FACIES	44	23-30	Pl. 7	4 Figs.	--	Erlangen 2001

Microbially Induced Sedimentary Structures Indicating Climatological, Hydrological and Depositional Conditions within Recent and Pleistocene Coastal Facies Zones (Southern Tunisia)

Nora **Noffke**, Harvard, Gisela **Gerdes**, Wilhelmshaven, Thomas **Klenke**, Oldenburg,
and Wolfgang E. **Krumbein**, Oldenburg

KEYWORDS: FACIES ZONE – COASTAL ENVIRONMENT – MICROBIAL MATS – MICROBIALLY INDUCED SEDIMENTARY STRUCTURES – – RECENT – PLEISTOCENE

Summary

Extensive tidal areas of the Recent coast of southern Tunisia are overgrown by microbial mats. Different mat types of which each are dominated by distinct and well adapted cyanobacterial species develop. Ecological response of the mat-forming microorganisms to climatological, hydrological and sedimentological factors produce characteristic sedimentary structures (= microbially induced sedimentary structures).

A succession of Pleistocene rocks crops out near the lagoon El Bibane, southern Tunisia. The stratigraphic section comprises structures that we regard as fossil equivalents to those microbially induced structures we observe in the Recent coastal area. Preservation of the structures is result of lithification of the microbial mats. This we conclude from fossil filaments of cyanobacteria visible within the rock matrix.

The Recent microbially induced sedimentary structures indicate facies zones within the modern tidal environment. Comparison of the Recent structures with the fossil analogues recorded in the stratigraphic section aids to identify the same distinct facies zones within the Pleistocene coastal environment also.

Erosion by water currents forms step-like cliffs, and the microbial mat is undermined and ripped off piece by piece. Shallows within the supratidal area are overgrown by copious microbial mats comprising structures like biolaminites and – varvites, as well as polygons of cracks. The features originate from effects triggered by seasonal variations of climate. Tufts and reticulate pattern of bulges indicate supernatant water films covering the mat surfaces. Morphologically higher parts of the Recent tidal area are overgrown by single-layered mats forming petees, induced by microbial mat growth and evaporitive pumping.

The study demonstrates that microbially induced sedimentary structures can be used to reconstruct small-scaled facies zones within coastal environments. They also include hints on paleoclimatological, hydrological and sedimentological conditions.

1 INTRODUCTION

Cyanobacteria are photoautotrophic prokaryotes that live in almost every habitat where water is present. In tidal ecosystems, benthic taxa are widespread. The single cells secret slimy and adhesive mucilages (=extracelluler polymeric substances, EPS), which aid the microbes to attach to the surfaces of depositional grains (Charaklis & Marshall 1989, Decho 1990, 2000, see also review by Stolz 2000). At favorable ecological sites, mainly of upper intertidal and lower supratidal zones, cyanobacteria form 'microbial mats'. These are significant, tissue-like organic layers that may cover large areas of depositional surfaces (see definitions by Krumbein 1983, or Gerdes & Krumbein 1987).

Tidal depositional systems are characterized by extreme environmental conditions, but cyanobacteria are able to react to different and changing ecological factors in various ways. E.g., they response to periodic dessiccation or wettening of the tidal surface by reduced or enhanced growth, or they secrete large amounts of EPS to protect themselves against tough solar radiation, or against osmotic pressure induced by high values of salinity. They escape burial by freshly deposited sediment by active migration towards the new sedimentary surface, or they show phototactic behaviour (movement triggered by favourable light infall) (Gerdes & Krumbein 1987, Gerdes et al. 1991). Such activities of cyanobacteria affect the sediments in which the bacteria colonize, and form characteristic 'microbially induced sedimentary structures (MISS)' (Gerdes et al. 1993, Gerdes et al. 1994a, Noffke et al. 1996, Noffke 1997, Gerdes et al. 2000 a, b).

Along the modern coast of southern Tunisia, we observed coherent cyanobacterial mats of up to several km2 in extension that colonize the supratidal zones. From the subtidal to the supratidal zones, different types of microbial mats can be distinguished. The microbial mats are con-

Addresses: Dr. N. Noffke, Harvard University, Department of Organismic and Evolutionary Biology, 26, Oxford Street, Cambridge, MA 02138, USA, nnoffke@oeb.harvard.edu; Dr. G. Gerdes, Carl von Ossietzky University Oldenburg, Marine Laboratory of the Institute for Chemistry and Biology of the Marine Environment (ICBM), Schleusenstr.1, D-26382 Wilhelmshaven, Fax: +49 (0) 4421 944 299; Dr. Th. Klenke, Prof. Dr. W. E. Krumbein, Carl von Ossietzky University Oldenburg, Institute for Chemistry and Biology of the Marine Environment (ICBM), P.O. Box 2503, D-26111 Oldenburg, Fax: +49 (0) 441 798 3384

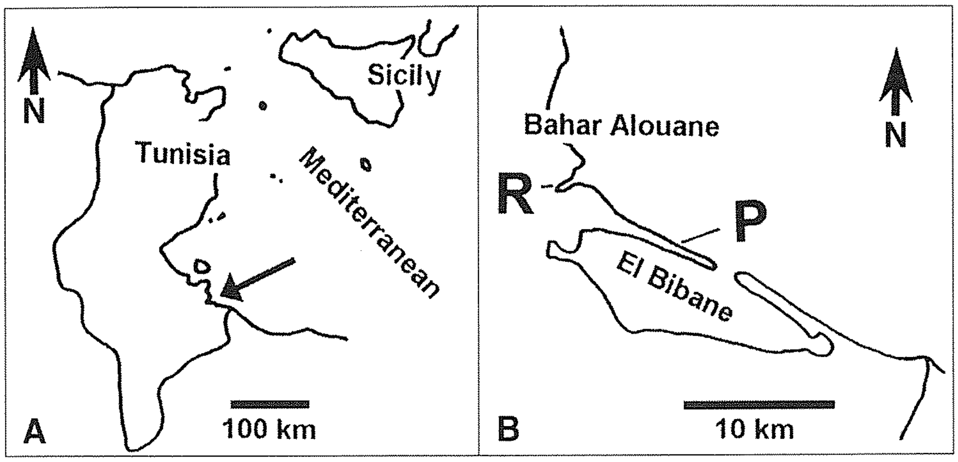


Fig. 1. A: Location of study sites at coast of southern Tunisia. B: Enlarged field map showing location of Recent tidal flats (R) near bay Bahar Alouane, and of outcrop of Pleistocene shoreline deposits (P) near to lagoon El Bibane.

structed by different cyanobacterial populations of which the dominant taxa are very well adapted to the particular environmental conditions. The bacteria response to the environmental factors in specific ways, and by this response, MISS are formed. The structures are widely distributed within the tidal deposits.

Close to the modern coast line of southern Tunisia, Pleistocene rocks crop out that record tidal and shoreline environments (Perthuisot & Floridia 1973, Paskoff & Sanlaville 1983). The stratigraphic section comprises a set of fossil microbially induced sedimentary structures that appear as analogues of those we found in the Recent tidal zones.

We studied the modes of formation of MISS of the Recent tidal flats and made a comparision with the equivalent Pleistocene structures. Aims of the study were (i) to distinguish different cyanobacterial assemblages and microbial mat types, (ii) to detect how the dominant species response to environmental parameters of each of the tidal areas, and (iii) which MISS result from the bacterial behaviors. We examine the use of the fossil structures as indicators for conditions of climate, hydrology, and sedimentology within the recorded Pleistocene coastal environment.

2 STUDY AREA

We studied modern tidal flats of the bay Bahar Alouane, and a Pleistocene section of tidal and shoreline deposits that crops out near the lagoon El Bibane (Fig. 1A).

The climate of southern Tunisia is mediterranean, semiarid. The sediments of the modern tidal flats consist of fine to medium-grained quartz sands, oolitic-bioclastic sands, clay and in situ evaporites (mainle halite, anhydrite, gypsum). Copious cyanobacterial mats occur (Figs. 1B, 2A). The mean low and mean high water lines are marked by small, 5 – 30 cm high, step-like cliffs, scarved out by tidal currents and wind-driven waves. Tidal range reaches 80 cm to 150 cm (Strasser et al. 1989, Davaud & Septfontaine 1995). Within the lower supratidal plains, shallows of about 5 - 25 cm depths and of some tens of meters in diameter occur. They are most of the time inundated by some cm deep water. The water had a salinity range from 60‰ (after several hours of rain fall) to 200‰, and showed pH-values from 8.6 to 9.2. The lower and the sabkha-like "middle" supratidal plains are characterized by evaporite pumping. A few bushes of halophytes are growing. Their number increases towards the dry land, the upper supratidal zone.

The Pleistocene outcrop (Figs. 1B, 2B) extents laterally for about 100 m and has a thickness of 1.00 to 1.50 m. During low tide, upper bedding planes become visible that are exposed to some m^2. The base of the stratigraphic section is covered by Recent marine sediment and therefore could not be investigated. The top is covered by soil (Terra Fusca).

3 METHODS

Recent tidal flats of Bahar Alouane: We studied a transect from E to W crossing the tidal setting from the subtidal/intratidal transition to the middle supratidal zone (sabkha) (Fig. 2A). At single stations, established with a distance of 10 m, we took mat samples of 1 x 1 cm sizes, and measured salinity and pH-values of the water. The mat samples were fixed in 4% formaldehyde diluted in filtered seawater that we collected at the stations. In the lab, the species composition of the microepibenthos was determined by light microscopy following Geitler (1932) and Rippka et al. (1979). We estimated the relative abundance of dominant cyanobacterial species according to the method described in Riege (1994). For the visualization of internal structures and textures of microbial mats, we made serial sections through mat layers, and investigated them with a dissecting microscope. At the stations along the transects, we also took undisturbed sediment samples with small box corers. To investigate composition and internal (micro-)structures of the unconsolidated, mat-interwoven deposits, the core samples were prepared by the use of SPURR, an epoxy resin (Spurr 1969, description of method in Wachendörfer 1991). From the artificially hardened material thin sections were made and examined by mineral optic methods. To detect carbonate minerals, thin sections were stained with calciumferricyanide and alizarine red-S (method described in Füchtbauer & M¸ller 1970). Grain size analysis was performed on unconsolidated deposits by dry sieving.

Pleistocene outcrop (Fig. 2B): We mapped and measured the section and the microbially induced sedimentary structures and we collected rock samples for petrographic

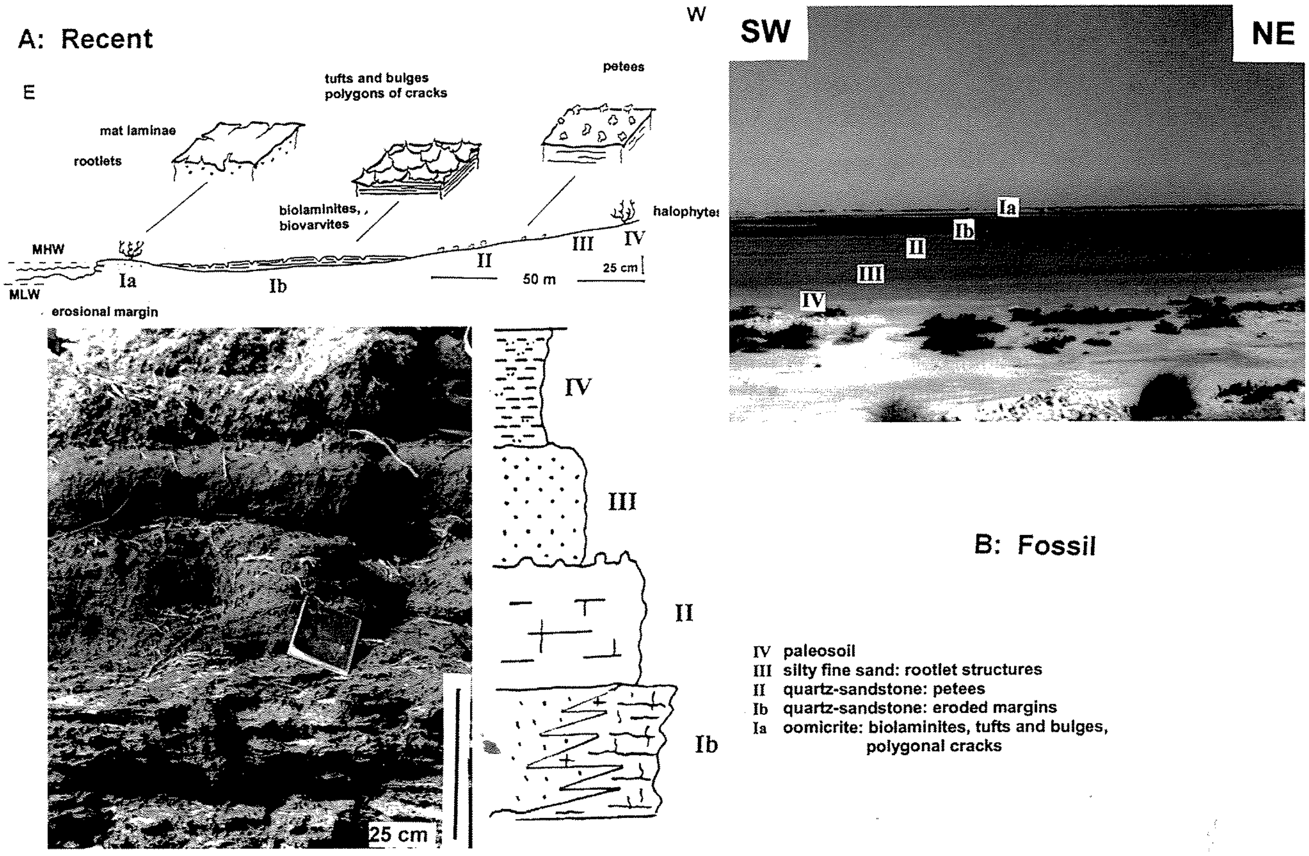


Fig. 2. Microbially induced sedimentary structures of Recent tidal flats (A) and of Pleistocene rocks (B). A: Sketch shows microbially induced sedimentary structures along E-W transect crossing the Recent coastal setting. Mat-covered sediment is eroded by water agitation at transition zones subtidal- intertidal (MLW = mean low water line), and intertidal-lower supratidal (MHW = mean high water line); Location Ia. Biolaminated microbial mats develop within water-covered shallows (Location Ib) forming mat surface structures like tufts and bulges, and exhibiting a polygonal pattern of cracks. At site of evaporite pumping (Location II), petees evolve at mat-covered surface. Halophytes produce rootlets in the sabkha-like, highest parts of supratidal zone (Locations III and IV). Photo shows Recent tidal flats, view into the field. Numbers indicate study locations. B: Photo shows outcrop of Pleistocene rocks. Sketch shows stratigraphic section and rock strata.

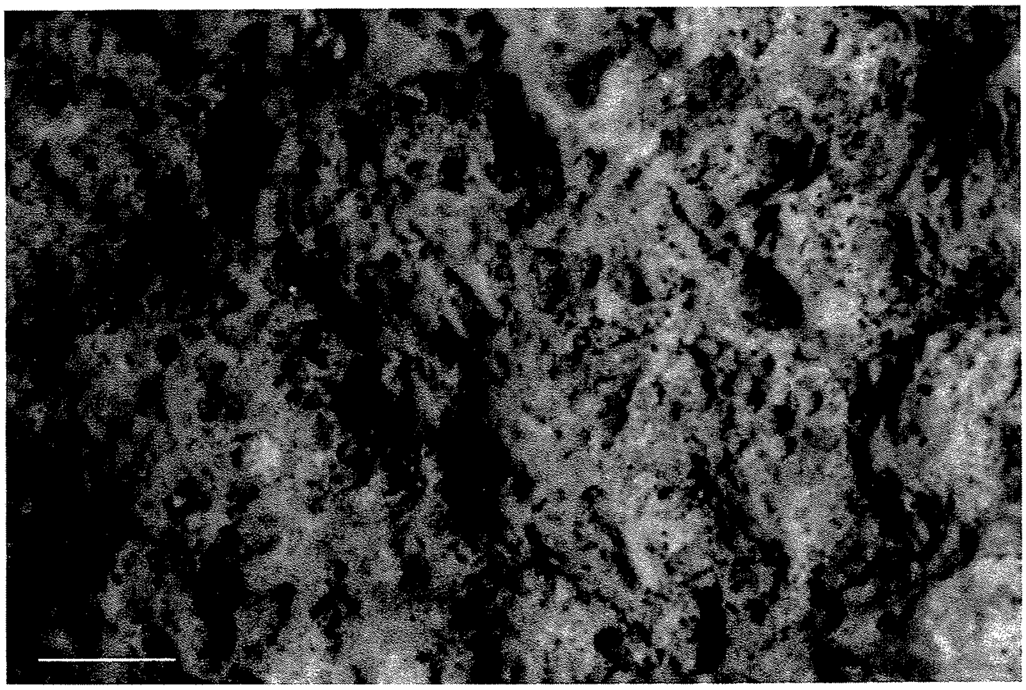


Fig. 3. Petrology of Pleistocene rock unit Ib. 1: Filament-like structures (in situ precipitated mineral matrix) entangling ooids; scale: 1 cm

investigations (thin-sectioning, staining).

4 RESULTS AND DISCUSSIONS

4. 1 Dominant cyanobacteria species and microbial mat types

Two main microbial mat types can be distinguished. The intertidal to supratidal zones are overgrown by a single-layered, and very coherent microbial mat (compare study by Gerdes et al. 2000b). This one-layered mat type is formed mainly by coccoid cyanobacterial taxa, of which *Synechococcus* sp. is most abundant. The bacterium contains a specific pigment, a carotinoid, which gives rise to a rose colour of this mat (Gerdes et al. 1994b). The mat has a thickness from 1 mm to 1 cm.

In the shallows of the lower supratidal zone, thick multilaminated microbial mats of up to 4 cm thickness develop. The significant mats are dominated by the filamentous taxa *Microcoleus chthonoplastes*, *Lyngbya aestuarii*, and *Phormidium fragilis*. Dominant coccoid taxa are *Synechococcus* sp., *Aphanothece* sp. and *Chrooccales* spp. On top view, the mat surface appears dark blue-greenish.

4. 2 Microbially induced sedimentary structures

We describe the Recent structures following the transect from the topographical lowest to highest points of the tidal flats. Because distinct structures occur exclusively in specific zones of the tidal area, they are highly facies-indicative. Fossil equivalents to these structures we could recognize in the Pleistocene stratigraphic section. We will show here, that they record similar facies zones like those we distingushed in the modern tidal area. We describe the structures from the base of the stratigraphic section to the top.

4.2.1 Eroded mat margins and chips indicating erosive processes along the shoreline

The step-like cliffs that mark the Recent shoreline are scarved out by wave action and tidal currents (Fig. 2A, Loc. Ia, Pl. 7/1). Because its substrate is eroded away, the microbial mat becomes undermined, and hangs down like a tissue. Pieces of the microbial mat, "chips", are ripped off by the water agitation.

At the base of the Pleistocene section, we found a fossil step-like cliff capped by a thin rock layer which resembles strongly an undermined microbial mat (stratum Ia, Pl. 7/2). Stratum Ia is a quartz-sandstone bed of 15 cm thickness. In thin-sections, it contains a few laminae that could be interpreted as the fossil equivalent to the Recent single-layered mats constructed by the coccoid species *Synechococcus* sp.. The quartz grains are 0.05-0.1 mm in size. A few ooids and shell fragments were also observed. Stratum Ia interfingers with well-laminated rock units (stratum Ib).

4.2.2 Structures indicating lower supratidal shallows periodically inundated by water

In shallows of the supratidal zone, thick microbial mats grow (Fig. 2A, Loc. Ib). They show structures like biolaminites and biovarvites, tufts and bulges, as well as shrinkage cracks.

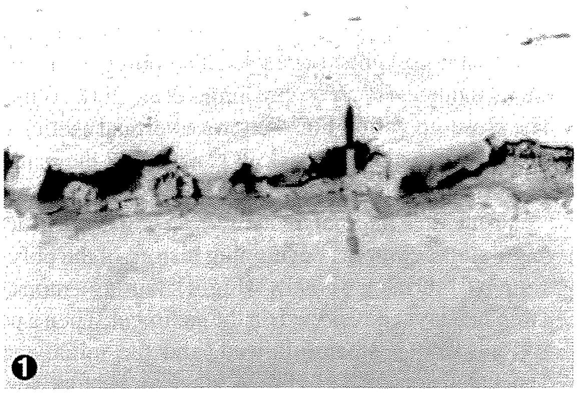
Biolaminites and biovarvites

In vertical sections through the microbial mats, a pile of subrecent organic laminae constructed by preceeding cyanobacteria generations become visible (=multilaminated mats) (Pl. 7/3). Such laminated patterns are termed biolaminite (Gerdes & Krumbein 1987, Gerdes et al. 1991). In closer view, bright and dark mat laminae alternate. Thin-sectioning of the mat laminae show that horizontally orientated trichomes of filamentous cyanobacteria (e.g. *Microcoleus chthonoplastes*) form the dark mat laminae, whereas EPS-rich clusters of coccoid cyanobacteria (e.g. *Synechococcus* sp., *Aphanothece* sp.) dominate the bright mat layers.

The separation of different cyanobacterial taxa into distinct bright and dark layers results from seasonal climatic fluctuations. In winter, when solar radiation is less intensive, the dark coloured cyanobacteria species establishes at the mat surface. In summer, with increasing intensity of sunlight, the coccoid bacteria dominate the mat surface. These species are protected against immense solar radiation by

Plate 7 Microbially induced sedimentary structures from Recent tidal flats, and from Pleistocene outcrop (Tunisia).

Fig. 1.	Recent: erosional margin indicates shoreline. Water agitation by tidal currents or wind-driven waves undermines and erodes microbial mat; location Ia.
Fig. 2.	Pleistocene: formerly undermined microbial mat preserved; rock stratum Ia.
Fig. 3.	Recent: vertical section through thick microbial mat reveals biolaminates (in this case: biovarvites). Biovarvites indicate seasonal climate; location Ib.
Fig. 4.	Pleistocene: biolaminite; rock stratum Ib.
Fig. 5.	Recent: surface of microbial mat covered by soft, organic pins, when inundated by water film. 'Tufts' (arrow a) are composed of filamentous cyanobacteria oriented perpendicularly to mat surface and projecting through thin water film. Below water, bulges, arranged to meshes (arrow b), are visible; location Ib.
Fig. 6.	Pleistocene: bedding plane dotted by lithificated tufts (dark spots, arrow); rock stratum Ib.
Fig. 7.	Recent: surface of microbial mat with a polygonal pattern of shrinkage cracks; location Ib; scale bar: 25 cm. The cracks rise from seasonal variations of moisture.
Fig. 8.	Pleistocene: bedding plane exhibiting polygonal pattern of former shrinkage cracks; rock stratum Ib.
Fig. 9.	Recent: petees covering surface of mats at sites of evaporite pumping; location II.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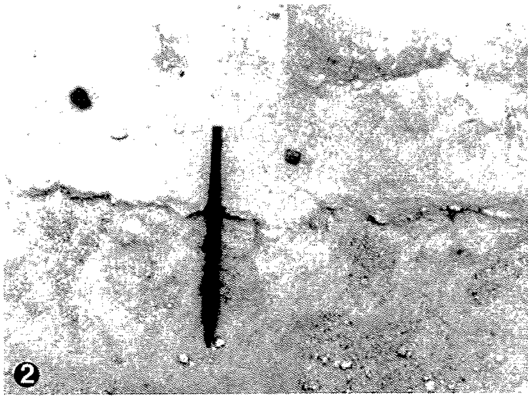
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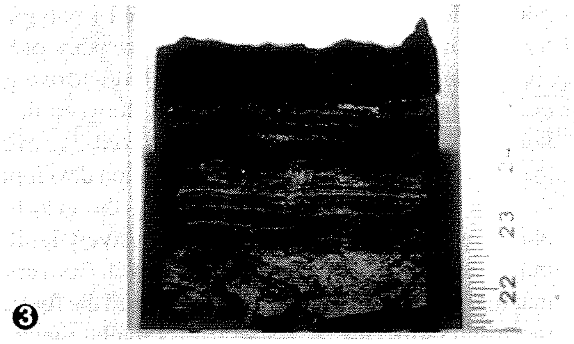
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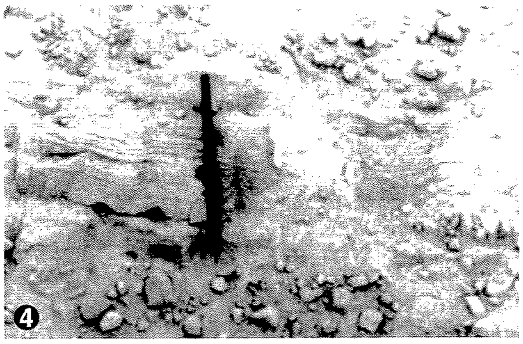
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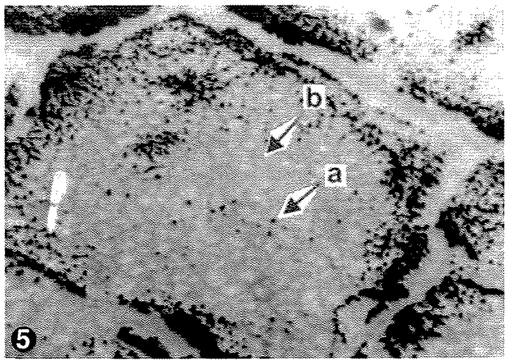
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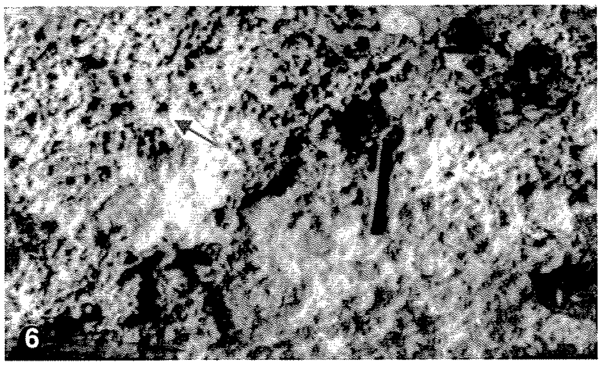
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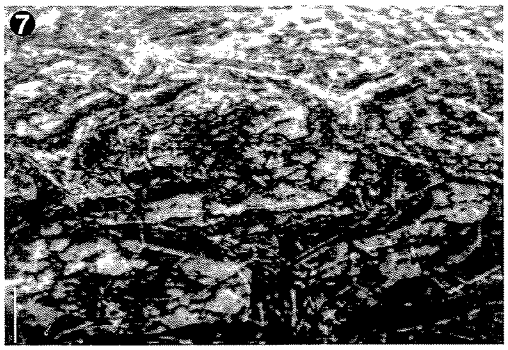
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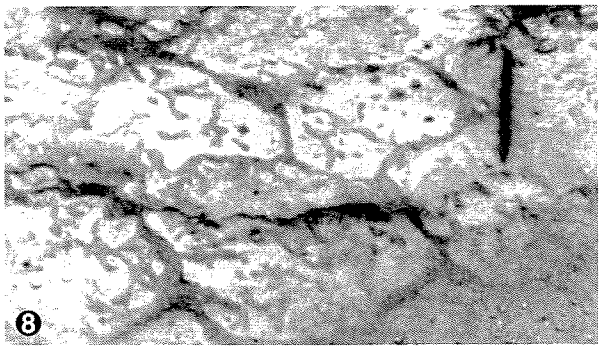
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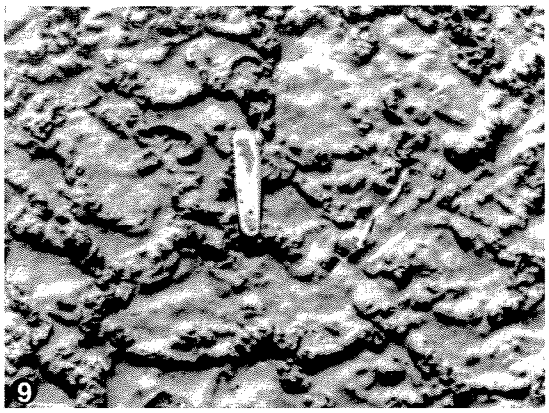
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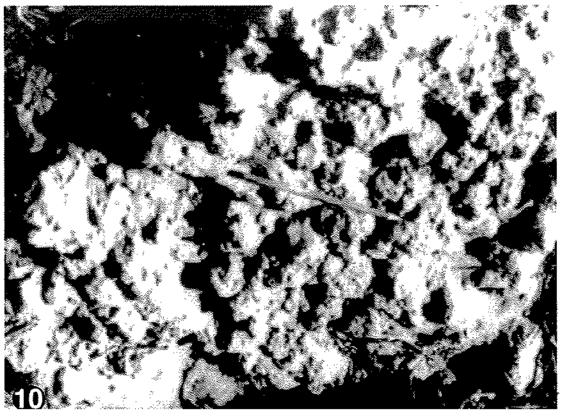
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specific pigments (carotinoids) that give rise to the rose colour of the mats (Gerdes et al. 1994b). Because the pattern of alternating dark and light laminae, the term biovarvite was introduced for this mat fabrics (Gerdes & Krumbein 1987, Reineck et al. 1990).

Stratum Ib interfingers Ia (Fig. 2B). It is a well-laminated oomicrite (classification after Folk 1959) showing a brownish matrix. The ooids measure between 0.1mm and 0.6 mm (mostly 0.2 mm) in diameter. Pl. 7/4 documents the laminated pattern of Ib. The single, sharply projecting laminae are about 0.5 mm thick. In thin-sections, we recognized threadlike structures within the matrix that resemble trichomes or filaments of cyanobacteria. The filament-like structures entangle the ooids forming a typical mat fabrics (Fig. 3).

The rock bed is interpreted as a pile of ancient thick and multilaminated mats that developed on oolitic sands. The sands were originally generated in agitated water, and then deposited at sites of low hydrodynamic energy. Mat-constructing cyanobacteria colonized the re-deposited ooid sands during a marine regression (compare study on sea level changes by Paskoff & Sanlaville, 1983). Significant mat development was probably enhanced by the warm and humid paleoclimate (Paskoff & Sanlaville, 1983).

The microbial mats are beautifully preserved, because of early lithification of each of the bacterial cells and trichomes. The latter are well visible within the in situ precipitated mineral matrix. Mineral formation induced by organic material is well understood from lab and field studies by e.g. Beveridge (1989), Chafetz & Buczynski (1992), Gerdes et al. (1994b), Castanier et al. (2000), or Folk & Chafetz (2000).

Tufts and bulges

The surfaces of the thick, biolaminite-forming mats are spotted by soft organic pins (Pl. 7/5). Such organic pins have been termed "tufts" by Logan et al. 1974. The tufts are from 3 mm to 15 mm in height, and are constructed by vertically orientated filaments and trichomes of *Microcoleus chthonoplastes* and *Lyngbya aestuarii*. Tufts form at the crossings of reticulate-like arranged organic bulges (Pl. 7/5) (compare also Gerdes et al. 2000b). Bulges are a few mm high, organic crests, and are like the tufts composed of cyanobacteria. In this case, the cyanobacteria are not oriented vertically, but more or less horizontally.

The bedding surface of the Pleistocene stratum Ib (Fig. 2B) exhibits meshlike contours and pins. Because these surface phenomena are of similar dimensions like bulges and tufts, they are interpreted as lithified equivalents (Pl. 7/6).

Tufts and bulges result probably from competitive growth among different cyanobacterial species dependant from precise environmental parameters, e.g. salinity, water depth, exposition to light, etc. (Gerdes & Krumbein 1994). This pattern of the mat surface indicates supernatant water, and the mats have been termed 'rhomboid-stellate tufted mats' (Logan et al. 1974). Fossil reticulate structures were named 'elephant skin' by Gehling (1991), or 'wrinkle structures' by Hagadorn & Bottjer (1997).

Polygonal pattern of shrinkage cracks

small, mm to cm-scaled tufts and bulges, but they also show significant polygons of cracks. The polygons reach 30-60 cm in diameter (Pl. 7/7) (cf. Gerdes et al., 2000, Figs. 5 E, F). The close-up within Fig. 4 shows a vertical section through a mat margin along a crack. It reveals that the mat laminae are forming "lobes".

From this internal mat fabrics, we reconstructed the multi-stage, complex developing history of the polygonally arranged "shrinkage cracks" (Fig. 4): During a moist season, a thin mat layer developed on the sediment. Then a period of hot and dry weather followed, and the initial mat layer desiccated and cracked (Fig. 4, stage a). On top view on the mat surface, the shrinkage cracks formed a polygonal pattern. With again increasing moisture probably due to seasonal change, the microbial mat recovered, and overgrew the cracks again (Fig. 4, stages b and c). Between the former bottom of the crack and the thickening, fold-like margins of the mat, niches of reduced light penetration developed (Fig. 4, stage c, arrows). Within the niches, the growth of the photoautotrophic microbes was progressively limited until mat growth at these points finally stopped. Conversely, the mat margins continued to grow, and closed the former crack more and more (Fig. 4, stages d-g). Finally, the crack was completely covered and levelled by biomass, and the mat surface was more or less planar (Fig. 4, stage g). But the former niches of reduced light penetration and decreased mat development show up as weak lines within the microbial mat. Along these weak lines, the mat could crack in future again and a new generation of polygons could form, as soon as dry weather conditions will re-establish.

A fossil example of polygonally arranged shrinkage cracks was observed in the Pleistocene section (Fig. 2B). The exposed bedding plane of stratum Ib shows a relic polygonal pattern (Pl. 7/8). The structures indicate a paleoclimate characterized by seasonal changes of moisture, like e.g., a semi-arid climate zone. Similar shrinkage cracks are known from lithified mats of the Namibian Precambrian.

4.2.3 Petees indicating evaporite pumping in the lower supratidal plains

Similar to the transition zone between subtidal to intertidal, also the topographically higher supratidal flats are overgrown by the one-layered, rose-coloured mats (Fig. 2A, Loc. II), built mainly by the coccoid cyanobacterial species *Synechnococcus* sp.. Here, the surface of this mat type is crinkled and forms cauliflower-like elevations of 0.5 – 2 cm height (Pl. 7/9).

The exposed bedding plane of stratum II of the Pleistocene section (Fig. 2B) shows similar small rises of 1-2 cm high (Pl. 7/10). The rock bed is a 20 cm thick, reddish coloured quartz-sandstone cemented by porcellane-like, rose coloured calcite. It comprises a few laminae, in where the cement is much thicker. The quartz grains are of angular shape and around 0.1 mm in size. Ooids are rare. Rootlet structures can be found, but are quite seldom.

Such cauliflower-like rises were classified as 'petees' (compare Warren 1982, Reineck et al. 1990, Gerdes et al.

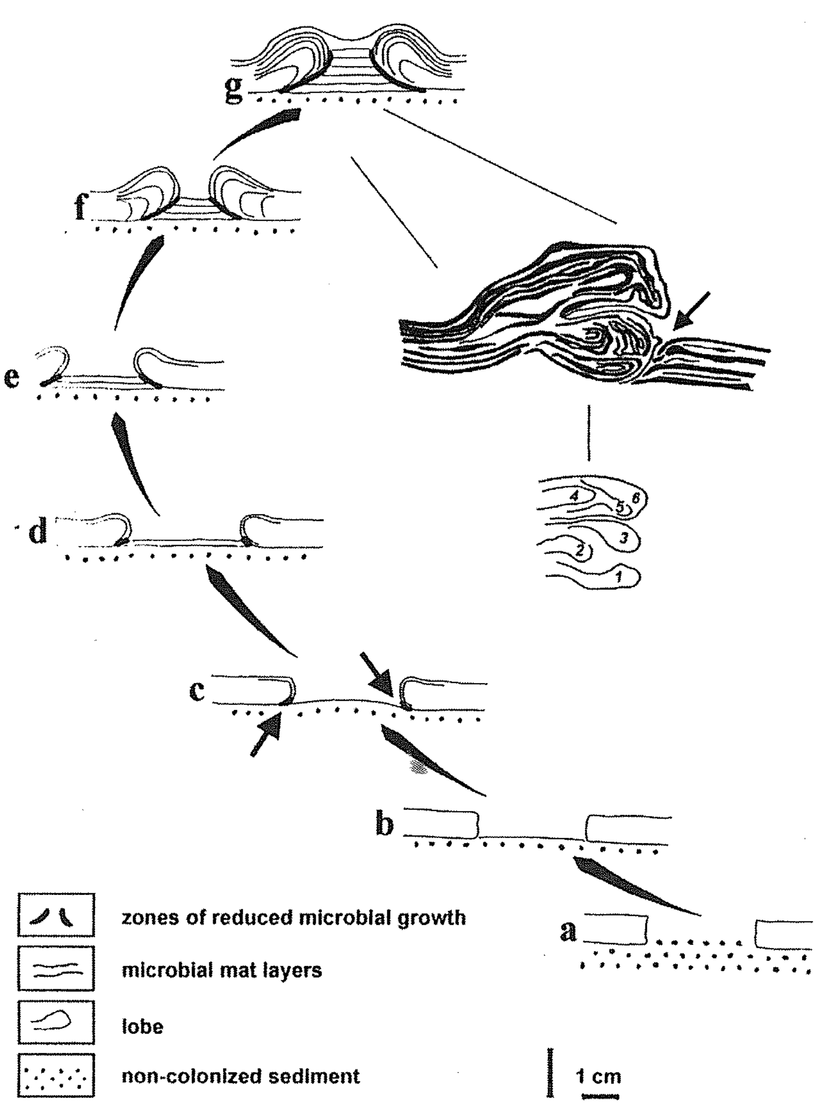

Fig. 4. Mode of formation of polygonal pattern of shrinkage cracks within Recent microbial mat (drawn from series of vertical sections through Recent mat). Left: different stages of formation. a: starting point: shrinkage cracks within initial, thin mat layer; b: development of microbial mat layer covering crack; c: due to reduced light penetration, areas of less biomass production locate between bottom of crack, and margins of preceeding cracks; d-f: ongoing microbial growth and formation of mat layers. Preceeding margins of shrinkage cracks are overgrown and organic ‚lobes' are formed; g: final stage: mat layers cover preceeding cracks completely. Right: vertical section through mat margin (close-up). Microbial mat layers are visible forming lobes each indicating periods of increased biomass production during periods of greater humidity. Sketch below shows number of lobes. At point between margin and bottom of crack (arrow) light penetration is very small, and microbial growth is reduced.

developing evaporite crystals forming at the sediment surface and acting against microbial growth. Evaporite pumping that characterizes this tidal area supports this process. The Pleistocene quartz-sandstone (unit II) that shows petees at its upper bedding plane probably form in a similar tidal paleoenvironment.

4.2.4 Structures of the middle supratidal area, the sabkha

In the supratidal area, we observed no microbial mats (Fig. 2A, Loc. III), and the silts and fine sands are affected only by abiotic factors like evaporation, deflation, etc. At the uppermost part of the transect (Fig. 2A, Loc. IV), where the dry land begins, soil has developed, and many bushes of halophytes grow. The roots of the bushes abundantly penetrate the sediment below.

In the Pleistocene section (Fig. 2B), sediment of similar grain sizes composes stratum III. This already strongly weathered red to brown coloured rock bed is about 17 cm thick, and exhibits rootlet structures. Microbial mat-induced phenomena lack. The stratigraphic section is capped by a paleosoil (stratum IV). The appearance of this stratum permits the conclusion that it records also such a sabkha-like transition zone between tidal-influenced area and dry land.

5 CONCLUSIONS

The Recent tidal flats along the coast of southern Tunisia are overgrown by extensive microbial mats, of which two main types can be distinguished. The mats are dominated by cyanobacteria species that are well adapted to the colonization site. Overlapping of bacterial activities and reaction of the mats with climatological, hydrodynamical, or sedimentological parameter originates specific microbially induced sedimentary structures in the deposits. We found similar fossil structures within a stratigraphic section of Pleistocene age. Our knowledge of processes that form the structures in the actual permits conclusions on the paleoenvironmental conditions prevailing during deposition of the Pleistocene sediments. Thus we can use microbially induced sedimentary structures as tools to define narrow facies zones within an ancient coastal area.

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