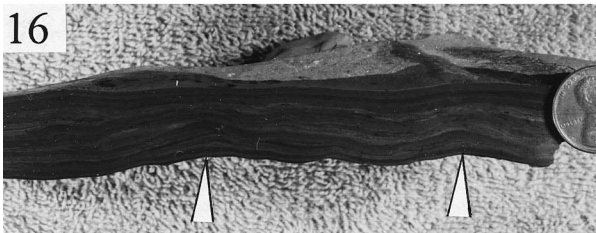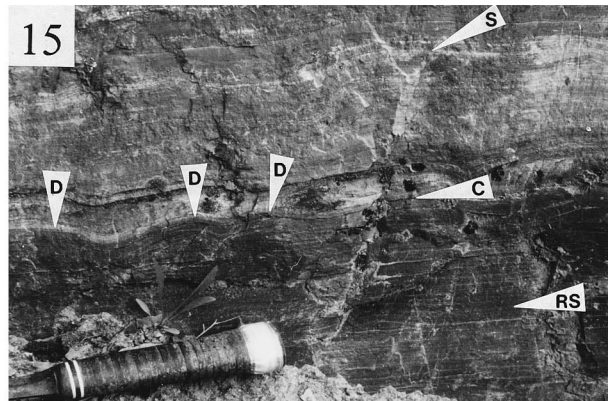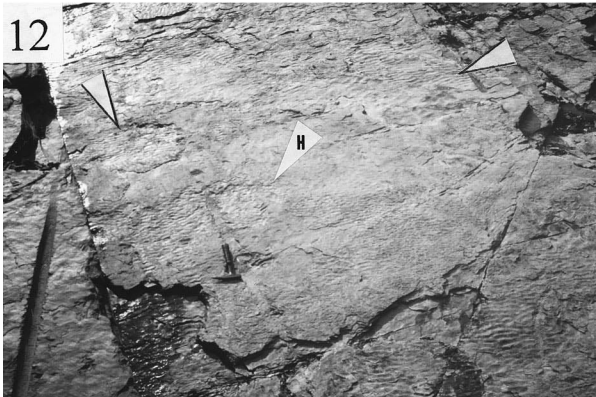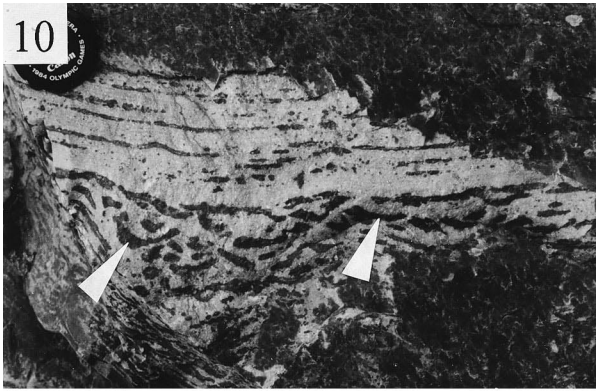
3.7. Domal structures

Domal to columnar laminated structures in Revett Formation quartzites (Fig. 14) were reported by Garlick (1988) and John Balla of ASARCO Inc. (pers. commun., 1990). In morphology they resemble what Logan et al. (1964) described as LLH (laterally linked hemispheres) stromatolites from carbonate rocks. In the Mt. Shields Formation small, moderately convex domal structures were observed within reddish shales below a dolomitic stromatolite horizon (Figs. 15 and 16). Morphologically more pronounced (steeply convex) and somewhat larger domal structures were found in some intervals of greenish shale (Fig. 17). They could be described as being of LLH (Logan et al., 1964) or cumulate habit (Walter et al., 1992). Winston (1986) reported possible domal structures from microlaminites of the Wallace Formation.

3.8. Uparching of laminae

Both red and green shale intervals of Belt sediments examined for this study contain polygonal desiccation cracks in variable abundance and size. Although modern desiccated muds may show pronounced development of concave-upward polygons, mud-cracked shales of the Belt Series typically do not show this feature. Instead, mud-cracked layers in the studied outcrops have very little surface to-pography, meaning that the rims of mud-cracks do not rise significantly above the surrounding surface (Fig. 18). In the Mt. Shields Formation, however, packages of mud-cracked sediment as characterized above, contain horizons of 2–5 cm thickness where the rims of mud-cracks are raised atypically above the surrounding surface (Fig. 18). Cross-sections of these intervals resemble cross-sections of polygonal mats described from modern and ancient environments (Aitken, 1967; Till, 1978).

3.9. Dolomitic laminae and ferroan carbonates

The unusual mud-cracked intervals described above not only differ from the 'normal' mud-cracked sediments by virtue of their raised polygon rims, but also by a relative abundance of dolomite in these intervals. In detail these intervals consist of alternating dolomitic and non-dolomitic laminae (laminae 0.1–2 mm thick). The dolomitic laminae are wavy–undulose (comparable to those shown in Fig. 16) and contain variable amounts of finely crystalline dolomite (Fig. 5), quartz silt, micas, and clays. Identical laminae are also found in evenly laminated greenish shales of Fig. 17, pass without disruption into the small domal structures in Fig. 17, and are interbedded with terrigenous laminae in reddish shales with small domal features (Figs. 15 and 16). In places where the dolomite content of these laminae

Fig. 10. Scour depression in Revett Formation, filled with sandstone that shows curved limonite stains (arrows), and overlain by sandstone with horizontal wavy–undulose limonite-stained layers. The curved limonite stains are interpreted as the remnants of desiccated and transported fragments of microbial mats. Lens cap is 45 mm in diameter.

Fig. 11. Patch of small current ripples in otherwise smooth bedding plane of the Mt. Shields Formation. The rippled surface (marked by an arrow in the lower right corner) passes without break into the surrounding smooth area (marked by an arrow at the left edge of the photo). Hammer handle is 180 mm long.

Fig. 12. Ripple patches (arrows) on bedding plane in McNamara Formation. This bedding plane shows considerable resemblance to partially eroded microbially stabilized surfaces as illustrated in Reineck (1979) and Gerdes et al. (1985). The rippled surface above hammer passes without break into surrounding smooth surface (arrow *H*). Hammer is 315 mm long.

Fig. 13. Detail of rippled erosion patch in Mt. Shields Formation. Shows the smooth transition between rippled surface and surrounding smooth area (arrows), an indication that the rippled surface and smooth surface were contemporaneous. Hammer is 31.5 cm long.

Fig. 14. Domal stromatolite (arrow) in upper portion of Revett Formation near Spar Lake mine, Montana. Hammer is 315 mm long. Photo courtesy of John Balla, ASARCO Inc.

Fig. 15. Light coloured laminated stromatolitic dolomite (arrow *S*) from the stromatolite interval shown in Fig. 22. The stromatolitic dolomite overlies a thin interval of reddish shale (darker, arrow *RS*). Note the sharp contact between the shale and stromatolite interval (arrow *C*), and the small domal structures in the upper portion of the shale interval (arrows *D*). Hammer handle is 180 mm long.

Fig. 16. Cut hand specimen from red shales shown in Fig. 15. Note irregular lamina structure and small domal buildups (arrows). Coin is 19 mm in diameter.
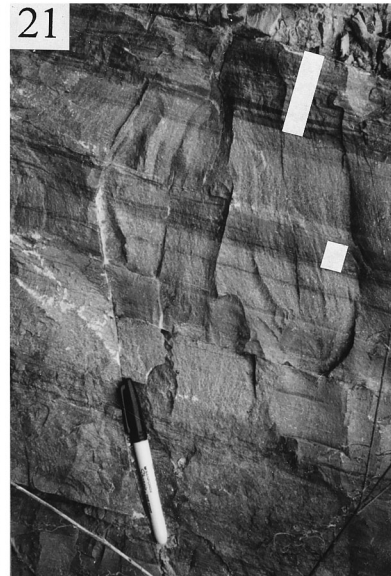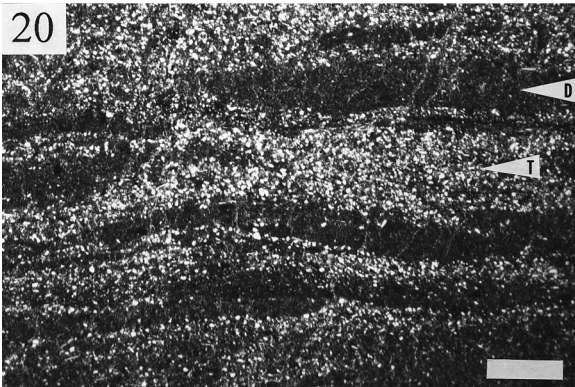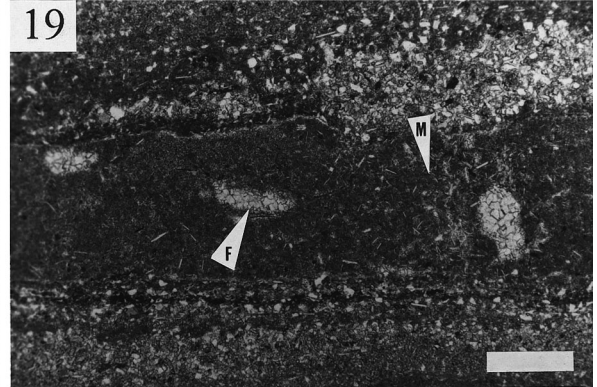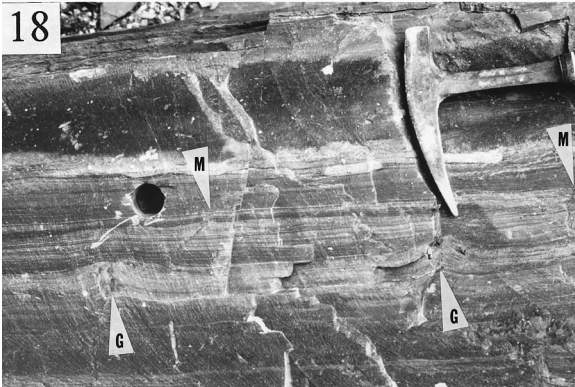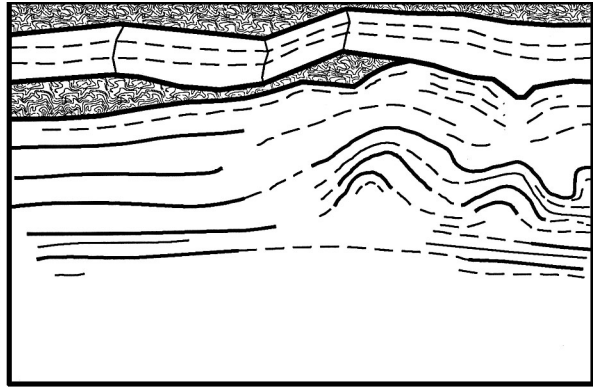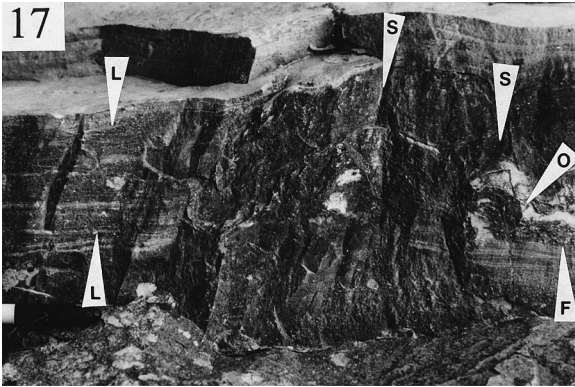
is large one can observe fenestrae filled with clear dolomite spar (Fig. 19). Finally, these dolomitic laminae are indistinguishable from laminae found in dolomitic stromatolites in the Mt. Shields Formation (Fig. 20).

Fe-stained layers and laminae in Revett (Figs. 8 and 9) and Mt. Shields Formation (Fig. 21) sandstones are due to the oxidation of ferroan carbonate cement (ankerite, ferroan calcite and dolomite) and pyrite. Petrographic studies of the Revett Formation by Hayes and Einaudi (1986) show that these minerals formed early in diagenesis. The original mineralogy of these layers is of importance because it indicates a reducing pore water environment that was laterally extensive but nonetheless confined to thin intervals within the accumulating sands.

Dolomitic laminae in suspected microbial mat deposits of the Newland Formation (Schieber, 1986) consist of finely crystalline, mostly irregular dolomite grains, and lack features observed in dolomitic laminae from the Mt. Shields (random micas, fenestrae) and Revett Formations (ferroan carbonates).

3.10. Mica enrichment and random micas

Fe-stained layers and patches in the Revett Formation contain noticeably more detrital muscovite flakes than interbedded and adjacent sandstones that lack early diagenetic ferroan carbonate cement (see also Garlick, 1988). Dolomitic laminae found in suspected microbial deposits of the Mt. Shields Formation (see above) also contain detrital muscovite. Detrital muscovite is proportionally more abundant in these dolomitic laminae than in normal terrigenous laminae. Muscovite flakes are randomly distributed and do not show alignment parallel to bedding (Fig. 5). In contrast, terrigenous laminae that are intercalated with these dolomitic laminae typically show size grading and parallel alignment of micas (Fig. 6). Although there is a low-grade metamorphic overprint, the micas in question are considered detrital for the following reasons: (1) they may be worn at the edges and be deformed due to compaction; (2) none of the rocks examined shows cleavage development; (3) comparison of micas with those observed in unmetamorphosed portions of the Belt Supergroup (Newland Formation), and those found in more strongly metamorphosed Formations (Prichard Formation) strongly suggests that the micas in question are of detrital origin.

4. Discussion of possible microbial mat features

4.1. Carbonaceous microlaminae

Laminated structures in sediments that are presumed organic in origin are usually described as stromatolites and interpreted as the deposits of an-

Fig. 17. Photo of greenish shale of Mt. Shields Formation with small stromatolite-like domal buildups (arrows *S*). These buildups developed on an originally flat sediment surface (arrow *F*), show oversteepened laminae (arrow *O*), and laminae pass into surrounding horizontally laminated shale. Arrows *L* indicate package of horizontal laminae that is lateral equivalent of buildup laminae. Marker pen (scale) is 12 mm in diameter. The illustration to the right of the photo is an ink tracing of laminae and domal buildups, in order to highlight domal features.

Fig. 18. Red shale in Mt. Shields Formation that has horizons with uparched laminae adjacent to mud-cracks (arrows *G*). These are possible microbially induced growth ridges, and the area between arrows G resembles the cross-section of a polygonal stromatolite. Note for contrast the very minor relief around mud-cracks in overlying shale layer (arrows *M*). Hammer head is 18 cm long.

Fig. 19. Detail of dolomitic lamina. Shows fenestrae filled with clear dolomite spar (arrow *F*). Arrow *M* points out area with abundant randomly oriented mica flakes. Scale bar is 0.5 mm long.

Fig. 20. Dolomitic laminae in stromatolite horizon of Fig. 22. Finely crystalline dolomitic laminae (arrow *D*) appear dark and have vertical hair fractures, and alternate with terrigenous laminae (arrow *T*) that contain abundant detrital quartz grains (coarse silt to very fine sand size). Scale bar is 1.0 mm long.

Fig. 21. Photo of quartzite in Mt. Shields Formation that has iron-stained intervals (marked with white bars). These intervals have ferroan carbonate cement, and show irregular wavy–undulose laminae, resembling those found in the Revett Formation. There is also resemblance to laminations seen in modern microbially stabilized sand flats ('versicoloured sand flats'; Gerdes et al., 1985). The marker pen is 135 mm long.

Fig. 22. Outcrop photo of Mt. Shields Formation with interval of dolomitic domal stromatolites (arrow). Scale bar is 1 m long.

cient microbial mats. Carbonaceous, wavy–crinkly laminated shale beds of the Newland Formation (Fig. 4) as well as carbonaceous microlaminae from the Wallace Formation and other stratigraphic units of the Belt Supergroup have previously been interpreted as microbial mat deposits (Schieber, 1986; Winston, 1986). Whereas a strong argument can be made for carbonaceous microlaminae in the Newland Formation to be of microbial origin (Schieber, 1986), such is not the case for carbonaceous microlaminae in the Wallace and Libby Formations. In the latter formations, observations indicate a preponderance of physical sedimentation processes, such as sorting by bottom currents (tiny silt lenses) and settling from suspension (graded laminae). Clear observations of cohesive behaviour and other possible microbial mat indicators are very rare. Thus, although carbonaceous microlaminae of the Wallace/Libby type may in places be of microbial mat origin (Grotzinger, 1981; Winston, 1986), microlaminae produced by physical sedimentation processes are considerably more common.

In contrast, carbonaceous microlaminae of the Newland Formation (Fig. 4) have a considerably more wavy–crinkly appearance than those of the Wallace Formation, and are dissimilar from the even parallel laminae observed in deeper water hemipelagic black shales (e.g. Conant and Swanson, 1961; O'Brien, 1989). They strongly resemble lamina structures from modern microbial mats (Horodyski et al., 1977; Krumbein and Cohen, 1977). Considering related sedimentary features (Schieber, 1986), the wavy–crinkly laminae of the Newland Formation (Fig. 4) have a much better chance to be of microbial mat origin than the carbonaceous microlaminae of the Wallace Formation. Similar appearing laminae have been reported from other Proterozoic sediments (Fairchild and Herrington, 1989), as well as from Jurassic black shales (O'Brien, 1990), and were in both cases interpreted as possible microbial mat deposits.

4.2. Wavy–crinkly laminae

Irregular wavy–crinkly laminae in shales and sandstones of the Mt. Shields (Fig. 2) and McNamara Formation (Fig. 3) resemble laminae from modern stromatolitic mats (e.g. Horodyski et al.,

1977; Krumbein and Cohen, 1977). In particular the internal laminae (Fig. 7) of pustular surfaces in the McNamara Formation (Fig. 3) are strongly suggestive of microbial mat laminae when compared with modern examples (e.g. Schwarz et al., 1975; Gerdes and Krumbein, 1987). The bed surface closely resembles microcolumnar buildups or microbial tufts observed on modern mat surfaces (Gerdes and Krumbein, 1987).

Through their similarity to microbial mat laminae in modern and ancient examples (e.g. Bertrand-Sarfati, 1976; Monty, 1976; Horodyski et al., 1977; Gerdes and Krumbein, 1987), it is always tempting to equate wavy–crinkly laminae in a sediment with the former presence of microbial mats. Yet, because comparable textures can also result from soft-sediment deformation, wavy–crinkly laminae alone are not considered sufficient proof for microbial origin of a laminated rock (Buick et al., 1981).

4.3. Possible mat fragment impressions

Irregularly wrinkled sediment surfaces are not uncommon on bedding planes of Belt Series shallow water shales. Judging from a study of Horodyski (1982), some of these may have been produced as impressions of dried out microbial mat fragments into partially dried mud surfaces. The details of these features are, however, quite subtle and probably can easily be mistaken for surface irregularities caused by small-scale load structures or wrinkle marks.

4.4. Cohesive behaviour

In modern environments, sediment binding and agglutination by microbial filaments and sheaths tends to transform originally loose surface sediment into cohesive layers. The microbially bound surface layer typically is only a few mm thick, but is able to withstand erosion by strong currents as well as mechanical tearing (Neumann et al., 1970; Reineck, 1979; Bauld, 1981; Reineck et al., 1990; Witkowski, 1990). Erosion of these surface layers produces thin (a few mm) and highly flexible shreds of variable size (mm to tens of cm) that consist of intertwined microbial filaments and enclosed sediment grains (Reineck, 1979; Reineck et al., 1990). The internal cohesion keeps mat fragments together and allows

them to become resedimented as wrinkled and contorted fragments on sand or mud surfaces (Gerdes et al., 1993). Mats can also desiccate and form wrinkled and rolled up fragments that may either remain in situ, or get transported and redeposited elsewhere (e.g. Schwarz et al., 1975; Gunatilaka, 1975). Working on modern sediments, Noffke et al. (1996) coined the term 'mat chips' for resedimented soft mat fragments, and the term 'mat curls' for dried out and rolled up (due to desiccation) mat fragments. Dried out mat material can show amazing strength and rigidity (Bauld, 1981).

Presumed microbial mat layers in shales of the Newland Formation (Schieber, 1986) showed cohesive and flexible behaviour during penecontemporaneous soft-sediment deformation, whereas interbedded muds behaved like a very viscous fluid (yogurt-like consistency). Erosion of presumed microbial laminae produced lamina fragments up to 4 cm in diameter, and these fragments were rolled up and folded over during transport. These features likewise indicate that the presumed mat fragments, although very thin and deformable, possessed considerable cohesive strength. From these observations it appears that carbonaceous shale beds in the Newland Formation behaved like tough leathery membranes during soft-sediment deformation and transport, rather than a soupy organic muck (details in Schieber, 1986). Sedimentary features resembling the rolled up 'mat' fragments from the Newland Formation have also been described in carbonates from the Proterozoic Hammersley Group in Australia and from the Proterozoic Transvaal Supergroup of South Africa, and were likewise interpreted as ripped up and transported microbial mat fragments (Beukes, 1987; Klein et al., 1987; Simonson et al., 1993). Similar looking, rolled up, deformed, and transported layers of supposedly microbially bound sand were described by Garlick (1981) from the Proterozoic of Zambia.

In a discussion of possible microbial mat features in the Revett Formation, the iron-stained layers are of importance. Examination of fresh material indicates that the Fe-stains are due to oxidation of Fe-carbonates and pyrite that were deposited as early diagenetic cement minerals (Hayes and Einaudi, 1986) that postdate soft-sediment deformation. In modern sediments, the deposition of ferroan carbonates and pyrite typically coincides with sediment layers rich in organic matter (Canfield and Raiswell, 1991), and thus the iron-stained portions of Revett sandstones most likely coincide with portions of the sediment that originally contained abundant organic matter.

Reducing conditions as required for the above minerals could have been generated (1) within a layer of sand that contained organic debris (Berner, 1984) or, alternatively, (2) in the lower portions of a microbial mat (e.g. Bauld, 1981; Gerdes et al., 1985). Either scenario can explain the presence of horizontal Fe-stained layers and laminae in Revett sandstones (Fig. 8).

Setting (1), however, cannot explain the observed soft-sediment deformation (Fig. 9). Disrupted and torn portions of presumed mat layers in the Revett Formation (Fe-stained sandstone layers) remained intact during further deformation (Fig. 9), suggesting that the sand grains were held together by some flexible binding material (layers are recognizable by the Fe-minerals that formed after deformation). If these layers had simply consisted of a mixture of sand and organic matter, the latter would likely have been dispersed during deformation, and instead of distinct Fe-rich layers we would probably see disseminated Fe-minerals. A comparable argument can be made for the curved limonite-stained portions shown in Fig. 10. The latter have been interpreted as pieces of dried out and cracked microbial mats that were piled up or swept together by waves or currents (Garlick, 1988). This phenomenon has been observed in several modern microbial mat environments (Fagerstrom, 1967; Gunatilaka, 1975; Horodyski et al., 1977; Gerdes and Krumbein, 1987). Likewise, the observation that limonitic portions of Revett sandstone behaved like cohesive sheets during soft-sediment deformation, is consistent with the properties of microbially bound sand layers (e.g. Reineck, 1979; Gerdes et al., 1985, 1993; Garlick, 1988; Reineck et al., 1990).

4.5. Ripple patches and 'smooth' bedding planes

Cohesive behaviour of sand bound by microbial mats also furnishes an explanation for the ripple patches in the Mt. Shields and McNamara Formation. Patches of rippled sand within otherwise smooth sandy surfaces, very similar to those shown

in Figs. 11 and 12, have in modern environments been observed on sand flats of Mellum (North Sea) and were described by Reineck (1979) and Gerdes et al. (1985). The mat surfaces tend to have an irregular wrinkled to pustular–tufted surface microrelief (e.g. Schwarz et al., 1975; Horodyski et al., 1977; Krumbein and Cohen, 1977; Gerdes and Krumbein, 1987). On Mellum, large portions of the sand flats are covered by cyanobacterial microbial mats. Typically the mats form comparatively smooth surfaces and stabilize the sediment surface sufficiently to prevent erosion during fair weather conditions. Only during storms can current velocities sufficient for erosion of these mats be achieved, and erosion occurs in a patchy fashion (Reineck, 1979; Gerdes et al., 1993; Noffke et al., 1996). Ripples form subsequently in the unconsolidated sand of these erosion patches. Ancient examples of this kind of sedimentary feature have been described from the Cretaceous Dakota Sandstone (MacKenzie, 1972) and were likewise interpreted as indicators of microbial mat stabilized sand surfaces.

That transitions between rippled surfaces and surrounding non-rippled areas be smooth is critical for the interpretation of ripple patches as microbial mat indicators. As long as transitions are smooth it is a fair assumption that the rippled and non-rippled areas are penecontemporaneous, and that the non-rippled areas had a cohesive property. In contrast, if there is a sharp step between the rippled and non-rippled surface, we can assume that we actually look at two different sediment layers. We basically look at an upper non-rippled layer, and a lower rippled layer. The ripple patch appearance is produced when weathering 'breaks out' patches of the upper layer and thus forms 'windows' that reveal the lower rippled layer. The smooth transition shown in Fig. 13 supports a microbial interpretation for smooth and irregularly wrinkled sediment surfaces with ripple patches. That surface textures found on 'smooth' portions of bedding planes (Figs. 2 and 3) resemble those observed in modern microbial mats (e.g. Schwarz et al., 1975; Horodyski et al., 1977; Krumbein and Cohen, 1977; Gerdes and Krumbein, 1987), and that lamina details resemble microcolumnar buildups and microbial tufts observed in modern mats (Gerdes and Krumbein, 1987) is consistent with a microbial mat interpretation.

When the abundance of ripple patches on bedding planes of modern and Phanerozoic examples is considered (MacKenzie, 1972; Reineck, 1979; Gerdes et al., 1985, 1993; Noffke et al., 1996), it appears that ripple patches as described above are less common in shallow water sandy deposits of the Belt basin. This could potentially be due to the absence of grazing and burrowing organisms in the Proterozoic. In modern examples erosion typically starts at places where the mat has been weakened or ruptured by metazoan grazers or by burrowing organisms, or where surface irregularities such as shells provide a starting point for erosion (Reineck, 1979; Gerdes et al., 1985). The absence of such damage in the Proterozoic could have made these mats more difficult to erode, giving rise to 'smooth' bedding planes with irregularly wrinkled or pustular–crinkled surface relief and ripple patches, within sediments that are otherwise characterized by wave ripples, and desiccation cracks.

4.6. Domal structures

Morphologically, domal structures in the Revett Formation (Fig. 14) strongly resemble domal stromatolites that have been described from carbonate rocks (e.g. Logan et al., 1964), suggesting that microbial mats indeed grew on sediment surfaces of the Revett Formation. These structures were also studied by Garlick (1988), who concluded that domal and columnar structures were due to competition for height and light by microbial mats. Domal stromatolites in sandstones have also been reported from Ordovician strata in Minnesota (Davis, 1968) and from the Proterozoic of Zambia (Garlick, 1981).

The small domal structures in red shales below a stromatolitic dolostone horizon (Figs. 15 and 16) in the Mt. Shields Formation might initially be dismissed as cross-sections of a rippled sediment surface. When examined in detail, however, the small domes are not ripples, but rather are small, upward-growing buildups that consist of successive wavy–wrinkled laminae (Fig. 16). The upward growth as well as the lamina style is suggestive of a microbial mat deposit.

Buildups in green shale beds of the Mt. Shields Formation (Fig. 17) look very similar to small stromatolite hemispheres in carbonates (e.g. Logan et al.,

1964). Formation as an organosedimentary buildup is also suggested by the rise above an initially flat sediment surface and the steep marginal slopes of the structures (Fig. 17). The latter are much steeper than the expected angle of repose of these sediments and suggest sediment binding by a cohesive microbial mat surface. Individual laminae can be traced from these buildups into the surrounding flat laminated shales, without noticeable change in composition and texture. Thus, if the assumption of a microbial origin is correct for the buildups (Fig. 17), the adjacent flat laminated areas should at least in part have been covered by microbial mats.

Outcrops of the Mt. Shields Formation that contain the suspected microbial buildups in shale intervals have been interpreted as sea marginal shallow water deposits that were influenced by sea level variations (Winston, 1986). The latter led to deposition of stacked regressive–transgressive cycles, which in the western Belt basin contain a number of extensive horizons of stromatolitic carbonates (Figs. 22 and 23). Horodyski (1975) found filamentous microfossils of cyanobacterial and bacterial affinity, apparently in growth position, within stromatolitic carbonates of the Mt. Shields Formation. The red and green shales that contain the domal structures shown in Figs. 15–17 are intercalated with the stromatolitic carbonate horizons mentioned above, and are also closely associated with other features suggestive of microbial mat colonization of terrigenous clastic surfaces (Fig. 23). This close association lends further support to a microbial interpretation.

Considering the age of the Belt Supergroup and the deformation that these rocks experienced since their deposition (Harrison et al., 1980), one might think that deformation may have caused some of the observed domal features. The deformation that these rocks show, however, is by and large restricted to broad, gentle folds, and block faulting. No tight folding that might have produced small folds or crenulations of the scale observed in Figs. 14–17 was observed anywhere near the examined exposures. Also, sediment intervals that show domal structures (usually between 5 and 30 cm thick) are conformably sandwiched between flat-lying sediments below and above (e.g. Figs. 8 and 17). Because the domes project upwards, rather than downwards, it is also very unlikely that they are an artifact of soft-sed-

Legend

⬚	lam. dolomite
⬚	dolom. oolite
⬚	quartz arenite
⬚	shale/siltst.
◠	stromatolite domes
≈	planar-undulose stromatolite
~~	dolomitic laminae
⫸	saucer polygons
=	parallel lamination
~	wavy bedding
⬥	current ripples
⟋⟋⟋	tabular x-strat.
⌇	wave ripples
⟍⟍	rip up clasts
⟳	soft. sed. deform.
△	halite casts
⊤	mud cracks
⤸	scours
1	ripple patches
2	limonitic laminae
3	dolomitic laminae
4	domes
5	pustular-crinkled surfaces
6	saucer polygons

microbial mat features in sandst. & shale

grain size: m.s. / f.s. / vf.s. / shale
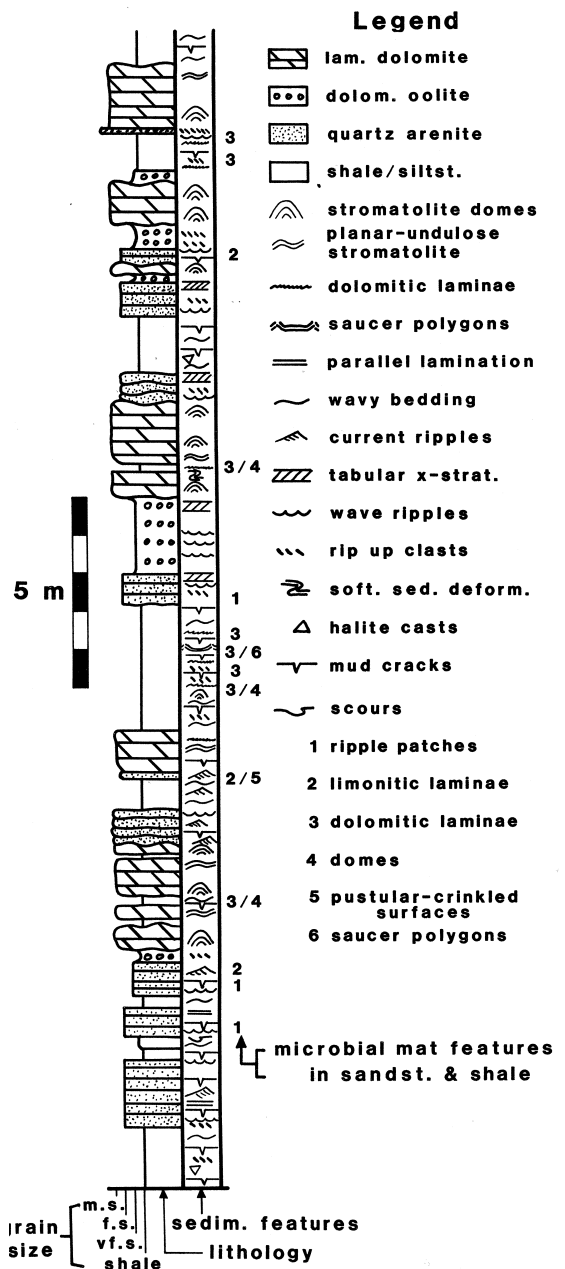
sedim. features — lithology

Fig. 23. Slightly generalized partial stratigraphic section of member 3 of Mt. Shields Formation along Hwy 2 near Montana/Idaho state line. Shows lithologies and sedimentary features observed in a 30 m section containing several Mt. Shields stromatolite cycles (there are two additional stromatolite horizons visible, but intervening lithologies are poorly exposed). Numbers to the right of profile indicate occurrence of suspected microbial mat features in sandstones and shales (identified by number in legend). Grain size markers at base of profile apply to terrigenous rocks only.

iment deformation (e.g. some sort of load structure).

4.7. Uparching of laminae

Although modern muddy sediments typically form curved/concave polygons during desiccation, most if not all of the concave character of these polygons is usually lost due to burial compaction. Thus, the typical lack of surface topography in mud-cracked layers of the Belt Series is what one would expect. In that general context, the raised rims of thin mud-cracked intervals in the Mt. Shields Formation (Fig. 18) are unusual. The fact that these intervals contain dolomitic laminae of suspected microbial origin (see below), and occur within mudstone packages that contain ripple patches and domal structures of likely microbial origin, suggests that the unusual raised rims may be another feature related to microbial mats. In cross-section, these mud-cracked intervals with raised polygon rims resemble cross-sections of polygonal mats in modern environments (Till, 1978), and the upturned/uparched laminae adjacent to cracks closely match what has been described as growth ridges from modern polygonal mats (e.g. Black, 1933; Ginsburg, 1960; Horodyski et al., 1977; Gerdes et al., 1993). In the latter, water standing in initial desiccation cracks results in non-uniform water distribution and preferential microbial growth adjacent to the cracks. Continued growth accentuates the resulting growth ridges and causes formation of concave-upward saucers. Morphologically very similar features have been described as polygonal stromatolites in ancient carbonate rocks (e.g. Aitken, 1967), and also occur in carbonate units of the Belt Series.

4.8. Dolomitic laminae

Dolomitic laminae associated with uparched laminae near mud-cracks, domal structures, and even laminated shales in the Mt. Shields Formation (Figs. 15–18) are of the same type as those found in closely associated dolomitic stromatolite horizons (Figs. 20 and 22). The latter have been carefully studied and their laminae are considered of microbial origin (Horodyski, 1975, 1983). Correspondences between dolomitic laminae in Mt. Shields shales and

dolomitic stromatolite horizons are textural as well as compositional. Most notable are randomly distributed and oriented micas (see below), the presence of fenestrae, and the wavy–undulose appearance of these laminae. These observations, in conjunction with the close spatial association to carbonate stromatolite horizons, all suggest that microbial mats were involved in the formation of the dolomitic laminae in question. Finding these laminae in even (flat) laminated shales as well as in intimately associated structures where a microbial origin is suspected for other reasons (Figs. 15–18), could indicate dolomite precipitation within a microbial mat in both instances (e.g. Gerdes and Krumbein, 1987).

4.9. Mica enrichment and random micas

A further parallel between suspected microbial deposits in Mt. Shields mudstones and Mt. Shields stromatolite horizons is the observation that dolomitic laminae in both rock types contain abundant and randomly oriented micas (Figs. 5 and 19). Considering that terrigenous grains become incorporated into a growing mat via agglutination, platy grains (such as micas) could be expected to show more or less random orientation, a feature that has actually been observed in modern microbial mats on terrigenous substrates (Gunatilaka, 1975; W.E. Krumbein, pers. commun., 1991). In a mat that only consists of organic matter and terrigenous grains, compaction will eventually cause the micas to align parallel to lamination. In contrast, in mats that experience in situ carbonate precipitation, the random orientation of micas can be preserved. Random fabrics in carbonate stromatolites of the Belt Supergroup have also been noted by Horodyski (1975).

The higher abundance of micas in suspected microbial laminae from the Mt. Shields Formation, as well as from the Revett Formation, may reflect a combination of microbially colonized sediment surfaces and selective transport of micas. Because particle shape affects settling velocity of sedimentary particles, mica flakes tend to be 'washed out' of nearshore sands and deposited separately (Folk, 1980). Organisms that build microbial mats often excrete extracellular slime or mucilaginous sheaths (Gerdes and Krumbein, 1987), which because of their sticky nature are able to trap sedimentary par-

ticles travelling across the mat (a 'flypaper' effect). The large abundance of micas in many of these laminae may thus indicate currents over these mats that were strong enough to transport mica flakes, but insufficient to carry large quantities of quartz, and that the 'flypaper' effect of microbially stabilized surfaces led to an enrichment with micas. An association of suspected microbial mats with mica enrichment was also noted by Garlick (1981) from sandstones of the Zambian Copperbelt.

5. The basic question

In none of the above examples of possible microbial mat occurrences have microfossils been found that were oriented or organized in a way indicative of organosedimentary interaction. Thus, strictly speaking one cannot assign a microbial mat origin for these occurrences (Buick et al., 1981). Nonetheless, there are a large number of features that indirectly point to microbial mat development, and most of these have also been reported from modern microbial mats. Differences in the relative abundance of various features between formations are most likely a consequence of differences in depositional setting (Table 1) and environmental parameters, such as water depth, sedimentation rate, sediment mix (sand/clay ratio), and wave fetch (size of water bodies).

Most significant are those features that indicate, or are related to, cohesive behaviour of thin sheets of surface sediment (0.1 to 5 mm thick). That such thin layers of sediment were fragmented, yet stayed together as shreds that underwent transport and deformation, makes it a necessity that the detrital grains of a given layer were somehow held together by a binding force. A loss of this binding force is indicated by ripple patches. In the Proterozoic, binding by intertwined microbial filaments of microbial mats represents the most plausible way to achieve such behaviour, and the fact that comparable features are commonly observed in modern microbial mats (Reineck, 1979; Gerdes and Krumbein, 1987) lends further support to such an interpretation.

Also, the presence of horizons of true carbonate stromatolites (Horodyski, 1975, 1983) in the Mt. Shields, Snowslip, and Shephard Formations, and their intimate association with terrigenous intervals

that are suspected of containing microbial mat deposits (Table 1), suggests according to Walther's Law (Walther, 1894) coeval development of microbial mats and terrigenous sedimentation along the shoreline. The fact that for example in the Mt. Shields Formation the suspected microbial laminae in terrigenous sediments show the same textural and compositional features as laminae from intercalated horizons of carbonate stromatolites, very strongly suggests that the former are indeed of microbial origin.

Whereas one should probably hesitate to take any single one of the above features as prima facie evidence for former microbial mat presence, once a number of these features is encountered simultaneously in the same sediment layer, a microbial mat interpretation becomes increasingly attractive. Buick et al. (1981) propose the term 'stromatoloid' for all those stromatolite-like features that do not pass their test of definite microbial origin (microfossils oriented or organized in a way indicative of organosedimentary interaction), and examination of the literature suggests that the great majority of 'stromatolites' described from the sedimentary record would fail this test (Walter et al., 1992). Even studies of modern microbial mat systems show clearly that microbes and microbial structures are rarely preserved after geologically very short times of burial and decay (Park, 1976; Krumbein and Cohen, 1977; Bauld et al., 1992). Therefore we have to conclude that the vast majority of modern microbial mat deposits would never make it to the status of 'stromatolite' once buried and lithified.

Although at the moment the available evidence for microbial mats in Proterozoic terrigenous sediments may not satisfy the stringent criteria of palaeomicrobiologists (e.g. Buick et al., 1981), that should not detract from seriously entertaining this possibility in sedimentologic investigations of Proterozoic strata. Ignoring the tantalizing indications of microbial mats in these strata could significantly handicap sedimentological interpretations and lead to erroneous conclusions. Microbial mats significantly increase the erosion resistance of a sediment surface (Neumann et al., 1970; Gerdes and Krumbein, 1987), and thus an environment with considerable current and wave activity where the sediment surface is stabilized by microbial mats might easily be mistaken for a tranquil one if the latter are not recognized (Witkowski,

1990). Identification of microbial laminae should also allow more realistic reconstruction of sedimentation conditions and history in finely laminated strata. Mat fragments can float or be transported by winds and carry with them any sediment bound to them regardless of grain size (Fagerstrom, 1967), resulting potentially in grain mixtures and textures that are incompatible with purely physical transport and deposition processes. Finally, microbial mats cause steep chemical gradients in the sediment and strongly influence early diagenetic mineralization (Krumbein and Cohen, 1977; Bauld, 1981). Their recognition may help to understand diagenetic patterns that are otherwise difficult to interpret.

From the preceding discussion two basic questions arise: (1) is it preferable to dismiss indications of microbial mats in order to avoid potential mistakes, and rather make erroneous but 'safe' environmental interpretations, or is it (2) preferable to entertain the potential contributions of microbial mats to Proterozoic terrigenous sedimentation, so that we will not lose part of the picture by misreading the significance of the sedimentary record? Possibly the following quote by Tukey fits our dilemma. "Far better an approximate answer to the right question, which is often vague, than an exact answer to the wrong question, which can always be made precise" (Tukey, 1962).

6. Conclusion

The 'right' question in the context of this paper might be the following: are there indications that a certain stratum *might* be a microbial mat deposit? Even if one is sceptical about the significance of microbial mat indicators in a given case, at least one has the option of an alternative working hypothesis that may eventually lead to a more comprehensive interpretation of ones data. Considering that microbial mats were most likely widespread in the Proterozoic (Awramik, 1984), it seems to me that this attitude is necessary if we are to gain new insights into the sedimentation of terrigenous clastics in the Proterozoic. Keeping this question in mind should over time lead to a better appreciation of microbial mats in terrigenous clastics of that age, and may lead to discovery of exceptionally well preserved (suspected) mat deposits that will finally yield the critical in-

formation on organosedimentary interaction sought after by palaeomicrobiologists (Buick et al., 1981).

Shales and sandstones of the Belt Series that were deposited in shallow water to episodically emergent environments show a variety of sedimentary features consistent with sediment surfaces that were at times colonized by microbial mats. In sandstones these features are:

(1) Domal buildups that resemble hemispherical stromatolites known from carbonate rocks.

(2) Rippled patches on otherwise smooth sediment surfaces.

(3) Upper bed surfaces with pustular and/or wrinkled appearance.

(4) Wavy–undulose horizontal laminae with early diagenetic ferroan carbonates and pyrite (orange-brown on weathered surfaces). These may also lead to limonite-stained curved and contorted features in sandstones.

(5) Suspected microbial laminae may be enriched with mica flakes relative to non-microbial laminae.

In shales these features are:

(1) Domal buildups resembling small hemispherical stromatolites which may show oversteepened laminae.

(2) Strongly uparched laminae near mud-cracks on certain horizons (saucer-shaped cross-sections).

(3) Wavy–crinkly laminae.

(4) Finely crystalline dolomitic laminae with randomly oriented micas.

(5) Above laminae (4) continue from domal buildups into surrounding flat laminated shales.

(6) Irregular, generally curved impressions on bedding planes.

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