Multidirected ripple marks rising from biological and sedimentological processes in modern lower supratidal deposits (Mellum Island, southern North Sea)

Nora Noffke
Carl von Ossietzky–University Oldenburg, Institute for Chemistry and Biology of the Marine Environment (ICBM), Section Geomicrobiology, P.O. Box 2503, 26111 Oldenburg, Germany

ABSTRACT

The sandy lower supratidal zone, called "Westplate," of Mellum Island (southern North Sea) is colonized by epipsammic cyanobacteria. The microbes form habitats of different stages of development adjacent to each other (biofilms: initial stages; mats: mature stages). Whereas biofilms do not contribute much to cohesion of sedimentary grains, mats significantly stabilize the supratidal surface, which leads to local conservation of a former physically shaped surface relief at microbially overgrown sites. In fall, the Westplate is covered by variously orientated ripple marks, termed "multidirected ripple marks." Field measurements and investigations on the epipsammon revealed that ripple marks of similar orientations were covered by microbial assemblages of similar stages of development. The results permit the following interpretation. The sediments of the Westplate are reworked by high-water spring tide flood currents, the directions of which are frequently changed by strong winds. Because the water depth of the flood current is very shallow, some parts of the uneven sedimentary surface are more affected by hydrodynamic stress than others. At sites of calmer hydrodynamic conditions, predominantly filamentous cyanobacteria settle in time, forming mats. Constant physical reworking of slightly deeper parts of the supratidal surface, however, only permits the development of less-sediment–stabilizing biofilms composed mainly of coccoid cyanobacteria. After the supratidal area drains, the deeper parts are also colonized by mat-constructing cyanobacteria, and the ripple marks become consolidated by the organic layer. Repetition of these interactive processes of physical reworking and microbial colonization is documented by the patchy ripple structure of the supratidal surface.

INTRODUCTION

Many sedimentary surface structures found in recent tidal flats are not formed exclusively by physical forces, but result from bacterial activities that influence the erosional and depositional dynamics.

The sandy lower supratidal zone of Mellum Island, southern North Sea, is widely overgrown by epipsammic microorganisms, among which photoautotrophic cyanobacteria are abundant (Gerdes and Krumbein, 1987; Stal, 1985; Villbrandt, 1992; Noffke and Krumbein, 1999). The coccoid cyanobacteria species *Merismopedia punctata* dominates the microbial assemblages at sites of greater hydrodynamic stress (Riege and Villbrandt, 1994). Its squarelike clusters of cells are dispersed through the interstices of the uppermost light-accessible layers of the deposits and are attached adhesively to the surfaces of the mineral grains by their slimy extracellular polymeric secretions (Decho, 1990). Following the definition of Characklis and Wilderer (1989), this type of microbial colonization is classified as "biofilm-like."

In addition to *Merismopedia punctata*, two filamentous cyanobacteria taxa are widespread on the tidal flats of Mellum Island: *Oscillatoria limosa* and *Microcoleus chthonoplastes. O. limosa* establishes itself at tidal areas of lower hydrodynamic stress. The species forms solitary trichomes. *M. chthonoplastes* usually colonizes tidal sites of very limited physical dynamics. The organism forms bundles of trichomes surrounded by a morphologically distinct sheath. When inundated by water, its filament bundles erect perpendicular to the substrate and project into the supernatant fluid. Behind these threadlike current obstacles, microzones of lower current velocities induce the fallout of suspended mineral particles (Noffke et al., 1997). The trapped grains become incorporated by the developing organic matrix over time. Such processes are known as baffling, trapping, and binding (Black, 1933; Dunham, 1962).

Advanced development of biofilms leads to the formation of thick organic layers covering the entire surface of tidal flats. Krumbein (1983) defined these layers as microbial mats.

Whereas cell clusters of *Merismopedia punctata* and their secretions envelop the grains of the deposits as biofilms, the elongated trichomes of the filamentous cyanobacteria entangle the particles as would tiny horizontal roots and generate a dense, extracellular polymeric lyanobacteria–enriched mesh interwoven through the surface layer of the sediment. Fixation of the formerly loose grains of the tidal deposits by organic fabrics stabilizes the sediment surfaces against erosion (Neumann et al., 1970; De Boer, 1981), a phenomenon termed "biostabilization" (Krumbein et al., 1994).

On the tidal flats of Mellum Island, biotic and physical interactions produce various characteristic sedimentary structures, classified as "microbially induced sedimentary structures" (Noffke et al., 1996; Noffke, 1997). Of those structures, "multidirected ripple marks" are described in this paper. The aim is to demonstrate how this pattern of ripple marks rises from a set of consecutive, opposed microbiological and physical processes prevailing in the lower supratidal zone of Mellum Island.

STUDY AREA

Mellum Island is situated seaward of the German mainland in the southern North Sea between the Weser estuary and Jade Bay (Fig. 1A). We studied the watchglasslike updomed lower supratidal flats of the Westplate (Fig. 1B). This area is inundated by seawater 0.5–5 cm deep during high-water spring tides. Strong winds, mainly from the southwest and northwest, are frequent. Commonly, when winds occur during high-water spring tides, they affect the flood current direction. Current velocities as fast as 50 cm/s were measured. The sediment consists of nearly pure quartz sand having grain sizes of ~0.125–0.160 mm.

In the spring, cyanobacteria begin to colonize the sediment of the Westplate. Initially, biofilms dominated by *Merismopedia punctata* are established on the substrate. Later, a few primary mat patches, tenths of a square meter in area, constructed mainly by *Oscillatoria limosa*, develop on the sand flats (Noffke and Krumbein, 1999). Through the summer months,

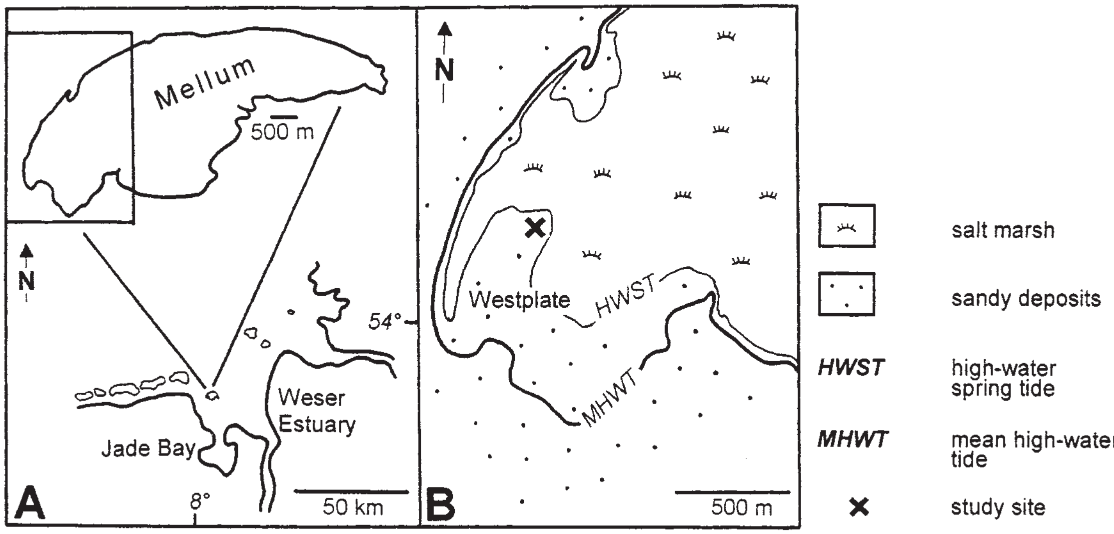

Figure 1. Location of study area. A: Location of Mellum Island seaward of German mainland between Weser estuary and Jade Bay, southern North Sea. B: Location of site of investigations on sandy Westplate, lower supratidal zone, Mellum Island.

bacterial production increases steadily (Wachendörfer, 1991), and the small mat patches enlarge until the surface of the Westplate is entirely covered by a microbial mat layer. During advanced mat development, *Microcoleus chthonoplastes* becomes the dominant species within the epipsammic microbial population and forms coherent mats (Stal, 1985; Villbrandt, 1992; Noffke, 1997). Because of the pattern of successive colonization of the lower supratidal area, different stages of development can be found adjacent to each other within the organic cover. This feature is documented by the changing composition of the cyanobacterial assemblage and the changing thickness of the microbial mat layer.

DESCRIPTION OF MULTIDIRECTED RIPPLE MARKS

In the autumns of 1994, 1995, and 1996, the surface of the Westplate, Mellum Island, was covered by ripple marks of various orientations, overgrown by a microbial mat. The patchy colors of the mat surface (Fig. 2) indicate that different stages of development are occurring adjacent to each other within the epipsammon. Because of the apparently chaotic pattern of the ripple marks, the term “multidirected ripple marks” was proposed for the surface structure (Noffke et al., 1996).

METHODS

Mellum Island was visited every two to three months from September 1994 to October 1996. During high-water spring tides, water depths were measured with a ruler and current velocities were determined by measuring the duration of transport of a swimming mark along a distance of 1 m. The directions of both flood currents and winds were estimated using a compass.

In October 1996, a 10 m × 10 m area was marked off on the lower supratidal flats for investigation of the surface morphology. Cording divided the area into nine subareas of about 3.5 m × 3.5 m each.

To determine any order in the apparently chaotic ripple pattern, the directions of the crests of as many as 30 ripple marks were measured within the subquadrates. The data were transferred onto a stereonet. The areas of those parts of the sediment surface that showed similar orientations of ripple marks were measured, totaled, and converted to a percentage of the total area of the quadrate of investigation.

In order to examine the microbial assemblages, a sample of about 1 cm^3 was taken from the surface of each area bearing ripple marks of a similar orientation. Control samples were taken from areas of indistinct ripple orientations. The samples were preserved in snap-cap glasses containing a solution of 5% formaldehyde and filtered seawater (~34‰). To determine the stage of development of the microbial colony, the relative frequencies of the cyanobacteria species *Merismopedia punctata, Oscillatoria limosa,* and *Microcoleus chthonoplastes* were estimated under light microscope by point-counting the cells and trichomes into three classes of abundance: dominant (>50% of the slide area covered by cells or trichomes of a species), frequent (10%–50% of slide area covered), and seldom (<10% of the slide area covered). The thickness of the organic layer was measured in cross sections of cores (5 cm in diameter) taken perpendicular to the sediment surface.

RESULTS OF INVESTIGATIONS

The total investigation quadrate was divided into four surface-area categories (A, B, C, D). Categories A, B, and C represent parts of the surface, a few tenths of a square meter in area, characterized by ripple marks of uniform orientation (Fig. 3). These three categories occupied 69% of the total investigation quadrate. For the remaining 31% of the tidal surface within the quadrate, neither a distinct ripple mark orientation nor a specific type of microbial colonization could be determined. These parts of the surface were summarized under category D.

Category A, containing ripple marks of azimuths of 158° to 178°, makes up 10% of the 10 m^2 area of investigation. The ripple marks were covered by an organic-mineral layer, as thick as 1 cm, dominated by *Microcoleus chthonoplastes* and trapped and bound sediment grains.

Category B surface areas compose 6% of the investigated area and include ripple-mark crests oriented from 135° to 152°. *Merismopedia punctata* and *Oscillatoria limosa* were common, forming mats to 3 mm thick.

Figure 2. Multidirected ripple marks, Westplate, Mellum Island. Lower supratidal surface shows ripple marks of various orientations covered by epipsammic cyanobacteria community. Different stages of development of cyanobacterial population are documented by patchy colors of sediment surface: light—initial stages (= biofilms), dark—advanced stages (= microbial mats). Knife for scale shows about 20 cm.

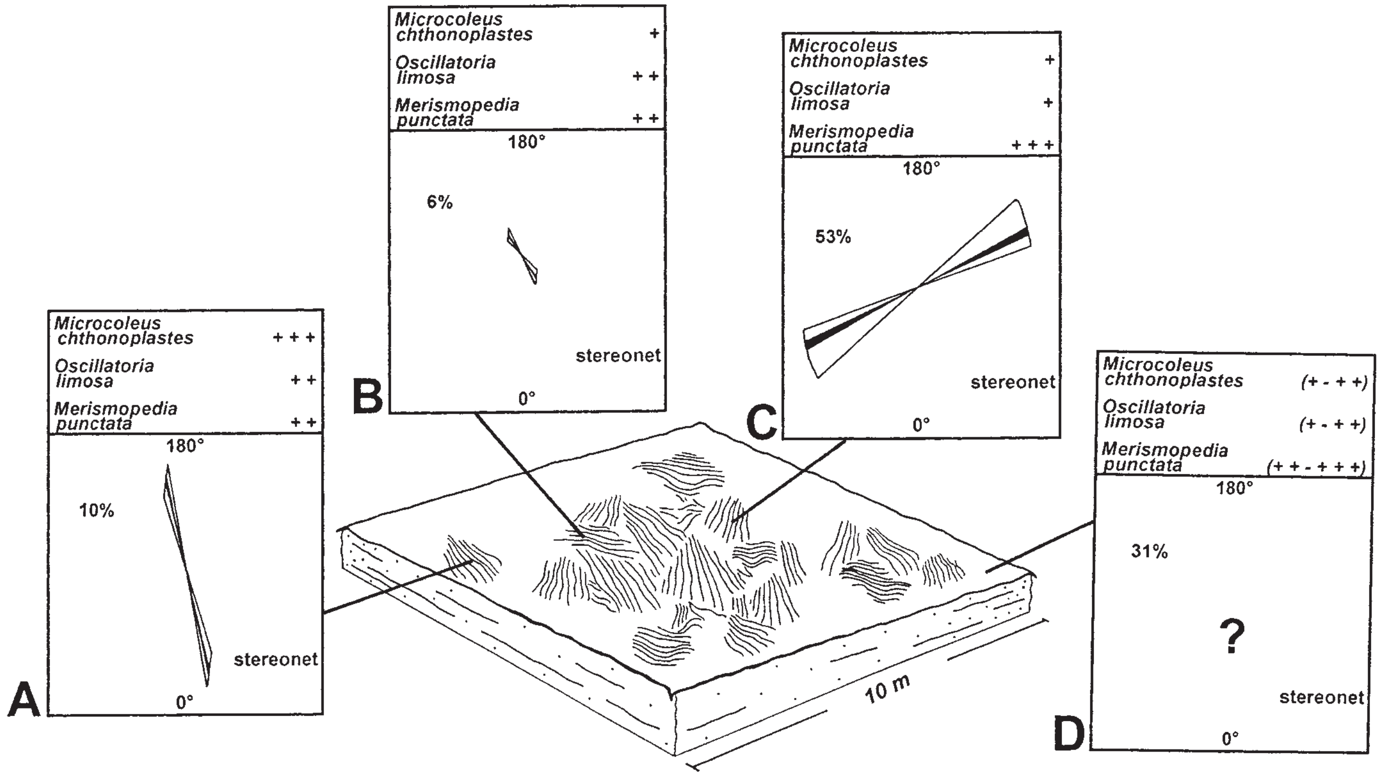

Figure 3. Results of investigations of multidirected ripple marks, Westplate, Mellum Island. Lower supratidal surface within area of investigation (10 m × 10 m) showed three categories (A, B, C) of similar ripple-mark orientations, each covered by cyanobacterial populations at similar stages of development. Category D contains indistinct ripple orientations and varying microbial communities of transition zones or of zones destroyed by humans. A, B, C: Species compositions of microbial assemblages that cover surface areas having distinct orientations of ripple marks. Three classes of abundance of cyanobacteria species are distinguished: +, seldom; ++, frequent; +++, dominant. In stereonet plots, black shows main orientations (80% of ripple marks measured). 1% of surface within area of investigation is represented by 1° of equator of stereonet.

Category C is composed of areas of the supratidal surface where ripple marks are directed from 52° to 60°. It represents 53% of the investigation quadrate. Surface areas were covered by a flimsy organic skin: *Merismopedia punctata* as well as a few trichomes of both the filamentous cyanobacteria taxa were found here. The type of colonization was determined as biofilmlike.

Category D represents surface parts of the area that showed relict or indistinct ripple marks having short or flattened crests. The composition of the microbial assemblages showed great variation and could not be associated clearly to one of the other three types.

INTERPRETATION

The results of the investigation indicate a relationship between distinct ripple-mark orientations and specific stages of development of the cyanobacterial coating. This relationship suggests that the tangled ripple-mark pattern evolves from spring to fall, as follows (Fig. 4).

During the winter months, the high-water spring tides inundating the Westplate are reinforced episodically by strong storms, which push the seawater (~5–15 cm deep) far up on the supratidal area. The high energy of reworking is one main reason for strongly inhibited microbial growth and mat formation (Noffke, 1997).

In the spring, storm frequency decreases, and the Westplate is inundated by a layer of seawater only a few centimeters deep during high-water spring tides. Ripple marks of direction A (Fig. 4, part 1a) are formed. The coccoid cyanobacterial species *Merismopedia punctata* is one of the first groups to recolonize the strongly reworked tidal sands, forming biofilms. Because the surfaces of the supratidal flats are slightly uneven, the degree of disturbance of the sediment surface by shallow water ascending the area during high-water spring tides is not the same at each point of the tidal flats. Over time, *Oscillatoria limosa* becomes dominant within the epipsammic microbial population. This species reacts to small-scale changes in the surface morphology and reworking dynamics by patchy colonization: slightly elevated parts of the supratidal surface, which undergo lower hydrodynamic stress, are preferentially overgrown. The microphytes form a thin primary mat covering these ecologically more suitable sites (Fig. 4, part 1b). The organic fabric of mats develops within several days (Gerdes et al., 1991), and the erosional stability of the sediments continually increases. Whereas biofilms constructed by *Merismopedia punctata* shelter the sediment surface only to a very small degree (Noffke and Krumbein, 1999), the stability of primary mats built by *Oscillatoria limosa* was estimated to be five times greater (Riege and Villbrandt, 1994). This means that ripple marks of direction A become sheltered at localities of preferential growth of *O. limosa*. To the contrary, ripple marks of the remaining parts of the supratidal surface, which are colonized only by biofilms, are less protected against physical reworking.

During the summer, a few high-water “spring” tides may be reinforced by strong wind, and the current direction of the ascending seawater is changed, a phenomenon commonly observed in tidal environments (Reineck and Singh, 1986). Such an event causes higher intensity reworking and ripple marks of orientation B are formed. However, the supratidal surface is not totally reworked: those parts of the surface sealed by mat layers of *O. limosa* remain unaffected, and the ripple marks of direction A are preserved at these localities. After the Westplate drains, the supratidal flats are covered by ripple marks of two orientations, A and B (Fig. 4, part 2a). With steadily increasing biomass production, *O. limosa* also settles on less-suitable parts of the surface, and the mat patches enlarge. The developing organic coating overgrows and consolidates the newly generated ripple marks of orientation B. On supratidal surfaces having ripple marks of orientation A, mat development is most advanced and stabilization persists. The long-lasting calm conditions allow the third cyanobacterial species, *Microcoleus chthonoplastes*, to

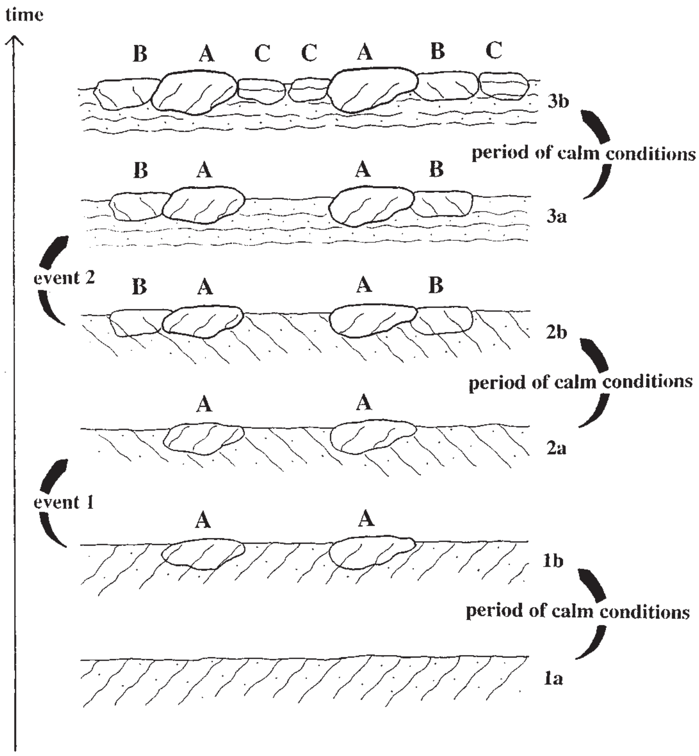

Figure 4. Formation of multidirected ripple marks (Westplate, Mellum Island). Repeated reworking by wind-affected high-water spring tides overlaps steadily increasing biomass production. Developing microbial cover stabilizes increasing part of supratidal surface over time. Surface relief shaped by physical processes becomes preserved. Final effect of these overlapping processes is area of multidirected ripple marks.

join the epipsammon (Fig. 4, part 2b). Because of the immense accumulation of biomass and the trapping and binding of mineral particles by *M. chthonoplastes*, these parts of the tidal area become increasingly elevated (up to 0.5 cm) relative to the original sedimentary surface. Such artificially elevated parts of the surface may function as current obstacles, forcing later shallow ascending water to flow around them.

A subsequent storm event of higher energy may rework the tidal deposits and produce a third generation of ripple marks (orientation C) (Fig. 4, part 3a). Those parts of the supratidal surface interwoven by mats are not disturbed. Führböter and Manzenrieder (1987) determined stabilization effects caused by thick mats on the lower supratidal flats of Mellum Island to be as much as nine times greater than the stabilization shown by pure sand. Yallop et al. (1994) estimated values of 12 times greater on the island of Texel, Netherlands.

At the end of the summer, the biomass productivity of the epipsammon reaches its maximum. During this period, the total area of the Westplate is overgrown.

Lower supratidal surface parts of category D are interpreted as transition zones between the three other types or as zones destroyed earlier by resting birds or by humans walking.

CONCLUSIONS

The example of multidirected ripple marks illustrates the formation and preservation of surface structures in microbially colonized sediments of the lower supratidal zone. The chaotic ripple pattern owes its geometry partly to microbial effects (biostabilization, baffling, trapping, binding) and partly to mechanical reworking of sand by repeated erosional and depositional events. According to the specific succession of processes creating multidirected ripple marks, this type of morphology is highly facies indicative. Identification of fossil occurrences would aid paleoenvironmental reconstruction.

ACKNOWLEDGMENTS

The study arose from a Ph.D. thesis carried out at the University of Oldenburg under the supervision of Gisela Gerdes and Wolfgang E. Krumbein; I am grateful for their valuable advice. I also thank Graham Evans, who improved the English of the manuscript. The study was funded by the Deutsche Forschungsgemeinschaft (DFG), project no. Ge 64/2-1.

REFERENCES CITED

Black, M., 1933, The algal sediments of Andros Islands, Bahamas: Royal Society of London Philosophical Transactions, ser. B, v. 222, p. 165–192.

Characklis, W. G., and Wilderer, P. A., 1989, Structure and function of biofilms: Dahlem Workshop Reports: Chichester, United Kingdom, Life Sciences Research Report 46, 386 p.

De Boer, P. L., 1981, Mechanical effects of microorganisms on intertidal bedform migration: Sedimentology, v. 28, p. 129–132.

Decho, A. W., 1990, Microbial exopolymer secretions in ocean environments: Their role(s) in food webs and marine processes: Oceanographic Marine Biology Annual Review, v. 28, p. 73–153.

Dunham, R. J., 1962, Classification of carbonate rocks according to depositional texture, *in* Classification of carbonate rocks—A symposium: American Association of Petroleum Geologists Memoir 1, p. 108–121.

Führböter, A., and Manzenrieder, H., 1987, Biostabilisierung von Sandwatten durch Mikroorganismen, *in* Gerdes, G., Krumbein, W. E., and Reineck, H. E., eds., Mellum-Porträit einer Insel: Frankfurt am Main, Kramer-Verlag, p. 123–138.

Gerdes, G., and Krumbein, W. E., 1987, Biolaminated deposits: Berlin, Springer-Verlag, 183 p.

Gerdes, G., Krumbein, W. E., and Reineck, H. E., 1991, Biolaminations—Ecological versus depositional dynamics, *in* Einsele, G., Ricken, W., and Seilacher, A., eds., Cycles and events in stratigraphy: Berlin, Springer-Verlag, p. 592–607.

Krumbein, W. E., 1983, Stromatolites—The challenge of a term in space and time: Precambrian Research, v. 20, p. 493–531.

Krumbein, W. E., Paterson, D. M., and Stal, L., eds., 1994, Biostabilization of sediments: Oldenburg, Germany, Bibliotheks und Informationssystem der Universität Oldenburg-Verlag, 526 p.

Neumann, A. C., Gebelein, C. D., and Scoffin, T. P., 1970, The composition, structure, and erodibility of subtidal mats, Abaco, Bahamas: Journal of Sedimentary Petrology, v. 40, p. 274–297.

Noffke, N., 1997, Mikrobiell induzierte Sedimentstrukturen (M.I.S.S.) in siliziklastischen Wattablagerungen [Ph.D. thesis]: Oldenburg, Germany, Universität Oldenburg, 127 p.

Noffke, N., and Krumbein, W. E., 1999, A quantitative approach to sedimentary surface structures contoured by the interplay of microbial colonization and physical dynamics: Sedimentology (in press).

Noffke, N., Gerdes, G., Klenke, T., and Krumbein, W. E., 1996, Microbially induced sedimentary structures—Examples from modern sediments of siliciclastic tidal flats: Zentralblatt für Geologie und Paläontologie, v. I, 1995, no. 1/2, p. 307–316.

Noffke, N., Gerdes, G., Klenke, T., and Krumbein, W. E., 1997, A microscopic sedimentary succession of graded sand and microbial mats in modern siliciclastic tidal flats: Sedimentary Geology, v. 110, p. 1–6.

Reineck, H. E., and Singh, I. B., 1986, Depositional sedimentary environments: Berlin, 542 p.

Riege, H., and Villbrandt, M., 1994, Norderney Survey, seasonal field studies, *in* Krumbein, W. E., Paterson, D. M., and Stal, L., eds., Biostabilization of sediments: Oldenburg, Germany, Bibliotheks und Informationssystem der Universität Oldenburg-Verlag, p. 339–360.

Stal, L., 1985, Nitrogen-fixing cyanobacteria in a marine microbial mat [Ph.D. thesis]: Groningen, Netherlands, University of Groningen, 213 p.

Villbrandt, M., 1992, Interactions of nitrogen fixation and photosynthesis in marine cyanobacterial mats (Mellum, southern North Sea) [Ph.D. thesis]: Oldenburg, Germany, Universität Oldenburg, 163 p.

Wachendörfer, V., 1991, Parahistologische und sedimentmikrobiologische Untersuchungen an einem potentiellen silikoklastischen Strometolithen [Ph.D. thesis]: Oldenburg, Germany, Universität Oldenburg, 209 p.

Yallop, M. L., De Winder, B., Paterson, D. D., and Stal, L. J., 1994, Comparative structure, primary production and biogenic stabilization of cohesive and non-cohesive marine sediments inhabited by microphytobenthos: Estuarine, Coastal and Shelf Science, v. 39, p. 565–582.

Manuscript received March 3, 1998
Revised manuscript received June 30, 1998
Manuscript accepted July 7, 1998