PERSPECTIVES

MICROBIALLY INDUCED SEDIMENTARY STRUCTURES—A NEW CATEGORY WITHIN THE CLASSIFICATION OF PRIMARY SEDIMENTARY STRUCTURES

NORA NOFFKE[1], GISELA GERDES[2], THOMAS KLENKE[3], AND WOLFGANG E. KRUMBEIN[3]
[1] *Department of Organismic and Evolutionary Biology, Harvard University, 26, Oxford Street, Cambridge, Massachusetts 02138*
[2] *ICBM-Marine Laboratory, Carl von Ossietzky-University, Schleusenstrasse 1, 26382 Wilhelmshaven, Germany*
[3] *ICBM, Carl von Ossietzky-University, Box 2503, 26111 Oldenburg, Germany*
e-mail: nnoffke@oeb.harvard.edu

ABSTRACT: **Cyanobacterial films and mats syndepositonally influence erosion, deposition, and deformation of sediments. The biomass levels surface morphologies, and microbial mats stabilize depositional surfaces and shelter the sediment against erosion or degassing. Growing microbial mats dredge grains from their substrate upwards, whereas cyanobacterial filaments that are oriented perpendicular to the mat surface reach into the supernatant water and baffle, trap, and bind suspended particles. These and similar biotic–physical interactions are reflected in syndepositional formation of microbially induced sedimentary structures. We distinguish structures on bedding planes (leveled bedding surfaces, wrinkle structures, microbial mat chips, erosional remnants and pockets, multidirectional ripple marks, and mat curls) and internal bedding structures (sponge pore fabrics, gas domes, fenestrae structures, sinoidal laminae, oriented grains, benthic ooids, biolaminites, mat-layer-bound grain sizes).**

We propose to place this group of microbially mediated structures as a fifth category (bedding modified by microbial mats and biofilms) in Pettijohn and Potter's (1964) existing classification of primary sedimentary structures.

INTRODUCTION

Sedimentary depositional systems can be characterized by a wide range of physical, chemical, and biological processes, all of which can produce a wide variety of sedimentary structures. Structures that form at the time of deposition or shortly thereafter while the sediments are still unconsolidated are generally referred to as primary sedimentary structures. Following Pettijohn and Potter (1964), physical sedimentary structures are those formed by the strictly physical processes of erosion, transport, deposition, and deformation. These primary physical sedimentary structures are well known and were classified by Pettijohn and Potter (1964) to include various types of bedding, markings on bedding surfaces, and deformational phenomena. They included stromatolites as positive growth structures projecting from former depositional surfaces, reflecting the fact that the microbes construct the structure in conjunction with synsedimentary cementation (see e.g., Reid et al. 2000 for overview). It is now recognized, however that microbes can also merely modify or induce a variety of other primary sedimentary structures that do not project upward from the substrate (e.g., Gerdes et al. 2000b). These microbially mediated structures result from epibenthic cyanobacteria interacting with the physical agents of erosion, deposition, transportation, or deformation and have been termed microbially induced sedimentary structures, MISS (Noffke et al. 1995, 1996; Gerdes et al. 2000b). They are highly facies-indicative and can aid in paleoenvironmental reconstruction. Like physical sedimentary structures, MISS are formed in settings where physical sedimentary processes dominate (both siliciclastic and carbonate depositional systems). Because the structures differ in appearance and origin from other physical sedimentary structures, however, we propose that they should be grouped into their own category.

Cyanobacteria are photoautotrophic prokaryotes, of which many taxa are epibenthic. Some of these species show phototactic behavior, which means that they can actively move to optimize their position with respect to light. The microorganisms and their mucous extracellular polymeric substances (Decho 1990) cover sedimentary grains like adhesive organic envelopes (e.g., Paterson and Black 2000, and literature therein). Such organic coatings are termed biofilms (Charaklis and Wilderer 1989; see also Decho 1990, 2000; Stolz 2000). At sites with favorable ecological conditions, biofilms continue to grow to form thick and significant organic layers termed microbial mats (Krumbein 1983; Neu 1994; also review by Stolz 2000). These can cover large areas of the sedimentary surface.

In this paper, we give an overview of the five main biological processes in MISS formation: (1) leveling, (2) biostabilization, (3) imprinting, (4) microbial grain separation, and (5) baffling, trapping, and binding. Additionally, we present examples of MISS from Recent tidal environments, as well as from the stratigraphic record. The proposal is then made to place MISS as its own category in the existing classification of primary sedimentary structures of Pettijohn and Potter (1964).

STUDY LOCATIONS

Three sites were studied (Fig. 1A): (1) the Recent tidal flats of Mellum Island, situated in the southern North Sea, (2) Ordovician siliciclastics of the Montagne Noire, France, and (3) an outcrop of Triassic rocks in southwestern Germany.

The Tidal Flats of Mellum Island

Mellum Island is located in the southern North Sea (Fig. 1B). The tidal sediments consist of 95% fine- to medium-grained quartz sand and 5% silt and mud. Medium-grained sands occur mainly within lower intertidal areas exposed to the strong currents passing the island along its western and eastern parts. The silt and mud content is enriched at localities of extreme low hydrodynamic energy, that is, within few very shallow depressions of some tens of square meters close to the upper supratidal zone. Fine sands occur in less hydrodynamically reworked areas of the lower to upper intertidal and lower supratidal zones. The sands are overgrown by epibenthic cyanobacterial films and mats (e.g., Stal and Krumbein 1985; Gerdes and Krumbein 1987; Villbrandt 1992; Noffke and Krumbein 1999a). Substrates of fine sand grain sizes are preferred colonization sites for the cyanobacteria, because capillary water ascends and constantly moistens the deposits even during subaerial exposure of the tidal surface (Gerdes and Krumbein 1987). Thin biofilms develop within areas of the lower intertidal zone, whereas biomass accumulation and mat formation increase toward the upper intertidal and lower supratidal zone. There, thick microbial mats occur over an area of several square kilometers extension (Noffke and Krumbein 1999a).

The Lower Arenigian of the Montagne Noire in France

The Montagne Noire forms the southern part of the Massif Central and consists mainly of Paleozoic rocks. Lower Arenigian (Ordovician) sedi-

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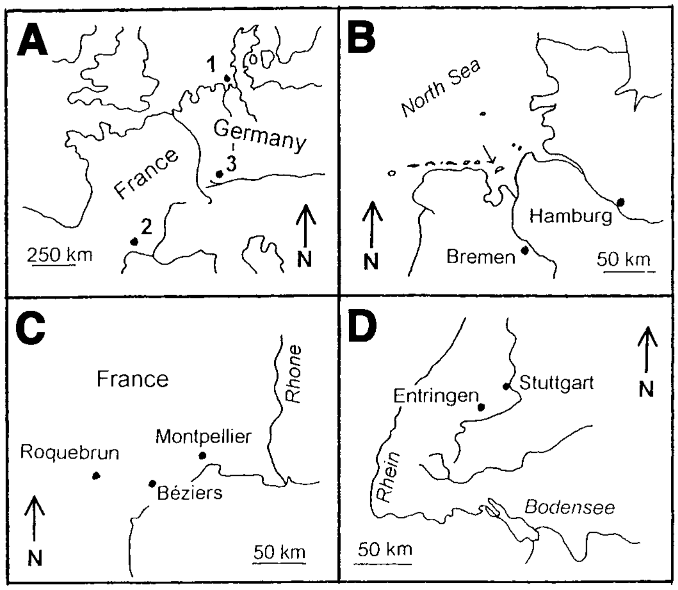

FIG. 1.—**A)** General setting of the three study locations within Europe: 1, Mellum Island (Recent tidal deposits); 2, Ordovician of the southern Montagne Noire, France; 3, Triassic of southwestern Germany. **B)** Mellum Island (arrow) is situated in the southern North Sea near the German maincoast. **C)** Lower Arenigian siliciclastics crop out near the village of Roquebrun in the Montagne Noire, France. **D)** Evaporite-rich siliciclastics of Triassic age were investigated in an outcrop located east of the village of Entringen (southwestern Germany).

ments crop out near the village of Roquebrun (Fig. 1C). They consist of mud- and siltstones, as well as fine- to medium-grained sandstones. The siliciclastics record a depositional environment comparable to the Recent coast of the North Sea (shallow shelf, barrier sands, lagoon, tidal zone, and beach), located within a cool-humid paleoclimate zone (Noffke and Nitsch 1994). In the rocks, hints of large microbial mat systems can be found (Noffke and Krumbein 1999b; Noffke 2000).

Triassic Rocks of Southwest Germany

Triassic (Keuper) rocks consisting of evaporite-rich mudstones, siltstones, and sandstones crop out near the village of Entringen in southwestern Germany (Fig. 1D). The rocks record a tidal depositional zone that was located within a semiarid–warm paleoclimate, and specific structures indicate the former presence of microbial mats (Nitsch 1995).

MICROBIALLY INDUCED SEDIMENTARY STRUCTURES (MISS)

Microbially induced sedimentary structures at the three study localities were formed by various modes of microorganism behavior in response to the prevailing physical dynamics (Table 1). The microbial activities are: (1) leveling, (2) biostabilization, (3) imprinting, (4) microbial grain separation, and, (5) baffling, trapping, and binding. We distinguish structures formed at bedding planes and structures that can be found within the beds.

Structures Induced by Leveling

A biofilm or a microbial mat can be regarded as ''stabilized and well structured water'' (Krumbein 1993). During growth, it accumulates at first in the deepest topographical parts of the sediment surface relief, and the original morphology of the sedimentary surface is leveled. We term such organically smoothed surfaces 'leveled depositional surfaces.' Advanced developing stages of a microbial mat show a planar mat surface (Fig. 2A), and the substrate below is not longer visible (Noffke and Krumbein 1999a). Low points of the depositional morphology (e.g., ripple troughs) are sites

TABLE 1.—*Primary microbially induced sedimentary structures found in the Recent tidal flats of Mellum Island, as well as in the Lower Arenigian of the Montagne Noire (France), and the Triassic near the village of Entringen (southwestern Germany).*

Primary Microbially Induced Sedimentary Structures
Structures Induced by . . .
. . . Leveling
leveled depositional surfaces, wrinkle structures
. . . Biostabilization
microbial mat chips, erosional remnants and pockets, multidirectional ripple marks (palimpsest ripple marks), mat curls, shrinkage cracks, sponge pore fabrics, and gas domes (fenestrae structures)
. . . Imprinting
sinoidal laminae
. . . Grain Separation
oriented grains, sedimentary augen structures (benthic ooids)
. . . Baffling, Trapping, and Binding
mat-layer-bound grain sizes, biolaminites

of increased microbial growth because they provide greater moisture and because they protect the organisms from erosion.

Leveling of ripple marks by a thick organic cover can frequently be observed in the lower supratidal zone of Mellum Island, where biomass production is high. Because of the organic infill of the ripple troughs, the amplitude of the ripples is reduced, and the ripple index (Tanner 1967) is changed to a modified ripple index (Noffke and Krumbein 1999a). In places, the ripples are totally obliterated by the mats, and no ripple index can be determined. Such flat mats were also described from Recent carbonate environments by earlier workers like Logan et al. (1964), Kendall and Skipwith (1968), and Park (1977).

In the fossil record, wrinkle structures (Fig. 2B) observed on upper surfaces of sandstone beds are considered lithified examples of leveled depositional surfaces. Wrinkle structures have been found in Proterozoic rocks (Hagadorn and Bottjer 1997, 1999) and in Lower Arenigian rocks of the Montagne Noire in France (Noffke and Krumbein 1999b).

Structures Induced by Biostabilization

The term biostabilization was first defined by Paterson (1994) to describe the fixation of sediment by microorganisms such as diatoms, cyanobacteria, fungi, and others (e.g., Neumann et al. 1970; DeBoer 1981; Grant and Gust 1987; Dade et al. 1990; Gerdes et al. 2000b; see also Paterson and Daborn 1991; Krumbein et al. 1994; and Paterson 1997 for review). Biostabilization changes the response of mat-overgrown sediments to erosion and pressure from intradepositional gases (Noffke 1997; Gerdes et al. 2000b). In contrast to baffling, trapping, and binding (see below), no sediment accumulation takes place in association with biostabilization, and only physical agents play a role in structure formation.

Cyanobacteria stabilize their substrate in three different ways: (1) fixation of the loose sediment grains by the mat fabrics (Fig. 3A), (2) smoothing of the formerly rough sediment surface by the extracellular mucilages of the microbes (Fig. 3B), and (3) sealing of the sediment by a microbial mat (Fig. 3C). Each of these processes is described more fully below.

Stability of a mat-covered surface is increased by (1) fixation of the formerly loose sand particles by the organic network produced by cyanobacterial filaments (Fig. 3A) and by (2) smoothing of the formerly rough sediment surface by the extracellular mucilages of the microbes (Fig. 3B) (Paterson 1994). The organic network prevents grains from being removed from the sediment by currents or waves, and the smooth and slippery mat surface leads to reduction of frictional forces at the interface sediment and water. On Mellum Island, this was shown in field experiments by Führböter and Manzenrieder (1987).

Biostabilization by grain fixation and by reduction of roughness of the

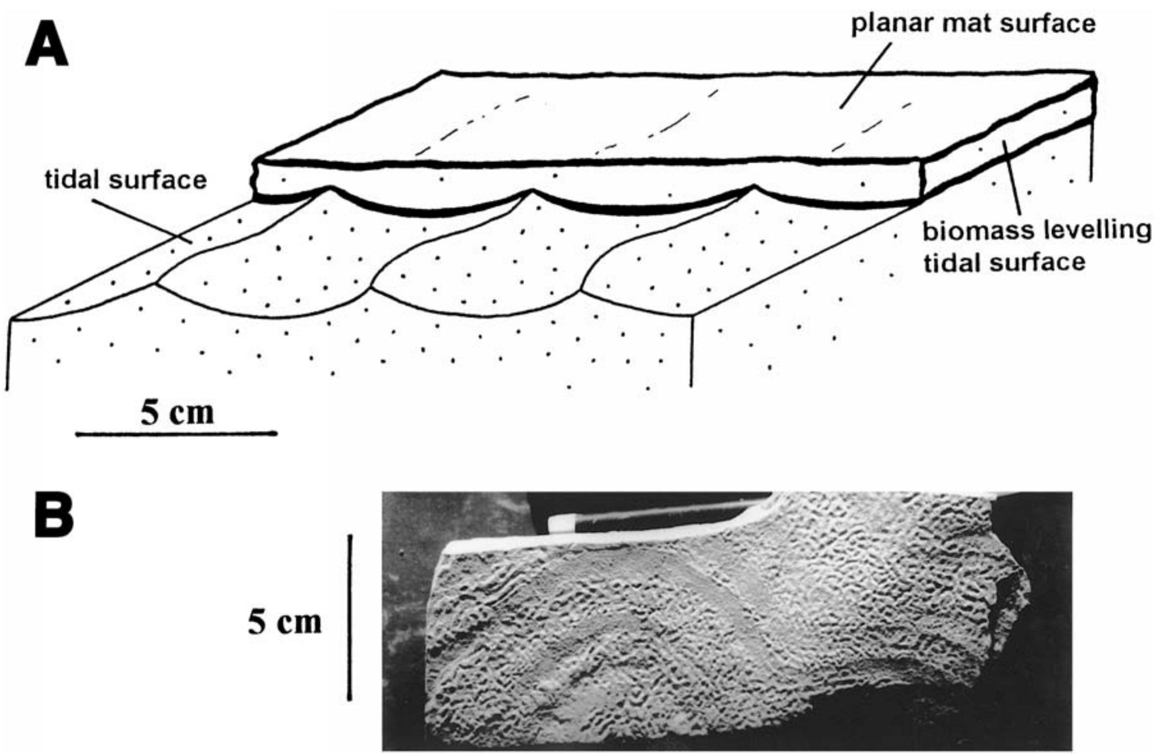

FIG. 2.—**A)** Diagrammatic sketch showing leveling of ripple marks on a tidal surface by a cyanobacterial mat. The biomass grows preferentially in deeper parts of the rippled relief. Further growth of the biomass forms a planar mat surface over time. **B)** Wrinkle structure atop a Lower Arenigian fine sandstone bed. The structure represents a fossil mat that formerly leveled its underlying substrate.

sediment surface lead to the formation of characteristic structures when counteracting dynamic forces. Flake-like organic-mineral aggregates with sizes of a few square centimeters are called 'microbial mat chips.' They are torn from their parent mat by water agitation during tides or storms (Logan 1961; Neumann et al. 1970; Gerdes and Krumbein 1987). On Mellum Island, large amounts of microbial mat chips litter the intertidal flats and are produced each year in fall when storm frequency increases (Noffke et al. 1996). Fossil fragments of mats are reported by Pflüger and Gresse (1996) and hollow impressions of mat pieces have been mentioned by Horodyski (1982) and Schieber (1998). Figure 4A shows impressions of mat pieces from the Lower Arenigian of the Montagne Noire, France.

On Mellum Island, examples of surface structures indicating increased resistance to erosion include erosional remnants and pockets (Reineck 1979; Gerdes et al. 1993; Gerdes et al. 1994; Noffke 1999), and multidirectional ripple marks (Noffke et al. 1995, 1996; Noffke 1998). Erosional remnants and pockets form a characteristic surface morphology in upper intertidal to lower supratidal sites. There, the surface of the sand flats is arranged into elevated and depressed areas of some square decimeters to square meters in extent. The elevated parts are covered by a microbial mat and therefore resist erosion or reworking. They are termed 'erosional remnants.' The depressed areas, where the sand is exposed and rippled, have been eroded into the former mat-secured tidal surface. Because of this

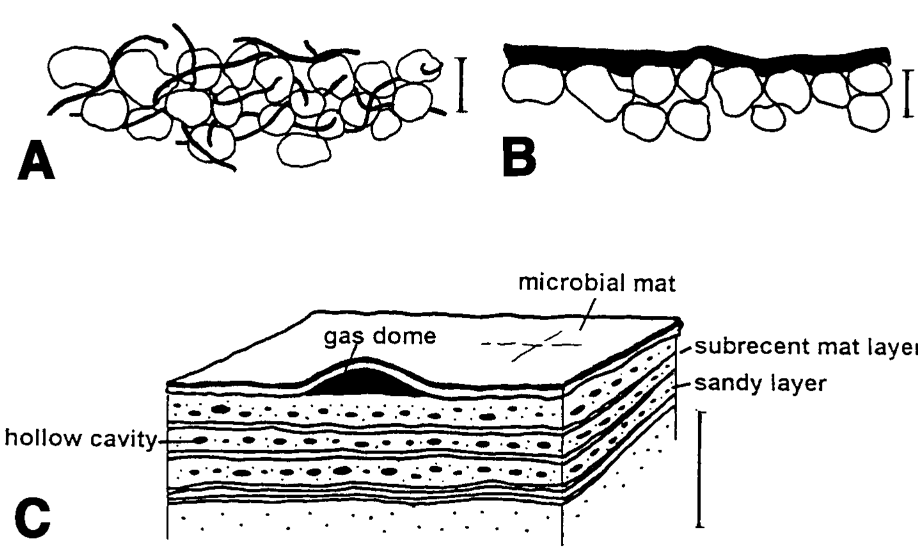

FIG. 3.—Biostabilization by benthic cyanobacteria. **A)** Sedimentary grains are interwoven by cyanobacterial filaments, and fixed in their position. The organic meshwork either increases the resistance of the organic-rich sediment against erosion or permits flexible deformation. Scale: 0.5 cm. **B)** Reduction of the surface roughness of the sandy deposits by the smoothing mucous-rich cyanobacterial cover (black). Smoothing of the sedimentary surface means reduction of frictional forces, which increases the stability against erosion. Scale: 0.5 cm. **C)** Dense mat layer seals the sediment and intrasedimentary gasses become entrapped. The gas pressure increases over time and generates hollow cavities within the sands. Scale: 10 cm.

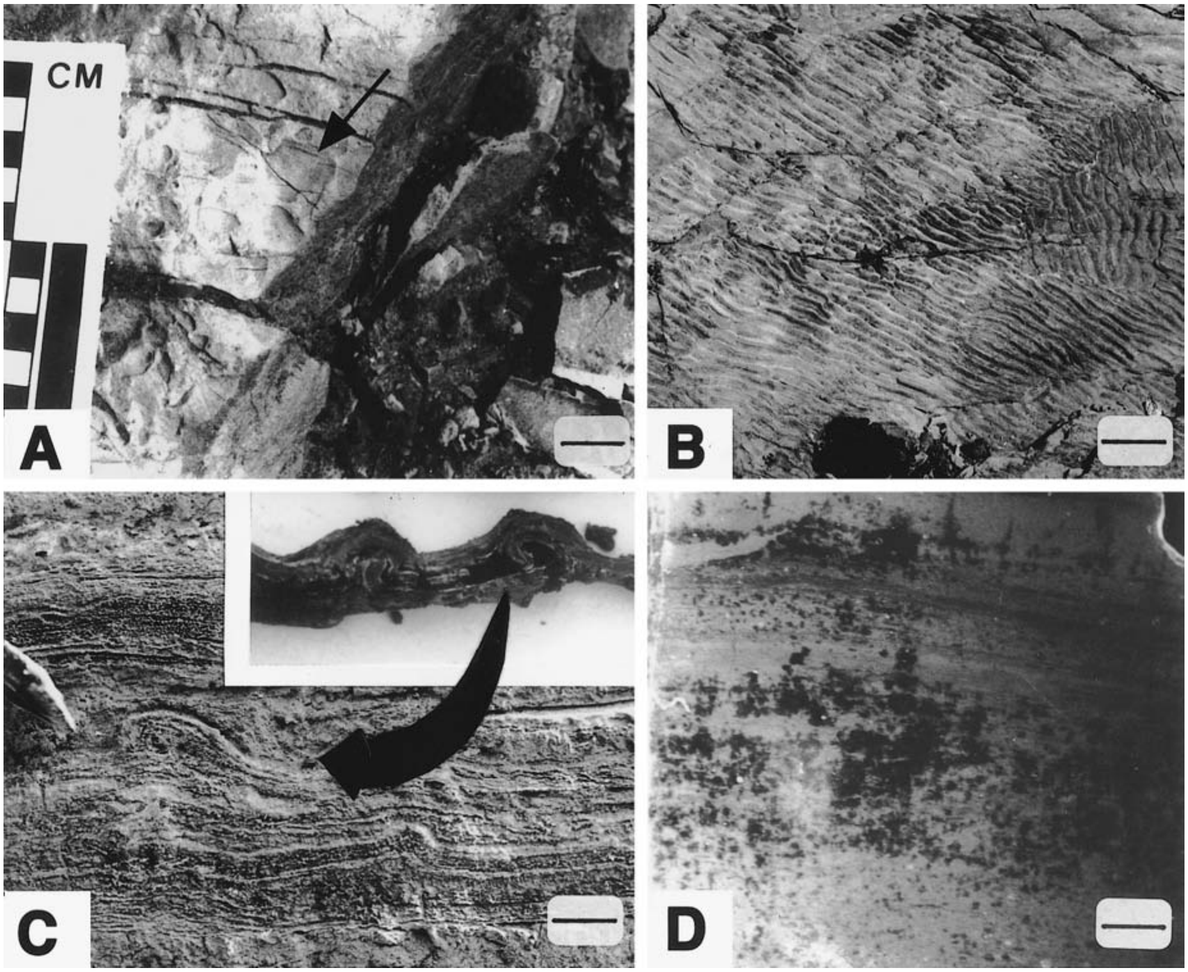

FIG. 4.—Fossil biostabilization structures. **A)** Impressions (arrows) of microbial mat chips on an upper bedding plane, Lower Arenigian, Montagne Noire (France). Scale: 2 cm. **B)** Multidirectional ripple marks (or palimpsest ripple marks) from a pre-Vendian sandstone belt, Dapango-Bombuaka Group, Burkina Faso, Africa (photo by courtesy of A. H. Knoll). Scale: 25 cm. **C)** Lateral view on the margin of shrinkage cracks in ancient mats (Triassic, southeastern Germany). Small photo shows vertical section through a shrinkage crack of a Recent microbial mat. Scale: 1.5 cm. **D)** Sponge pore fabrics (or fenestrae structure) in Triassic rocks of southwestern Germany. Note laminae and pores (now infilled with dolosparite). Scale: 3 cm.

origin, the deeper-lying surface parts were named 'erosional pockets.' An ancient surface morphology of erosional remnants and pockets is reported from Proterozoic rocks by Schieber (1998).

Multidirected ripple marks cover wind-exposed tidal surface areas of the upper intertidal to lower supratidal zones of Mellum Island in late summer to early fall (Noffke 1998). Ripple marks with similar orientations (determined by field measurements) are overgrown by cyanobacterial mats of equivalent developing stages and mat thicknesses. This means that ripple marks were formed by storms or wind-reinforced spring high tides and then overgrown by cyanobacteria. Stabilization of the rippled sediment by the mats prevented the ripple marks from being destroyed by later reworking events. The final chaotic ripple pattern results from the interplay between steadily increasing microbial mat development in the course of the summer and episodic disturbance of the sediment during reworking events (Noffke et al. 1996; Noffke 1998). Fossilized multidirectional ripple marks (palimpsest ripple marks; Pflüger 1999) have been found frequently in Proterozoic rocks (Fig. 4B). In the Lower Arenigian of the Montagne Noire and the Triassic rocks of southwestern Germany, erosional remnants and pockets or multidirectional ripple marks have been not detected.

Biostabilization by grain fixation not only prohibits erosion but also permits flexible deformation of desiccating sands including organic material without fracturing. If desiccated, the sand and the mucous-rich, flexible microbial mass shrink differentially. Increased shrinkage of mat chips littered on tidal surfaces produces mat curls (Noffke et al. 1996). Desiccation of a subaerially exposed microbial mat originates cracks, because of immense shrinking of the water-rich organic layer. Figure 4C shows a vertical section through such a shrinkage crack found in the Triassic rocks of southwest Germany, together with a similar vertical section through a Recent mat. Similar features have been found in the Proterozoic Newland Formation of the Belt Supergroup (Schieber 1986, 1999).

Biostabilization, thirdly, means sealing of the sediment by a microbial mat (Fig. 4C). The sandy sediment is covered by a dense mat layer containing abundant extracellular mucilages. This layer prohibits any gas exchange between the underlying deposits and water or atmosphere. This can be deduced from the formation of hollows within the sediments, visible in vertical sections. These hollows are formed by intrasedimentary gases trapped beneath the sealing organic layer above the deposits. This effect is reflected by sponge pore fabrics (Noffke et al. 1996; Noffke et al. 1997a, 1997b; Gerdes et al. 2000b), and gas domes (Goemann 1939; Gerdes et al. 1993, 2000b; Noffke et al. 1996), which are widely distributed in the mat-covered tidal sands of Mellum Island. These and similar fenestrae structures are well known in Recent and fossil carbonate environments (e.g., Black 1933; Dunham 1962; Tebutt et al. 1965). The preservation potential of the

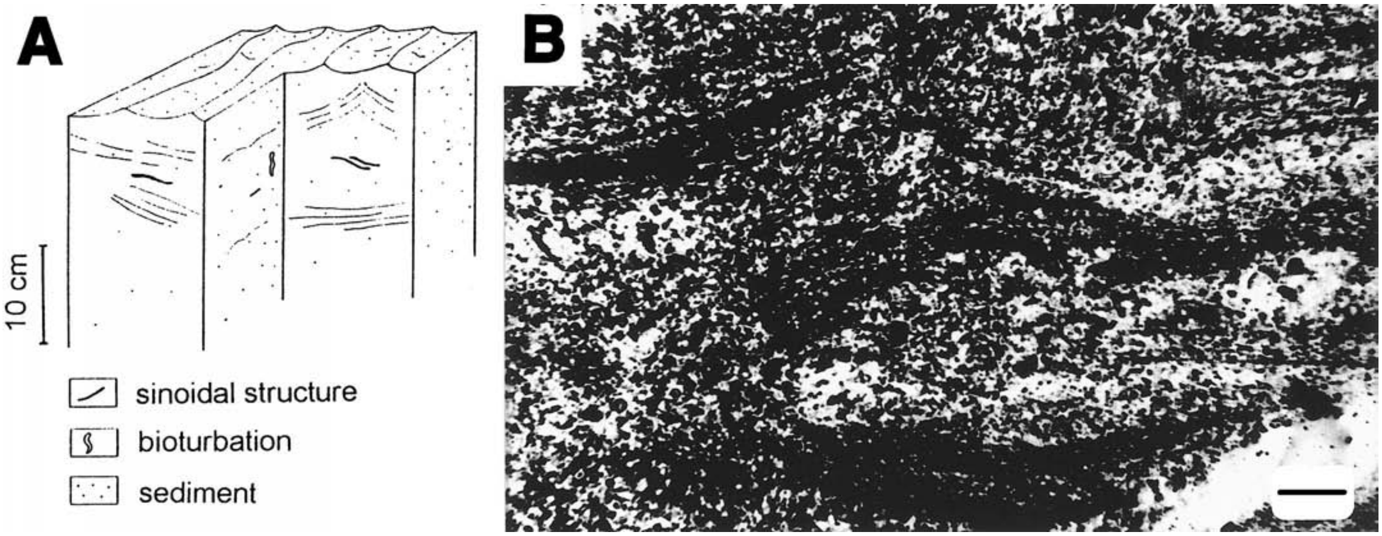

FIG. 5.—Imprinting of a primary sedimentary structure by cyanobacterial films. **A)** Biofilms do not alter the original surface relief of ripples, but in vertical sections through the deposits, the former ripples become visible as sinoidal structures because they are lined by organic films. **B)** Similar sinoidal structures defined by pyrite laminae are found within Lower Arenigian sandstone beds (Montagne Noire, France). Scale: 0.5 cm.

porous structures within sands is probably quite low, because no early cementation or rapid infilling of the hollows by evaporite crystals takes place. Experiments by Shinn and Robbin (1983) showed that compaction of cores of uncemented carbonate supratidal sediments led to complete obliteration of fenestrae. Because no early cementation took place, the Lower Arenigian siliciclastics do not document sponge pore fabrics. Conversely, the evaporite-rich Triassic rocks (southwest Germany) contain this specific fabric (Fig. 4D).

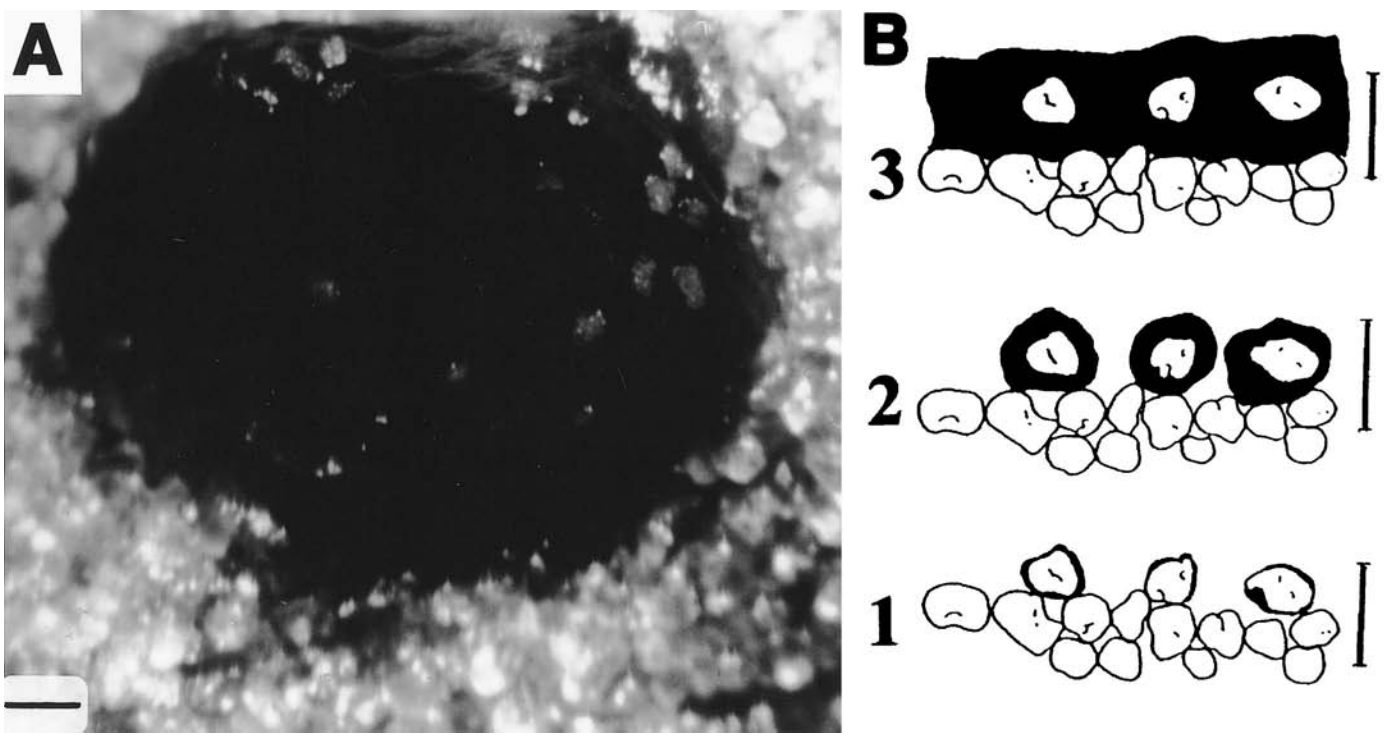

FIG. 6.—Sediment grain separation by growing biofilms of benthic cyanobacteria. **A)** Top view of a small patch of a developing microbial mat (dark) growing on a sandy substrate. Single quartz grains (light spots) can be seen that were separated from the substrate during development of the microbial mat. This sample is from a laboratory experiment in a closed system, so bacterial trapping of any transported grains is excluded. Photograph taken by binocular microscope. Scale: 2 mm. **B)** Schematic showing progressive development of separated grains on a biofilm. Stage 1, thin biofilms (black) of cyanobacteria adhere to the surfaces of grains; stage 2, biofilms (black) develop and become thicker; stage 3, biofilms of all grains are joined together. They form a continuous microbial mat (black) containing the grains that became oriented over time. Scales: 2 mm.

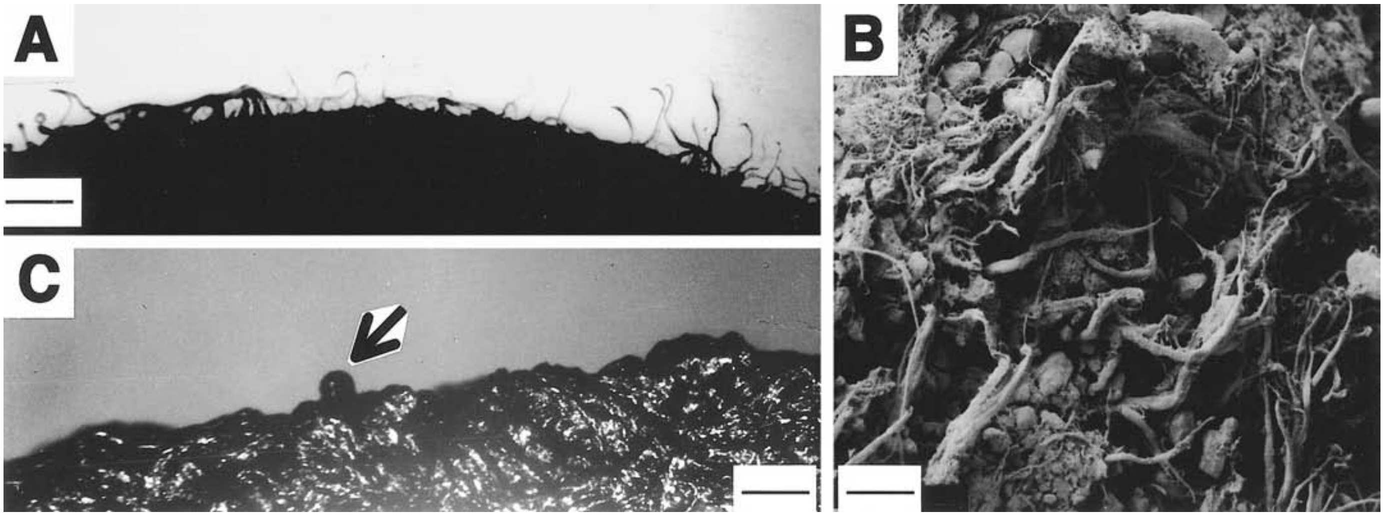

FIG. 7.—Baffling, trapping, and binding of sedimentary grains by benthic cyanobacteria (Recent). **A)** Baffling. Filaments of *Microcoleus chthonoplastes* are oriented perpendicular to the mat surface. They reach into the supernatant water and function like small current obstacles. Photo taken under dissecting microscope. Scale: 3 mm. **B)** Trapping. Mineral grains ''caught'' passively by cyanobacteria because of sudden reduction of current velocity behind the filaments. Photo taken under SEM. Scale: 200 μm. **C)** Binding. Mineral grain (arrow) upon the surface of a microbial mat incorporated by mat growth over time. Photo taken under dissecting microscope. Scale: 1 mm.

Structures Imprinted by Biofilms

Physically shaped sedimentary structures can be overgrown by biofilms with the original morphology conserved. The biofilms only line the former surface structures, visible in vertical sections through the sediment or rock (Noffke et al. 1995) (Fig. 5A). Examples are sinoidal laminae, which are commonly visible in sediment cores from the tidal flats of Mellum Island (Noffke et al. 1997b; Gerdes et al. 2000b) but which were also found as pyritic laminae in Lower Arenigian rocks of the Montagne Noire, France (Fig. 5B). Sinoidal laminae are formed by biofilms coating the single grains of the uppermost sediment layer of a rippled tidal surface. If the tidal surface is reactivated, the ripple marks are buried by freshly deposited sediment. The buried ripple marks can be detected later in vertical sections through the sediment, because their surfaces are marked by the organic films.

Structures Induced by Microbial Grain Separation

Microbial grain separation means upward transportation of mineral grains by the ongoing growth of biofilms that coat the particles. In contrast to baffling, trapping, and binding, no sediment is accumulated, and in contrast to biostabilization, erosion or gas pressure plays no role in structure formation.

Initially, thin biofilms are adhesively attached to the surfaces of depositional grains of the tidal flat surface. During periods of favorable ecological conditions, the biofilms grow more or less equally at each point around the grain. Experiments in which organic envelopes are grown show how the mineral grains are elevated and separated from each other by the biomass (Fig. 6). Finally, single sand grains ''float'' without contact with other grains in the newly developed microbial mat layer. In thin sections of tidal sediments, it can be seen that the grains in the mat layers often are oriented with their long-axes parallel to the depositional surface, whereas the grain orientation is random within the fabrics of the underlying substrate. In the mats, this predominant orientation of grains may indicate an energetically suitable position of the grains to gravity. Rotation of grains is permitted by the soft organic matrix of the mat. We chose the term mat-layer-bound oriented grains to describe this texture (Noffke et al. 1997a). In carbonate environments, the process of grain rotation may perhaps support the formation of mat-related, benthic ooids (Gerdes et al. 1994b; Gerdes et al. 2000a, Gerdes et al. 2000b), or sedimentary augen structures (e.g., Dahanayake et al. 1985).

Structures Induced by Baffling, Trapping, and Binding

Baffling, trapping, and binding means sediment accumulation by bacterial activities and incorporation of the grains into the mat fabrics by microbial growth. In contrast to biostabilization, erosion or gas pressure play no role in structure formation (Noffke and Krumbein 1999b).

Some filamentous cyanobacterial species are able to orient themselves perpendicular to the mat surface, and they reach into the floating bottom water (Fig. 7A). The filaments function as thread-like obstacles (e.g., ''baffles'') that generate microzones of reduced flow velocity. The lowered current velocity induces settling of suspended particles, a process termed baffling and trapping (Black 1933; Dunham 1962) (Fig. 7B). The baffled and trapped grains are incorporated into the mat by upward growth of the developing organic matrix of the microbial layer (Fig. 7C) (''binding'' *sensu* Black 1933; Dunham 1962). Such processes are reflected by mat-layer-bound grains that show significantly smaller sizes than the components of the sediment below the mat without any vertical gradation of the grain sizes (Noffke et al. 1997a).

A sediment-agglutinating bacterial community induces a pile of baffled and trapped sediment laminae, visible in vertical sections (Fig. 8) and generally termed biolaminites (Gerdes and Krumbein 1987; Gerdes et al. 1991). Biolaminites in purely physical sedimentary systems are non-cemented and planar, which is in contrast to the domal stromatolites. Mat-lamina specific selection of heavy-mineral grains may highlight biolaminites, as observed in Recent tidal flats of the North Sea (Gerdes et al. 2000b). Similar features are reported by Gunatilaka (1975), and Cameron et al. (1985).

INTEGRATION OF 'MISS' INTO THE CLASSIFICATION OF PRIMARY SEDIMENTARY STRUCTURES

The classification of primary sedimentary structures by Pettijohn and Potter (1964) consists of four main groups each of which is separated into various classes (Table 2). The first group consists of four classes of external forms of bedding, described by varying (or not varying) thicknesses, by lateral (non-)uniformities, or by (non-)continuity of the beds. The second

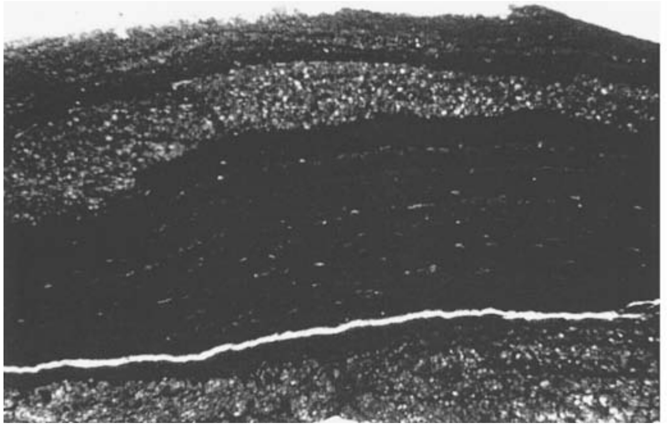

FIG. 8.—Biolaminite in a thin-section from the Lower Arenigian, Montagne Noire (France). Biolaminites originate from baffling, trapping, and binding and are characterized by their closely spaced laminae. In contrast to stromatolites they are planar, mainly uncemented, and do not form a positive relief. Scale: 1 cm.

group contains bedding categorized into five classes according to the internal organization and structure of rock beds. Stromatolites are included therein. The third group consists of bedding plane markings and irregularities on bases of beds, within beds, or on tops of beds. The fourth group contains bedding overprinted by more or less syndepositional deformation processes. We here propose a fifth group: bedding, modified by microbial mats and biofilms. Two classes (A, B) of MISS are recognized (Table 2): A) structures atop bedding planes, such as multidirectional ripple marks, and B) internal bedding structures, such as sinoidal laminae.

The fossil examples illustrated, and referenced herein, show that MISS are distributed in the stratigraphic record, even if their existence in physical sedimentary systems is not yet very well documented (but see volume by Hagadorn et al. 1999 and literature cited therein).

Our proposal of an additional group of structures within the classification of primary sedimentary structures is surely not complete and will need further work in the future. On the other hand, the existence of bacterially mediated structures besides stromatolites, and the knowledge of microbial activities in erosional and depositional processes within physical sedimentary systems, should give rise to new questions and perspectives in sedimentology.

TABLE 2.—*Classification of primary sedimentary structures following Pettijohn and Potter (1964) including the new category of microbially induced phenomena.*

Classification of Primary Sedimentary Structures	
1. Bedding, external form	
Class A: 1) equal or subequal in thickness 2) laterally uniform in thickness 3) continuous	Class C: 1) unequal in thickness 2) laterally variable in thickness 3) continuous
Class B: 1) unequal in thickness 2) laterally uniform in thickness 3) continuous	Class D: 1) unequal in thickness 2) variable lateral thickness 3) discontinuous
2. Bedding, internal organization and structure	
Class A: Massive	Class C: Graded
Class B: Laminated 1) horizontal laminations 2) cross-laminations (simple and multiple)	Class D: Imbricated Class E: Growth structures (including stromatolites)
3. Bedding plane markings and irregularities	
Class A: On base of bed 1) load structures 2) current structures 3) trail and burrow casts	Class C: On top of bed 1) ripple marks 2) erosional marks 3) pits and impressions 4) cracks 5) traces
Class B: Within the bed	
4. Bedding deformed by penecontemporaneous processes	
Class A: Founder and load structures	Class D: Injection structures
Class B: Convolute bedding	Class E: Burrows
Class C: Slump structures	
5. Bedding modified by microbial mats and biofilms	
Class A: On bedding planes 1) leveled depositional surfaces, wrinkle structures 2) microbial mat chips 3) erosional remnants and pockets 4) multidirectional/palimpsest ripples 5) mat curls, shrinkage cracks	Class B: Within beds 1) sponge pore fabrics, gas domes, fenestrae structures 2) sinoidal laminae 3) oriented grains, benthic ooids 4) biolaminites, mat-layer-bound grain sizes

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