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Microbially induced sedimentary structures – examples from modern sediments of siliciclastic tidal flats

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With 4 figures in the text

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Abstract: The structural characteristics of modern siliciclastic sediments in tidal flats are controlled by two dominant factors, namely, by depositional dynamics, and by the activity of phototrophic microorganisms colonizing the sediment. The study deals with the related structural inventory of sedimentary systems in moderate humid climate. Varied sedimentary structures are described and their origin is related to different microbially mediated processes, e. g. biostabilization, gas production, and the interplay between sedimentation and microbial growth.

The studies suggest a complementary interpretation of siliciclastic sedimentary structures, defined as "microbially induced sedimentary structures (M.I.S.S.)". Comparative studies of "M.I.S.S." reveal a significant difference to physical structures of similar appearance.

Zusammenfassung: Die Strukturen heutiger silikoklastischer Wattsedimente werden zum einen durch die Ablagerungsdynamik, zum anderen durch die Aktivität phototropher Mikroorganismen bestimmt. Die Untersuchungen befassen sich mit dem Formeninventar in Sedimentationsräumen feucht gemäßigter Klimate. Verschiedene Sedimentstrukturen werden beschrieben und ihre Genese auf unterschiedliche, mikrobiell induzierte Prozesse, wie z. B. Biostabilisierung, Gasproduktion und die Wechselbeziehung zwischen Sedimentation und mikrobiellem Wachstum, zurückgeführt.

Die Untersuchungen ergeben eine ergänzende Ansprache von Strukturen silikoklastischer Sedimente, die als "mikrobiell induzierte Sedimentstrukturen (M.I.S.S.)" zusammengefaßt werden. Ein Vergleich dieser "M.I.S.S." zeigt deutliche Unterschiede zu phänomenologisch ähnlichen Strukturen physikalischer Genese.

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1. Introduction

Microorganisms, like cyanobacteria, bacteria and diatoms, are widespread in sediments of shallow marine environments. Their role in carbonate depositional systems, e. g. in stromatolite formation and cementation processes, is well known (KRUMBEIN 1979, 1983). However, much less knowledge exists about the influence of microorganisms on primary and secondary structures in siliciclastic sediments of coastal systems, especially of the temperate climate zone.

There has been a number of studies of microorganisms capable of sediment stabilization on the tidal flats of Mellum Island (FÜHRBÖTER & MANZENRIEDER 1987, PATERSON et al. 1995). Most of the work emphasizes the stabilization potential of benthic microorganisms, termed "biostabilization".

Cyanobacteria are phototrophic prokaryotes and several taxa are able to active movement corresponding with the most suitable light condition. In case of lower sedimentation rates, the organisms can escape burial by migration towards the freshly deposited sedimentary surface. The interaction of microbial growth with depositional dynamics is well known (GERDES et al. 1991).

Cyanobacteria form benthic communities and are found in a variety of ecophysiological relations to other microorganisms, e. g. chemotrophic bacteria (STAL 1984, GERDES & KRUMBEIN 1987).

The aim of this study is the description of modern sedimentary structures that are indicative of syndepositional microbial activity. These structures could represent a valuable tool for recognizing similar features in the fossil record and probably permit environmental interpretation of ancient sediments.

2. Study area

Studies were carried out on the tidal flats of Mellum Island (North Sea) (Fig. 1). The tidal flats represent a depositional system in a temperate humid climate zone. Mean summer temperatures range about 17 °C and rainfall is frequent. Winter conditions are characterized by common west storms that often inhibit drainage of the flats during ebb tide. Also drift ice accumulation on the flat surface occurs.

The sediment of the tidal flats is composed of quartz sands. The main fractions are of fine to medium size, while silt and clay just reach up to 5 % of the whole grain population in maximum (GERDES & HOLTKAMP 1980). The well sorted sediments are colonized by various benthic microorganisms.

Two main types of colonization of the sediments by cyanobacteria can be distinguished: biofilms and microbial mats.

Generally, the dominant biofilm producers are coccoid cyanobacteria attached to particles and occupying pore spaces (CHARACKLIS & WILDERER 1989). On Mellum Island, biofilms mainly develop on the intertidal flats, and the microorganisms are distributed dispersely in the surface layer.

Filamentous taxa, which are the predominant constructors of microbial mats, interweave the mineral components of the sedimentary surface.

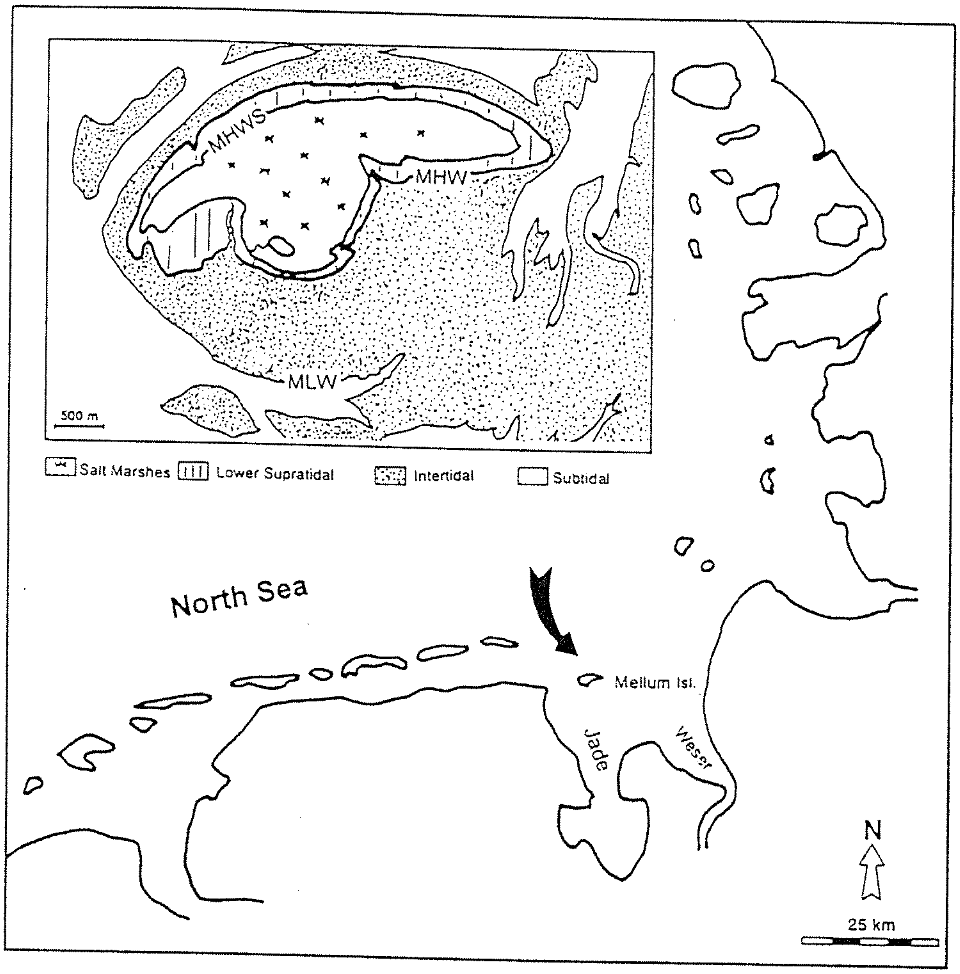

Fig. 1. Location of study on the tidal flats of Mellum Island, southern North Sea (modified after GERDES & KRUMBEIN 1987).

Mats can develop at sites, where plant cover and deformative burrowing are excluded, so that space competition and disturbance by grazing and bioturbation is restricted. Low sedimentation rates and low physical agitation do allow microbial biomass accumulation on the sedimentary surface leading even to tissue-like mats (GERDES & KRUMBEIN 1987). Since environmental conditions of the lower supratidal sand flats are suitable to the development of microbial mats, the typical versicoloured sand flat forms, which is a multilayered mat system composed of different bacteria and cyanobacteria (OERSTEDT 1842, SCHULZ 1936, HOFFMANN 1942, STAL et al. 1984, GERDES & KRUMBEIN 1987, GERDES et al. 1993).

3. Methods

To study internal sedimentary structures, box core samples were taken. The samples were dryed and hardened by a two component epoxy resin (Araldite F; REINECK 1970).

For thin section preparation, SPURR, an epoxy resin of several components (WACHENDÖRFER 1991), was used.

Sedimentary grains were collected from microbial mats and fractioned by sieving. The microbes have been determined by light microscopy.

Gas samples were collected from cavities within the sediments using vacuum syringes, and the samples were frozen in the field. The gas was analysed in the laboratory by gas chromatography (using a Hewlett Packard 5890 series II gas chromatograph).

4. Results

The studied siliciclastic sediments exhibit a multitude of sedimentary structures that can be attributed to microbial impact, e. g. baffling effects, biostabilization or gas production. In the following, some examples are described and the genesis of the structures is explained.

Internal structures

Both biolaminations and fenestrae-like cavities in the sediments have been observed to originate from biomass accumulation by the development of initially surficial microbial mats.

Biolamination

Box core profiles reveal a laminated pattern of the upper decimeter of mat-covered parts of lower supratidal sediments.

The lamination generates by the alternating processes of deposition and microbial growth (GERDES & KRUMBEIN 1987). Single laminae are named biolaminites. While the in situ production of biomass at the sedimentary surface corresponds with periods of non-burial or non-erosional conditions (GERDES et al. 1991), the non-colonized layers reflect periods of deposition. If the sedimentation rate is low, the microorganisms can escape burial by upward migration to the new surface. Microbial sheaths and slime are left behind and mark the former mat-covered surfaces (Fig. 2).

Another pattern, often visible in biolaminations, is a sudden or gradational change of grain sizes.

In thin sections, mat layers are characterized by a condensed meshwork of microorganisms enclosing quartz grains. Grains enclosed by the mats are distinctly of smaller size than those of the sedimentary layers non-influenced by microbial mats. The correlation of smaller-sized grains with the presence of mats compared with particles of those intercalated parts of the sediment indicates the potential of mats to interfinger with back-ground sedimentation, probably due to baffling effects of the microorganisms.

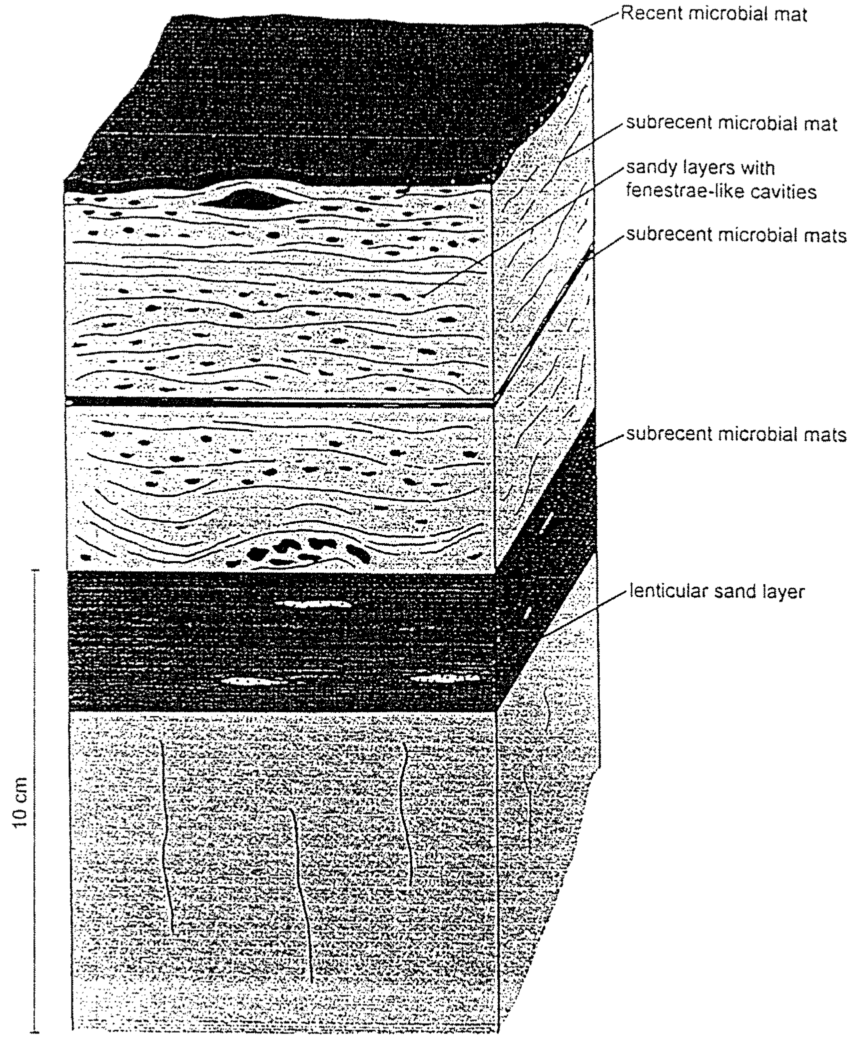

Fig. 2. Sponge sand: Intrasedimentary gas production, due to microbial activity reshapes the former internal structure of the sand layers that initially was related to the adequate physical depositional dynamics. The geometry of the structure, seen in cross section, resembles the morphological construction of sponge sceletons, so the feature was termed "sponge sand".

Sponge sand

In sediment cores, cavities of some millimetres in diameter are arranged in a pearlstring-like pattern in sandy layers between subrecent mats. The cavities originate due to gas production in deeper parts of the sediment from the decay of microbial mats. Gas analyses reveal the existence of CH_4, CO_2 and H_2S.

The gas accumulates in the organic-poor porous sand layers inbetween the subrecent mats.

As the gas-filled sediment is sealed by the cohesive organic layers, the pressure of the entrapped gas rises. Gas pressure greater than the friction of the sand grains results in the formation of cavities.

The geometry of the structures resembles the constructional morphology of sceletons of sponges, so the term "sponge sand" was chosen (Fig. 2).

Surface structures

In the mat-covered areas, surface structures occur, which can be traced back to microbial stabilization effects. Typical are erosional remnants and pockets, multidirectional ripple marks, domal upheavals, and the deposition of mat chips.

Erosional remnants and pockets

Erosional remnants are flat, table-like rises of the sediment surface that are covered by microbial mats. The remnants alternate with ripple-marked, deeper surface parts characterized by low microbial abundance.

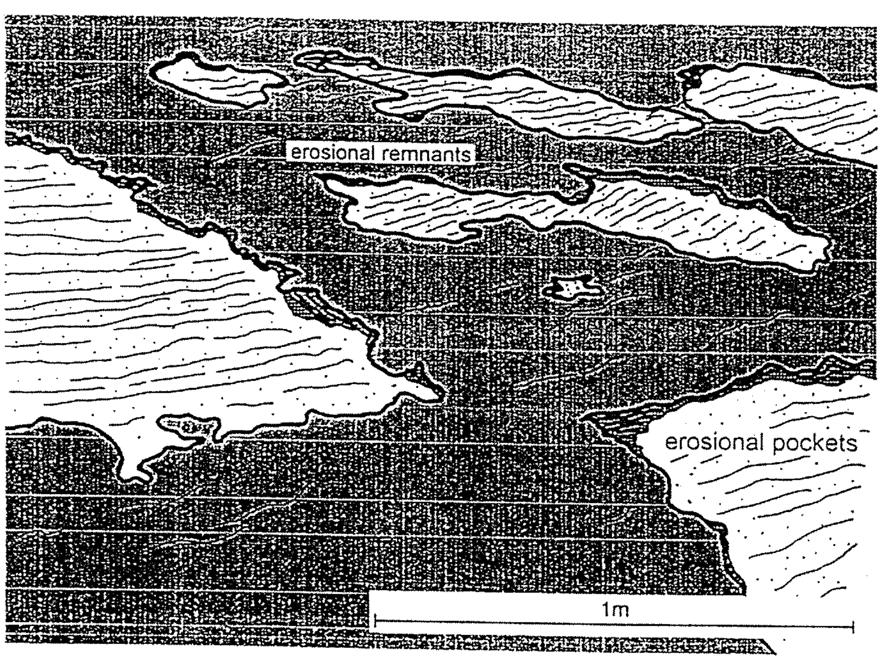

Fig. 3. Partial destroyment and erosion of a mat-covered sedimentary surface leads to decomposition of the initially flat surface relief into table-like erosional remnants and ripple-marked pockets. The effect of the erosional forces is controlled by the colonization of the surface by microbial mats.

The microbial mats affect a higher degree of biostabilization and if the tissue-like organic cover is destroyed somewhere, the effect of stabilization is reduced and erosional forces can become effective. This produces erosional depressions that show ripple marks at the base (Fig. 3).

A fossil example of such a surface morphology indicative of the presence of microbial mats is described from the Dakota Sandstone, Colorado, U. S. A. (MACKENZIE 1972, REINECK 1979).

Multidirectional ripple marks

At some areas of the tidal flats, ripple marks of different directions occur. A characteristical feature of these areas is material transport by tidal inundation in very shallow water. Some local parts are subaerically exposed, where no erosion by the water movement occurs. These local parts are the predominant sites of microbial growth.

After drain off, microorganisms settle on the newly shaped lower surface parts and consolidate the physically generated morphology by overgrowing. The repetition of the process and the spacial lateral transition creates the patchiness of the surface, indicating several redeposition events (Fig. 4).

Domal upheavals

Locally on the surface of mat-covered sediments individual domal upheavals arise (GERDES et al. 1993). The upheavals are of 5-20 cm in diameter and of 2-5 cm height. In cross section, a cavity is situated below the rised microbial mat.

The cavity is filled with gas that originates from decaying subrecent mat material in deeper parts of the sediment and accumulates in the sponge sand layers already described.

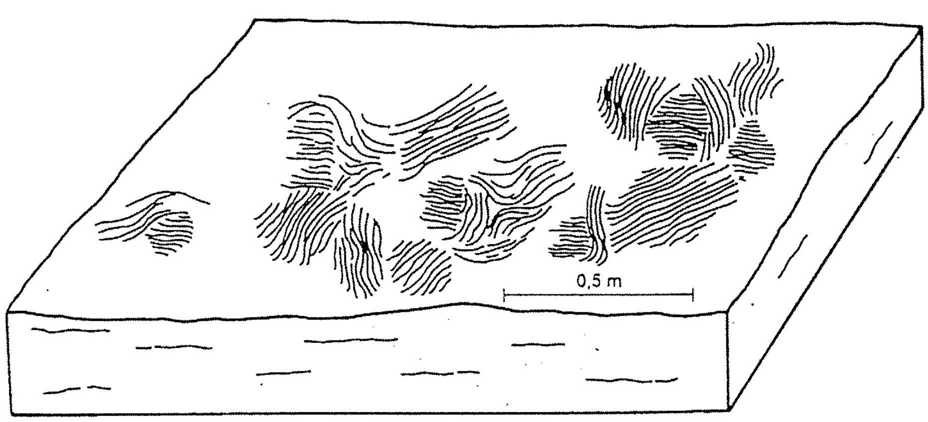

Fig. 4. Directions of the ripple marks in parts of the sedimentary surface apparently change chaotically. This can be deduced from the complex interplay between physical agitation by water movement and microbial impact.

The gas becomes entrapped below the coherent organic mat, and the increasing gas pressure pushes the microbial cover up and separates it from the sediment.

Mat chips and mat curls

Furthermore, various mat pieces were found, teared off from mat edges and redeposited. These are termed "mat chips". If the pieces are enrolled due to desiccation, the term "mat curls" is used.

5. Discussion and conclusive remarks

Tidal flats are environments exposed to both tidal influence and atmospheric conditions. Additionally, tidal flats harbour an extensively rich benthic microflora that mediates the accumulation of biomass and supports the influence on the sediment by processes like biostabilization and gas production.

Sediments colonized and influenced by microbial mats or biofilms clearly demonstrate morphological differences of internal fabrics and surfaces as opposed to exclusively physically derived structures. This will be discussed for the following aspects.

When repeatedly buried by sedimentation, microbial mats and biofilms can produce a multitude of sharply projecting bedding planes visible in vertical sections of the otherwise homogeneous quartz sand. These findings indicate microbial impact on the formation of bedding. Counterparts are abiotic bedding factors such as freezing or subsequent wetting of surface layers studied by REINECK et al. (1995).

The findings of this study suggest that the capacity of microbial mats for grain size selection results in structural changes of the sediments.

Another example of a biologically mediated sedimentary structure is sponge sand. This type can be contrasted to the physically derived bubble sand (REINECK 1956, WUNDERLICH 1979). Between both types of fenestrae-like structures, the following differences can be observed: Bubble sand performs a multitude of irregularly arranged internal cavities, the origin of which is due to intrasedimentary entrappment and compression of atmospheric air according to wave action and similar hydrodynamics. On the other hand, the pearl-like arrangement of cavities of sponge sand clearly follows the biostabilized bedding surfaces that seal each internal layer of quartz sand. Compared with the well described fenestrae or birds eyes in subtropic carbonate deposits, sponge sand may indicate the equivalent of siliciclastic sediments of temperate climate zones.

Impressive are also modifications of the surface relief where sediments are stabilized by the sediment-binding activities of microbes against tidal currents and wave actions. Examples are the erosional remnants and pockets which evolve from wave and current energy that reshape the relief morphology of mat-covered surfaces. Table-like erosional remnants are left behind after water agitation has eroded parts of the former biostabilized surface layer.

Erosion pockets evolve where obstacles (e. g. hard parts of molluscs or other objects), lying in the path of currents, cause the injury of the surface. The shape of such erosional marks is striking different from obstacle marks which occur in sediments lacking biofilms or mats (REINECK & SINGH 1986).

Domes are products of intrasedimentary gas migrating upward from deeper buried organic matter to the surface. Ongoing accumulation of gas beneath the surficial mat increases gas pressure, so that domes are formed locally. Also these structures differ from abiogenic counterparts. BEAUDOIN (1954) and SHEPARD (1967) describe domal upheavals of sediment at sandy beaches. The short-termed local elevations can be observed during rising water of the high tide. Sand volcanoes are of similar origin (HÄNTZSCHEL 1941).

In summary, modern coastal quartzose microbial mats and biofilms are widespread at higher latitudes and affect physical sedimentation in various patterns. Mainly on Recent carbonate sediments the influence of phototrophic bacteria is well understood, although these microbes play a more important role also in siliciclastic sediments. Their recognition in the geological record may be supported by investigations of modern counterparts as described in this study.

Since the microbially-related structures differ from those physically generated, the authors propose the term "Microbially Induced Sedimentary Structures (M.I.S.S.)" to define structures and textures in siliciclastic sediments that can be related to microbial activity.

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