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Erosional remnants and pockets evolving from biotic–physical interactions in a Recent lower supratidal environment

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Abstract

Sedimentary structures characterizing tidal depositional systems are not in all cases produced by physical dynamics alone. The activities of epibenthic cyanobacteria such as biostabilization or surface levelling may also play a significant role in structure formation. One example of bio-induced structures are 'erosional remnants and pockets', a specific surface morphology that can be observed in the lower supratidal zone of Mellum Island, southern North Sea. This surface relief rises from partwise erosion of a microbial mat-covered and biostabilized tidal surface. On the basis of detailed field measurements of the geometric dimensions of the surface relief, the tidal current system of the area and the history of formation of the morphology can be reconstructed. Erosional remnants and pockets are highly facies indicative and fossil occurrences would help in reconstruction paleo-environments. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

Sandy sediments of lower supratidal environments frequently are colonized by a vast epibenthic microbial population, within which cyanobacteria are very abundant. Especially, the cyanobacterial species *Microcoleus chthonoplastes* is a cosmopolitan representative (Gerdes et al., 1994). It forms fascilates of trichomes ensheathed by a thick, resistant glycocalix, and produces copious amounts of extracellular polymeric substances (EPS, Decho, 1990).

The elongated bundles of trichomes are slightly wound around the mineral components of the uppermost layers of the sediment, and a dense meshwork is built that may cover large areas of the tidal surface. Such fabrics constructed by microorganisms are termed 'microbial mats' (Krumbein, 1983).

Microbial mats shelter their substrate against erosion by hydrodynamics and mat-secured tidal surfaces therefore may show an immense stability. For this feature, the term 'biostabilization' was introduced (Krumbein et al., 1994). Führböter and Manzenrieder (1987) determined values of stabilization by *Microcoleus chthonoplastes*-dominated mats about 9 times higher compared with non-colonized deposits, and Yallop et al. (1994) measured values of 12 times greater.

Trichome bundles of *Microcoleus chthonoplastes* standing upright, perpendicular to the substrate, may function as 'bafflers', trapping grains suspended in the supernatant seawater (Noffke et al., 1997a). The

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grains become incorporated in the upwardly growing microbial mat. Accumulation of mineral particles as well as enrichment of biomass leads to levelling of a surface morphology shaped earlier by physical forces, and a flat plain results (Noffke and Krumbein, in press).

Microbial activities such as sediment stabilization and surface levelling interact with erosion by physical dynamics of tidal currents or storm waves. Such complex systems of different forces model characteristic ‘microbially induced sedimentary structures’ in tidal environments (Noffke et al., 1996; Noffke, 1997).

One example for these structures are ‘erosional remnants and pockets’ (Reineck, 1979; Gerdes et al., 1993) covering the tidal surface. Relict, mat-protected and flat-topped rises of several centimeters in height (= erosional remnants) alternate with deeper lying sediment surface parts (= erosional pockets). The depressions are not overgrown by a mat layer and their bottom is rippled. Erosional remnants and pockets were thought to be produced by part-wise erosion and destruction of a mat-covered tidal surface.

The aim of this study was to reconstruct in particular the hydrodynamic system and erosive mechanisms originating erosional remnants and pockets.

2. Study area

Investigations were carried out on the tidal flats of Mellum Island, which is located in the southern North Sea (Fig. 1a). The study site is located in the lower supratidal zone (Fig. 1b). The area dips gently towards the W. The sediment consists of 95% quartz sand of fine grain size and 5% silt and clay. *Microcoleus chthonoplastes* dominates the cyanobacterial epipsammon and is the main mat constructor. The flood currents of high water spring tides ascend the tidal area from the SW. At the study locality, the sedimentary surface is arranged into characteristic erosional remnants and pockets.

3. Description of erosional remnants and pockets

The sediment surface at the study site located in the lower supratidal zone of Mellum Island is arranged into two structural elements: (i) planar, table-like rises covered by a thick microbial mat layer that preserves a formerly physically shaped tidal surface, and, (ii), deepened surface parts not overgrown by a microbial mat (Fig. 2). Vertical sections through the rises reveal a laminated pattern of alternating mat and sand layers that reflects vertical development of the mat system. The sediment of the bottom of the depressions is exposed and shows ripple marks, which means that these parts of the tidal surface are still active, in contrast to the raised, immobile areas. In top view, many depressions are more or less v-shaped and of several dm^2 to m^2 in area. Some depressions cover larger parts of the tidal surface and show irregular outlines as they consist of many v-shaped parts joining each other. The depths of the bottoms of each ‘v’ are uneven: the deepest parts are the peaks and the lateral sides of the ‘v’.

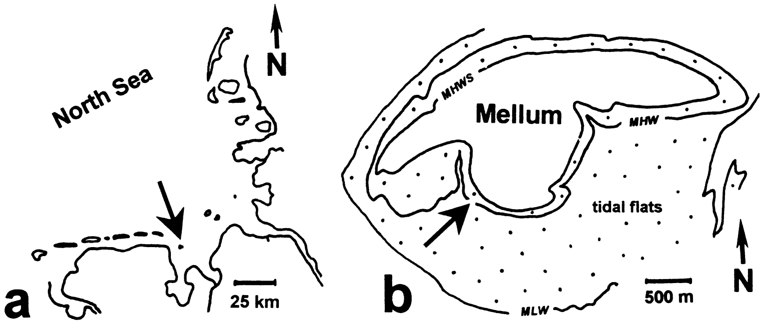

Fig. 1. Location of study area. (a) Arrow indicates setting of Mellum Island in the southern North Sea. (b) Location of site of investigations (arrow) on lower supratidal zone, Mellum Island. *MLW* = mean low water, *MHW* = mean high water, *MHWS* = mean high water spring.

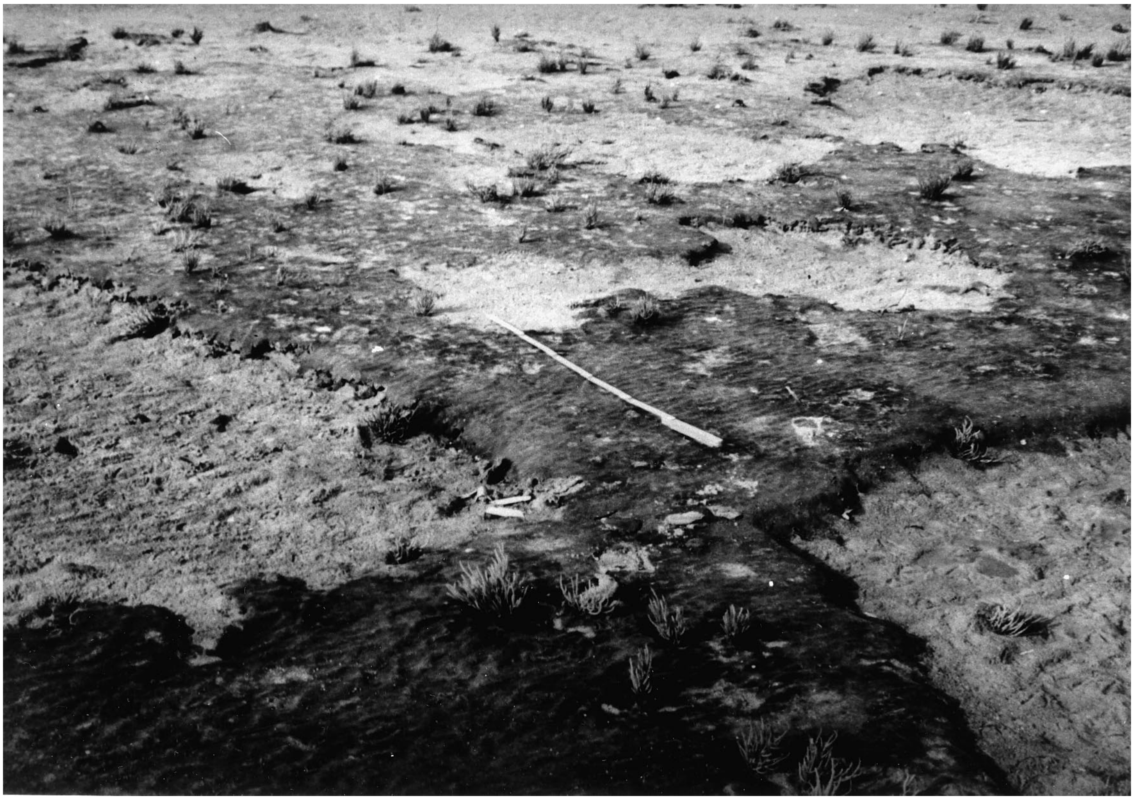

Fig. 2. Erosional remnants and pockets of lower supratidal zone, Mellum Island. The morphology of the tidal surface is arranged into elevated mat-covered surface parts (= erosional remnants) and rippled depressions (= erosional pockets) that are not visibly colonized by microorganisms. The bar (scale) indicates flood current moving upward from right to left. Scale: 1 m (after Noffke et al., 1997b, modified)

4. Methods

A rectangular area of investigations of about 100 m^2 was established on the lower supratidal flats. In order to determine the current system shaping the specific surface morphology, the geometric dimensions of three structural elements of the erosional remnants and pockets were measured (Fig. 3). The orientations of the crests of 294 ripple marks covering the sandy bottom of the erosional pockets were determined with a compass (Fig. 3a). According to the values obtained, the main directions of the currents generating the ripple marks were calculated. The orientations of 142 lines of greatest depths along the lateral slopes of the v-shaped depressions were measured (Fig. 3b). The data of orientations of both ripple marks and deep lines were plotted into a circular chart. In order to determine the inclinations of the bottoms of the depressions, short transects crossing 43 erosional pockets from their deepest to their shallowest points were established by cording. The degree of dipping of the transects related to a horizontal line was measured with rulers (Fig. 3c). The investigations were carried out in September 1996.

5. Results of investigations

The crests of the ripple marks at the base of the erosional pockets run from WNW to ESE (Fig. 4). The lines of greatest depths along the lateral slopes of the v-shaped depressions had four directions: two very significant ones of NNW and ENE, and two less important ones to the opposite (SSE and WSW) (Fig. 4). Therefore, the orientations of the depressions are asymmetric and the v-shaped pockets

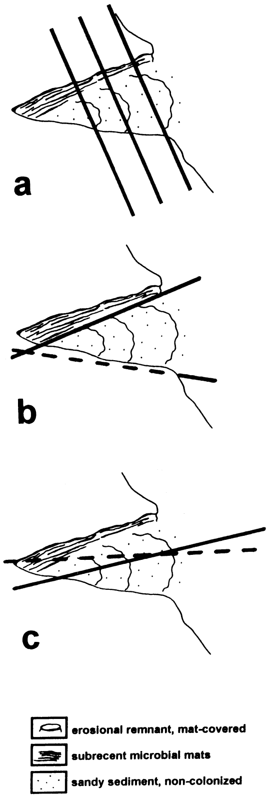

Fig. 3. Geometric elements of erosional remnants and pockets. (a) Ripple marks within erosional pockets. (b) Lines of greatest depths along the lateral slopes of erosional pockets. (c) Dipping bottoms of erosional pockets related to horizontal line (dashed).

open mostly towards the shoreline of the island. Fig. 4 also shows that the deepest lines along the lateral slopes of the depressions are not exactly orientated with an angle of 45° to the course of the ripple mark crests. The bottoms of the depressions showed a gradient of about 3.5% on average.

6. Interpretation and discussion

Aim of the study was to elucidate the dynamic processes modelling erosional remnants and pockets in the lower supratidal zone of Mellum Island.

The mat-sealed, raised erosional remnants represent a former tidal surface immobilized by the organic shelter. Within the erosional depressions, disturbance of the sediment hinders the reestablishment of a new microbial mat (Gerdes et al., 1991), and the sand stays exposed. Ripple marks are formed. The orientations of the ripple mark crests show that the flood current ascending the tidal flats from SW is the producer (Fig. 5).

In order to explain the lines of great depths along the lateral slopes of the depressions, the way of formation of the characteristic surface morphology must be more closely looked at. According to the field observations, different stages of formation of the structure can be distinguished (Fig. 6): At first, an obstacle, e.g. a mollusc shell, is deposited onto the mat-overgrown sediment surface (stage 1). It may cause local shadow, and the cyanobacteria, being photoautotroph, may react upon those effects forming a less dense mat layer at these sites with time. Also, the interface between the rigid mollusc shell and the soft organic tissue could permit local destruction of the microbial mat cover by water agitation (stage 2). The v-shaped pattern of the sedimentary structures indicates that erosional remnants and pockets initially form in a way resembling the model of erosion of Peabody (1947) (stage 3, part 3a): The flood current meets an obstacle on the sediment surface and becomes divided into two branches each flowing aside the obstacle. Here, a greater amount of water has to pass a defined cross-section than in the surroundings which leads to zones of higher current velocities. With increasing current velocities, erosive effects intensify within the zones. Thus, in the course of time, the lines of greatest depths of the depressions are notched and the lateral slopes of the erosional pockets are sculptured. As the zones of greater current velocities form an angle of 45° to the original direction of the course of the flood current, the lines of greatest depths of the depressions form a ‘v’. This shows that the flood current originates not only the ripple marks, but also the significant lines of greatest depths orientated NNW and ESE within the depressions. The weaker ebb current causes the few lines of greatest depths of opposite orientation. Figs. 4 and 5 show, that the deepest lines along the lateral slopes of the depressions are not exactly orientated with an angle of 45° to the course of the tidal currents. This could be the result of resonance of the current ascending obliquely towards the inclination of the tidal area and being deflected by the rim of the upper supratidal zone of Mellum Island.

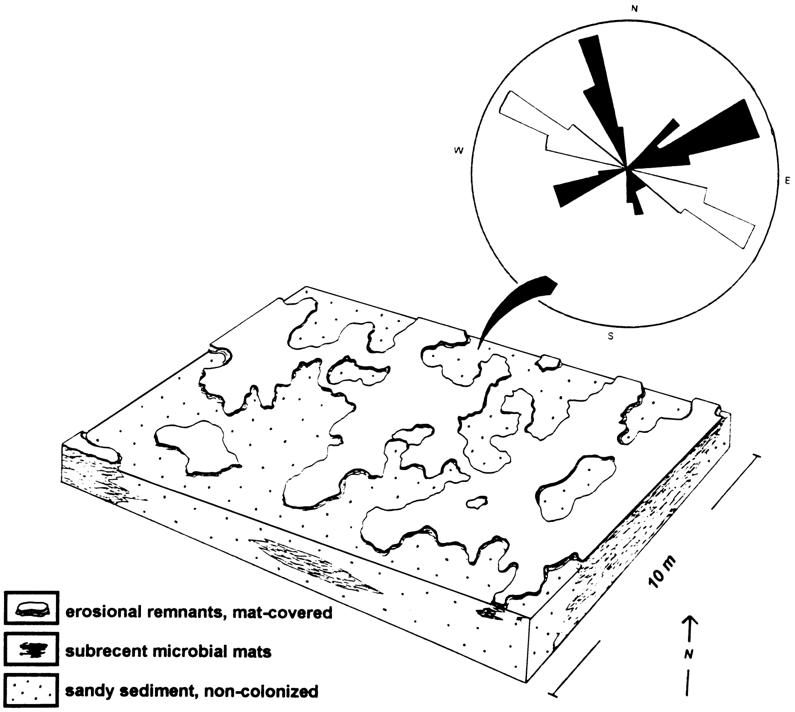

Fig. 4. Geometric dimensions of erosional remnants and pockets indicate current system. Circular chart: orientations of ripple marks (white) and lines of greatest depths along lateral slopes (black) of erosional pockets.

The peak of the 'v' generally is the deepest point of the erosional pockets: most erosion takes place in front of the obstacle, opposite to the current direction. The sediment washed out from the zones of highest current velocities, becomes redeposited behind the obstacle where current velocity is reduced. This could be the reason for slight dipping of the bottoms of the depressions. In the course of time, the obstacle itself may be undermined by water agitation and washed away (stages 4, 5). Later, erosional pockets enlarge and may join each other (stage 6).

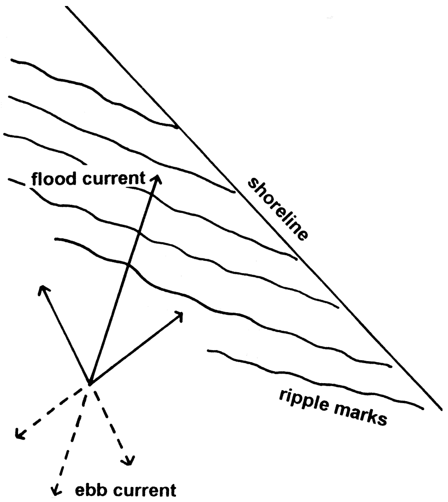

Fig. 5. Current system of lower supratidal site as indicated by erosional remnants and pockets.

Surface morphologies like these can be also found in the ancient record and can indicate microbial activities. Examples include fossil erosional remnants and pockets that are known from the Dakota Sandstone, CO, USA (MacKenzie, 1972; Reineck, 1979).

7. Conclusions

Erosional remnants and pockets evolve from bio-sedimentological processes interacting in Recent tidal systems. The surface relief is not only very indicative of lower supratidal zones, but also permits deductions with regard to the hydrodynamic system.

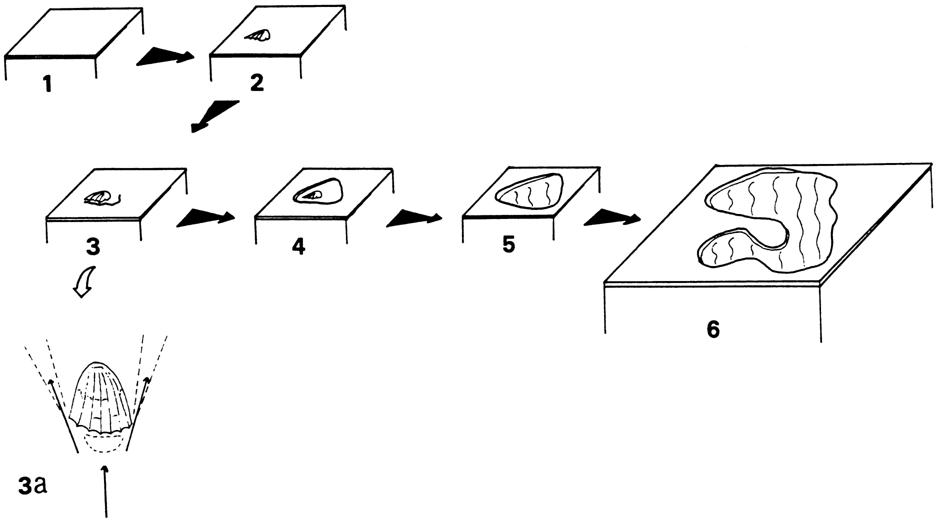

Fig. 6. Formation of erosional remnants and pockets. Stage 1: undisturbed microbial mat covering sediment; stage 2: deposition of obstacle upon microbial mat surface; stage 3: erosion of microbial mat around obstacle; 3a: top view on hydrodynamic pattern rising from current meeting obstacle. Erosion is increased at the side and in front of obstacle; stages 4, 5: obstacle becomes undermined and is removed, erosional pocket evolves; stage 6: erosional pockets enlarge in course of time and join each other.

Fossil occurrences of this surface morphology may help to reconstruct a paleoenvironment.

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References

Decho, A.W., 1990. Microbial exopolymer secretions in ocean environments: their role(s) in food webs and marine processes. Oceanogr. Mar. Biol. Ann. Rev. 28, 73–154.

Führböter, A., Manzenrieder, H., 1987. Biostabilisierung von Sandwatten durch Mikroorganismen. In: Gerdes, G., Krumbein, W.E., Reineck, H.E. (Eds.), Mellum — Portrait einer Insel. Kramer-Verlag, Frankfurt am Main, pp. 123–138.

Gerdes, G., Krumbein, W.E., Reineck, H.E., 1991. Biolaminations — ecological versus depositional dynamics. In: Einsele, G., Ricken, W., Seilacher, A. (Eds.), Cycles and Events in Stratigraphy. Springer, Berlin, pp. 592–607.

Gerdes, G., Claes, M., Dunajtschik-Piewak, K., Riege, H., Krumbein, W.E., Reineck, H.E., 1993. Contribution of microbial mats to sedimentary surface structures. Facies 29, 61–74.

Gerdes, G., Krumbein, W.E., Reineck, H.E., 1994. Microbial mats as architects of sedimentary surface structures. In: Krumbein, W.E., Paterson, D.M., Stal, L.J. (Eds.), Biostabilization of Sediments. BIS, Oldenburg, pp. 165–182.

Krumbein, W.E., 1983. Stromatolites — the challenge of a term in space and time. Precambrian Res. 20, 493–531.

Krumbein, W.E., Paterson, D.M., Stal, L.J. (Eds.), 1994. Biostabilization of Sediments. BIS, Univ. of Oldenburg, 526 pp.

MacKenzie, D.B., 1972. Tidal sand deposits in lower Cretaceous Dakota Group near Denver, Colorado. Mt. Geol. 9, 269–277.

Noffke, N., 1997. Mikrobiell induzierte Sedimentstrukturen in siliziklastischen Wattablagerungen. Ph.D. Thesis Univ. of Oldenburg, 127 pp.

Noffke, N., Krumbein, W.E., in press. A quantitative approach to sedimentary surface structures contoured by the interplay of microbial colonization and physical dynamics. Sedimentology.

Noffke, N., Gerdes, G., Klenke, Th., Krumbein, W.E., 1996. Microbially induced sedimentary structures — examples from modern sediments of siliciclastic tidal flats. Zbl. Geol. Paläontol., I, 1995H 1/2, 307–316.

Noffke, N., Gerdes, G., Klenke, Th., Krumbein, W.E., 1997a. A microscopic sedimentary succession of graded sand and microbial mats in modern siliciclastic tidal flats. Sediment. Geol. 110, 1–6.

Noffke, N., Gerdes, G., Klenke, Th., Krumbein, W.E., 1997b. The impact of sediment-stabilizing biofilms on the architecture of sedimentary structures (Mellum Island, southern North Sea). Cour. Forsch.-Inst. Senck. 201, 297–305.

Peabody, F.E., 1947. Current crescents in the Triassic Moenkopi Formation. J. Sediment. Petrol. 17, 73–76.

Reineck, H.E., 1979. Rezente und fossile Algenmatten und Wurzelhorizonte. Nat. Mus. 109, 290–296.

Yallop, M.L., De Winder, B., Paterson, D.M., Stal, L.J., 1994. Comparative study on primary production and biogenic stabilization of cohesive and non-cohesive marine sediments inhabited by microphytobenthos. Estuar. Coast. Shelf Sci. 39, 565–582.