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The impact of sediment-stabilizing biofilms on the architecture of sedimentary structures (Mellum Island, Southern North Sea)

With 7 Figures

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Abstract

Sedimentary structures described in this paper evolve from the impact of physical forces on biostabilized sediments in modern siliciclastic tidal flats: (i) erosional remnants are more or less sharp-edged planar rises mainly occurring in the intertidal-supratidal transitional zone where microbial mats develop. (ii) In deposits composed of a multitude of subrecent mats buried by quartz-sandy sediments, gas diffusion is recorded by hollow pores of 0.5-3 mm in diameter arranged like pearl strings in the sandy interlayers. (iii) In contrast to the grain-supported interlayers, microbial mat-supported sediments are more often of finer grain size, usually without contact to each other and predominantly arranged with their long-axis parallel to the sedimentary surface. The particle orientation may be the result of reduction of mechanical friction by the soft matrix surrounding the quartz grains that aid the rotation of the grains to an energetically suitable position. In grain-supported interlayers between mat horizons, there is no similar orientation of grains. (iv) Organic layers resulting from the overgrowth of ripples by biofilms and microbial mats show a specific intrasedimentary sinoidal pattern. To recognize such a sedimentary record of tidal flat deposits both ecological and hydrodynamic knowledge of the environment is necessary.

Keywords: siliciclastic, tidal flats, biofilms, microbial mats, diatoms, cyanobacteria, biostabilization, sedimentary structures

Introduction

In siliciclastic tidal flats, hydrodynamic conditions produce a variety of sedimentary structures. The structural record, however, is also influenced by the consistency of the material upon which these forces act. Frequently, sedimentary surfaces in tidal flats are strongly influenced by biofilm-forming diatoms and cyanobacteria. Biofilms are aggregates of cells enveloped in extracellular polymeric substances (EPS) that are able to stabilize sedimentary surfaces (KRUMBEIN et al. 1994, PATERSON et al. 1994). Such stabilized sediments behave specifically in response to the physical forces. In consequence, the antagonistic interplay between erosion and biostabilization produces a structural record that is different from non-stabilized sediments (NOFFKE et al. 1996, NOFFKE 1997).

In particular, filamentous cyanobacteria can interweave and incorporate mineral particles into a coherent biogenic mat. Filamentous cyanobacteria locally produce such an immense biomass that thick organic layers develop on sedimentary surfaces. These structures, termed microbial mats, usually initiate a community succession including the enrichment of phototrophic sulphur bacteria, sulphate reducing and methanogenic bacteria.

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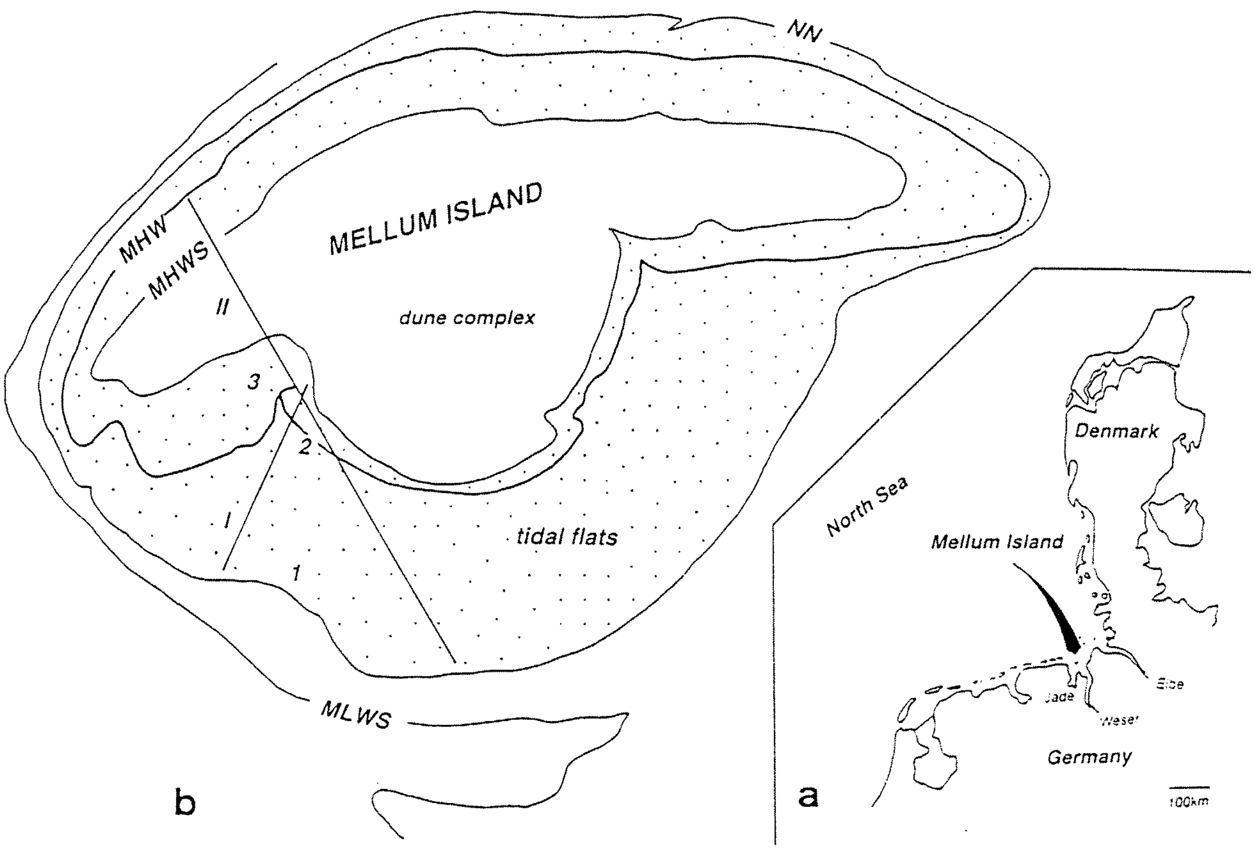


Fig. 1: a) Location of Mellum Island: b) Close-up of the island with position of transects along which mapping of biologically induced surface structures was conducted. The numbers indicate study sites mentioned in the text: 1: lower intertidal zone: 2: upper intertidal zone: 3: lower supratidal zone.

Thick multilayered mats dominated by filamentous cyanobacteria develop in low-energy areas (GERDES et al. 1991). Because of a discrete vertical zonation of cyanobacteria (bluegreen), phototrophic sulphur bacteria (purple) and sulphate-reducing bacteria (inducing black iron sulphide coatings on sediment grains), the name "Farbstreifen-Sandwatt ("versicoloured sand flats") was created by SCHULZ (1936). The enrichment of methanogenic bacteria usually increases in deeper buried organic matter (KIENE et al. 1986). From there, gas diffuses upwards through the sediment and becomes captured by former mat-contoured bedding planes. This produces characteristic arrangements of secondary pores (NOFFKE et al. 1996).

Aim of this paper is to demonstrate that the geometries of sedimentary structures evolving from physical impact (erosion, sedimentation, gas production) in a biostabilized sediment markedly differ from structures in ordinary and less microbially affected siliciclastic sediments.

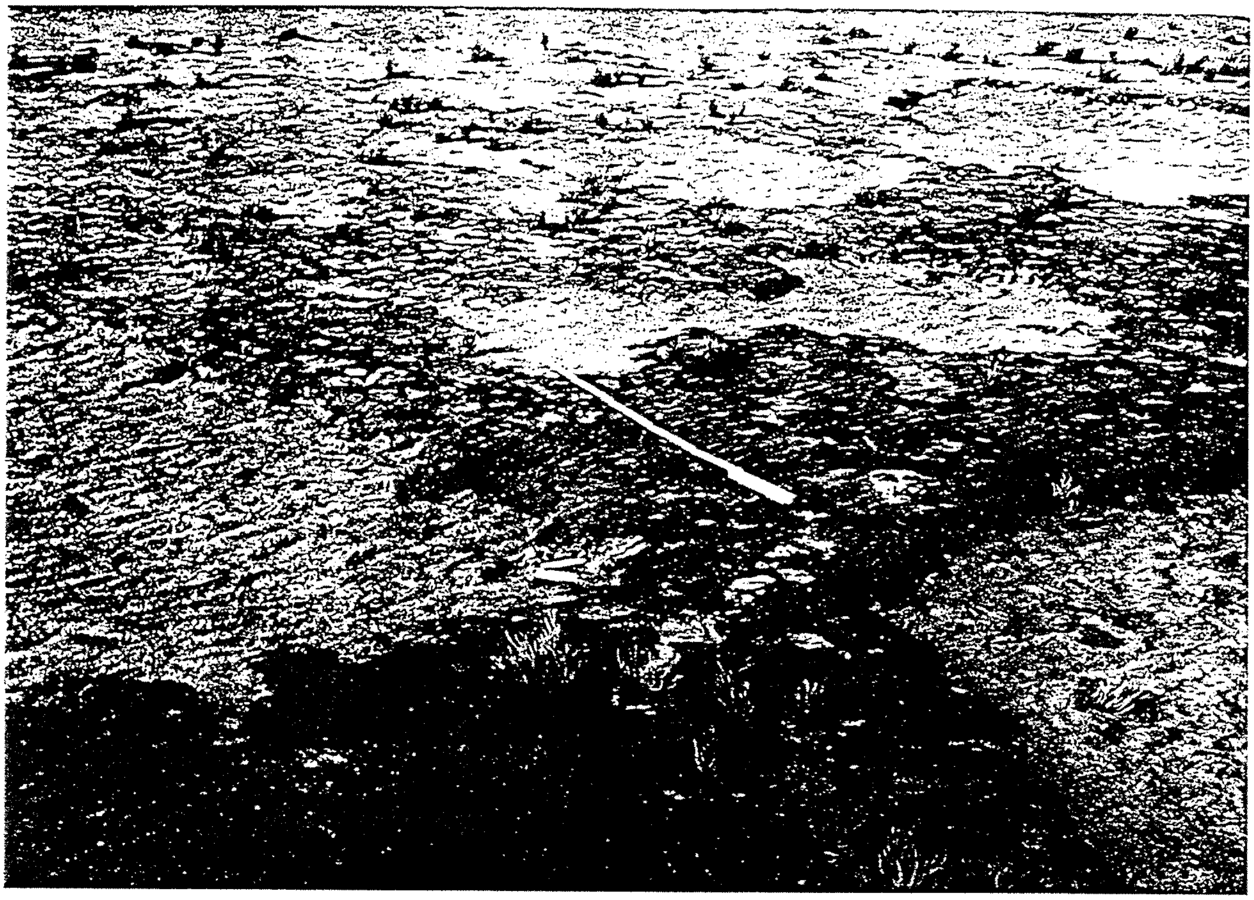
Study area

The structures were studied on the tidal flats of Mellum Island (fig. 1). In this area, mean temperatures are 17 °C in summer and 4 °C in winter. Winds frequently are directed from W to NW. Storm periods are mainly in autumn and winter. The mean tidal range is 3.20 m.

The tidal flats of Mellum Island consist of fine to medium quartz sands. The biofilms colonizing the area are dominated by cyanobacteria and diatoms. Various studies exist on the microbial mats in this area (e.g. STAL & KRUMBEIN 1985). In the lower intertidal zone (fig. 1b, site 1), coccoid cyanobacteria colonizing individual sand grains are relatively more abundant than filamentous forms. This leads to a biofilm consistency that is less effective in sediment stabilization than in middle and upper tidal flat zones. In the middle part, (fig. 1b, site 2) mat-forming filamentous cyanobacteria gradually increase in abundance. The transition between the upper intertidal and the supratidal zone (fig. 1b, site 3) is characterized by thick multilayered microbial mats of the versicoloured sand flat type. These mats are built by dominance of the filamentous cyanobacterium *Microcoleus chthonoplastes*.

Methods

The distribution of biofilm-induced sedimentary structures was mapped in the field. To obtain information on the direction of flood currents, ripple mark orientations were measured with a compass.



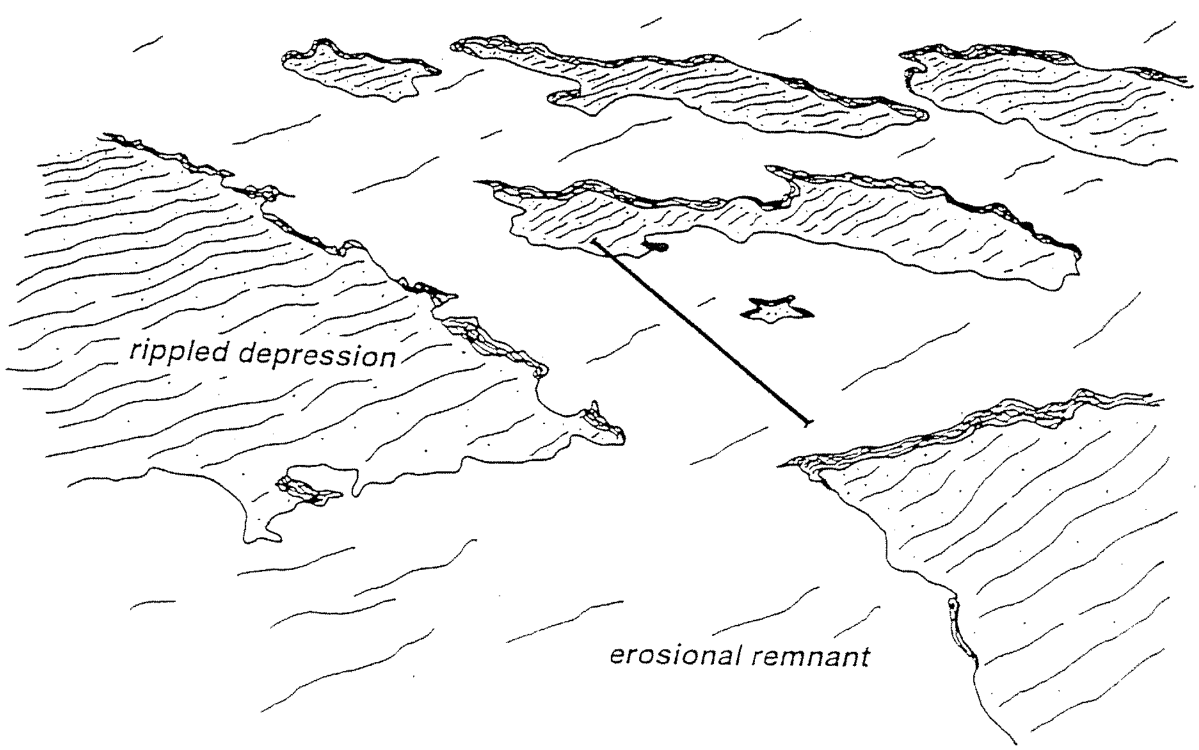


Fig. 2: Planar rises and depressions from site 3 (lower supratidal zone), the former being sharp-edged erosional remnants. Intercalated rippled depressions indicate selective erosion of the former surface.

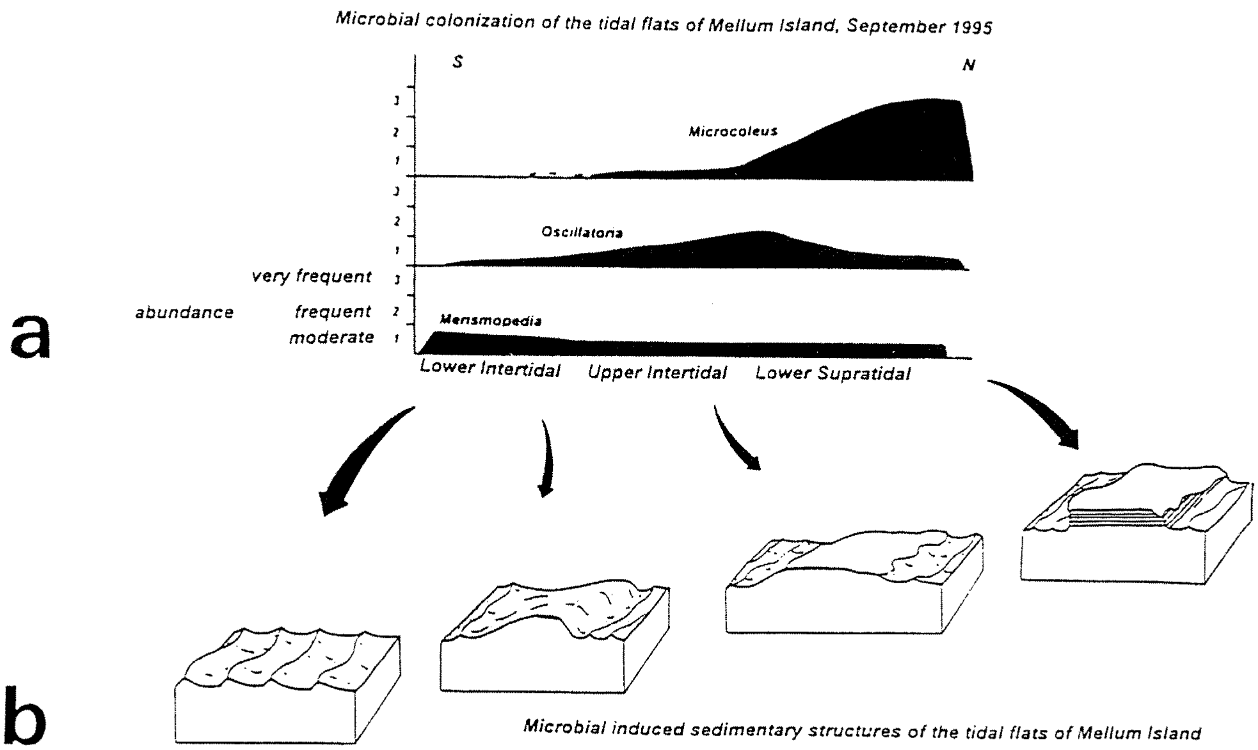


Fig. 3: Results of mapping along transect I: a) Distribution of dominant cyanobacteria in relation to increasing topographic height above the low water line; b) Changes of sedimentary surface structures in relation to the distribution of dominant cyanobacteria.

To study internal textures and structures, relief casts (REINECK 1970) and thin sections were prepared (SPURR 1969, WACHENDÖRFER 1991). Thin sections were analyzed by light microscopy. The orientation of long-axes of quartz grains visible in the thin sections was measured and the values transferred into a circular chart.

To estimate the degree of intrasedimentary porosity, sediment cores 10 cm long and 4 cm in diameter were taken from biostabilized areas. In the laboratory, the cores were compressed for 5 seconds with a stamp (wt/cm² 500 g). Lengths of cores were measured before and after this treatment, and the difference between both values expressed as compactibility. Intrasedimentary gas was analyzed qualitatively using a Hewlett Packard 5890 series II gas chromatograph.

To produce secondary pores artificially in the laboratory, alternatingly pure sand and microbial mat material was filled into perspex cylinders. The top of the cores was sealed by a living mat, and the outer walls of the cylinders were darkened to allow degradation of the intrasedimentary organic material.

Dominant forms of cyanobacteria in biofilm- and microbial mat-secured surface sediments were determined by light microscopy, and their relative abundance estimated (RIEGE 1994).

Sedimentary structures – description and interpretation

Erosional records of biostabilized surfaces

The surface morphology of the lower supratidal zone (fig. 1b, site 3) is characterized by two main elements: (i) more or less sharply projecting planar rises covered by microbial mats, and (ii) rippled depressions (fig. 2). The planar rises are erosional remnants of the biostabilized sedimentary surface. The erosional depressions are not colonized by coherent microbial mats, although thin biofilms may occur. Ripple orientation in the depressions indicates that they are a product of the incoming tide ascending the tidal flats from southwest (fig. 1b).

Mapping of erosional remnants across transect I (compare fig. 1b) revealed that their dimensions and geometry change considerably in relation to different topographic heights and successional stages of microbial mats (fig. 3)

In the lower supratidal zone, erosional remnants are about 5-25 cm high and some tens of square metres large. In this zone, the biomass production of cyanobacteria is relatively highest of the areas studied, and the microbial succession reflects a perennial mature stage. Vertical sections through the edges of the erosional remnants demonstrate internal biolaminated buildup of sediments (fig. 4) characteristic of this area (GERDES et al. 1991).

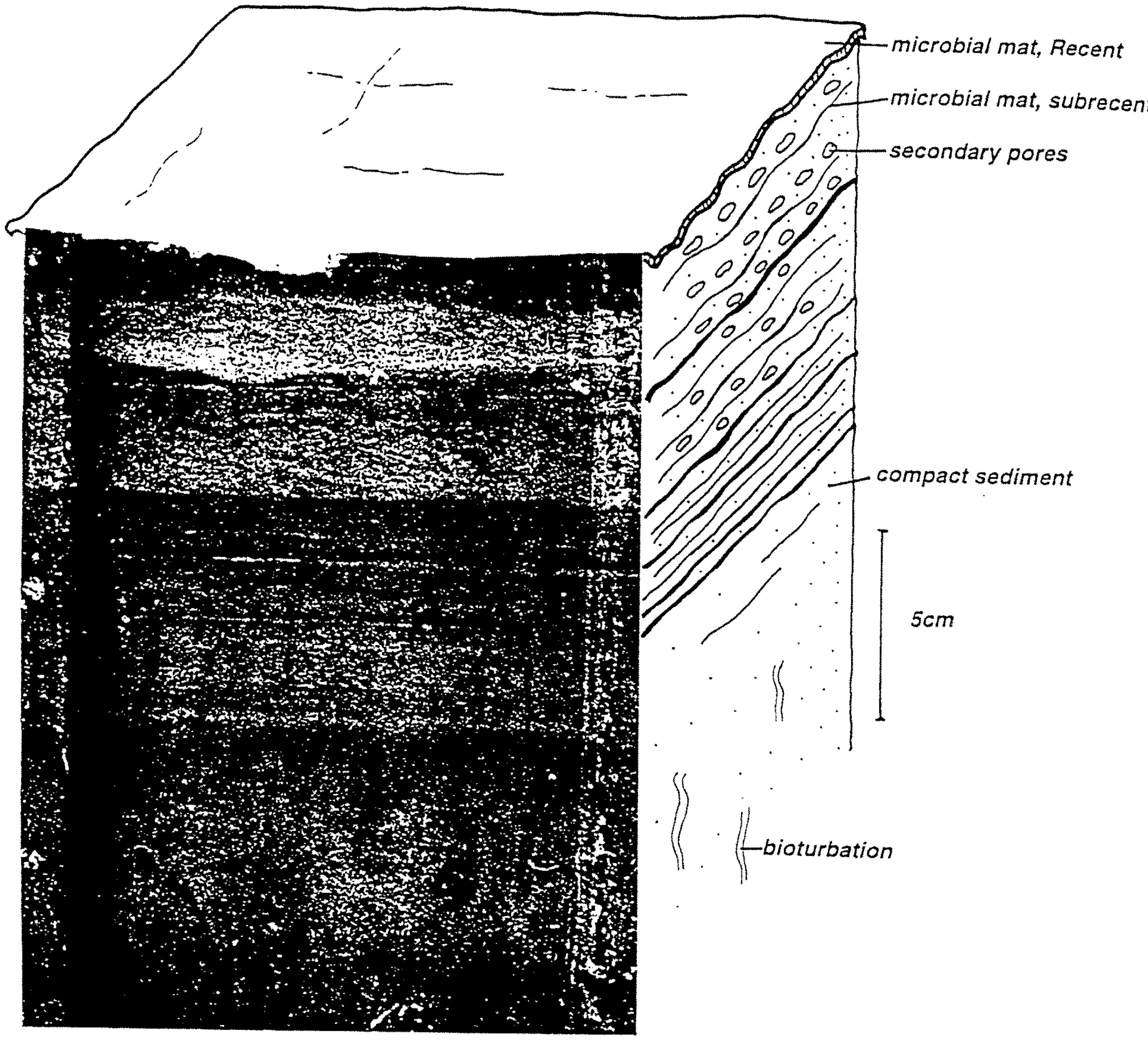


Fig. 4: Vertical section of sediments sampled with a box corer, showing the arrangement of secondary pores between subrecent microbial mats, called sponge pore structures. The vertical section reflects a buildup produced during alternating periods of sedimentation and non- or low sedimentation in which microbial mats have developed. In the lower part, bioturbation structures are visible that extend through the gradual buildup of the biolaminated deposit.

In the upper intertidal zone, erosional remnants are about 3-5 cm high, 2-3 square meters large and do not possess sharply projecting edges. The rises rather resemble very small whale backs. In this zone, cyanobacteria are less productive, and microbial mats tend to annual stages.

Towards the lower intertidal zone, erosional remnants and pockets gradually disappear corresponding with the decreasing abundance of filamentous cyanobacteria (fig. 3). In this zone, coccoid cyanobacteria occur that are less effective in biostabilization than filamentous cyanobacteria.

Records of diffusive gas in biostabilized sediments

Vertical sections of biolaminated sediments from site 3 (fig. 1b) reveal a multitude of subrecent mats buried by sediment rich in quartz sand (fig. 4). Records of gas diffusion are hollow pores of 0.5-3 mm in diameter arranged like pearl strings in sandy interlayers between the organic laminae. Whereas in the upper parts of the sediment cores, numbers of pores increase, their amounts and sizes decrease with depth due to compaction.

The degree of intrasedimentary porosity was determined by artificial compaction of the sediments. Cores taken from the upper 10 cm of the sediments revealed an intrasedimentary porosity of 30 %. Sediments below this depth reached values of 13%. The gas accumulating in the porous layers was mainly methane.

Also in sediment cores experimentally set up in the laboratory, hollow pores developed with ongoing decomposition of the organic material. As the resulting structures of regular pores intercalated between thin laminae

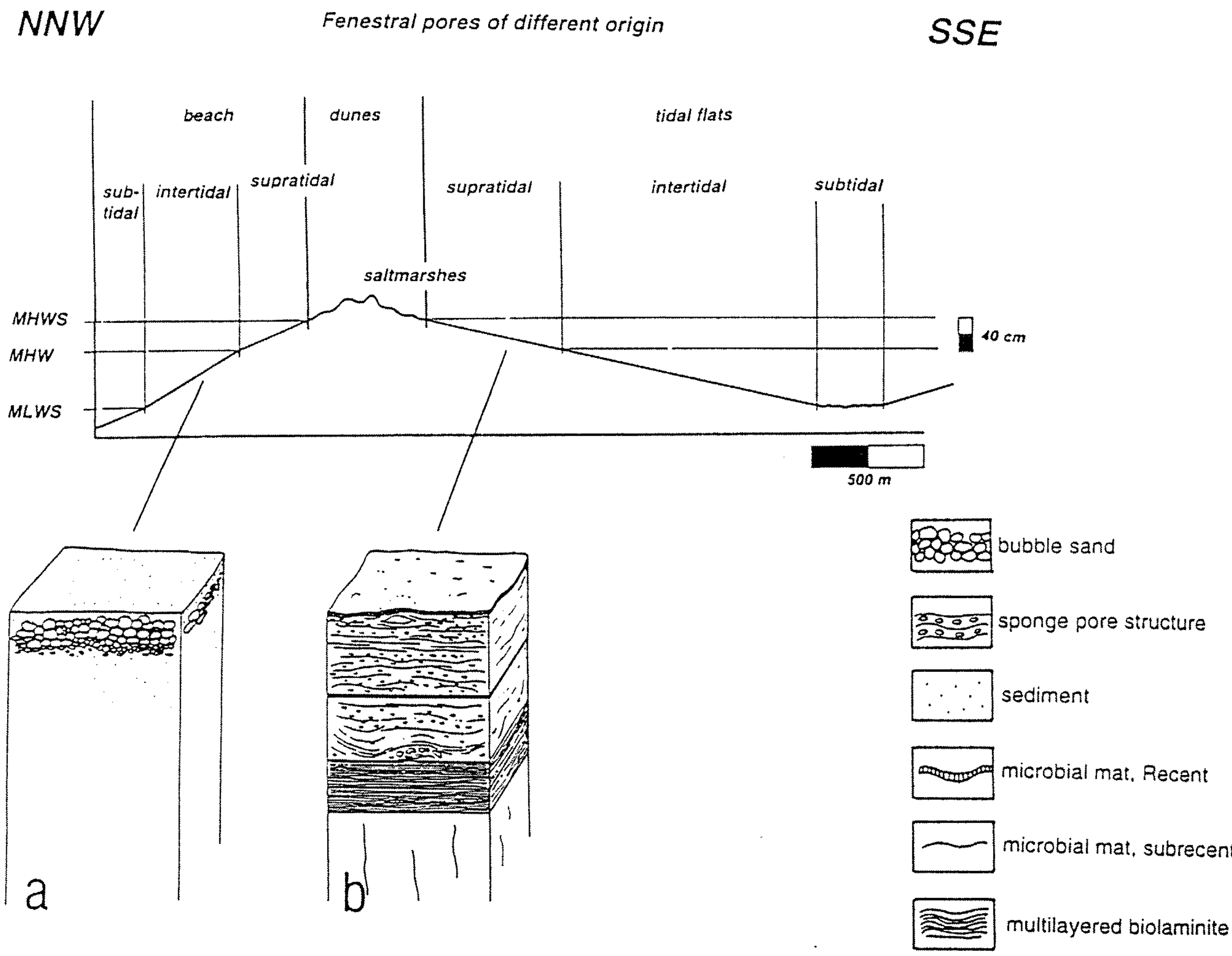


Fig. 5: Comparison of fenestral pores in tidal sediments of Mellum Island: a) bubble sand formed in high energy beach sands at the northwestern parts of the island. b) Sponge pore structures formed in the mat-protected tidal flats south of the dune complex.

resemble the texture of sponges, the phenomenon was termed sponge pore structure (NOFFKE et al. 1996). The structures differ from the physically-derived bubble sand that forms in high energy beach sediments (fig. 5).

Along transect II (fig. 1b), bubble sand is a typical feature of areas near the active shoreline (NW of the dune/salt marsh complex) where no microbial mats are developed. Sponge pores correlate always with the appearance of mats on the southern tidal flats where lower energy conditions prevail (fig. 5).

Records of decreasing transport velocity

Thin section studies of biolaminated sediments from site 3 (compare fig. 1b) reveal that silt-sized quartz grains are more common in microbial mats than in the grain-supported interlayers (fig. 6b). This pattern may indicate, as one possible reason, decreasing transport velocities. Additionally, conditions of decreasing energy also favour the growth of microbial mats. Since depositional events in the study area are frequently followed by periods of lower hydrodynamic impact, silt-sized quartz grains and microbial mats correspondingly indicate decreasing transport velocities.

Another phenomenon is that quartz grains in microbial mats do not touch each other. The grains are predominantly arranged with their long-axis parallel to the sedimentary surface (fig. 6c). The particle orientation may be the result of reduction of mechanical friction by the soft matrix surrounding the quartz grains that aid the rotation of the grains to an energetically suitable position. In grain-supported interlayers between mat horizons, there is no similar orientation of grains. This may indicate that in closely packed sediments, a gravity-related displacement is not possible (fig. 6c).

Records of ecological response of biofilms to ripple marks

In vertical sections of sediments from the upper intertidial zone (fig. 1b, site 2), a characteristic sinoidal pattern of organic layers a few centimetres in length appear (fig. 7).

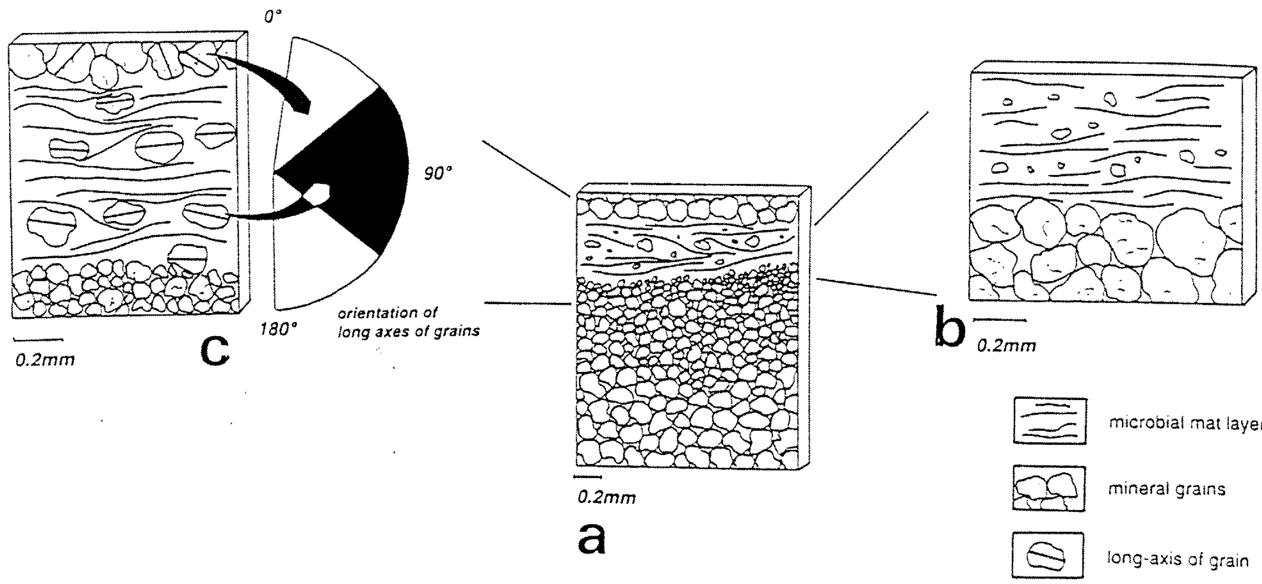


Fig. 6: Schematic drawings made from a thin section of tidal sediments, Mellum Island; a) thin section overview; b) and c): close-ups: b) mat-bound selection of grain sizes; c) orientation of grains in mat layers (left), directions of long-axes of grains transferred into a circular chart (right): black: directions of mat-bound grains, white: directions of grains from sandy interlayers.

These structures develop during a lower hydrodynamical regime and indicate the colonization of troughs and lee faces of ripples by biofilms. At the study site, mats become buried by repeated sedimentation, and in some cases, the sand layer atop the mats becomes rippled before the microbes can react by migrating through the freshly deposited sand. During subsequent longer periods of non-sedimentation, recolonization by microbes takes place. The organisms, ecologically responding to the irregular surface topography, preferrentially settle in the ripple troughs and on the lee faces. If the surface again becomes reactivated by an increase in the hydrodynamic energy, the less stabilized luff faces of the ripple marks in cases become eroded, and the lee faces with their organic coatings will be buried. From such coinciding processes sinoidal organic layers evolve. Such patterns may help to reconstruct the path of ripple marks in the sedimentary record.

Discussion

Aim of this paper was to demonstrate specific influences of sediment-stabilizing biofilms on sedimentary structures of modern siliciclastic tidal flats. Recognition of the sedimentary record requires both ecological and hydrodynamic knowledge of the environment. The case studies clearly indicate that in four of the case studies (erosional remnants, sponge pore structures, refinement of sediments, grain orientation within microbial mats), physical events occurred subsequently to the biological colonization of sediments, whereas in case of sinoidal structures, the physical event happened prior to the development of biofilm drapes.

Physical processes acting upon already biostabilized surfaces

(i) The studies of erosional remnants revealed considerable changes of dimensions and geometry in relation to the maturity stages of biofilms and microbial mats. Sharp-edged planar rises of relatively largest dimensions occur only in the upper intertidal-supratidal transitional zone where the microbial mats develop perennial, mature stages. With decreasing height, erosional remnants change into rounded forms similar small whale backs, and towards the lower intertidal zone, they gradually disappear. In the fossil record, such a distribution pattern may support reconstruction of paleoecological and paleohydrodynamic conditions. Ripple orientation in the erosional pockets may also indicate directions of the dominant tide ascending the tidal flats (REINECK 1979, NOFFKE 1997).

(ii) Another type of microbially modified physical structures are the layered secondary pores between subrecent microbial mats, called "sponge pore structures" (NOFFKE et al. 1996). In deposits of the "Farbstreifen-Sandwatt" (versicoloured tidal flats) of Mellum, a regular spacing of interbedded organic and quartz sand layers is a characteristic feature (GERDES & KRUMBEIN 1987). The sealing of the surface by living microbial mats and internally intercalated subrecent mats reduces the diffusion velocity of gas from decay of more deeply buried organic matter. This may be mainly responsible for the intrasedimentary cavities in the sandy interlayers between subrecent microbial mats. Experiments have

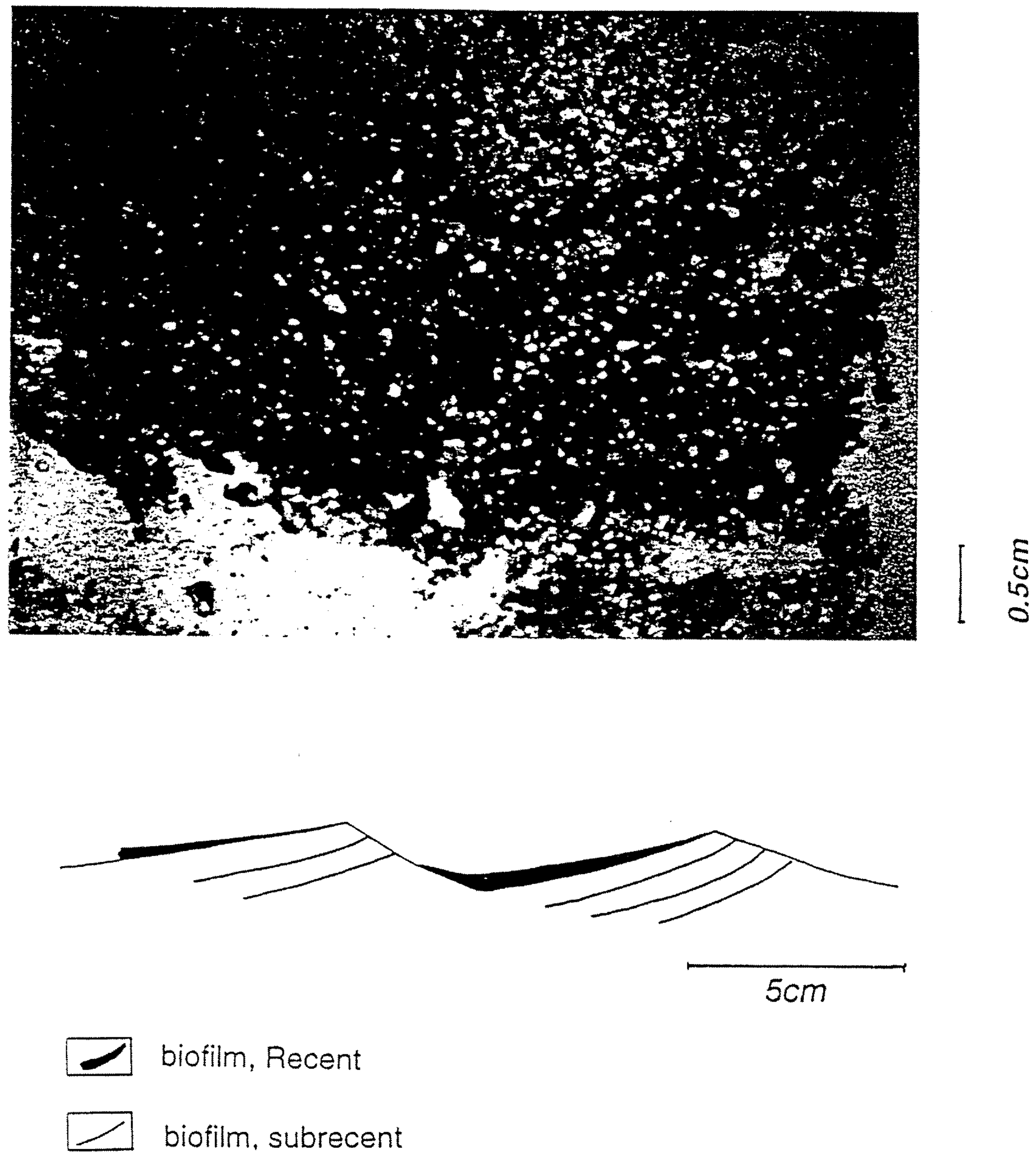


Fig. 7: Sinoidal structures: Microscopic photography and schematic drawing from a thin section: Dark sinoidal curves are microbial mat drapes of ripple mark troughs and leeward faces.

shown that gas diffusion in microbial slime is reduced about 10 000 times (KRUMBEIN 1979). The internal gas pressure therefore increases until the friction of sand particles is surmounted and hollow pores are generated (NOFFKE et al. 1996).

(iii) The specific sedimentary textures in microbial mats belong to the category of biologically modified physical structures and may reflect lower hydrodynamic energy which also permits mat growth (GERDES et al. 1991). During mat development, quartz grains of finer sizes are transported by water movement and deposited on the biofilms and mats. The particles are glued to the sticky mat surface, a process known as "trapping" (BLACK 1933). Also "baffling" (DUNHAM 1962) could occur: filamentous cyanobacteria can stretch upwards forming an organic "comb" perpendicular to the mat surface. The trichome bundles standing upright create microzones of lower current velocity that aid the settlement of smaller grains. As the mats grow, deposited material becomes enclosed by the organic material, a process described as "binding" (BLACK 1933).

Physical processes acting prior to biostabilization

Usually, sand flats occupy the lower portion of most tidal flats. However, tidal flats along more exposed coasts such as those of Mellum Island, exhibit sandy deposits at all littoral levels. In such areas, ripples rarely are draped by mud that characteristically indicates slack water stages in tidal cycles (VISSER 1980). Due to the lack of regularly spaced internal discontinuities, succeeding sand deposits of migrating ripples may be amalgamated. In higher-lying sand flats, however, biofilms are temporarily stable elements that interfere with depositional dynamics and drape the troughs and leeward faces of ripples. The organic material draping the ripples can be seen in analogy to mud drapes, however, conditions of formation are quite different. The in-situ produced microbial biomass forms during periods of non-sedimentation that lasts at least some days (GERDES et al. 1991). Mud drapes, on the other hand, are deposited on the lee face during slack-water periods, if suspended sediment concentrations are high enough.

Acknowledgements

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