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ORIGINAL ARTICLE

Microbial stabilization of sediments in a recent Salina, Lake Aghormi, Siwa Oasis, Egypt

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Abstract Stabilization of sediments by microbial mats and biofilms were studied in detail in Lake Aghormi, Siwa Oasis, Egypt. The study has shown that microbial mat assemblages, particularly filamentous cyanobacteria, with their extracellular polymeric substances (EPS) are capable of effectively stabilizing sediments. The microbial mats in the siliciclastic environments of Lake Aghormi display distinctive sedimentary structures (microbially induced sedimentary structures), including multidirected ripple marks, microbial patches, petee structures, erosional remnants and pockets, and gas domes. Scanning electron microscopy study of the sediment surface colonized by cyanobacteria revealed that filamentous types are the most effective stabilizing organisms. Filamentous cyanobacteria and their EPS construct a network, interweave depositional grains of the sediment surface, envelope the particles, and glue them together. The studied biofilm is so thick forming a spider-web structure that totally coat the particles in such a way the morphology of the particles is masked.

Keywords Biostabilization · Gas domes · Halite · Microbial mats · Siwa Oasis

Introduction

The growing interest of microbial mats in siliciclastic sediments was stoked by a rising awareness that microbes play a vital role in their accretion and diagenesis (Krumbein et al. 1994; Hagadorn et al. 1999; Riding and Awramik 2000; Schieber et al. 2007; Hagadorn and McDowell 2012). The importance of microbial biomass for biogeochemical cycles throughout Earth history has been discussed by Madigan and Martinko (2006) and Falkowski et al. (2008). The dominant microbial mat builders are cyanobacteria. Cyanobacteria are readily adaptable and thus comprise the most successful mat-builders within clastic sedimentary realms; essentially, they are able to grow on any moist clastic sedimentary surface where their nutritional and energy requirements are met, within settings where metazoan grazers and burrowers are either absent or ineffective (Schieber et al. 2007).

Microbial mats occurring in siliciclastic environments produce distinctive and particular sedimentary structures, named microbially induced sedimentary structures (MISS) arising from the biotic-physical interaction of microbial mats with the sedimentary dynamics of aquatic environments (Gerdes et al. 2000; Noffke et al. 2003; Noffke 2010). Systematic studies of modern and older deposits revealed that MISS occurs in tidal flat and shelf environment. The morphologies and paleoenvironmental distribution of such structures record the former presence of photoautotrophic microbial mats (Schieber 1998; Noffke 2007, 2010; Wehrmann et al. 2012). They appear not to have changed identifiably since at least 3.2 Ga (Noffke et al. 2002; Eriksson et al. 2004, 2012; Calner and Eriksson 2012; Gamper et al. 2012).

In many tidal flats, benthic phototrophic microbes are involved in biofilm production and cyanobacteria play a major role (Decho 1990). Many studies comprising both field and laboratory analysis have already considered the biostabilization processes in sandy and silty sediments due to the presence of biofilms (Grant 1988; Taher 1996; Noffke 1998; Noffke and Krumbein 1999; Friend et al. 2008; Cuadrado et al. 2011; Hagadorn and McDowell

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2012). A biofilm can be regarded as microbially stabilized water (Krumbein 1993). Biofilms bind grains, decrease the availability of material for resuspension, decrease bed roughness and have a direct effect on the size and migration of bedforms such as ripples (Westall and Rince 1994; Noffke et al. 2002; Schieber 2004; Noffke 2007, 2010). In this respect, biostabilization processes are not only vital for understanding the biotic-physical interactions that occur in modern tidal flats but are also critical for the reinterpretation of their fossil counterparts.

The main objective of this paper is to discuss the occurrence of MISS and biostabilization processes observed within Recent siliciclastic sediments of Lake Aghormi in the northwestern desert of Egypt.

Study area

The Siwa Oasis, the most distant Egyptian oasis from the Nile Valley, forms a structural depression that is situated 120 km east of the Libyan border and 300 km south of the Mediterranean coast between longitudes 25°05′ and 26°18′ E and latitudes 29°05′ and 29°24′ N (Fig. 1). The oasis extends in an east–west direction and is 23 m below sea level. It has an internal area of about 1,018 km^2 (Hammad et al. 2000). The oasis surface has an overflow of about 146 springs and more than 1,000 wells that all are naturally flowing.

The surrounding geology is characterized by horizontal layers of porous limestones alternating with marls and clays of Miocene age. The marl and limestone layers can reach a thickness of several meters, while clay layers for the most part are no more than 10 cm thick (Gindy and El Askar 1969).

The expansion of Lake Aghormi with its surrounding sediments is around 80 km^2. It is essentially fed by historical and recent springs. The recent spring orifices are located within the lake and are observed as active water and gas bubbles. The lake extends from west to east and its water level is 20 m below sea level (Fig. 1).

Siwa Oasis is characterized by a desert climate. It has mild winters and hot summers. The average daily temperature ranges between 10.6 °C in January and 28.8 °C in July. The daily evaporation varies between 4.32 and 13.54 mm. The annual rainfall amounts to 10.43 mm and the maximum rainfall in 1 day was 28 mm (Cassandra 2000).

Materials and methods

Lake Aghormi is one of the saline lakes of the Siwa Oasis with luxuriant microbial mats and biofilm-forming assemblages. Selection was based on mat development and accessibility. Samples of the microbial surface were collected by inverting a Petri dish and pressing it into the mat. The dish was then removed, and the shallow mat core carefully lifted and placed right-side-up in the Petri dish. The samples were studied and investigated as follows:

(a) Scanning electron microscopy (SEM)

All samples were investigated under the binocular microscope and 11 were placed in small glass tubes (diameter 0.5 cm) fixed immediately in 4 % glutaraldehyde solution diluted with water from the sampling site. This treatment prevents osmotic shock and artifacts. The water was then removed in an ethanol series from 10 to 95 % followed by two passages through absolute ethanol. The

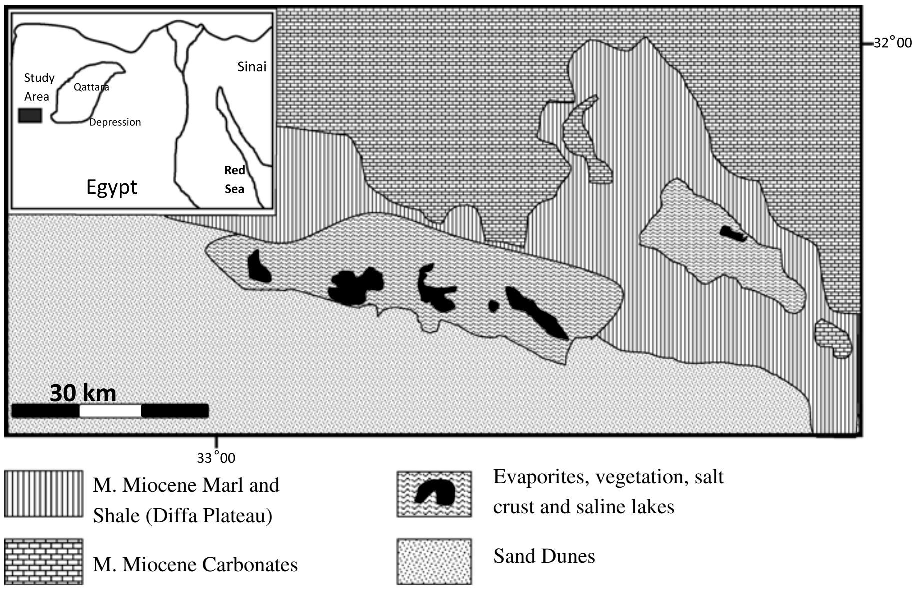

Fig. 1 Geologic map of Siwa area, Egypt

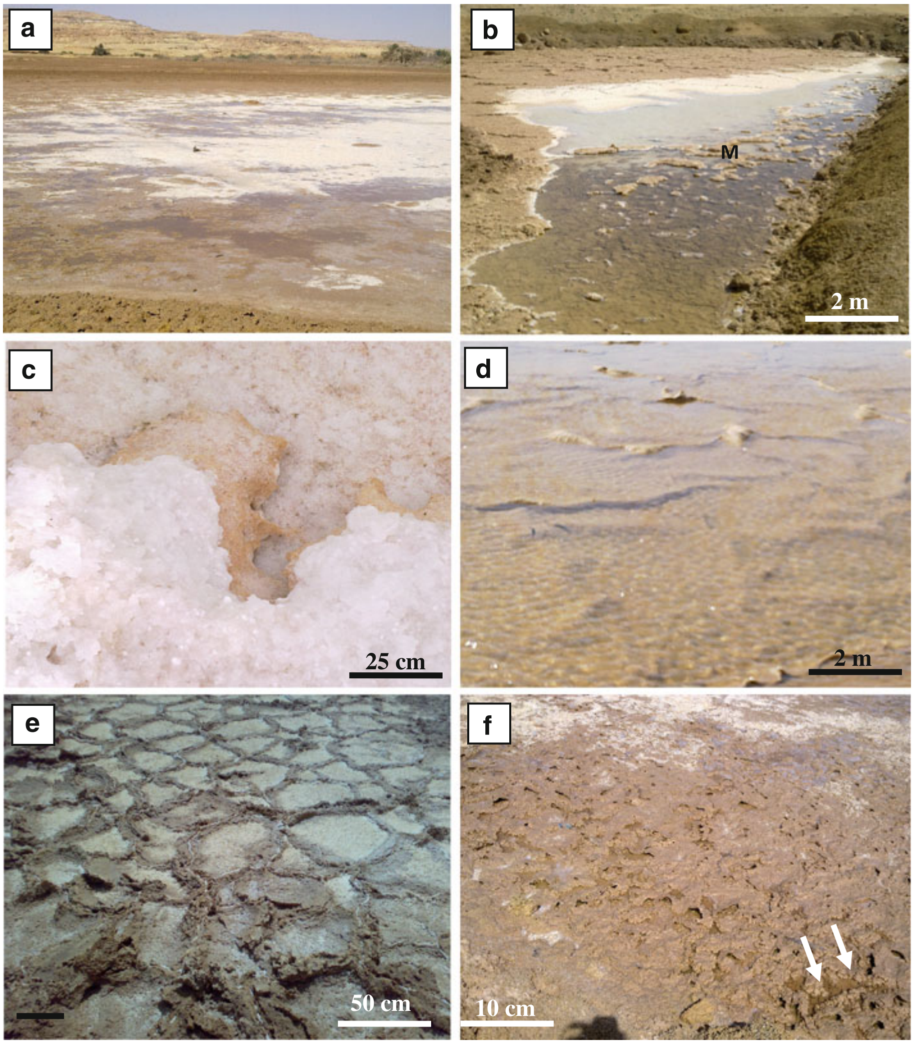

Fig. 2 Field photographs of the geomorphological units of Lake Aghormi, Siwa Oasis. **a** Hill slopes with about 20° inclination. The sandy mud flats extend from the base of the hill slope to the lake shore. The sediments are *greyish brown* and form hummocks bordering the lake. **b** Shallow ephemeral saline pool with hard surficial halite layers and isolated patches of microbial mats (*M*). **c** Close-up view of floating crusts of euhedral halite crystals. **d** Multidirected ripple marks with microbial mats reflecting a set of subsequent storms each forming a generation of ripple marks. **e** Petee structure with a distinctive polygonal pattern. **f** Erosional remnants and pockets form a characteristic morphology of elevated and depressed areas. Notice the halite precipitation inside the erosion pockets. Gas domes (*arrows*) with rounded opening are also seen

samples were then critical-point dried, gold-sputtered, and studied under the SEM Jeol JSM 35 CF, Tokyo.

(b) Parahistological sediment petrography

Seven samples were selected for petrographic examination. The technique used is that of Walting (1988) and its modification by Wachendörfer et al. (1994), which combines histological methods for fixation and dehydration with petrological methods for embedding undisturbed samples of siliciclastic sediment to maintain the microorganisms and organic matrices.

Results

Geomorphology of Lake Aghormi

The field investigation showed that Lake Aghormi could be subdivided from geomorphological point of view into genetically related depositional subenvironments as follows:

Hill slopes

The lake is bordered by a sandy mud flat that passes laterally into grassy hill slopes less than 2 m high with an inclination of around 20°. Where slopes are gentler, there is a transition from lake marginal flats through to grassy slopes (Fig. 2a). These hill slopes are sites of erosion rather than sedimentation, and mostly show little evidence of dissection. Micro-channels are filled with gravel, sand, and finer sediments, together with plant debris, rhizoliths are transported into the adjacent sandy mud flat. The sediments are generally trapped by rhizofilaments and rhizocretion.

Sandy mud flats

Sandy mud flats occur as a distinct minor transitional subenvironment and commonly extend from the base of the hill slope to the lake shore (Fig. 2a). The width of this subenvironment is up to 2 m and delineates the hill slope. The sediments of the sandy mud flat are predominantly siliciclastic. Texturally, they are variable, but wt % of silt and mud is more than 75. The sediments are greyish brown at the surface, and darkening with depth. These deposits in parts form hummocks bordering the lake and partly form undulating sheets of silt landwards (Fig. 2a). Field observation revealed the presence of polygonally cracked, weakly laminated medium- to fine-grained sand, silt, and mud.

Ephemeral saline pools

These pools occupy irregular depressions along the shore of the perennial Aghormi saline lake. They dry up periodically leaving a low central area of exposed salt dolines and depressions up to 6 m in width and 0.5 m in depth (Fig. 2b). Due to the climatic setting, several ephemeral pools precipitate halite during summer months, producing hard surficial duricrusts up to 10 cm thick. The larger pools are composite and contain several smaller pools. Within the pools, an ephemeral layer of clear halite crystallizes annually by evaporative concentration in summer. Permanent salt layers, usually more than 2 cm thick, are observed. Brownish grey inclusion-rich halite forms a loose collection at the base of some pools and penetrates interstitially into the underlying mud.

Small, isolated patches of microbial mats are common around spring and early summer. Locally, desiccated microbial mats and salt crusts are commonly broken into small porous polygons as a result of dewatering and drying. Pink and orange strandlines of *Artemia* eggs and pupae of the brine fly *Ephydra* are common both on and within the salt crusts of the lake. White ephemeral efflorescent crusts up to 5 cm thick occur at the surface, usually growing between April and August. Such surficial efflorescent crusts are composed predominantly of halite and more soluble polyhalite.

Perennial saline lake (Lake Aghormi)

The lake extends along the deepest part of the oasis in an axial position deviated towards the eastern side (Fig. 1). The depth varies between 20 and 18 m below sea level. During the winter season, when several bodies of water form one single lake, the lake attains its maximum surface area. Spring water flows into the lake and since the basin is closed and evaporation is high, water levels and salinity fluctuate seasonally, the lake being much smaller in summer. At that time, the lake is subdivided into a group of smaller remnants. Variable windblown barriers of sand, common in the Western Desert of Egypt, also influence the subdivision of the lake to some extent.

Evaporite minerals predominate in the lake. Halite is the main mineral, gypsum and polyhalite being subordinate. Halite consists of crystals that precipitate at the air–water interface and sink to the bottom of the brine, forming a crust. They are typically represented by thin plates of euhedral crystals that commonly aggregate into floating crusts (Fig. 2c). The crystal aggregates float on the brine interface held by surface tension until they are large and sink. The evaporate minerals accumulate and coalesce on the lake bottom as a layer of loosely packed crystals. The crusts form as early diagenetic overgrowths on these layers. Small biscuits may result from crystal growth at local nucleation centers (Warren 1985).

Microbial mats grow to a considerable thickness at the margin of the lake. Field observations revealed the presence of laminated mats; the dominating micro-organisms are cyanobacteria at the top followed by colorless and purple sulfur bacteria and sulphate-reducing bacteria.

The lake exhibits many features such as multidirected ripple marks, petee structures, gas domes, and erosional remnants and pockets. The ripple systems are produced during the commonly wind-reinforced seasons and form along the shallow margin of the lake. They formed extensively during the spring months when growth conditions of cyanobacteria are optimal. Smooth microbial patches alternate with the ripple system (Fig. 2d). The mat surface is slippery and slimy due to secretion of extracellular polymeric substances (EPS). During late summer, when the mat dies, it tends to break apart into saucer-like petee structures (Fig. 2e). The petees are thin crusts with small, mostly <10 cm high surface relief and develop into a distinctive pattern of polygonal ridges in plane view. The diameter of the polygons usually ranges from 20 to 50 cm and the relief is directly related to the ground-water level; the deeper the water table, the higher the relief of the petee structure is. Polygonal structures of much higher relief (>50 cm), characterized by the absence of microbial mats, occupy the outermost flanks of the lake.

Erosional remnants and pockets contour the margins of Lake Aghormi. They form at shallow water depths not exceeding 5 cm and spread over several square meters. Erosional remnants are laminated, left over from the destruction of the former biostabilized surface layer. They have a characteristic elevated topographic relief, 2–3 cm high, and form irregular-shaped crinkled surfaces (Fig. 2f). Erosion pockets were found to be rounded depressions with soft margins. Their depths vary between 1 and 3 cm. In summer, due to high temperature and high rate of evaporation, a thin veneer of halite can be observed crystallizing and filling such pockets.

Gas domes occur around the erosion pockets (Fig. 2f). They form due to gas accumulation below the mat. The surface of the gas domes may be closed or occasionally has rounded openings where the gas escaped.

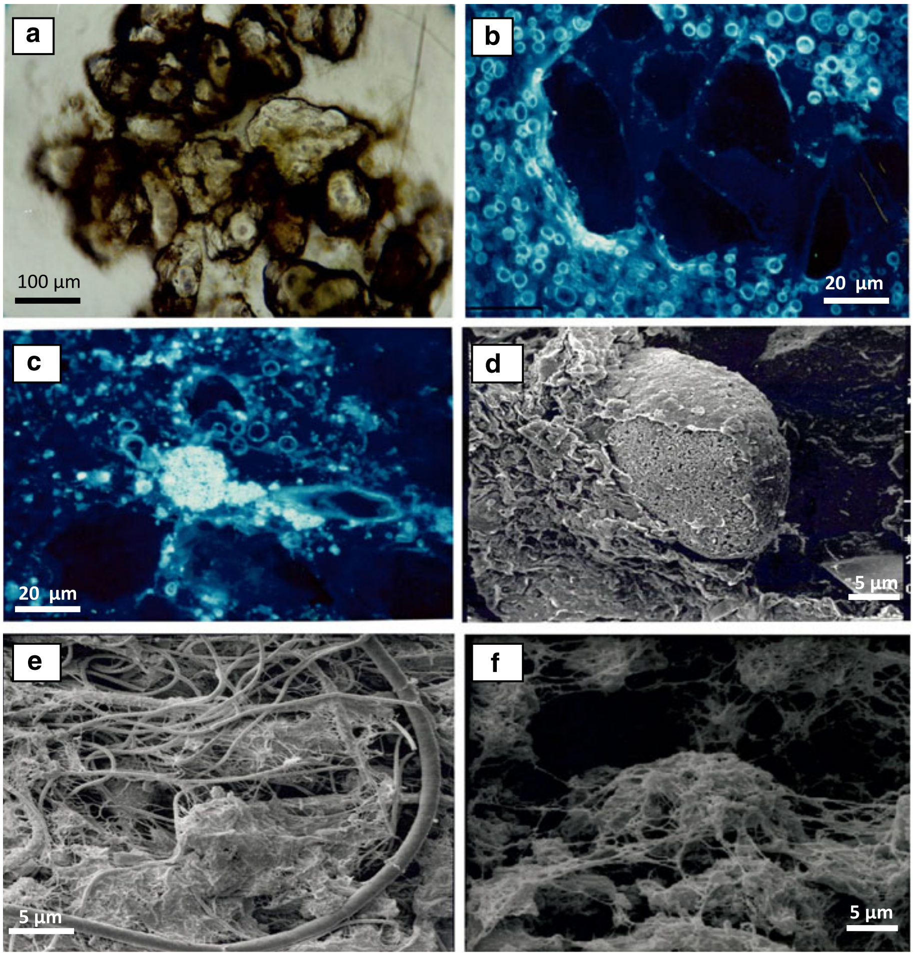

Fig. 3 Parahistology and SEM photomicrographs of stabilized sediments. **a** Particulate organic matter associated with the sand grains. The organic matter occurs both between the grains and more closely attached to grains producing their irregular outlines. **b** Colonies of coccoid cyanobacteria attached to sand grains. **c** Densely settled pore cavity with numerous large cocci and short filamentous cyanobacteria with their EPS. **d** Encrusted layer of organic materials coating the whole sand grain and showing strong cohesive bonds to the grain. **e** Filamentous cyanobacteria and its EPS constructing a network and enveloping the sand grains. **f** Thick biofilm-forming spider web structure that fixes and stabilizes the sand grains. The morphology of the underlying particles is completely masked

In some parts around the lake, irregular patches of oxidized organic material with reddish brown color are observed.

Biostabilization of sediments

A characteristic area at the margin of the perennial saline lake with abundant microbial mat growth was chosen to investigate the biostabilization process. No sign of surface bioturbation was observed. Qualitative microscopical examination of sediments from the upper 2 cm of the study area showed substantial differences in the distribution of organic matter, which is represented by a distinct layer of fine organic mineral aggregates always attached to grains of sediment (Fig. 3a). The observed fine organic material is not uniform in density where the grains show higher relief. Occasionally, autofluorescence showed that these higher density areas are occupied by EPS, cyanobacteria, and detrital mineral aggregates that deposited from the water column (Fig. 3b, c). When the sediment is disrupted, the organic matter remains attached to the grains, resulting in an "encrusted" grain. There is some evidence from SEM study of representative samples that encrusted grains possess a layer of material with stronger cohesive bonds to the grain than to the surrounding matrix (Fig. 3d). Clean grains are probably those without such microbial attachment and, when the sediment is disrupted, therefore become separated from the matrix.

Microbial mat assemblages are capable of effective stabilization of suitable substrate. An SEM study of the sediment surface colonized by cyanobacteria revealed that filamentous types were the most effective stabilizing organisms. Filamentous cyanobacteria construct a network and interweave depositional grains of the sediment surface. Additionally, their EPS excretion envelopes the particles and glues them together (Fig. 3e). In some parts of the same surface, the biofilm is such a thick spider-web structure that the morphology of the underlying particles is completely masked (Fig. 3f). By this mechanism the depositional surface is stabilized and protected against erosion.

Discussion

Lake Aghormi is one of only a few hypersaline ecosystems in the Western Desert of Egypt. It exhibits characteristic geomorphologic units consisting of hill slopes, sandy mud flats, ephemeral saline pools, and perennial saline lake.

The most common evaporite mineral recorded in Lake Aghormi is halite. Subordinate amounts of gypsum and polyhalite could also be observed. Halite concentrations in form of coalesced rafts are restricted to extremely shallow areas. Handford (1990) and Schreiber and El Tabakh (2000) mentioned that floating halite concentrations can form at the surface or within brines of any depth, but their accumulation and preservation as abundant coalesced rafts in relatively deep water is unlikely. The floating crystals would be disrupted by waves and sink to the bottom where they would accumulate as sub-millimetric cubic crystals leaving little or no evidence of their origin as larger structures. Lowenstein et al. (1989) documented the presence of sub-millimetric halite crystals in laminated halite rocks from the Miocene (Messinian) evaporites of the Mediterranean Basin and suggested that they represent mechanical accumulations of cubes that precipitated in the water column and settled to the bottom of a possibly deep brine body. The rarity of coalesced rafts in these deposits may argue for a comparatively deep water origin.

Microbial mats grow extensively at the margin of Lake Aghormi. The most common microbial mats are those produced by cyanobacteria. Cyanobacteria are unique micro-organisms as they are well adapted to peritidal conditions. MISS were recorded at the lake margin. These are ripple systems and microbial patches, gas domes, and erosional remnants and pockets.

Multidirected ripple marks are characteristic features of sabkha deposits. Noffke (1998) recorded similar ripples in the upper intertidal to lower supratidal zones of Mellum Island, northern Germany. She attributed their origin to storms or wind-reinforced spring high tides. Stabilization of such ripple systems by cyanobacteria prevented the ripples from being destroyed by later reworking events, the final chaotic ripple systems resulting from the interplay between steadily increasing microbial mat development in the course of the summer and episodic disturbance of the sediment during reworking events (Noffke 1998). Smooth microbial patches were observed alternating with the ripple systems. These microbial patches reflect the immobilization of the surface sediments (Gerdes et al. 2000).

Erosional remnants and pockets are another example of MISS (Noffke et al. 2001). Erosional remnants are elevated surfaces covered with mats, which therefore resisted erosion or reworking. Erosion pockets are depressed areas, where sand is exposed and eroded into the former mat-secured surface. Erosion pockets act as windows to explore the underlying sediments, which commonly display a rippled surface (Noffke 1998; Cuadrado et al. 2011). In Lake Aghormi, halite is always seen precipitating inside such pockets (Fig. 2f), which could serve as conduits for light and could help preserving the original morphology of the mat.

After death of the mat, decay begins; decomposition gases dislocate the sediment beneath the mats and also disturb the mats themselves, forming gas domes. The gases have different origins, being commonly derived from organic matter decay, activity of photosynthetic microbes, and/or from the gases present within intergranular spaces during sedimentation trapped below the impermeable mat layer (Bose and Chafetz 2009; Cuadrado et al. 2011). The mat is rich in EPS which, prohibits any gas exchange between the underlying deposits and water or atmosphere (Noffke et al. 2001). Noffke et al. (2001) have shown that the preservation potential of such structures within sand is quite low because no early cementation or rapid infilling of the domes by evaporite crystals takes place.

According to SEM observations, thick microbial mats protected the substrate, because they are coated in a biofilm of EPS able to protect the community from exposure to solar radiation and desiccation during the dry season. Filamentous cyanobacteria were found to be the most effective stabilizing mechanism. The evolution of a filamentous growth habit may also have been important to enhance the potential for stable biofilm formation (Paterson et al. 2008). The production of extra-cellular organic substances plays a vital role in the stabilization of biofilm and microbial mats. EPS is often cited as one of the major mechanisms of biogenic stabilization (Paterson and Black 2000). The capacity of EPS to stabilize sediments has been widely demonstrated in laboratory and field studies (Grant and Gust 1987; Dade et al. 1990; Neu 1994; Taher 1996; Noffke and Krumbein 1999; Gerdes et al. 2000; Cuadrado et al. 2011). Noffke et al. (2001) have shown that cyanobacteria stabilize their substrate in three different ways: (a) fixation of the friable grains by the mat fabrics (Fig. 3f), (b) smoothing of the formerly rough sediment surface by EPS of the microbes (Fig. 3f), and (c) sealing of the sediment by a microbial mat thereby trapping intrasedimentary gases (Fig. 2f).

Microbial stabilization of sediments increases stability against erosion. Taher (1996) studied experimentally the biostabilization of sediments in salina area along the Mediterranean coast of Egypt and showed that the stability of sandy sediments inhabited by microbial mats and biofilms was significantly higher than sand without mat. In some areas, the mat was not eroded using the highest possible pressure of 150 kPa. Cady and Noffke (2009) have shown that microbial binding of sand-sized siliciclastic sediment on intertidal flats may increase erosional resistance by as much as 100–1,600 %.

The binding and stabilizing of sediments by microbial mats and biofilms is vital for the formation and persistence of ancient stromatolites. The initial biogenic stabilization of depositional systems may be an essential requirement to allow or enhance future lithification of the sediments (Paterson et al. 2008). It is well known that bacteria are rarely preserved in lithified microbial mats but authigenic precipitation of minerals within the mat environment due to microbial metabolism and fossilization of the EPS itself does take place (Gerdes and Krumbein 1987). Preservation of EPS and biofilms depends on their rapid lithification before degradation. Lithification of microbial mats, even partial lithification, will greatly improve their stabilization and preservation potential (Chafez 1994; Gerdes et al. 1994).

The fingerprint of life in ancient evaporites with microbial mats has been documented by many authors. Goodall et al. (2000) studied the Lower Triassic Ormskirk Sandstone Formation of the Irish Sea Basin and found thin laminae with halite reflecting the micromorphology of biogenic mats common in ephemeral pools. After these pools dried out and the mats decomposed, the surface usually became encrusted with efflorescent halite, which preserved the original morphology of the mat. Barbieria et al. (2006) studied the Upper Pleistocene evaporite deposits of a wide continental sabkha in southern Tunisia and found that biosignatures are mostly contained in gypsum lithofacies that have precipitated from high salt-concentrated waters. These biosignatures include mineralized microbial-interpreted morphologies, such as mucilage, rods, and microfibers.

Conclusions

The buildup of microbial mats and biofilms in the study area was found to be highly variable. The area is characterized by a low sedimentation rate, little wave action, lack of bioturbation, and is protected by vegetated patches of sea grasses, which results in an optimal development of microbial mats and biofilms. It was difficult to recognize distinct seasonal trends, although generally coccoid and filamentous assemblages were more abundant in the warmer months. Coccoid cyanobacteria grew on the surface of sand grains, occasionally filling the pore space between them to some degree. The EPS produced by these organisms did not generate a surface stability comparable to that produced by filamentous cyanobacteria.

The microbial mats of Lake Aghormi produce distinctive sedimentary structures such as multidirected ripple marks, microbial patches, erosional remnants and pockets, and gas domes. The erosion pockets were found to be filled with halite. Filamentous cyanobacteria and their EPS construct a network, interweave depositional grains of the sediment surface, envelope particles and glue them together. The studied biofilms are dense and form spiderweb structures, whereas the morphology of the associated sand particles is masked.

The climate of Siwa is hot and dry almost all the year and solar radiation is intensive, favoring the deposition of halite, which serves as a good conduit for light, reduces the effect of intensive harmful solar radiation, and provides protection from high cosmic radiation, which allow microbial mats to survive and flourish (Kminek et al. 2003; Noffke et al. 2003).

The stability of coastal sediments, which is improved by biogenic binding of sediment particles, is potentially increased by biofilms and mat forming communities of variable composition. Microbes were found to bind and stabilize sediments through cohesive effects, EPS secretion, and network formation. Mats and biofilms seem to be more readily preserved in the geological record than their producers.

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