The possible role of benthic microbial mats during the formation of carbonaceous shales in shallow Mid-Proterozoic basins

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ABSTRACT

A considerable portion of the upper member of the Mid-Proterozoic Newland Formation, Meagher County, Montana, consists of carbonaceous silty shales (striped shale facies). This type of shale facies is common in Proterozoic basins and is host to several major base metal deposits. The striped shales were deposited in a subtidal setting, basinward of carbonates characterized by cryptalgal laminites, mudcracks and flat pebble conglomerates. The carbonaceous silty shales are considered remnants of benthic microbial mats. Irregular internal laminae, patterns of particle trapping, mechanical deformation during penecontemporaneous soft-sediment deformation and filamentous microbiota provide evidence for this interpretation. The dolomitic clayey shale contains graded silt-clay couplets, and these are interpreted as storm layers. Modern subtidal microbial mats can only survive under special conditions, but in the Proterozoic, it is suggested that benthic microbial mats colonized the shallow seafloor during periods of low sediment input, leading to the formation of carbonaceous shales.

INTRODUCTION

This study attempts to show that benthic microbial mats were an important factor in the formation of carbonaceous shales in the Proterozoic. Deposits of microbial mats in sediments are commonly described as stromatolites, but the carbonaceous shale deposits described in this paper do not completely satisfy the criteria for a stromatolite origin put forward by Buick, Dunlop & Groves (1981) and Krumbein (1983).

The study area is located in the Little Belt Mountains, Montana, and the shales in question belong to the Newland Formation (Walcott, 1899), which is part of the Mid-Proterozoic Belt Supergroup. The Newland Formation occurs in the Helena embayment, an eastern extension of the Proterozoic Belt basin (Fig. 1). The shales occur as thick packages (50-120 m thick) that alternate with carbonate horizons (10-70 m thick), containing current ripples, wave ripples and flat pebble conglomerates. Dolostones with cryptalgal laminates (as defined by Aitken, 1967) are found towards the basin margins. Several types of shale facies are recognized, and the most widespread type has a characteristic striped appearance (Fig. 2). The interlayering of three compositionally different rock types, dolomitic clayey shale, carbonaceous silty shale and siltstone, causes the observed colour banding of these striped shales. The carbonaceous silty shales, which contain as much as 2% organic carbon, resemble oil shales (e.g. Bitterli, 1963 ; Eugster & Hardie, 1975). Thick sequences of shales that are very similar to the Beltian striped shales are found in the Mid-Proterozoic Mt Isa and McArthur Groups, Australia, and also in the Mid-Proterozoic Nonesuch Shale (Michigan, U.S.A).

DESCRIPTION OF STRIPED SHALES

The striped shales consist of interlaminated carbonaceous silty shale, dolomitic clayey shale, siltstone and lithoclast beds. The thickness of individual beds ranges from a few millimetres to several centimetres.

The *carbonaceous silty shale is* black and consists of three textural components: drapes of dolomitic clayey shale, carbonaceous silty laminae and tiny silt-rich lenses (Fig.

Fig. 1. Location map. Stipple pattern outlines Belt basin. Study area pointed out by arrow.

3.). The wavy-crinkly carbonaceous silty laminae consist of carbonaceous matter, clay minerals, tiny pyrite crystals (Fig. 3) and scattered silt grains. They are interlaminated with drapes of dolomitic clayey shale and tiny silt-rich lenses. Laminae of carbonaceous silty shale are in sharp contact with the other components of the striped shale facies.

The *dolomitic clayey shale is* grey and because of the aligned clay minerals shows a preferred extinction parallel to bedding in thin section (this effect diminishes with increasing dolomite content). Tiny carbonaceous flakes, which are oriented parallel to bedding, are found in the clay-dolomite matrix.

The *siltstone* is light grey in colour and forms lenses and wavy beds with cross-laminae. It can be parallellaminated, and it also forms graded rhythmites. Most siltstone beds are overlain by beds of dolomitic clayey shale (gradational contact) and form a silt/mud couplet (Figs 5, 6 and 7). Where dolomitic clayey shale is dominant, laminae of lenticular bedded siltstone occur.

Lithoclast beds are up to 50 mm thick, consisting of clasts of carbonaceous silty shale, dolomitic clayey shale, siltstone and dolostone (clast size 1-20 mm). Thicker beds of lithoclasts may show erosive bases, and lenticular bodies may be small channel fills. Thinner beds and lenses of lithoclasts, without a scoured base, overlie carbonaceous silty shale, and are overlain by a silt/mud couplet, thus forming a clast/silt/mud triplet (Fig. 5). In general, the thick, coarse clast beds are not covered by silt/mud couplets, whereas the thinner, finer clast beds are. The latter rarely show erosion at the base.

Beds of medium to coarse grained sandstone (as much as 400 mm thick) are found within the striped shale fades. These sandstone beds have a sharp undulating

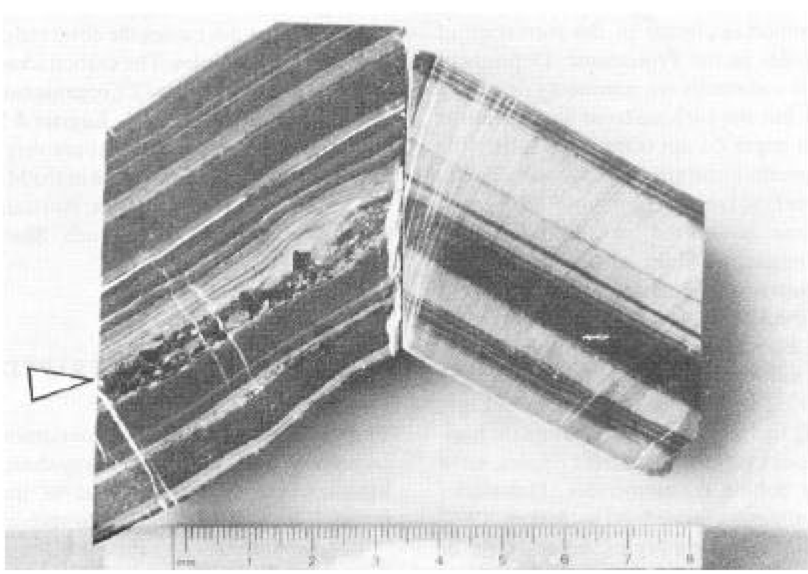

Fig. 2. Two drill core specimens of striped shale, showing variable proportions of carbonaceous silty shale and dolomitic clayey shale. The specimen on the left contains a clast/silt/mud triplet (arrow). Scale is in centimetre divisions.

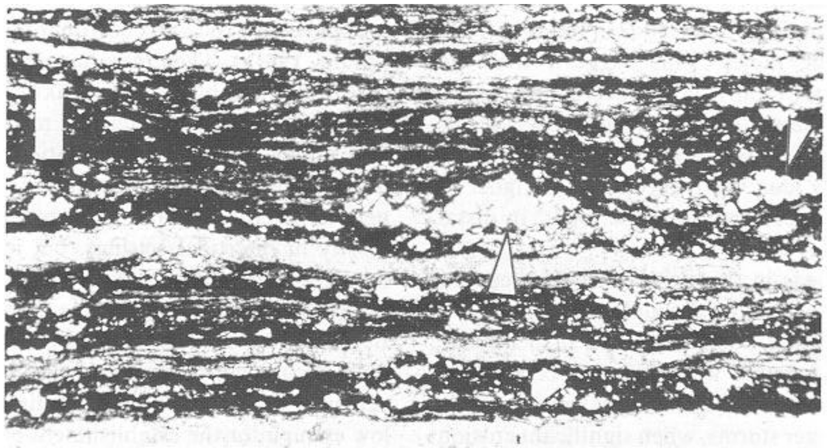

Fig. 3. Carbonaceous silty laminae, shale drapes and silt lenses (arrows) in a layer of carbonaceous silty shale. Most of the silt grains are within the carbonaceous laminae. Scale bar is 0.1 1 mm long.

base and display hummocky cross-stratification (Harms *et al.,* 1975).

THE DEPOSITIONAL SETTING OF THE STRIPED SHALES

The striped shale fades is one of four shale fades which have been distinguished in the Newland Formation on the basis of bedding characteristics, internal structures and the proportions of clay, silt and carbonate (Schieber, 1985). Each type can be located relative to the basin margin and centre, and the depositional environment of the shales can be deduced from associated sandstone and carbonate units. The first shale type (most marginal) consists of wavy interlaminated silt and mud, with small desiccation cracks and sandstone beds with curved mud-chips. It was intermittently exposed in a nearshore environment. The second type consists of silty mud with nonparallel bedding planes, randomly oriented clays, and possibly ripped up fragments of microbial mats (see Horodyski, 1980). It was deposited in a shallow subaqueous environment with frequent agitation. The striped shale fades occurs basinward of the silty mud facies. The fourth shale type consists of even laminae of a mixture of mud, silt and lumpy carbonaceous particles (possibly algal mat fragments). This shale type was deposited in the deepest part of the basin and was not subject to reworking and erosion.

Siltstone clasts in the lithoclast beds of the striped shales are petrographically identical to siltstones in the first shale type. Carbonate units that are found as lateral equivalents and interstratified with packages of striped shale contain cryptalgal laminates and flat pebble conglomerates. Dolostone clasts in lithoclast beds were probably derived from nearby carbonate banks or coastal carbonate mudflats, and they indicate contemporaneous carbonate production and terrigenous sedimentation in the basin.

The silt/mud couplets and clast/silt/mud triplets of the Newland Formation are interpreted as storm deposits by comparison with modern storm beds of the North Sea (Reineck, Gutmann & Hertweck, 1967; Gadow & Reineck, 1969; Reineck *et al.,* 1968; Reineck & Singly 1972), the Niger delta (Allen, 1965) and the Gulf of Gaeta (Reineck & Singly 1972). These modern storm deposits show the same sedimentary structures (parallel lamination, cross-lamination, graded rhythmites, post-storm mud drapes) as their Beltian counterparts, are similar in thickness, and were deposited in shallow basins. The storm layers of the Newland striped shales are also similar to thin, parallel and cross-laminated interbeds in Late Precambrian laminated limestones of Norway. These limestones were described by Tucker (1983), who interpreted the interbeds as storm deposits.

Hummocky cross-stratification in sandstones is commonly interpreted as an indicator of storm-wave activity (Harms *et al.,* 1975), and the presence of hummocky cross-stratified sandstone beds in the striped shale facies therefore suggests intermittent storms. The medium to coarse sandstone beds occur sporadically in the striped shale facies, whereas the silt/mud couplets and clast/silt/mud triplets constitute about 50% of the facies. This suggests that the sandstones represent only very exceptional major storms, whereas the silt/mud couplets and clast/silt/ mud triplets were the result of more frequent, weaker storms. The same idea was expressed by Aigner & Reineck (1982) concerning `proximal beds' in distal shelf muds.

Thicker clast beds in the striped shale facies that are not covered by a silt/mud couplet are only found in relatively proximal portions of the striped shale facies, and occur together with thin clast beds in the same sequence. These thicker clast beds were probably produced by stronger storms, when significant erosion of the seafloor took place in nearshore areas. When they were deposited the currents were still too strong to allow settling of silt and mud which were swept deeper into the basin by storm backsurge and came to rest on top of the distal, fine clast beds.

The environment of deposition of the striped shales was probably subtidal because they occur basinward of sediments that show evidence of strong currents and emergence. No indications of emergence have been found within the striped shale facies. Most of the silt, clay and carbonate mud was derived from the basin margins during storms. The carbonaceous silty shales accumulated in the long periods of low sediment influx between storms. Hummocky cross-stratification of sandstones has its greatest preservation potential between a few metres to several tens of metres water depth, according to Dott & Bourgeois (1982). The presence of hummocky cross-stratified sandstones in the striped shales of the Newland Formation, together with the relatively limited wave fetch of the Helena embayment (150 km or less), indicate that the maximum water depth for the striped shales did not exceed a few tens of metres. In several locations along the basin margin, intervals of striped shale contain abundant sandstones and flat pebble conglomerates. Scours are common at the base of the coarse clastic beds, and planar cross-bedding is present. These striped shales probably were deposited in fairly shallow water.

The origin of carbonaceous silty shale

There are several environmental requirements that must be satisfied in order to create a carbonaceous shale. The most important factors are a source of organic matter, reducing conditions at the site of deposition and low sedimentation rates. During the Mid-Proterozoic cyanobacteria (or blue-green algae) probably were the sole contributors of organic matter (Bauld, 1981a). They may have contributed organic matter through blooms of planktonic cyanobacteria, through fragments of intertidal microbial mats swept into a quiet basin, by accumulation of organic matter in algal marshes (Monty & Hardie, 1976) or as in situ benthic microbial mats. Microbial mats occur today mostly in intertidal settings, but in the Proterozoic they also occupied subtidal environments (Hoffman, 1974; Young & Long, 1976; Serebryakov, 1976). Because of the absence of grazing organisms they may have occupied practically all places where there was sufficient light and where the sedimentation rate was low enough for the establishment of a microbial mat (Bauld, 1981 a). Brock (1976) considered, for example, that cyanobacterial mats can extend down to a water depth of about 50 m, as far as their light requirements are concerned.

The striped shales lack any features of subaerial exposure, and therefore intertidal microbial mats and cyanobacterial and algal marshes can be excluded as possible depositional environments for the carbonaceous silty shales in the Newland Formation. This leaves two hypotheses: accumulation of planktonic and redeposited microbial matter (microbial mat fragments), and in situ burial of subtidal benthic microbial mats.

In the following paragraphs observations are presented supporting the view that the carbonaceous silty shales in the Newland Formation formed as subtidal benthic microbial mats, rather than accumulating from a planktonic `rain' of microbial matter. They therefore could be described as stromatolites.

Crinkly laminae

In thin sections, the wavy-crinkly lamination of the carbonaceous silty shale is the most striking indication of a cyanobacterial mat origin (Figs 3, 6, 7 and 8). The lamination fabric is the composite alternating type of Monty (1976), where one lamina of the couplet is characterized by the shale drape and the other by carbonaceous silt. Bertrand-Sarfati (1976) described comparable laminae in stromatolites as `film microstructure', consisting of carbonaceous micritic films alternating with microsparitic laminae. Laminar structures formed by cyanobacteria-dominated microbial

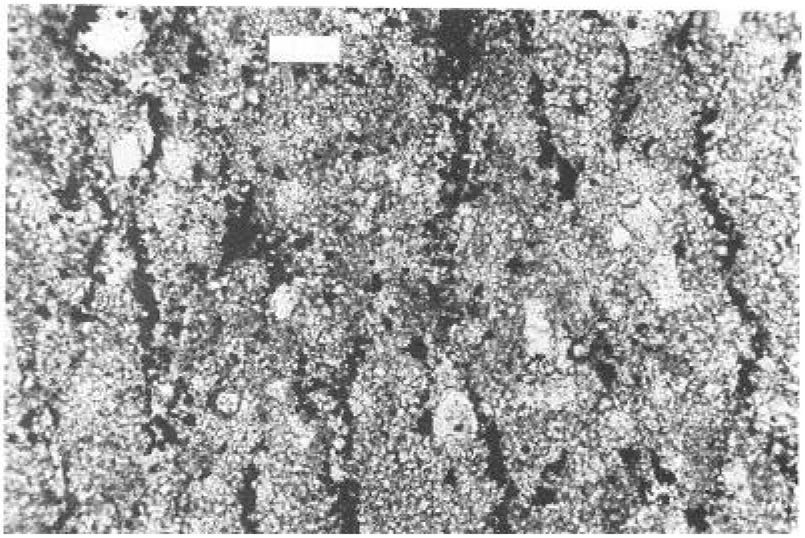

Fig. 4. Carbonaceous silty shale (dolomite-rich striped shale facies), with concentration of pyrite cubes (black) along carbonaceous laminae. Scale bar *is* 0035 mm long.

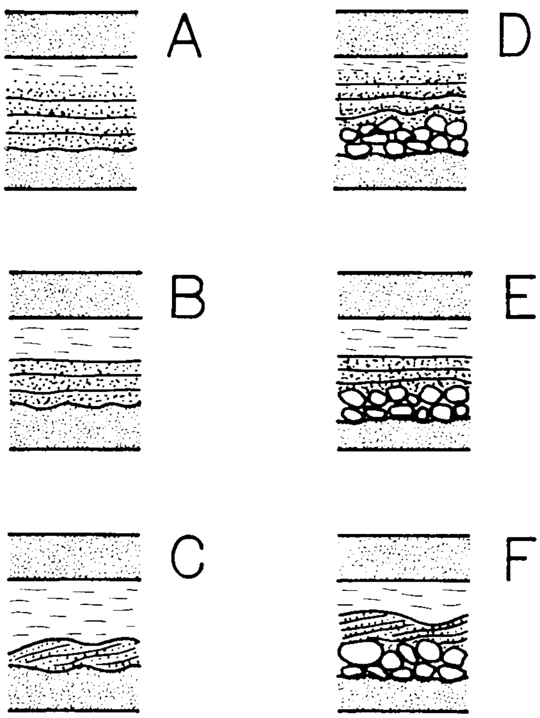

Fig. 5. Small-scale depositional sequences. (A), (B), (C) = silt/mud couplets: (A) with graded rhythmite; (B) with laminated silt; (C) with cross-laminated silt, (D), (E), (F) = clast/silt/mud triplets; (D) with graded rhythmite; (E) with laminated silt; (F) with cross-laminated silt. Beds *of* carbonaceous silty shale are indicated by a stipple pattern.

California (Horodyski, Bloeser & Von der Haar, 1977) strongly resemble the lamination in the carbonaceous silty shale. A similar lamination was depicted by Krumbein & Cohen (1977) from modern microbial mats of Solar Lake, Sinai. The irregular lamination of the highly dolomitic beds of carbonaceous silty shale (Figs 4 and 7) is strikingly similar to lamination in Pliocene and Late Miocene dolomites from the Black Sea basin that were interpreted by Stoffers & MüIler (1979, fig. 6c). By way of contrast, photomicrographs from the Chattanooga Shale (Conant & Swanson, 1961), which is believed to have formed in a quiet basin with sporadic sediment influx associated with the accumulation of detrital and planktonic organic matter under reducing bottom conditions, show very even and parallel laminae, and not the wavy-crinkly laminae of the carbonaceous silty shales. Müller & Stoffers (1974, fig. 5b), in an investigation of Black Sea sediments, show a recent mudstone with strong textural resemblance to the carbonaceous silty shale of the striped shale facies. However, this mudstone has a pore volume of about 90% (Keller, 1974). After compaction the lamination would essentially be flat and parallel. In the author's opinion the laminae of carbonaceous shales deposited from suspension in a quiet basin under reducing conditions will, in most cases, be even parallel laminae and not wavy-crinkly laminae of the type present in the carbonaceous silty shale of the Newland Formation.

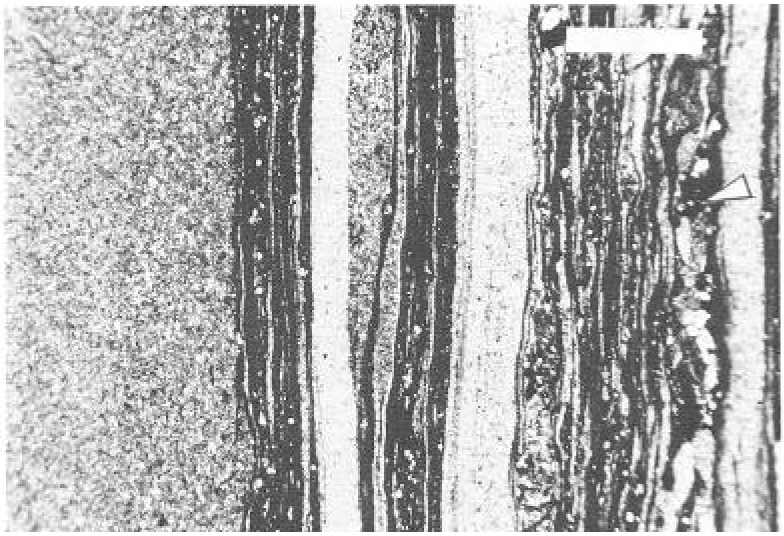

Fig. 6. Several beds of carbonaceous silty shale inter-layered with beds of dolomitic clayey shale (dolomite-poor) and silt/mud couplets. The carbonaceous silty shale bed towards the top is overlain by a silt bed that grades upwards into dolomitic clayey shale. The thick bed of carbonaceous silty shale in the lower half contains small lithoclasts in the basal part (arrow). Scale bar is 0.5 mm long.

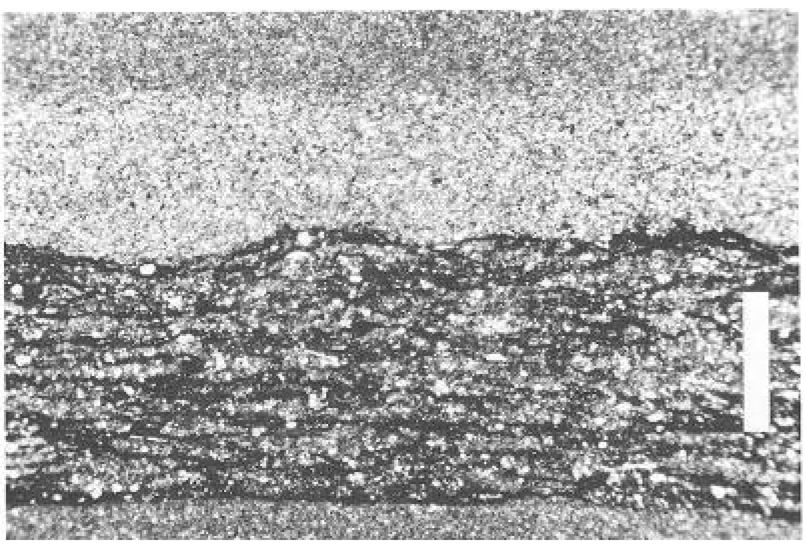

Fig. 7. Carbonaceous silty shale in strongly dolomitic striped shale facies is overlain by silt bed that grades upwards into dolomitic clayey shale. Scale bar is 0.5 mm long.

Mat-margin relationships

Another indication of a possible microbial mat origin is a kind of false cross-lamination. Carbonaceous silty laminae seem to terminate towards the underlying layer of dolomitic clayey shale and show a low angle viewing thin sections in detail, one can see that the drapes of dolomitic clayey shale within the carbonaceous silty shale are continuous into the underlying layer of dolomitic clayey shale, whereas laminae of carbonaceous silty shale pinch out between drapes of dolomitic clayey shale. The pinch-out of laminae of carbonaceous silty shale shifts sideways in a systematic

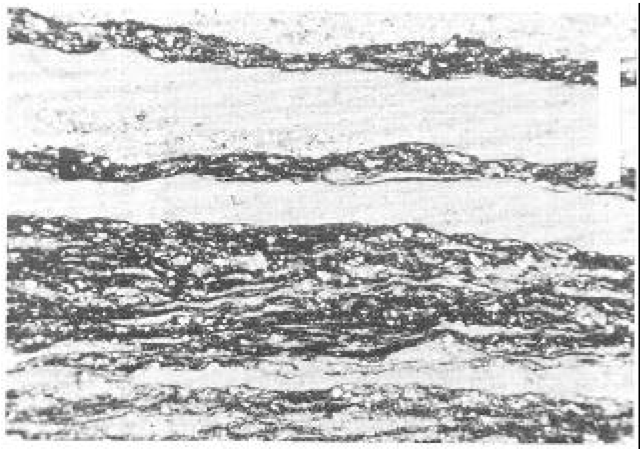

Fig. 8. Irregular carbonaceous laminae in carbonaceous silty shale beds (dolomite-free striped shale facies). The thick shale drapes in the upper part of the photo contain silt lenses at the base. Scale bar is 0-5 mm long.

way, as shown in Fig. *9*. Most of the silt is found in the carbonaceous laminae.

The observation that drapes of dolomitic clayey shale within a carbonaceous silty bed are continuous into underlying beds of dolomitic clayey suggests that the depositional interface cuts across the boundary between the two shale types. Laminae of silt and clay, which are similar in appearance to the shale drapes in beds of carbonaceous silty shale, have been described from recent microbial mats of Solar Lake, Sinai, by Krumbein and Cohen(1974, 1977). The terrigenous sediment laminae in the Solar Lake mats are deposited by sheet floods caused by strong, sporadic rainfalls (Krumbein and Cohen, 1974). The drapes of dolomitic clayey shale in beds of carbonaceous silty shale of the striped shale facies could have a similar origin. They could have been deposited during seasonal floods and strong rainfalls, when the basin received a small pulse of sediment. The pinch-out of carbonaceous silty laminae between drapes of dolomitic clayey shale indicates that carbonaceous silty sediment was deposited on a surface of dolomitic clayey mud but did not cover the whole surface. It also indicates that deposition of carbonaceous silty sediment was interrupted by the deposition of dolomitic clayey muds. The systematic sideways shift of the pinch-out of carbonaceous silty laminae is difficult to explain if the organic matter is considered a detrital component, be it as planktonic ‘rain’ from phytoplankton blooms or as material swept in from productive areas from the basin edge. In case of a plankton bloom, the deposition of organic matter should be widespread, and the area of organic matter deposition, during consecutive plankton blooms, would most likely not show the systematic lateral shift that is observed in Fig.9. If organic matter was swept in from the basin margins the systematic lateral shift of the pinch-out of carbonaceous laminae is again difficult to explain, and additionally it is hard to explain why the silt is mostly found in carbonaceous laminae. If organic matter were detrital and swept in by currents, the difference in specific weight quartz silt and fragments of organic matter should result in effective sorting of particulate organic matter and silt grains. Carbonaceous material and silt should be concentrated in discrete laminae.

There is, however, an alternative explanation. If foe example a pioneer microbial mat colonized a storm-deposited mud layer and was covered by a shale drape before it occupied the whole area, then the carbonaceous silty laminae would pinch out between two layers of dolomitic clayey shale. Motile filamentous micro-organisms would move upwards and establish a new mat on the mud surface, leaving behind sheaths and dead filaments. This new mat would expand laterally until it was covered again by a shale drape. If this happened repeatedly, the pinch-out point would shift in a systematic way because the met margin would move outward(after re-establishment) from the already colonized area during further growth (Fig.10). The association of silt and carbonaceous matter can be explained by the particle trapping property of the mucilaginous mat. If silt grains travel over an area that is in part covered by a microbial mat, they would be trapped preferentially in the areas that are covered by the sticky mat.

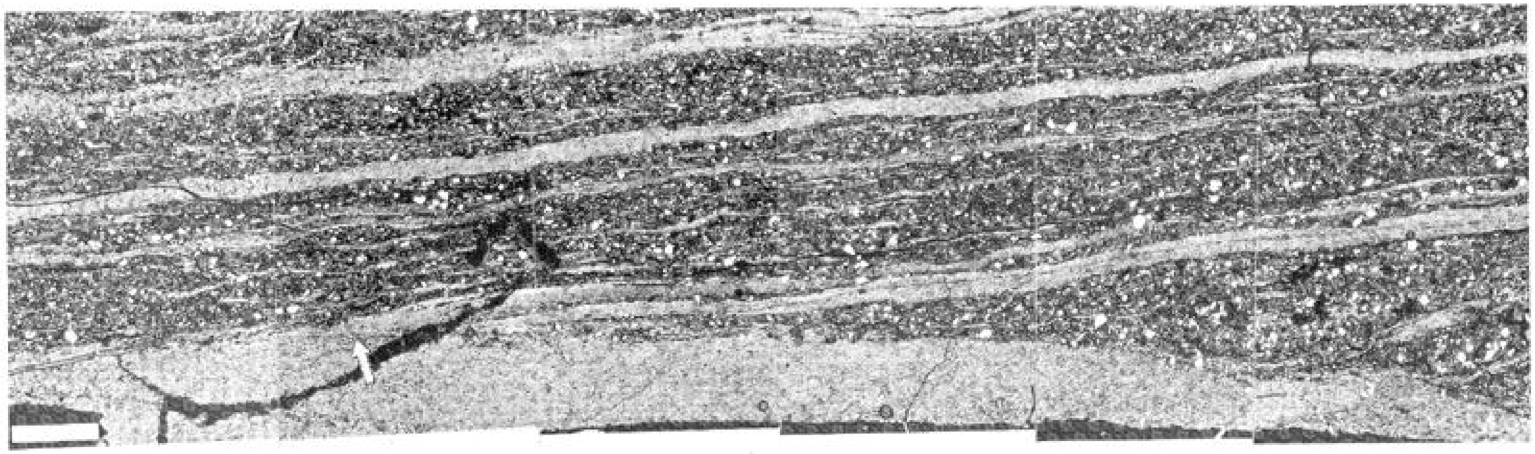

Fig. 9. False cross-lamination in a bed of carbonaceous silty shale. Shale drapes range from 0·01 to 0·1 mm in thickness. Thicker shale drapes are clearly visible, form an angle of about 5° with the base of the carbonaceous silty shale bed and continue into the underlying bed of clayey shale (arrow). Note also that most of the quartz silt is found within the carbonaceous laminae. Scale bar is 0·5 mm long. A schematic sketch of this false cross-lamination is shown in the upper portion of Fig. 10 (view along page).

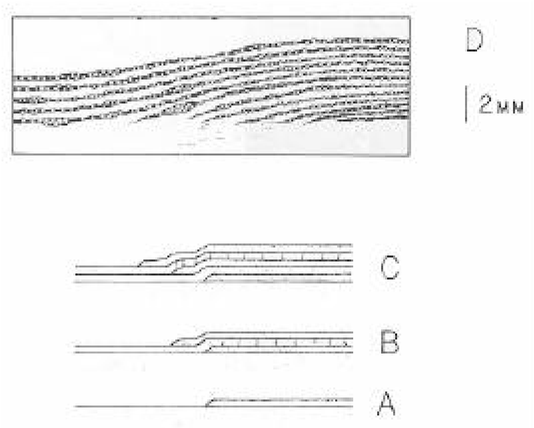

Fig. 10. Formation of false cross-lamination in carbonaceous silty shale. (A) Growth of microbial mat on mud surface. (B) Pioneer mat is covered by mud-drape, microbial filaments move upwards and re-establish new mat. New mat expands laterally. (C) Same as in (B), further lateral growth of mat after re-establishment. (D) End product of the process in (A), (B) and (C). Silty carbonaceous laminae are black, clay drapes are white. The under- and overlying beds of clayey shale are white with horizontal dashing.

Differential deformation

The third point in favour of a microbial mat origin is the mechanical behaviour of the carbonaceous silty shale during penecontemporaneous deformation. It appears that the beds of carbonaceous silty shale behaved as a coherent layer, whereas the dolomitic clayey shale beds behaved more like a very viscous fluid during early soft sediment deformation. This is demonstrated by completely overfolded but intact layers of carbonaceous silty shale, whereas the dolomitic mud in the fold noses is entirely squeezed out (Fig. 11). In some samples, deformed and overfolded beds of carbonaceous silty shale have even undeformed beds of carbonaceous silty shale above and below them, indicating that deformation happened very soon after deposition, presumably before deposition of the overlying bed. In places where beds of carbonaceous silty shale were disrupted during soft sediment deformation, dolomitic mud flowed into the gap (Fig. 12). There appears also to be a difference in mechanical properties between dolomitic clayey shale and carbonaceous silty shale with respect to loading by silt beds. If, for example, a silt/mud couplet overlies a bed of dolomitic clayey shale (Fig. 13), the loadcasts at the base of the silt bed are considerably stronger than where a silt/mud couplet of comparable thickness overlies a bed of carbonaceous silty shale (Fig. 14).

All these observations indicate that the carbonaceous shale beds were more cohesive and had higher mechanical strength than the beds of dolomitic clayey shale. The carbonaceous silty shale beds behaved like a tough leathery membrane, rather than like a soupy organic muck.

Redeposited algal mat fragments

Beds of dolomitic clayey shale that are interbedded with carbonaceous silty shales contain variable amounts of carbonaceous flakes. These carbonaceous flakes are usually less than 0.1 1 mm thick and may be as much as 20 mm in diameter. Relatively thick flakes may show lamination that is identical to that in beds of carbonaceous silty shale (Fig. 15). These carbonaceous flakes appear to have been rolled up (Fig. 16) and folded over (Fig. 17) during sedimentation. The internal textures of these carbonaccous flakes indicate that they were eroded from beds of carbonaceous silty shale. The carbonaceous flakes in Figs 15 and 17 show silt grains surrounded by carbonaceous matter and thus show the same close association between carbonaceous matter and silt that has been found in the carbonaceous laminae of carbonaceous silty shale

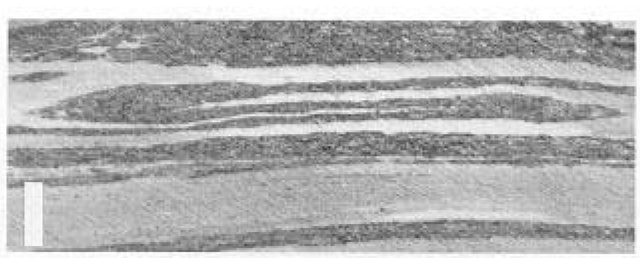

Fig. 11. Overfolded but intact bed of carbonaceous silty shale in dolomitic clayey shale. Most of the dolomitic clayey shale has been squeezed out of the fold noses and limbs. This indicates that beds of carbonaceous silty shale were considerably more cohesive than beds of dolomitic clayey shale, and that dolomitic clayey shale behaved like a highly viscous fluid during penecontemporaneous deformation. Scale bar is I mm long.

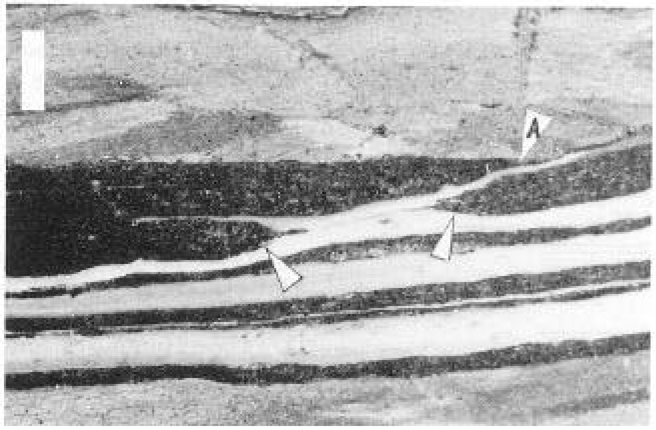

Fig. 12. Ruptured bed of carbonaceous silty shale (arrows). The left part of the ruptured bed shows overfolding during early soft sediment deformation like that shown in Fig. I I . The outer hinge of the overfolded portion of the bed is marked by arrow, A. Scale bar is I mm long.

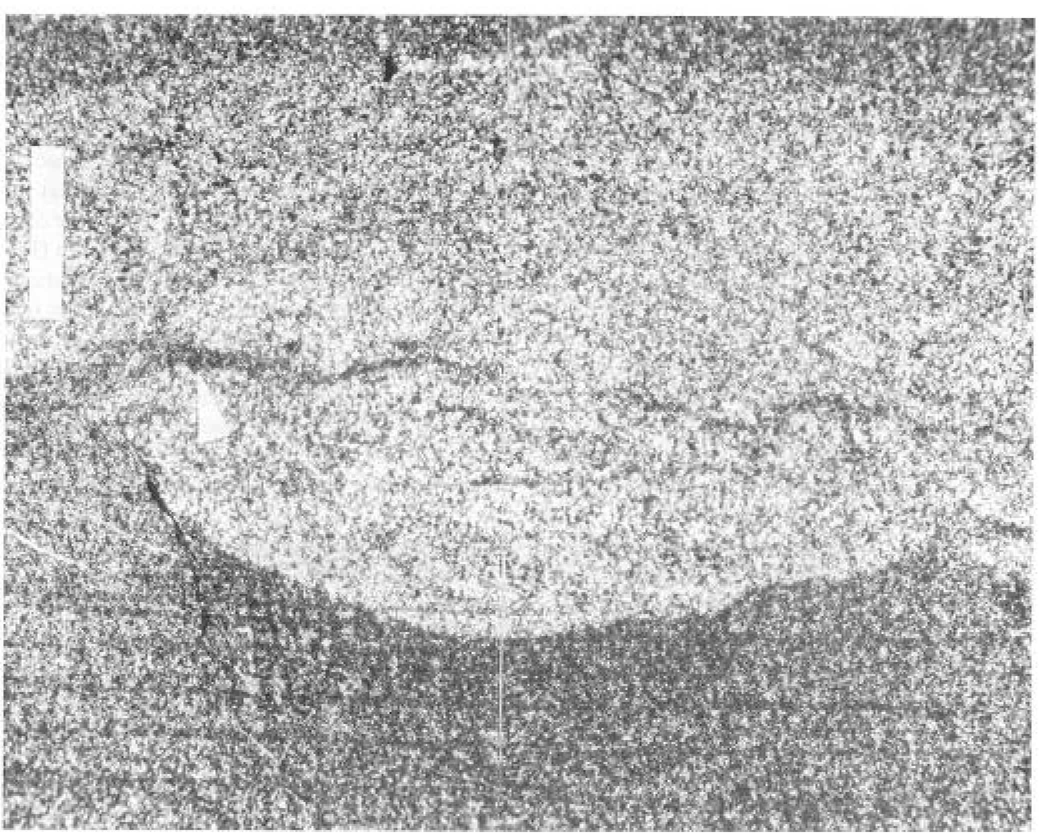

Fig. 13. A silt bed overlying a bed of dolomitic clayey shale. The silt sank into the underlying soft mud to form a pillow at the base of the silt bed. Mud was squeezed up between the silt pillow and the silt bed (arrow). Scale bar is 0.5 mm long.

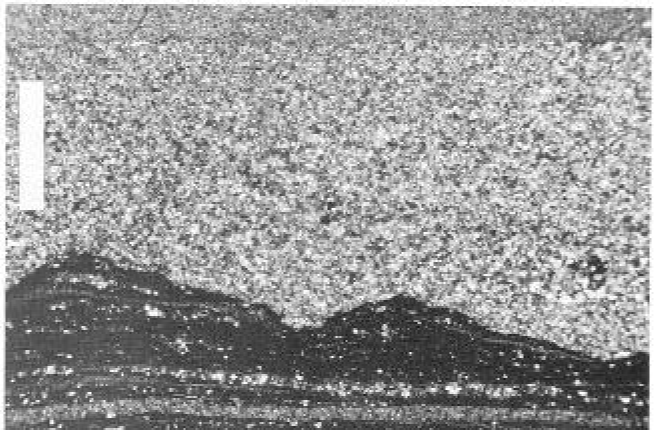

Fig. 14. A silt bed of the same thickness as in Fig. 13, overlying a bed of carbonaceous silty shale. Note that the load structures at the base of the silt bed are much less pronounced than the ones at the base of the silt bed in Fig. 13. Comparison between Figs 13 and 14 suggests that the carbonaceous silty shale beds were more cohesive than beds of dolomitic clayey shale during penecontemporaneous deformation. Scale bar is 0.5 mm long.

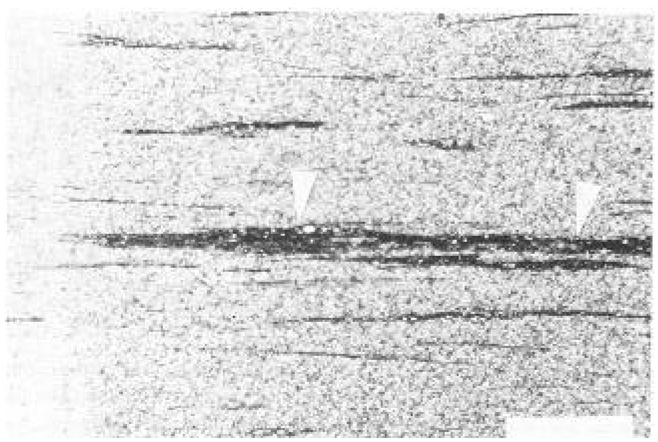

Fig. 15. Carbonaceous flakes in dolomitic clayey shale. Note that silt grains are associated with and included in carbonaceous flakes. Lamination in the large fragment in the centre has internal laminae (arrows) that are the same as in beds of carbonaceous silty shale. Scale bar is 0 5 mm long.

beds. Rolling-up and folding-over of these flakes indicate that they possessed considerable cohesive strength during transport and deposition. Carbonaceous flakes from shales of the Newland Formation contain abundant filamentous microorganisms (Horodyski, 1980), interpreted as remnants of filamentous bacteria and cyanobacteria. The carbonaceous flakes were probably derived from nearshore microbial mats. This motion raises the possibility that the carbonaceous silty shale beds in the striped shale facies are mere accumulations of microbial mat fragments, swept into the basin from the shoreline. However, the sharp boundaries between the beds of carbonaceous silty shale and silt/mud couplets are an argument against an accumulation of detrital organic matter. In marginal areas where input of mud would be higher and where there is evidence for slow but continuous sediment input between storms, gradational boundaries are to be expected between beds of carbonaceous silty shale and dolomitic clayey shale. This, however, is not the case. Carbonaceous laminae do not consist of distinguishable carbonaceous fragments but appear rather homogeneous.

The presence of probable bacterial and cyanobacterial filaments

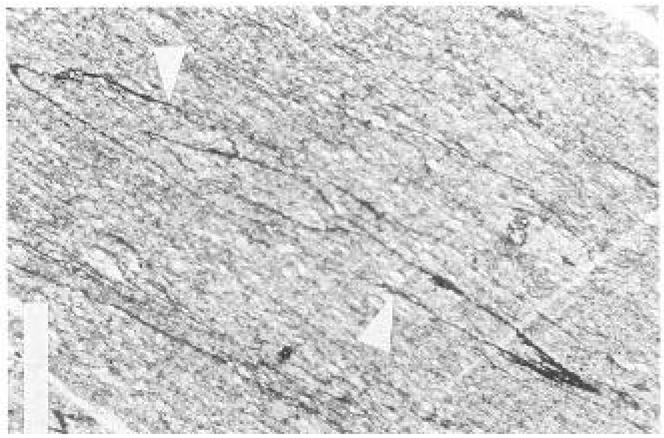

Fig. 16. Rolled up carbonaceous flake (arrows) in shale. Scale bar is 0-5 mm long.

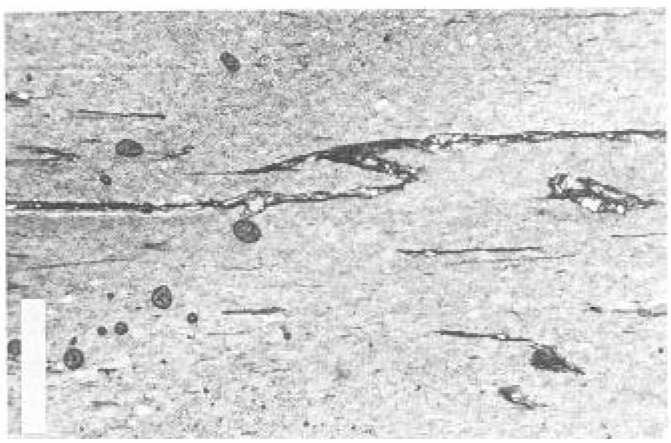

Fig. 17. Carbonaceous flakes in dolomitic clayey shale. The large carbonaceous flake in the centre is folded over twice. Note that silt is more abundant in the carbonaceous flakes than in the surrounding shale matrix. The silt grains of the carbonaceous flakes are surrounded by carbonaceous matter, suggesting that the silt grains were incorporated into the carbonaceous flakes prior to their deposition. Scale bar is 0.5 mm long.

within carbonaceous flakes (Horodyski, 1980), as well as the occurrence of larger carbonaceous flakes in dolomitic clayey shales that show an internal lamination very similar to that of the carbonaceous silty shales, is an additional indication of the microbial origin of the beds of carbonaceous silty shale.

Discussion

Laminated structures in sediments that are presumably organic in origin are usually described as stromatolites, and the carbonaceous silty shale beds in the Newland Formation may thus also be termed stromatolites. However, since Kalkowsky's (1908) original definition of the term, a bewildering variety of definitions has been put forward. Buick *et al.* (1981) and Krumbein (1983) reviewed the various definitions and showed that there are two conflicting views among stromatolite specialists. One view holds that stromatolites must have a particular form of laminated morphology but may have any type of sedimentary origin. The other view suggests that stromatolites may have any morphology but must have a microbial origin. The basic conflict is the relative importance of morphology and biogenicity with regard to the term stromatolite. Another problem is that microbiologists have accumulated much information on living microbial mat communities (termed `potential stromatolites' by Krumbein, 1983), but that most of this has not yet been applied to ancient stromatolites. Part of the problem is that it is not yet easy to predict what the eventual fossilized form of recent microbial mats will be. Bridging the gap between recent microbial mats and fossil (in particular Precambrian) stromatolites is hampered because most of the microstructures of the living mat are destroyed through time with diagenesis and fossilization (Cohen, Castenholz & Halvorson, 1984). Definitions of stromatolite, as they have been put forward by Buick *et al.* (1981) and Krumbein (1983), require stromatolites to have a biogenic origin. The lithmus test for the definite recognition of a stromatolite is that `microfossils within the structure must be oriented or organized in a way indicative of organosedimentary interaction' (Buick *et al.*, 1981). However, even in modern (potential) stromatolites all remnants of the constructing microbiota may be destroyed within the first few hundred years of burial (Park, 1976). If Buick *et al.'s* (1981) and Krumbein's (1983) criteria are employed, most of the stromatolites that have been described from the geological record would not qualify as such, and neither would the carbonaceous silty shale beds that are described in this study.

However, the author thinks that even though there is no direct evidence for the participation of microbial mats in the formation of these carbonaceous shales, indirect indications of microbial mat activity can be shown. For example, the false cross-lamination and preferred silt concentration in carbonaceous laminae is very difficult to explain if the carbonaceous silty shale beds are supposed to be the result of detrital organic matter accumulation in a stagnant basin, but can be reasonably explained as the product of pioneer mat growth and silt trapping by a mucilaginous mat. Likewise, the considerably higher mechanical strength of beds of carbonaceous silty shale (as compared with beds of dolomitic clayey shale) during soft sediment deformation is more consistent with a cohesive microbial mat than with that of a soupy organic muck. The irregular, wavy-crinkly lamination of carbonaceous shale beds resembles that from other microbial mat deposits. The additional presence of filamentous microbiota in carbonaceous flakes (Horodyski, 1980) that have the same type of internal laminae as do the carbonaceous silty shale beds at least indicates the possibility that microbial mat communities were involved in the formation of carbonaceous silty shale layers.

One of the problematic points with interpreting the carbonaceous silty shale beds as microbial mat deposits is that no `stromatolitic' structures with surface relief have been noted in the striped shale facies. Whether permanently submerged microbial mats should always show surface relief like domal and columnar structures is still a matter of debate among stromatolite specialists. This point of disagreement is also embodied in the two conflicting views on stromatolite definition mentioned above.

Permanently submerged microbial mats with essentially flat morphology (no formation of domal and columnar structures) have been observed in recent environments (Gebelein, 1969; Neumann, Gebelein & Scoffin, 1970; Bathurst, 1967). Gebelein (1969) demonstrated that thick microbial mats of flat morphology form in subtidal areas off Bermuda, and that flat mats formed in areas of low sediment movement and slow currents, whereas domal mat structures formed in areas of increased current velocities. A compilation of recent occurrences of benthic microbial mats in saline lakes (Bauld, 1981b) showed that flat microbial mats can cover large areas of the submerged portions of these lakes. Thus both Gebelein's and Bauld's investigations showed that microbial mats can grow in a submerged position without necessarily forming structures of strong surface relief. Recent flat microbial mats may have minor surface relief on the order of millimetres, and one may wonder if such microrelief should not be expected to be preserved in fossilized flat microbial mats. However, recent microbial mats contain 7080% water (Park, 1976; Krumbein, Cohen & Shilo, 1977) and undergo strong compaction due to fluid loss after burial, unless they experience early cementation. Bacterial degradation of organic matter causes further volume loss of a buried microbial mat, and Krumbein *et al.* (1977) calculated for the case of recent microbial mats of Solar Lake, Sinai, that between 180 and 250 mm of microbial mat growth are necessary to form 1 mm thickness of stromatolite rock. Therefore any previously present surface relief would be strongly reduced after burial. The presumed microbial mat deposits that are presented in this paper were deposited in an environment that was dominated by terrigenous mud and there is no evidence of early carbonate cementation. Thus one should not expect to find surface relief features of minor magnitude preserved.

Several of the criteria that were employed in this study to identify microbial mats, such as false crosslamination, preferred silt concentration in carbonaceous laminae, and mechanical strength of carbonaceous silty shale during penecontemporaneous deformation, have not been used previously to recognize microbial mat activity in sediments. Furthermore, the great majority of stromatolites has been described from carbonate depositional environments, and therefore the established criteria for stromatolite recognition may have only limited usefulness when applied to microbial mat deposits in shales. The cumulative indirect evidence of microbial mat activity probably justifies the description of the carbonaceous silty shale beds as flat laminated stromatolites, even though these beds do not qualify as stromatolites according to the criteria proposed by Buick *et al.* (1981) and Krumbein (1983).

In Phanerozoic and recent carbonaceous shales and muds, the absence of trace fossils (or bioturbation) is commonly taken as an indication of prevailing anoxic conditions in the overlying water column (e.g. Morris, 1979). In the Mid-Proterozoic burrowing organisms had not yet evolved, and therefore the absence of trace fossils in carbonaceous shales of that time does not necessarily imply that the shales were deposited under anoxic conditions. Surface waters of Mid-Proterozoic seas were probably oxygenated because free oxygen was present in the atmosphere when the Belt Supergroup (1500-900 Ma) was deposited (Schidlowski, Eichmann & Junge, 1975). Striped shales in the Helena embayment that were deposited relatively close to the basin margins are in places interbedded with cross-bedded sandstones and flat pebble conglomerates. These shales were deposited in fairly shallow, agitated water, and it is therefore quite likely that the overlying waters were oxygenated. Under modern conditions carbonaceous shales would be unlikely to form in a shallow, agitated, aerated setting, unless a microbial mat was present, mainly because the cohesive filamentous matrix of recent microbial mats acts as an `ecological membrane' at the sediment-water interface, causing abrupt changes in several environmental parameters, such as dissolved oxygen, E,,, sulphide concentration and light intensity (Bauld, 1981a). This property of microbial mats allows the formation of strongly reducing sediments immediately below the living surface layer. Thus in the Proterozoic, the presence of subtidal benthic microbial mats may have allowed the formation of highly carbonaceous sediments in shallow, aerated environments.

CONCLUSIONS

The striped shale facies of the Newland Formation was deposited in a subaqueous setting, seaward of marginal mudflats. The carbonaceous silty shale beds in this shale facies probably originated as microbial mats. An irregular lamination, false cross-lamination, and mechanical strength during soft sediment deformation are the main arguments in favour of a microbial mat interpretation. It is considered that subaqueous flat microbial mats were widespread and that occasional storms mobilized mud in marginal areas and spread it out over the mats. After the settling of storm layers, microbial mats recolonized the sediment interface. Smaller pulses of sediment, caused by floods etc., may have led to the deposition of shale drapes within the microbial mat beds. Recurring deposition of storm layers on microbial mats was probably responsible for the intimate interlayering of lithologies and for the striped appearance of this facies. The microbial mats may have acted as a membrane that separated strongly reducing sediments below from oxygenated waters above, thus allowing the accumulation of highly carbonaceous shales in shallow sedimentary environments. Comparable shales are present in several other Proterozoic basins, and therefore submerged microbial mats may have been very common in mud-dominated Proterozoic basins. The high organic carbon content of these shales identifies them as potential hydrocarbon source rocks.

ACKNOWLEDGMENTS

I would like to thank Dr G. J. Retallack for helpful discussions concerning the sedimentological aspects of these shales, and Drs G. J. Retallack, R. W. Castenholz, S. Boggs, R. S. Agatston, M. H. Reed and also C. M. Soja for helpful reviews of the manuscript. Reviews by Drs W. E. Krumbein, M. E. Tucker and one other referee helped to improve the final version of the paper. Field-work in Montana was supported by Anaconda Minerals Co.

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