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Extensive microbial mats and their influences on the erosional and depositional dynamics of a siliciclastic cold water environment (Lower Arenigian, Montagne Noire, France)

N. Noffke*

Institute of Geology and Paleontology, Johann Wolfgang Goethe University, Senckenberganlage 32-34, 60054 Frankfurt am Main, Germany

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Abstract

Lower Arenigian (Ordovician) rocks of the Montagne Noire, France, represent a shallow-marine environment of a high latitude position along the northern margin of Gondwana. Within the weakly metamorphosed siliciclastics six depositional units were recognized: (1) outer shelf; (2) foreshore zone, below wave base; (3) foreshore zone, above wave base; (4) sand bars of shoreface zone; (5) intertidal deposits; and (6) lagoonal zone. Wrinkle structures and various other phenomena were mediated by coherent (cyano-)bacterial mats. The structures can be related to the different facies zones of the paleoenvironment. Whereas the muddy outer shelf, and the high-energetic sand bars were not overgrown by any mat-constructing microbial populations, fine sands of the foreshore zone, the tidal flats and lagoonal areas were widely colonized. Restriction of mats due to competition of space by endobenthic macroorganisms, or by grazers was low. The microbially induced structures are composed of organic material, pyrite, clay minerals (illite, chamsonite, chlorite), and chert. The minerals precipitated in situ during degradation of the organic layers by the activity of heterotrophic bacteria at low temperatures. Because the microorganisms formed a dense organic carpet covering extensive areas of the ancient sea-bottom, they influenced significantly the erosional and depositional dynamics of the sedimentary system of the local Arenigian. Biostabilization counteracted erosion, and baffling, trapping and binding enriched mineral particles. Additionally, the in situ formed minerals contributed to the total amount of sediment. The biotic influence lead to increased accumulation of sediment within the depositional area. The study shows that microbial mats of great extension occur within Phanerozoic siliciclastics of cold paleoclimate zones, and that preservation of the mat fabrics was possible. The significant mats influenced the local sedimentary system, an aspect scarcely taken into account for such paleo-environments. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: extensive microbial mats; erosional and depositional dynamics; siliciclastic cold water environment

1. Introduction

Many sedimentary structures indicate the former presence of microbial mats in ancient siliciclastic environments (especially of Proterozoic age, compare volume by Hagadorn and Bottjer, 1999). Wavy-crinkly laminae, overfolded structures, pyrite beds, and various other features were reported by Schieber (1998) and Schieber (1999), wrinkle structures have been comprehensively examined by Hagadorn and Bottjer (1997), Hagadorn and Bottjer (1999), and Pflüger (1999). The formation of these and similar

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* Department of Organismic and Evolutionary Biology, Harvard University, 26, Oxford Street, Cambridge, MA 02138, USA.

E-mail address: nnoffke@oeb.harvard.edu (N. Noffke).

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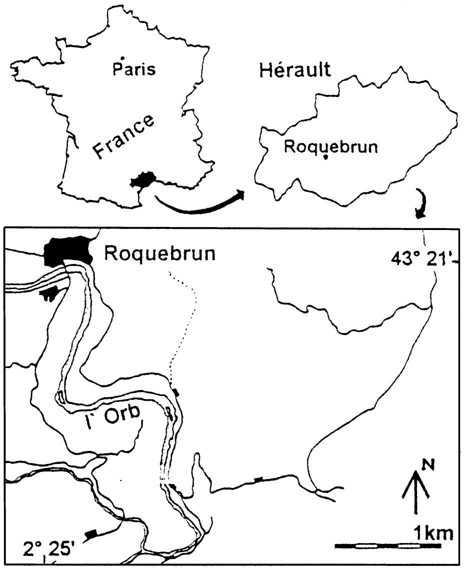

Fig. 1. Location of study area. Lower Arenigian (Ordovician) siliciclastics crop out south of village of Roquebrun, Département Hérault (Montagne Noire, France).

structures within sandy deposits can be related to specific activities of epibenthic bacteria responding to environmental parameters like water agitation. Studies conducted in Recent siliciclastic, shallow-marine environments of a cool-temperate climate zone showed that mainly photoautotrophic cyanobacteria construct significant and coherent mats (Gerdes and Krumbein, 1987). The activities of the benthic microbial communities interfere with the physical dynamics prevailing in the environment, and this biotic–physical interplay forms characteristic structures (Gerdes et al., 1993, 1994; Noffke et al., 1996; Noffke, 1997, 1998, 1999; Gerdes et al., 2000).

Two important bacterial activities that effect the formation of sedimentary structures are: (i) biostabilization, or (ii) baffling, trapping and binding. Biostabilization by sticky extracellular polymeric substances (EPS, Decho, 1990, 2000), in addition to the organic meshwork of bacterial filaments interweaving the mineral grains, protects the depositional surface against erosion (e.g. Gebelein, 1969; Neumann et al., 1970; De Boer, 1981; Paterson and Daborn, 1991; Paterson, 1997; Noffke et al., 1997a). Baffling, trapping and binding (sensu Black, 1933) results in suspended sedimentary particles being combed out by cyanobacterial filaments oriented perpendicularly to the mat surface, and then overgrown by the organic matrix (Noffke et al., 1997a,b; Gerdes et al., 2000). “Tufts” of vertically oriented filaments can be observed for example on the surfaces of “rhomboid-stellate tufted mats” (Logan et al., 1974).

Heterotrophic bacteria decompose the primary producers, and induce in situ formation of minerals like pyrite and others (e.g. Ferris et al., 1987; Giblin, 1988; Pye et al., 1990; Canfield and Raiswell, 1991; Urrutia and Beveridge, 1993b).

The aim of this paper is to show, that extensive microbial mats occurred in well-aerated sandy sediments of the early Phanerozoic. The example of the Lower Arenigian of the Montagne Noire demonstrates that significant mats covered large areas of the ancient bottom sediments in a shallow sea situated within a colder paleoclimate. Furthermore, it will be outlined how the bacterial epibenthos by various mechanisms influenced significantly the erosional and depositional dynamics of the local sedimentary system.

2. Study area

Lower Arenigian (Ordovician) rocks cropping out near the village of Roquebrun in the southern Montagne Noire, Départment of Hérault, France (Fig. 1) were studied.

The weakly metamorphosed deposits form the inner core of the “Synform of Roquebrun” (Arthaud, 1970; Engel et al., 1978). They represent a shallow-marine environment along the northern margin of Gondwana, and consist of lithologically monotonous siliciclastic sediments (Noffke, 1992; Noffke and Nitsch, 1994). Six lithofacies types [1–6] are recognized (Noffke and Nitsch, 1994): (1) outer shelf below storm wave base: muddy sediment; (2) foreshore zone below storm wave base: mud and fine sands; (3) foreshore zone above storm wave base: fine sands, mud, medium-grained sands; (4) high-energy barrier sands: medium to coarse grained; (5) intertidal zone: fine sands and mud; (6) lagoonal (subtidal) zone (mud) with spill-over lobes (mica-rich fine sands). The paleo-latitude of the depositional area was adjacent to a subpolar low-pressure belt.

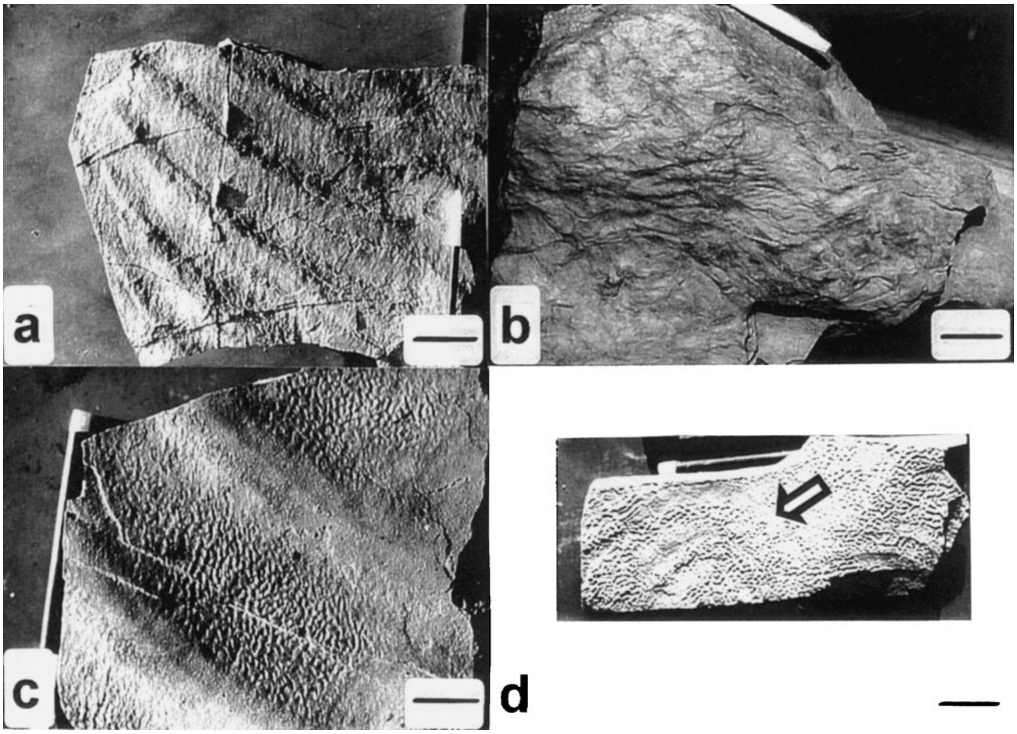

Fig. 2. Wrinkle structures representing fossil microbial mats (Lower Arenigian, Montagne Noire, France). (a) Fine-scaled irregular wrinkles, facies zone 2, scale bar: 5 cm; (b) Larger-scaled irregular wrinkles, facies zones 2, 3, 5, 6, scale bar: 3 cm; (c) Ornament-like wrinkles, mainly found within ripple troughs, facies zones 3, 5, 6, scale bar: 3 cm; (d) Torn structures (arrow) within mat, facies zones 5, 6; scale bar: 3 cm.

3. Methods

Along stratigraphic sections, microbially induced structures were mapped, collected, and thin sections were prepared. Transmitted and reflected light was used for petrological light microscope studies, and a point-counter analysis was conducted to investigate the texture of the ancient mat layers. The organo-mineral composition was investigated by EDX and microprobe analyses. Clay minerals were determined using a Philips X-ray diffractometer.

Table 1
Wrinkle structures (ws) related to facies zones (1–6)

	1	2	3	4	5	6
WS1	0	21	0	0	0	0
WS2	0	12	17	0	15	11
WS3	0	0	3	0	1	1
WS4	0	0	0	0	22	19

4. Results

Fine-grained sandstone beds of facies zones 2, 3, 5 and 6 show different wrinkle structures at their bedding planes (Fig. 2). One can distinguish very fine-scale, irregular wrinkles (Fig. 2a), and below these ripple marks are visible. Conversely, irregularly wrinkled structures of larger scales completely cover any original surface structures (Fig. 2b). A few wrinkle structures occur exclusively within ripple mark valleys (Fig. 2c), whereas ornament-like contours (Fig. 2d) smooth out the former surface relief. The various types of wrinkle structures occur in relation to the different facies zones (Table 1).

Polished sections and thin sections of wrinkle structures reveal the composition of organic material, pyrite, clay minerals (mainly illite, chamosite, some chlorite), and chert (Fig. 3a).

Almost all fine-grained sandstone beds of facies zones 2, 3, 5 and 6 contain continuous laminae that

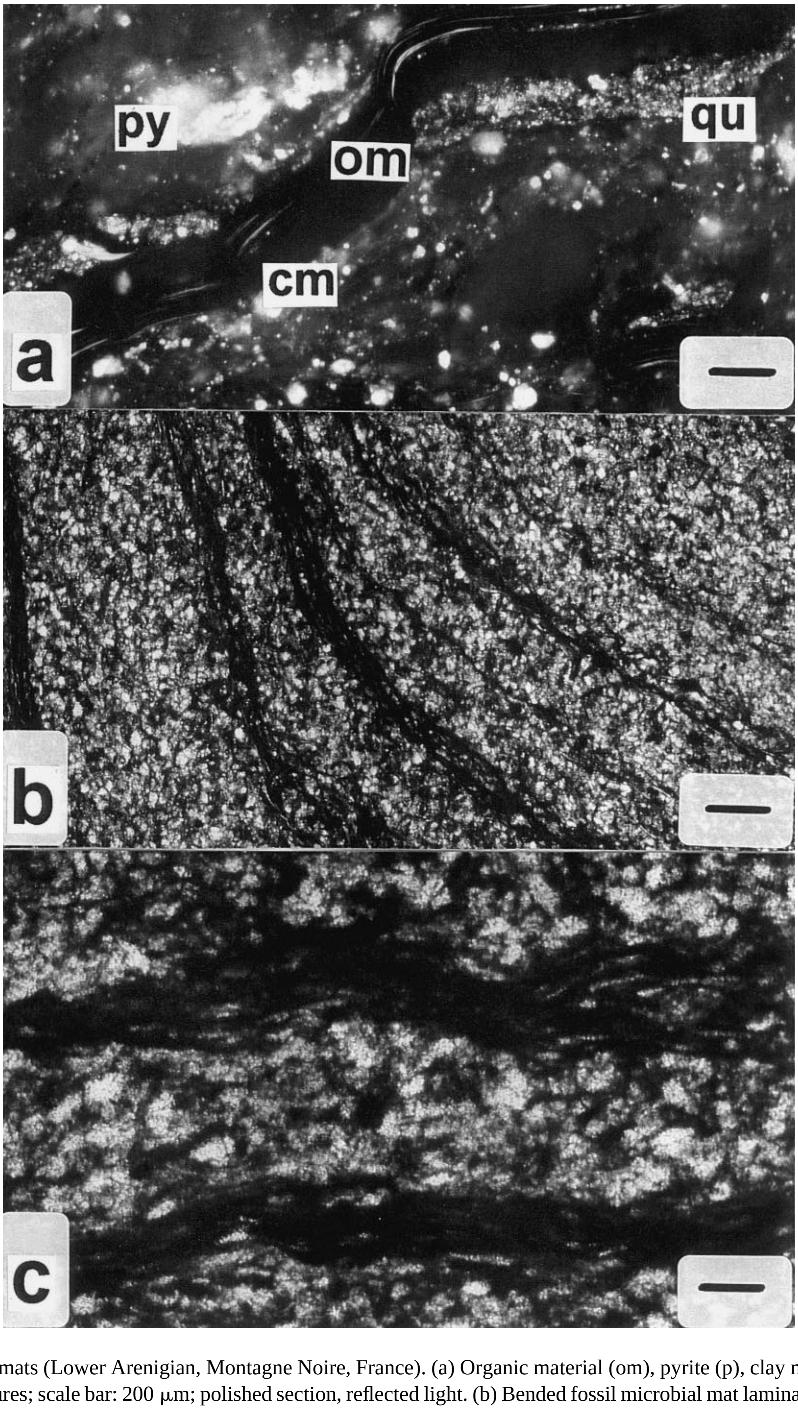

Fig. 3. Fossil microbial mats (Lower Arenigian, Montagne Noire, France). (a) Organic material (om), pyrite (p), clay minerals (cm), chert (qu) compose wrinkle structures; scale bar: 200 μm; polished section, reflected light. (b) Bended fossil microbial mat laminae, scale bar: 0.5 mm. (c) Microfabrics of laminae resemble strongly cyanobacterial mat fabrics; thin section, transmittent light; scale bar: 1 mm.

Table 2
Rocks (%) of specific laminae content (category A–D) for facies zones (FZ 1–6) (Category *A* represents rocks containing 1–5% laminae with regard to total rock composition; *B* represents 5–15%; *C* 20–30%; and *D* 30–60%)

	A	*B*	*C*	*D*
FZ1	–	–	–	–
FZ2	–	5	7	58
FZ3	1	12	34	53
FZ4	–	–	–	–
FZ5	8	10	45	37
FZ6	30	37	31	12

irregularly alternate with variably thick quartz–sand-interlayers (Fig. 3b; Table 2, also compare Fig. 4a). One rock sample shows bent laminae, of which one reaches the upper bedding plane, where it forms a wrinkle structure. The single laminae are about 100 μm thick, but are mainly stacked in sets of many layers (up to 3 cm) mostly showing high inheritance (compare Fig. 4c). They show microfabrics resembling in size and shape of the meshwork of mats constructed by filamentous cyanobacterial species interweaving quartz grains (Fig. 3b and c). Up to 50% of individual laminae contain interwoven quartz grains.

Commonly, the laminae increase upward to the bedding planes. They can be unconformable to each other or to the intercalated fine sand strata (Fig. 4a), or they may line ripple marks within the sandstone beds. Wavy thin rock beds are common, and single beds containing overfolded laminae can also be found. Two or three rock beds of facies zones 2 and 3 are composed of rolled-up fragments of laminae of some millimetre to some centimetre length. Tuft-like structures are visible on top of many laminae of sandstones of facies zones 5 and 6 (Fig. 4b). The sizes of the tufts range from 0.2 to 1.0 cm. The tufts are of the same composition as the laminae. Wavy-crinkled laminae can be seen frequently (Fig. 4c).

Shales of facies zone 1 show single, very thin organic-rich and pyritic laminae that do not always persist laterally. Also, within shales and siltstones of the other facies zones no hints on such significant laminae could be found. In addition, no laminae were detected in medium to coarser grained sandstones (especially of facies zone 4).

5. Discussion

The wrinkle structures are interpreted as fossil microbial mats that were widely distributed within the ancient shallow-marine environment: facies zones 2, 3, 5 and 6 (compare Fig. 2, Table 1) were abundantly overgrown by mat-constructing bacteria. The mats were interpreted to be of different thicknesses, because some wrinkle structures are “transparent” (that is, ripple marks below are visible), whereas others are “non-transparent” (that is, the original surface relief is smoothened) (Noffke, 1997; Schieber, 1998; Noffke and Krumbein, 1999). Fossil microbial mats within ripple valleys have also been described by Gehling (1999) from lower shoreface sandstones of the Proterozoic Flinders Range in Australia.

There is evidence that the former mats were probably built by cyanobacteria. These are proposed to be major mat-constructors in shallow-water environments during the Phanerozoic (Horodyski, 1980). Carbonate systems of the Silurian and Ordovician show a high prevalence of stromatolites and thrombolites, which is explained by higher levels of carbon dioxide perhaps stimulating photosynthetic activity during the early Paleozoic (e.g. Riding, 1997).

The distribution of wrinkle structures within the study area indicates dependence on the photic zone, on fine sand substrate, and on low degrees of rework. Mud and silt of all facies zones either contained none or very less cyanobacteria. This can be explained, because these microbes prefer substrates of fine sand sizes (e.g. Gerdes and Krumbein, 1987; Noffke, 1997; Noffke et al., 1997a). Evidence of microbial mats is lacking also within the amalgamated sand bars of the high energetic facies zone 4. Additionally to immense disturbance by water agitation, these sands were strongly bioturbated by endobenthic polychaetes that produced the trace fossil *Daedalus halli* Rouault (Seilacher, 1991, personal communication; Noffke, 1992). It is known from the Recent that mat development is restricted by water agitation or bioturbation (Gerdes et al., 1991). In the local Lower Arenigian, the impact of other macroorganisms on mats is low, perhaps as a function of evolution: grazing or space occupying organisms were still lacking. Grazers (e.g. Cruziana producing trilobites) occurred only in greater water depths (facies zone 2) (Noffke and Nitsch, 1994). “Space occupiers” (macroorganisms

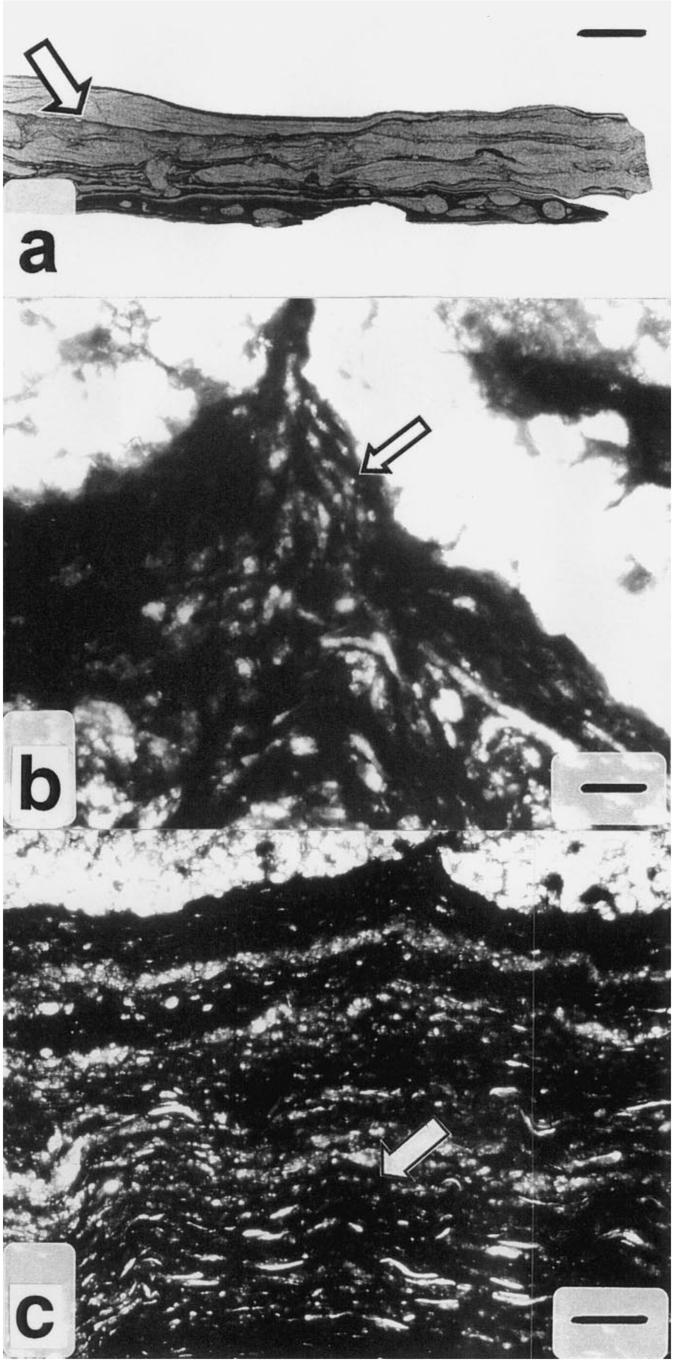

Fig. 4. Fossil microbial mats, thin sections, Lower Arenigian, Montagne Noire, France. (a) Undisturbed fossil mat laminae (e.g. arrow) indicate biostabilization; thin section; scale bar: 1 cm. (b) Tuft. Note dark coloured bacterial filaments (e.g. arrow); facies zones 5, 6; scale bar: 0.7 mm. (c) Wavy crinkled laminae (e.g. arrow) of great inheritance; scale bar: 2 mm.

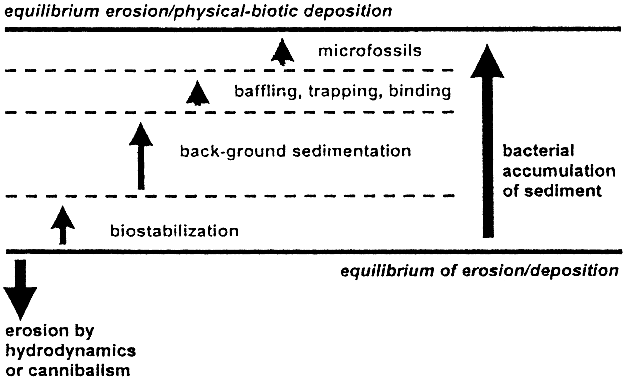

Fig. 5. Microbial mats influenced depositional and erosional dynamics of the ancient sedimentary system (Lower Arenigian, Montagne Noire, France). Biostabilization acted versus erosion; baffling, trapping and binding induced fall-out of mineral particles; in situ-precipitated minerals form a bulk of "microfossils". Biotic influences supported sediment accumulation.

competing with mats for space) like the producer of the burrow *Phycodes circinnatum* Richter formed clusters (Noffke, 1992), covering only a few square metres of the former sea bottom otherwise colonized by mats.

The microfabrics of the mat layers (Fig. 3b and c) and the presence of tufts (Fig. 4c) atop surfaces of the ancient mats also provide hints on cyanobacteria (e.g. Logan et al., 1974; Gerdes and Krumbein, 1987; Gerdes et al., 2000). Tufts observed on Recent mats of the Tunisian coast are quite rigid and may withstand pressure by freshly deposited sediment (Gerdes et al., 2000). The primary vertical habit is supported by early precipitated minerals like carbonates (Gerdes et al., 2000), or silica (Kah and Knoll, 1996).

The mat fabric of Recent cyanobacteria induces high degrees of biostabilization (Führböter and Manzenrieder, 1987; Krumbein et al., 1994; Yallop et al., 1994; Noffke, 1998; Noffke, 1999; Noffke and Krumbein, 1999). Within the Lower Arenigian rocks, one crinkled bedding surface was found that shows sigmoidal, not wrinkled areas (Fig. 2d). These areas are interpreted as torn structures within a former coherent microbial mat, like that described and defined by Bérnier et al. (1991) from mats of Kimmeridgian limestones. Schieber (1999) and Simonson and Carney (1999) inferred that overfolded structures or thin wavy rock beds reflect the cohesive properties of bacterially bound deposits. Strata, composed of eroded mat fragments can be interpreted as storm event layers (compare Schieber, 1998, 1999).

The microfabrics of the mats (Fig. 3b and c) are clearly lined by the scummy, brownish to black organic material and the mineral assemblage of pyrite, clay minerals, and chert. Thus, textures of the original mat are preserved, as well as its density and thickness. This exact preservation permits the conclusion that the outer walls of bacterial filaments (or trichomes) provided sites for mineral precipitation, which is well known from degradation of organic matter by heterotrophic bacteria at low temperatures: the formation of pyrite induced by sulfate-reducing bacteria was investigated by e.g. Raiswell, 1987; Giblin, 1988; or Canfield and Raiswell, 1991. Lower levels of oxygen may have reduced oxidation of pyrite. Clay minerals (e.g. chamositic clay) were artificially produced in lab experiments on decaying bacterial surfaces (Ferris et al., 1987; Beveridge, 1989; Urrutia and Beveridge, 1993b; Konhauser et al., 1994; Schulze-Lam et al., 1996, see also review by Douglas and Beveridge, 1998). Precipitation of silica (later mineralized to chert) is supported by acidic pH-values near degrading organic material, as interpreted by Leo and Barghoorn, 1976, or Knoll, 1985. This shows that mats can become preserved also within sediments of colder climates, where common evaporites or carbonates lack.

The following results of the study document that large microbial mats syndepositionally influenced the erosional and depositional dynamics of the ancient sedimentary system (Fig. 5): firstly, the well preserved and more or less undisturbed laminae (e.g. Fig. 4a) show that stabilization by the microphytes successfully protected the depositional surfaces against erosion. Under the line, loss of bottom surface sediment because of water agitation or cannibalism was reduced. Secondly, the mat laminae entangle mineral particles (Fig. 3b) that have been probably incorporated and enriched by baffling, trapping and binding (Noffke et al., 1997a). Biostabilization (counteracting erosion) and microbial sediment enrichment rose the depositional surface over time, similarly as it was shown in lab experiments on living microbial mats (Gerdes and Krumbein, 1987; Gerdes et al., 1991). Thirdly, the mass of bacteria, now forming microfossils, contributed to the total amount of sediment (Fig. 3b, Table 2). Summarized, physical–biotic deposition surmounted the rate of erosion, which means that generally accumulation of sediment took place. For example, the formation of the fine sand beds could have been supported by bacterial presence.

It can be concluded that extensive microbial mats occurred during the early Phanerozoic even in a siliciclastic and well-aerated environment, but where pressure by space occupiers or grazers was low. Growth of mats and their preservation was possible even in a subpolar paleoclimate zone. Further, the benthic bacteria acted syndepositionally as controlling factors within the ancient depositional system of the Lower Arenigian of the Montagne Noire, and contributed to sediment accumulation.

Supposition is that the distribution of extensive microbial mats within Phanerozoic siliciclastics of colder climate zones is far higher than documented until now. The influence of epibenthic bacterial communities on such sedimentary systems seems to be underestimated, and should be the aim of studies in the future.

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