Evaporite Microbial Sediments

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Abstract. Signatures of microbial life in shallow evaporite systems are discussed using examples from modern coastal hypersaline settings. Organisms contributing to microbial sediments are assigned to moderate halophiles (e.g. cyanobacteria, other phototrophic bacteria, diatoms, non-phototrophic eubacteria) and extremely halophilic taxa (e.g. green algae and halobacteria). Primary production creates the organic base upon which biogeochemical cycles are based that produce a variety of authigenic minerals found in deposits of hypersaline settings. Characteristic microbial sediments include stromatolitic laminae, biolaminoid facies and sedimentary augen structures. Communities dominated by stenotopic major taxa often contribute with less unambiguous laminated structures, e.g. flocculent organics, to the sedimentary record. Based on the criteria of brine depth and salinity, a biofacies classification of marine-derived microbial sediments is proposed.

1
Introduction

Evaporite microbial sediments are depositional records of microbial life in the presence of salt. These sediments occur in systems at different depths in which evaporites accumulate either within sediments, on the bottom of shallow bodies of brines, or due to pelagic crystal rains. Similarly, organics interlayered with evaporites either may originate from the pelagic rain of plankton blooms, or from benthic in situ formation of biomass.

Whereas in deeper evaporite basins benthic autotrophic processes may be due to colorless sulfur bacteria and ammonia oxidizers (Javor 1989), basin-margin evaporite systems are characterized worldwide by the abundance of photoautotrophic species. Mainly benthic cyanobacteria are producers of the organic substrate which supports the succession of numerous other microbes and metabolic pathways. Benthic cyanobacteria contribute to layered accretions of microbial biomass termed microbial mats. In the light of studies on modern hypersaline microbial mats, it is assumed that stromatolites were produced by similar diverse ecosystems.

Modern microbial systems of shallow surface brines provide ecologic models for the biomineralization capacity of analogous ancient systems, but nowadays do not have the extent shown by the evaporites of ancient epeiric seas. Under brine depths of a few meters or even less, evaporites in association with microbial mats have covered areas over hundreds of thousands of square kilometers (Decima et al. 1988). Such habitats concentrate organic matter that provides the base for biogeochemical cycles that have played a role in the formation of stratiform ore deposits (Brongersma-Sanders 1992). Sulfide-enriched microbial mats in contact with metal-enriched brines favor the accumulation of metal-sulfide complexes. When buried, the polymer-enriched mats act as permeability barriers that reduce brine migration and thus favor the contact of metal-bearing brines with organics produced and concentrated via microbial primary production. A well-known metalliferous deposit associated with significant amounts of organics is the Zechstein Kupferschiefer (Renfro 1974). Other metals associated with evaporite microbial sediments are gold (Dyer et al. 1994), lead, zinc and cobalt. A thorough discussion has been given by Javor (1989).

Microbial mats and related forms create and diversify the structural phenomena of evaporite sediments. The purpose of this chapter is to: (1) document characteristic depositional signatures of microbial life in shallow evaporite systems using examples from coastal hypersaline settings, and (2) introduce a biofacies classification that emphasizes the ecologic role of brine depth and salinity.

2
Heterogeneity of Coastal Evaporite Environments

Hypersaline settings favoring evaporite microbial sediments can be classified using the parameters listed in Table 1. The composition of athalassic (continental) brines is usually more variable than that of thalassic (marine-derived) saline waters. Various coastal evaporite settings take an intermediate position in as much as they receive water from both the sea and continental run-off. Microbial mats which thrive luxuriously in coastal evaporite settings are thus in contact with a great variety of dissolved ions from continental and marine sources.

The variation in environmental conditions in shallow evaporite settings is also a function of brine depth. This ranges from intrasedimentary brine tables (referred to as sabkhas) to several meters of surface brines (Table 1; Fig. 1).

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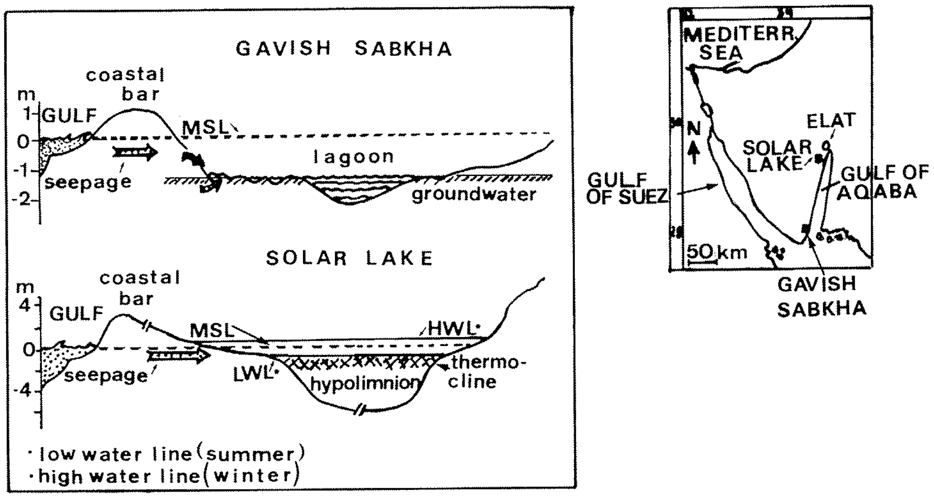


Fig. 1. Schematic cross-sections of the Gavish Sabkha (*top*) and Solar Lake (*bottom*), on the western shore of the Gulf of Aqaba, Sinai. Both are anchialine-type basin-marginal evaporite systems: depressions below sea-level closed by permeable bars, and constantly fed by seepage seawater. Both contain shallow littoral zones and deeper parts constantly filled with brine. Sabkha Gavish lagoon is 30–60 cm deep; Solar Lake basin is up to 6 m deep, and density-stratified during most of the year. (Modified after Gerdes and Krumbein 1987)

Table 1. Types of evaporite settings in which microbial sediments form

Continental vs marine evaporite settings (geographical terms)	
Continental	Focus of internal drainage, subterranean aquifers and/or streams, springs and surface run-off (Friedman 1980)
Marine	Fed by seawater (coastal settings often also by ephemeral streams and sheet floods from adjacent mountains)
Athalassic vs thalassic saline waters (brine composition)	
Athalassic:	Systems receive water from continental sources (see above)
Thalassic:	Systems fed by seawater
Shallow vs deep evaporite systems (bathymetric view)	
Intrasedimentary brines	Sabkhas (saline/dry mud flats)
Ephemeral surface brines	Ephemeral playas, salt pans
Perennial surface brines	
0.01 - 0.1 m	Shallow rims of lagoons
0.1 - 1 m	Peritidal lagoons, anchialine pools (e.g. Gavish Sabkha lagoon, 0.60 m)
1 - 10 m	Deeper anchialine pools (e.g., Solar Lake, Sinai, 6 m)
10 - 100 m	Playa lakes (e.g., Great Salt Lake, Utah, 10 - 12 m
> 100 m	*Salt lakes (e.g., Dead Sea, 340 m); deep sea brines (Javor 1989)
Stratified vs non-stratified systems	
Stratified:	Most perennial surface brines more than a few meters deep
Non-stratified:	Shallow surface brines (water-mixing due to wind drift or imbalance between rates of evaporation and influx)
Plankton- vs benthos-dominated evaporite habitats	
Plankton dominance	Possible factors: greater basin depth, higher nutrient (phosphate) concentrations, competition (planktonic forms compete best for environmental resources), extreme salinity
Benthos dominance:	Possible factors: shallowness, ephemeral surface brines, benthic forms compete best under conditions of broader ranges of environmental factors (salinity and others)

2.1
Sabkhas

The Arabic word "sabkha" means a salt enriched flat (Kinsman 1969). Friedman et al. (1992) defined sabkhas as surfaces of deflation formed by the removal of dry, loose particles down to the top of the capillary water zone (For discussions of sabkha variation see Purser 1985 and Kendall 1992). In this chapter, the term sabkha refers to settings of subsurface groundwater. Because biofilms and mats are able to develop even at the lowest moisture levels, sedimentary surface layers wetted by capillary water are still ecologically important.

2.2
Shallow Surface Brines

Settings characterized by shallow surface brines are referred to as salinas, playas, hypersaline peritidal lagoons and "anchialine pools". Anchialine pools (Por 1985) are bodies of water within depressions below sea level closed by emergent reefs or porous bars and constantly fed by seepage seawater. Solar salt works are man-made anchialine pools controlled by dykes and flood gates. The Gavish Sabkha (Gulf of Aqaba) contains a natural anchialine pool (Fig. 1A). This area includes a variety of different facies (dry and moist saline flats, ephemeral and perennial surface brines, metahaline, moderate- and extremely-hypersaline water bodies). Such systems are traps of salts and nutrients which are concentrated to extraordinarily high values. They provide important models for understanding stromatolite diversification and biogeochemical cycles (Javor 1989; Cornée et al. 1992).

2.3.
Stratified Surface Brines

Shallow surface brines are rarely density- or temperature-stratified since wind drift or the imbalance between rates of evaporation and influx cause short-term water mixing. On the other hand, perennial surface brines more than a few meters deep usually establish a stratification with denser brines at the bottom. Effects of stratification on the distribution of evaporites are considered by Kendall (1992). Solar Lake (Gulf of Aqaba) shows that stratification also has consequences for the composition of microbial communities. This marine-fed lake, up to 6 m deep, is density stratified during most of the year (Fig. 1B). The hypolimnion is anaerobic, hypersaline up to 180% TDS, and the temperature of the bottom brine can reach 65 °C. The complex, seasonally controlled hydrologic system of the lake causes mixing of the water body between July and September (Cohen et al. 1977). The shallow shelf of the lake is covered by microbial mats dominated mainly by eurytopic cyanobacteria (Fig. 2). In contrast, the anoxic hypolimnion reveals a clear dominance of soft flocculent fabrics composed of halophilic cyanobacteria (*Oscillatoria limnetica, Aphanothece halophytica*). Sulfur-dependent anoxy-photobacteria and anaerobic bacteria increase in number (Krumbein et al. 1977).

3
Major Groups Contributing to Microbial Sediments

At the level of primary production, hypersaline settings are dominantly characterized by few, but highly pro-

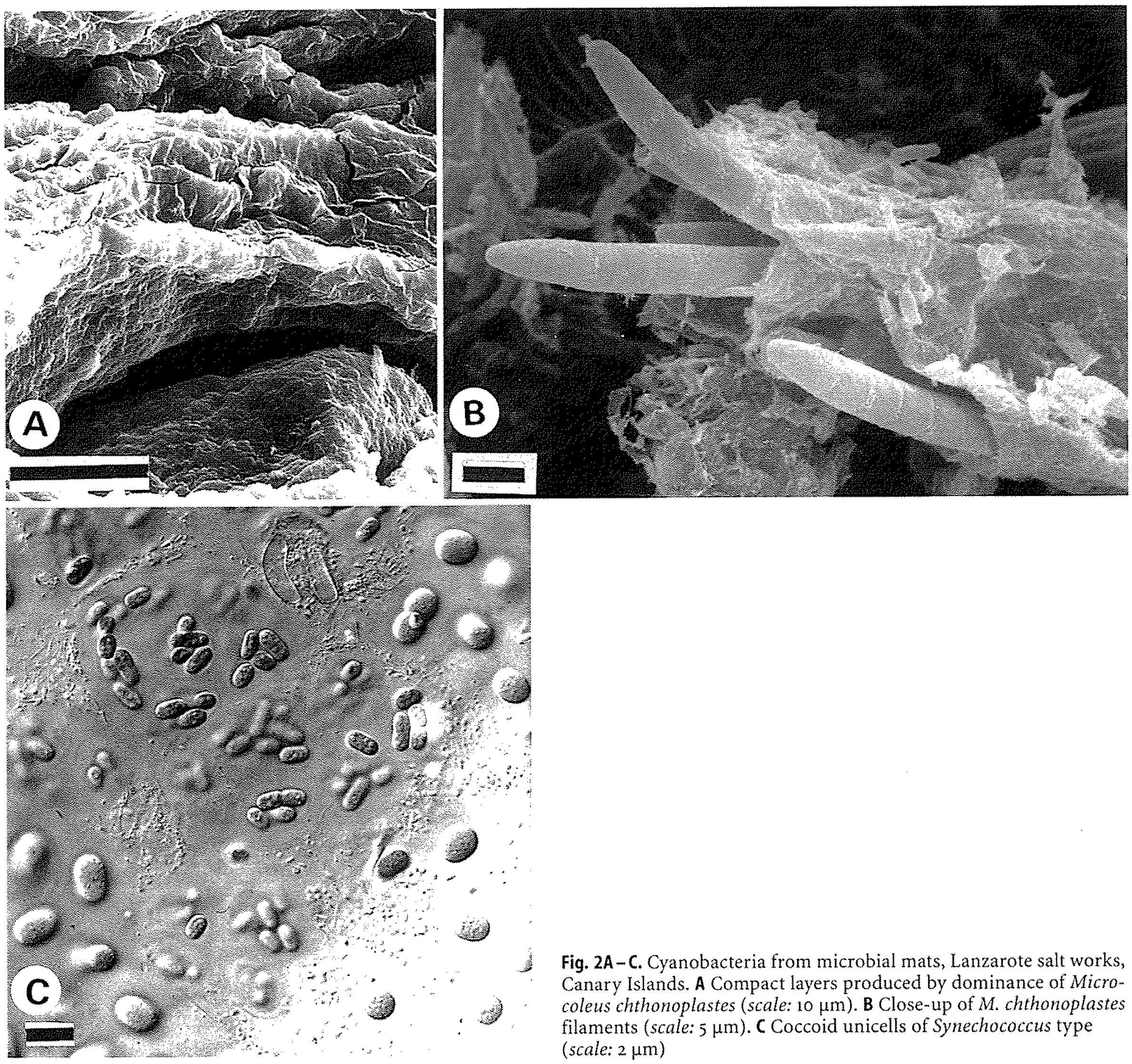


Fig. 2A–C. Cyanobacteria from microbial mats, Lanzarote salt works, Canary Islands. **A** Compact layers produced by dominance of *Microcoleus chthonoplastes* (*scale:* 10 µm). **B** Close-up of *M. chthonoplastes* filaments (*scale:* 5 µm). **C** Coccoid unicells of *Synechococcus* type (*scale:* 2 µm) ductive, major groups. Among these are cyanobacteria, other phototrophic bacteria, diatoms and halophilic green algae.

Sabkhas and shallow brine bodies exhibit high levels of environmental variability. In such settings, microbial mats formed by benthic eurytopic cyanobacteria make the greatest contribution to sediments and sedimentary structures. Several of these systems exhibit regular recurrence of the species *Microcoleus chthonoplastes, Lyngbya* sp., *Entophysalis* sp. and *Synechococcus* sp. (Fig. 2). These mat-forming taxa are embedded in matrices of extracellular polymeric substances (EPS) which hold large amounts of water and thus serve as a protective mechanism against the osmotic stress that is particularly high in shallow surface brines. The EPS also buffers extreme temperatures and light intensity.

Distributional limits of mat-forming eurytopic cyanobacteria appear to correlate with a complex interaction of factors, rather than with a single factor such as salinity (Fig. 3). In the extremely shallow surface brines of the Gavish Sabkha, cyanobacteria-dominated microbial mats occur in almost all salinity ranges, beginning at the metahaline fringe (4–7%) and ending almost at the level of potash salts (>30%). In other hypersaline settings, perhaps only a few decimeters deeper, salinities just above the saturation value of gypsum (14–16%) limit the distribution of mats. Another aspect that probably controls mat-forming cyanobacteria is nutrient supply. Studies of solar salterns show that phosphate availability is a determinant of plankton dominance rather than benthic microbial mat development. Plankton dominance additionally has a shading effect on the benthic community development (Javor 1989).

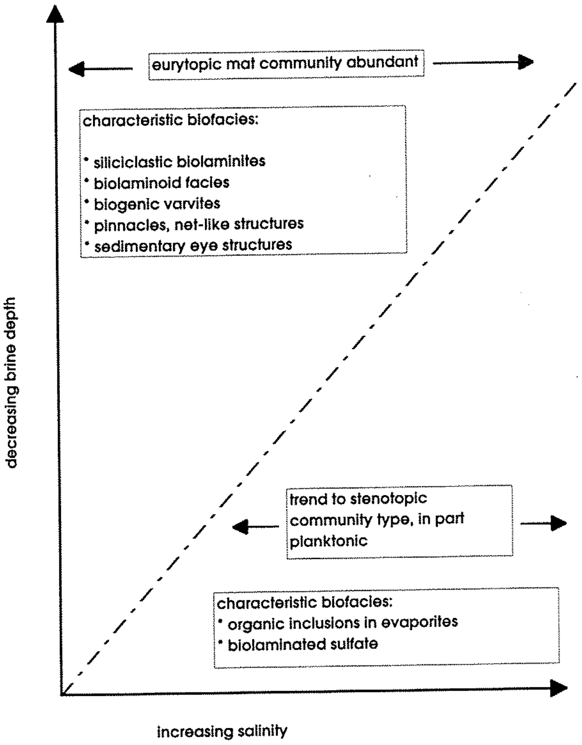


Fig. 3. Distribution model of major groups contributing to microbial sediments in evaporite settings, in relation to salinity and brine depth. Although both factors are not necessarily correlated, both control the local abundances of major microbial taxa and, thus, biofacies. Local decrease of brine depth usually correlates with broader environmental fluctuations that select for increased abundance of eurytopic major taxa that produce characteristic biogenic fabrics (summarized as biofacies characteristics). The shallower the setting, the less the eurytopic community type is limited by increasing salinity. Both increasing depth and extreme salinities select for increasing abundance of specialists (stenotopic taxa) only tolerating narrow ranges of environmental factors

Mats built by the eurytopic species mentioned above are not restricted to thalassic hypersaline environments. Javor (1989, Table 2.1) also reported their distribution in inland lakes and playas. As in the marine realm, true benthic microbial mats are restricted to lake margins. This may correlate with the plankton dominance in these lakes. In the Great Salt Lake, Utah, microbial mats made by filamentous cyanobacteria are restricted to shallow water areas. Javor (1989) refers to several alkaline hypersaline lakes that are nutrient enriched and plankton-dominated.

Increasingly uniform environmental conditions select for the distribution of specialized microbes (Fig. 3). Examples cultured from Solar Lake are *Oscillatoria limnetica, Phormidium* sp. and *Aphanothece halophytica* (Golubic 1980). These species can tolerate only narrower changes in salinity, thus, their distribution is restricted to zones where salinity fluctuations are minimal. In Solar Lake, this is mainly the hypolimnion (Fig. 1B). Mats produced by the halophiles are flocculent and differ considerably from the compact, rubber-like mats built by the eurytopic shallow-water community.

Purple sulfur bacteria (Chromatiaceae, Ectothiorhodaceae), and purple non-sulfur bacteria (Rhodospirillaceae) are well-documented in hypersaline microbial mats. Their enrichment obviously is favored by the gelatinous and fibrillar meshwork of cyanobacteria that acts as a light filter and oxygen protection shield. Extreme halophile phototrophic bacteria of the genus *Ectothiorhodospirillum* are also abundant in continental salt lakes. A detailed review is presented by Imhoff (1988; see also Javor 1989).

Planktonic eukaryotic green algae of the genus *Dunaliella* are abundant and widespread in inland lakes (e.g. the Great Salt Lake and the Dead Sea), in various solar salt ponds, and in the Gavish Sabkha lagoon. Most species are extremely halophilic, maintaining osmotic balance by the production of low molecular organic compounds such as glycerol.

Relatively large numbers of diatom species are abundant in hypersaline environments and contribute to microbial mats, but never appear to dominate the benthic microbial biomass.

Almost ubiquitous in evaporite settings are halophilic archaebacteria and non-phototrophic eubacteria. Halobacteria possess specialized mechanisms to control Na^+Cl^- ion concentrations by the uptake of inorganic compounds such as KCl. This group is particularly abundant in extremely hypersaline brines where cyanobacteria-dominated microbial mats almost disappear. Various physiological groups of non-phototrophic eubacteria join in the evaporite microbial sediments. Their distribution in extremely hypersaline brines has been discussed by Javor (1989). It is assumed that Mg^{2+} intolerance may be an important factor limiting moderate halophile eubacteria in marine-derived strong brines. Moderate halophiles are relatively intolerant of Mg^{2+} and Cl^-, but relatively tolerant of K^+ and SO_4^{2-}. Halobacteria, on the other hand, show an opposite behavior with respect to Mg^{2+}, Cl^- and SO_4^{2-} (Javor 1989).

4
Depositional Records

Biogenic fabrics occurring in evaporite settings occupied by microbial mats are related to (1) species dominance, (2) biomineralization processes, (3) evaporite precipitation, and (4) stress deformation of mat-stabilized sediments.

4.1
Mat Facies Related to Species Dominance

Species diversity is defined as the degree to which different species in a given community are evenly distributed over the total number of individual organisms. In evaporite environments, a numerically even distribution of species does not occur or is rare. Numerical dominance of individual species is more common. The facies relevance of dominant morphotypes (filamentous or coccoid) is emphasized in the next section.

4.1.1
Stacks of L_h-/L_v-Laminae, Biolaminoids

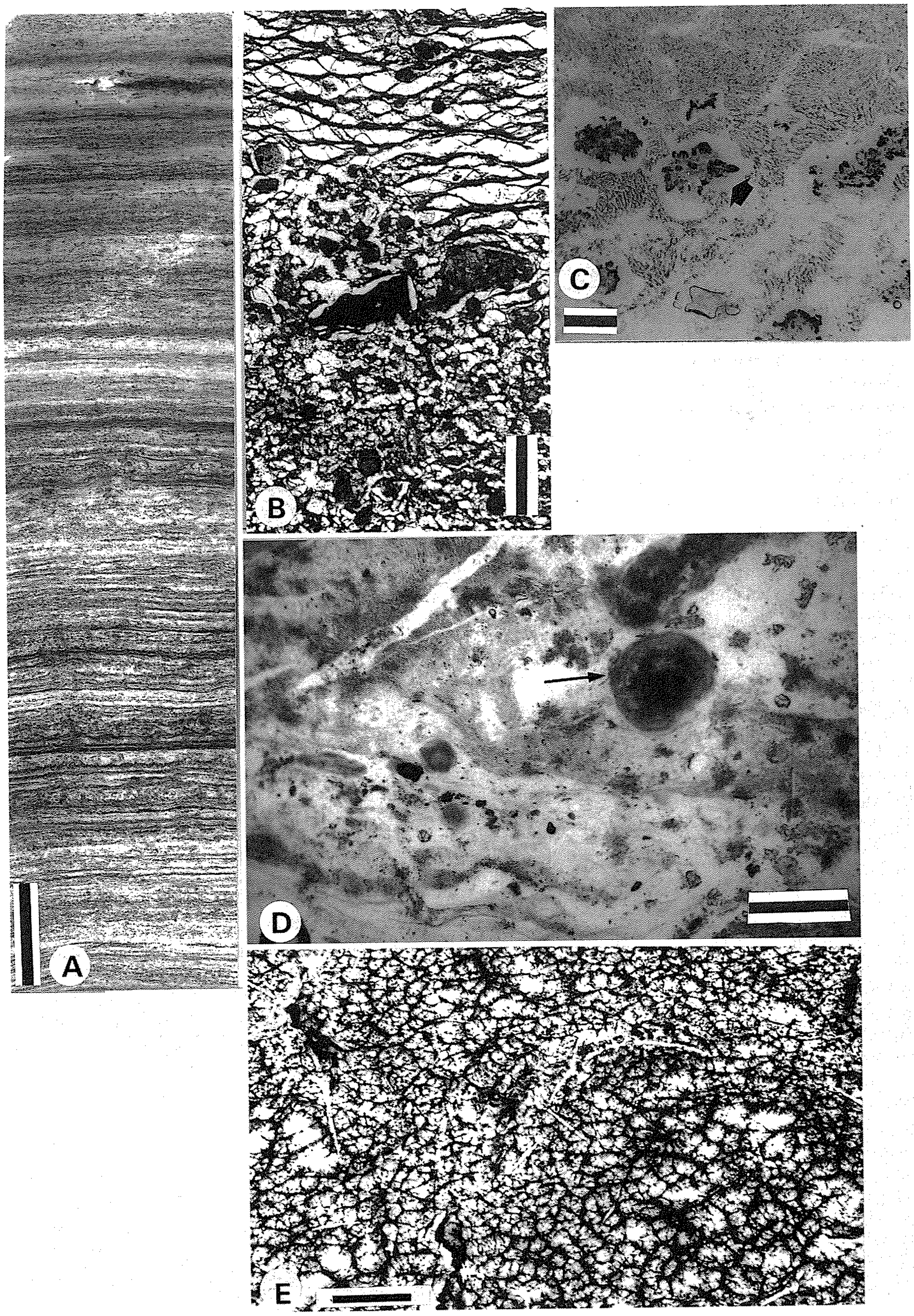
Ensheathed filamentous cyanobacteria are very common in evaporite settings (Fig. 2). *Microcoleus chthonoplastes* is a cosmopolitan species found in various environments (discussions in Gerdes and Krumbein 1987). Multiple ensheathed filament bundles are typical of this species. The organisms are able to glide up and down in order to position themselves as close as possible to optimal light intensities. Mainly hormogonia, which differentiate from longer cell filaments, are motile. If the surface cover increases, or light conditions are reduced due to increasing water cover after intermittent exposure, hormogonia are able to respond phototactically and move upwards accumulating on or close to the new surface (Gerdes et al. 1991). Such repositioning establishes well-laminated internal structures (Fig. 4A). The buried organic matter, consisting of empty abandoned sheaths, immotile filaments and unicells, and EPS of other mat biota, provides significant cohesive strength.

Coccoid slime-ensheathed cyanobacteria with binary fission represent another very common type in evaporite systems. Examples are *Gloeothece* sp. and *Synechocystis* sp. These organisms increase their slime production in order to escape phototoxic conditions when they form the surface mats. Slime production is also stimulated by increase in salinity and temperature. Sediments composed of, or interwoven with, the polysaccharides are yogurt-like if brine is maintained, due to the dispersal and partial dissolution of the mucilage. All these conditions are particularly characteristic of shallow evaporite environments. Photosynthetically active populations of other species under the translucent mat benefit from the production of large quantities of gel since it is an ideal medium for the channeling of light.

In vertical section, *Microcoleus*-dominated mats appear as horizontally layered, bedding plane concordant laminae, which we call L_h-laminae. Since slime-supported coccoid mats are thicker than the flat and bedding-plane concordant L_h-laminae, we term them L_v-laminae (Fig. 4A,B). Under superficial surface brines, couplets of L_h- and L_v-laminae produce more or less regularly spaced biolaminated sequences. Guerrero and Mas (1989) postulated a physical sediment intercalation necessary to prevent the L_h- and L_v-laminae from mixing. In the shallow shelf of Solar Lake and in various solar salt works studied, such physical base is almost lacking due to the rarity of sedimentation events.

▷

Fig. 4A – E. Fabrics of evaporite microbial sediments. **A** X-ray of a vertical section showing various couplets of dark (L_h-) and light-gray (L_v-) laminae. L_h-laminae are made by winter populations of filamentous cyanobacteria (*M. chthonoplastes* dominant); L_v-laminae are made by summer populations of coccoid cyanobacteria (Solar Lake shallow shelf mats; *scale:* 2 cm). **B** Light microscopy of a stained thin-section showing a couplet of L_h-/L_v-laminae. *Top* L_h-lamina; *lower part* L_v-lamina (only laminoid). (Lanzarote salt works, *scale* 50 μm). **C** Thin section of calcareous ooze intermixed with coccoid cyanobacteria and EPS. *Arrow,* Pleurocapsalean nodules and faint sheaths of filamentous taxa (Gavish Sabkha, rim of lagoon; *scale:* 500 μm). **D** Thin-section showing the laminoid fabric due to dominance of coccoid cyanobacteria (compare *lower part* of **B**). *Arrow* In situ-formed carbonate particle. Gavish Sabkha lagoon (*scale:* 200 μm). **E** Macroscopic view of mat surface resembling "elephant skin texture" due to the formation of micropinnacles and net-like structures (Tunisia, shallow surface brines; *scale:* 3 cm)


A
B
C
D
E

Nevertheless, *Microcoleus*-dominated and EPS-dominated couplets of laminae are clearly developed (Fig. 4A). This kind of lamination proceeds via mat-by-mat overgrowth. The microbes overgrow other surface mats in order to gain the most favorable positions within environmental gradients. The main triggering factor may be self-shading, although a chemocline shifting in day-night rhythm across the mat-water interface may also account for overgrowth phenomena. In salterns studied, the recurrence of lamina sets seems most likely to be a pattern of change in seasonal dominance between *Microcoleus*-dominated mats (associated with diatoms) in winter and coccoid cyanobacteria in summer (Gerdes et al. 1991). Dor and Paz (1989) described a similar seasonal dominance change between surface populations. We termed the regular spacing of vertically stacked laminae evolving from seasonal patterns "biogenic varvites" (Gerdes et al. 1991).

Another type of microbial sedimentary feature characteristic of shallow evaporite systems is "biolaminoid" fabric (Fig. 4C,D). The matrix material often consists of a mixture of mucilaginous polysaccharides, unicells and microcrystalline carbonates. Although filamentous taxa or their tubular relicts of empty sheaths are not infrequent, the unambiguous structure of horizontally continuous L_h-laminae is lacking. Only vague signs of lamination (laminoids) occur (Fig. 4D). This type of microbial sediment is dominantly characterized by unicellular cyanobacteria. The slime producers are mainly species of the genera *Gloeothece, Synechococcus* and *Synechocystis.*

4.1.2
Nodules, Pinnacles, Net-Like Surface Structures

In shallow surface brines of moderate hypersalinity, common coccoid cyanobacteria with multiple fission are pleurocapsaleans. Species of this group form colonies wherein each individual cell is encased by thick concentric lamellar sheaths. Pleurocapsalean colonies do not form flat and bedding-plane concordant mats but develop discontinuous, more or less concentric nodules (Fig. 4C). Sediment surfaces colonized by these populations exhibit a pustular structure. Other characteristic surface structures of microbial mats are pinnacles and net-like ornamental features (Fig. 4E). Both preferentially form under calm sheets of shallow surface brine. James G. Gehling (pers. comm.) found similar textures on fossil microbial mats of the Ediacara Member (South Australia) that resemble an "elephant skin".

4.2
Microbial Sediments in Evaporite Systems Associated with Carbonates

4.2.1
Basic Processes

Calcium carbonates are the dominant biogenic minerals precipitated in microbial mats of sabkhas and anchialine pools. Ca^{2+} enrichment is characteristic of hypersaline waters, but precipitation of carbonates in the water column above the microbial mats is rare (Javor 1989). However, various studies have provided clues that the microbial degradation of the in situ-formed organic matter and biogeochemical reactions lead to $CaCO_3$ precipitation (Fig. 5), thus governing the carbonate equilibrium in these mats (Krumbein et al. 1977; Cornée et al. 1992; Riege and Krumbein, this Vol.).

Several authors have stressed that bacterial sulfate reduction may be the main agent that also supports dolomite precipitation. However, although bacterial sulfate reduction is particularly active in microbial mats of hypersaline areas, precipitates more often consist of high Mg-calcite. Friedman et al. (1985) observed high Mg^{2+} enrichment of Solar Lake water and the organic material of the mats, but low dolomite contents in the carbonates. Instead, high Mg-calcite (up to 40% $MgCO_3$) was found. Conversely, gypsum and dolomite both occur where bacterial sulfate reduction is limited by extremely high salinities, as in salt pans or below the pycnocline of salt lakes (Friedman 1980). Hardie (1987) assumed that the increase in dissolved HCO_3^- due to metabolic activity is more important for dolomite formation than sulfate reduction.

Similarly, dolomite in ancient microbial deposits may be post-depositional, resulting from the high Mg^{2+} concentration in carbonates and organic matter. A bituminous character of many ancient dolostones may reflect the involvement of microbial communities (Fan et al. 1992).

Sulfate reduction is involved in a great variety of other secondary mineral formations (Ehrlich 1990). The presence of chemosynthetic sulfide-oxidizing bacteria (e.g. *Thiobacillus* sp.) suggests that it is possible that sulfur forms from the sulfide. Biochemically enriched elemental sulfur usually is ^{32}S-enriched relative to the associated sulfate. Ehrlich (1990) related ^{32}S enrichment in Messinian (Late Miocene) sulfur deposits of Sicily to processes within the narrow sulfur cycle of microbial sediments. Non-phototrophic chemolithotrophic sulfur bacteria in sediments and microbial mats of Australian saline lakes, isolated by Wood et al. (1991), contribute to the oxidative phase of the sulfur cycle in addition to oxidation by phototrophs or *Beggiatoa* sp. Such environments support a remarkably diverse range of physiological types of bacteria.

4.2.2
Mat Facies Associated with Carbonate Particles

In biolaminated buildups of hypersaline origin, in situ formation of non-skeletal carbonate particles is common (Friedman 1978; Krumbein 1979, Cornee et al. 1992; see also Riege and Krumbein, this Vol.). By analogy with structurally similar "augen" gneiss, the in situ formation of nonskeletal carbonate particles in microbial sediments is termed "sedimentary augen structure" (Fig. 5A,B; Dahanayake et al. 1985). Particle types precipitating in the microenvironment of microbial mats include oncoids, ooids and grapestone (Krumbein et al. 1977; Friedman et al. 1985). Folk (1973) mentioned peloid formation in microbial mats presumably by crystallization processes. Concentrically laminated phosphorite and iron particles are also interpreted to have formed in microbial mats (Soudry and Champetier 1983; Dahanayake and Krumbein 1985, 1986).

Coexistence of different morphotypes (ooids, oncoids, peloids and aggregate grains) in one and the same unit of microbial sediments reflects in situ formation (Gerdes et al. 1995). Within mat laminae, the particles characteristically are irregularly distributed. This points to the usually heterogeneous fabric of the microbiogenic matrix. If a small number of cells or cell colonies providing nucleation centers occur within large portions of viscous slime, this may give rise to separate carbonate particles (Fig. 4D). If groups of cells occur close together, this evidently favors the formation of grain aggregates (Fig. 5A). Particle growth causes the deformation of elastic tissues of filamentous mats (Fig. 5B).

4.3
Mat Facies Associated with Evaporites

In vertical sections of sabkha sequences, intrasedimentary gypsum crystals penetrate buried mats (Fig. 6A). Park (1977) stressed that evaporite minerals distort and even destroy lamination. In the Gavish Sabkha and several solar salt works studied, massive evaporite crusts develop at the sedimentary surface. The protective

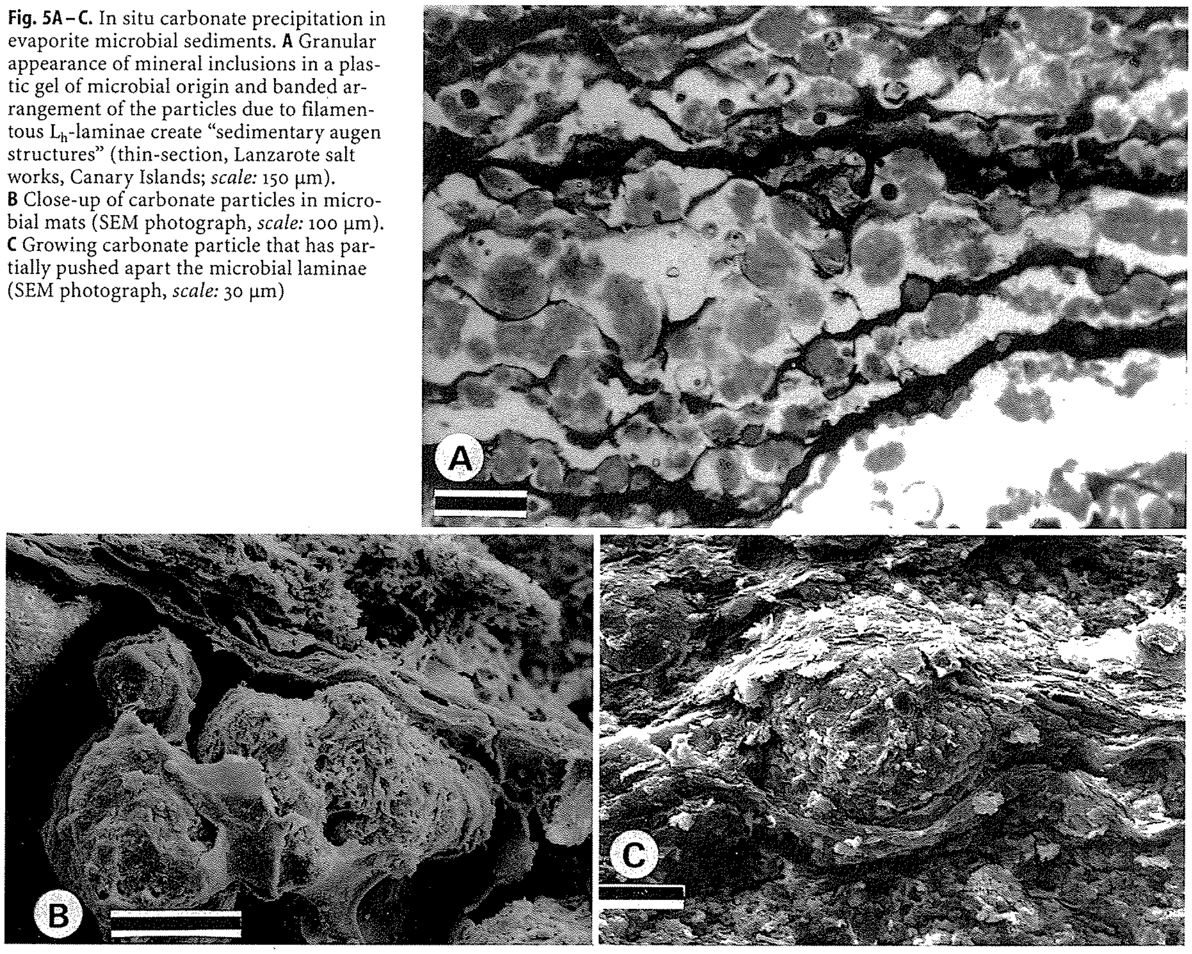


Fig. 5A–C. In situ carbonate precipitation in evaporite microbial sediments. **A** Granular appearance of mineral inclusions in a plastic gel of microbial origin and banded arrangement of the particles due to filamentous L_h-laminae create "sedimentary augen structures" (thin-section, Lanzarote salt works, Canary Islands; *scale:* 150 μm). **B** Close-up of carbonate particles in microbial mats (SEM photograph, *scale:* 100 μm). **C** Growing carbonate particle that has partially pushed apart the microbial laminae (SEM photograph, *scale:* 30 μm)

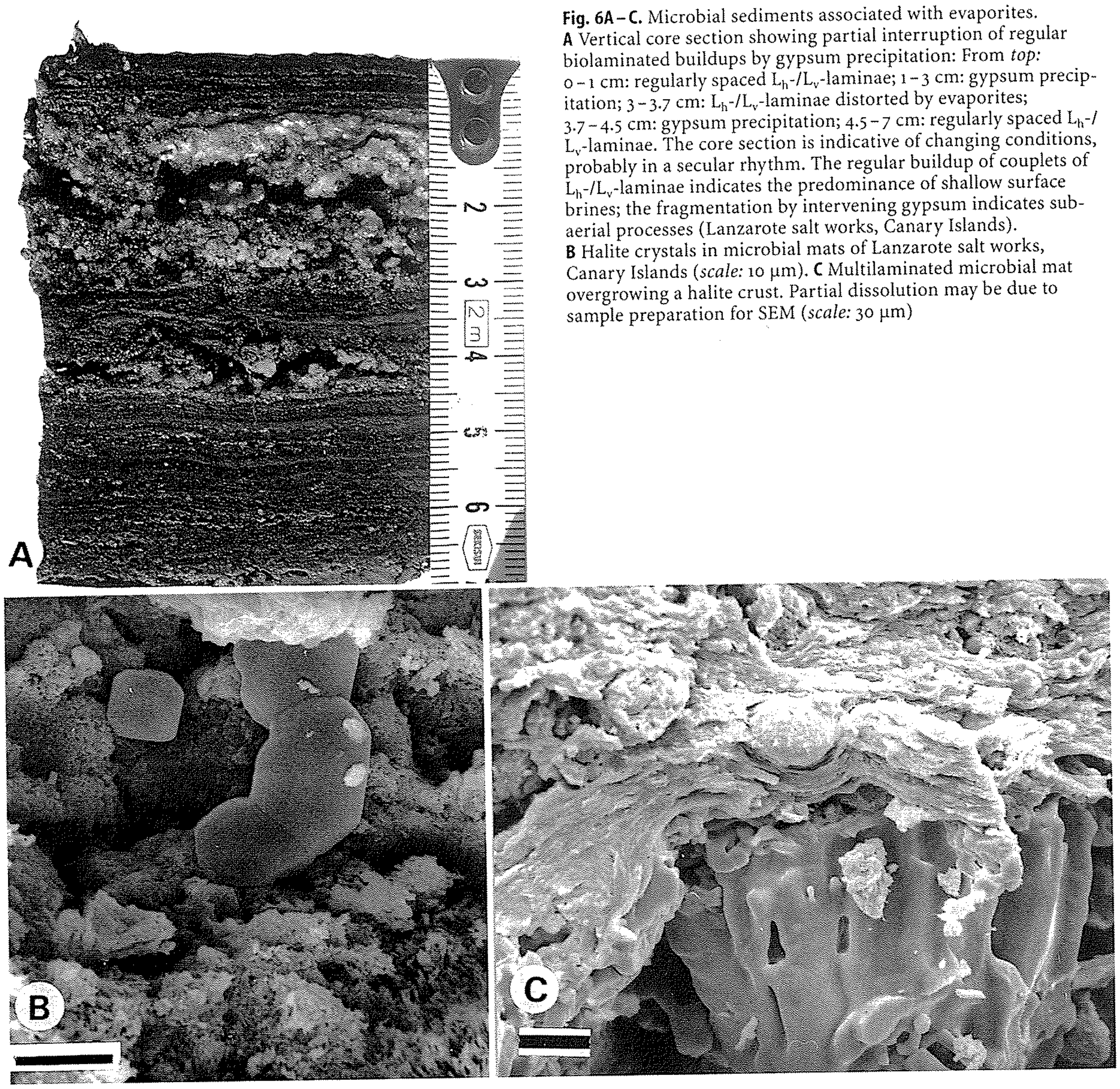


Fig. 6A–C. Microbial sediments associated with evaporites. **A** Vertical core section showing partial interruption of regular biolaminated buildups by gypsum precipitation: From *top:* 0–1 cm: regularly spaced L_h-/L_v-laminae; 1–3 cm: gypsum precipitation; 3–3.7 cm: L_h-/L_v-laminae distorted by evaporites; 3.7–4.5 cm: gypsum precipitation; 4.5–7 cm: regularly spaced L_h-/L_v-laminae. The core section is indicative of changing conditions, probably in a secular rhythm. The regular buildup of couplets of L_h-/L_v-laminae indicates the predominance of shallow surface brines; the fragmentation by intervening gypsum indicates subaerial processes (Lanzarote salt works, Canary Islands). **B** Halite crystals in microbial mats of Lanzarote salt works, Canary Islands (*scale:* 10 µm). **C** Multilaminated microbial mat overgrowing a halite crust. Partial dissolution may be due to sample preparation for SEM (*scale:* 30 µm)

crusts retain moisture and act as light-transferring systems. Since nutrients are also concentrated by evaporative pumping, the growth of prolific microbial mats is favored below and within the crusts. Massive gypsum often shows inclusions of vertically stratified microbial mats. Individual layers are yellow, orange, purple-red, and light and dark green, due to the distribution of different taxonomic and physiological groups (e.g. coccoid and filamentous cyanobacteria, phototrophic and chemoorganotrophic bacteria). In salt crusts, each single microbial layer usually is thicker than in similar sediment-supported microbial mats. This may be traced back to the ideal light channeling system of a salt crust (Gerdes et al. 1985).

Mats at or close to the bottom of stratified brines contribute to biolaminations in subaquatic gypsum (Fig. 3). In the Solar Lake hypolimnion, the filamentous cyanobacterium *Oscillatoria limnetica*, in association with coccoid cyanobacteria, anoxy-photobacteria and anaerobic bacteria, forms flocculent layers undergoing rapid anaerobic decay. Gypsum crystals form within and around these flocculent fabrics. Thin-section studies of the bottom sediments reveal a vertically laminated succession in which 5–10 mm thick layers composed of gypsum crystals alternate with thin organic laminae usually 100–500 m thick. The loose form of the flocculent mats provides hollow space filled with brine and fine-grained gypsum mush. The microbial assemblages are refractory and scattered within the gypsum mush.

Microbial inclusions and interlaminations in large gypsum crystals may reflect recrystallization of originally fine-grained gypsum mush during diagenesis. Krumbein cored Solar Lake sediments and found gypsum crystals more than 4 cm in size, with laminated mats embedded in them (Gavish et al. 1985). Microbial inclusions appear as thin laminae, often also showing faint, refractory and clotted microfabrics. Other origins of microbial mat layers within large gypsum crystals may be related to the replacement of carbonate sediments upon burial of former surface mats (Purser 1985).

In shallow brines, e.g. the Gavish Sabkha lagoon (Fig. 1A), salinities in the range of gypsum saturation (at about 14%) do not limit in situ production of biomass, and sulfate reduction proceeds as long as water is available. Thus, low gypsum contents are preserved in the sediment. Carbonate coatings around single sulfate particles commonly indicate solution and replacement of the sulfate by microbial activity. Only further salinity increase, decreasing water availability, or both, leads to the enrichment of gypsum in microbial sediments, since microbial productivity and sulfate reduction decrease (Fig. 6A).

In extremely hypersaline brines, large cell densities of halobacteria can change the precipitation behavior of halite (Krumbein 1985; Lopez-Cortes et al. 1994). Crystals contain more and larger fluid inclusions than crystals formed in sterile salt solutions (Norton and Grant 1988). Lopez-Cortes et al. (1994) found that the cells serve as templates for halite formation, resulting in a larger number of cubic crystals of smaller size than in sterile control experiments. They also observed that the proteinaceous compounds of the surface layers of the cells contribute to a modification of the halite crystal structure resulting in a dendritic shape. In Fig. 6B,C, some examples of halite crystals are shown in microbial mats.

4.4
Stress-Deformation Behavior of Biostabilized Sediments

In shallow evaporite settings, a variety of different physical processes (desiccation, crystal pressure and gas upheaval) affect the sedimentary surfaces and initiate deformation. Microbial mats embedded in the sediments act as a kind of soft tissue which effectively alters the effects of physical deformation (Reineck et al. 1990).

Drying, tearing of mats, and upcurling of mat margins may give rise to microbial chips (Fig. 7A). In shallow surface brines, subaqueous biofilms loosely attached to the substrate tend to scour and tear. Results are folds and tears, also known from ancient examples (Bernier et al. 1991).

Another reason for surface folding and doming is gas accumulating beneath surface mats. Hypersaline settings occupied by biofilms and microbial mats and enriched in reduced sulfur compounds are known for their high potential of gas production, mainly methane (Kiene et al. 1986). Gas accumulation elevates the cohesive biostabilized surface that retards the escape of gas into air or water, respectively (Fig. 7B). In ephemeral surface brines, such gas domes experience changes of flooding and exposure that in turn have a considerable influence on the microbiology and mineralogy of the area, inasmuch as wetting enables microbes to form new mats, and desiccation adds new gypsum crusts to the mats. Results are multilaminated domes resembling cabbage heads (Fig. 7C).

Taher et al. (1995) found selenitic gypsum mounds in a salina near Port Said, Egypt, produced by continu-

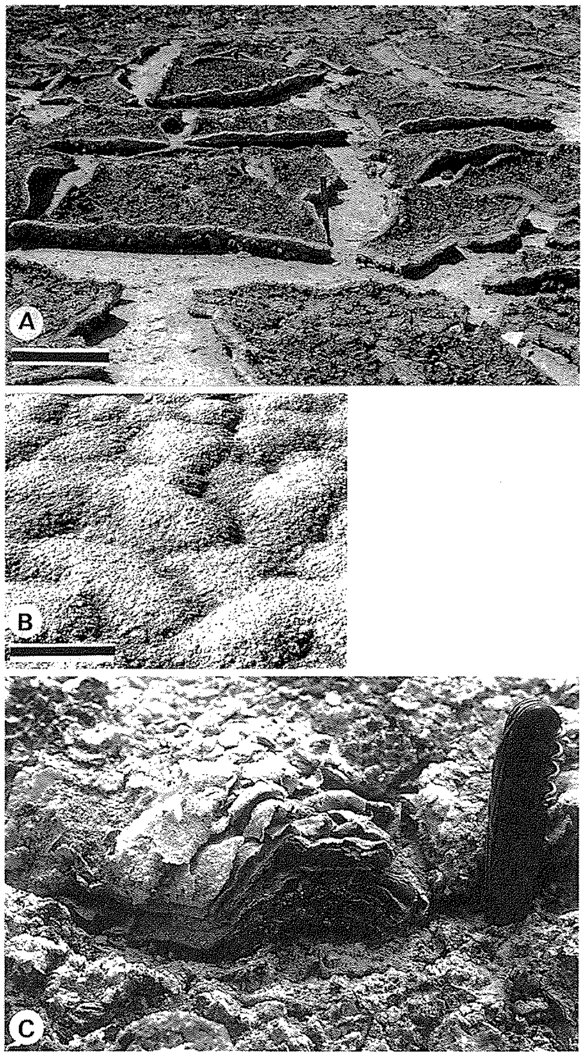


Fig. 7.A Desiccation cracks and upcurling of mat margins giving rise to chip formation (Lanzarote, Canary Islands, abandoned salt works, *scale:* 30 cm). **B** Gypsum-encrusted gas domes in microbial mats (*scale:* 20 cm). **C** Repeated exposure and gypsum encrustation of the gas domes, followed by re-establishment of surface brines and recolonization by microbial mats, create typical "cabbage heads" (length of knife = 9 cm; photographs courtesy of Professor H.E. Reineck)

ous gypsum laminae interlayered with microbial mats. The mounds were hard, massive, more or less circular, and up to about 35 cm in width. The topmost part of the domes was a thick layer (2–4 cm) of light brown, loosely packed coarse aggregates of tabular to block-like selenite crystals, more-or-less vertically orientated and highly twinned. The lower parts of the domes were more or less circular and formed of multi-layered porous masses of randomly orientated gypsum crystals. Comparable domes have been found in solar salt ponds (Reineck et al. 1990; Schreiber and Kinsman 1975) along the Red Sea coastal sabkhas of Egypt (Taher 1988), and in the Quaternary gypsum deposits of South Australia (Warren 1982).

Lateral expansion of surface crusts by the continual increment of evaporite minerals is particularly active at zones of weakness, causing buckling and folding of surface crusts (Assereto and Kendall 1977). The addition of crystals usually generates folds in consolidated crusts. Upfolding of the surface due to mineral encrustation is typical of subaerial conditions in arid climate. Another type of folding structure, termed enterolithic folds, develops from the conversion of gypsum mush above the mats to anhydrite. Additional anhydrite, derived from occasional storm flood water after evaporation, contributes to the expanding anhydrite zone (Hardie 1984; Shinn 1986).

5
Biofacies Classification of Marine-Derived Evaporite Microbial Sediments

Based on brine depth and salinity (Fig. 3), a classification of the biofacies types described in the foregoing section can be proposed. Although both factors are not necessarily correlated, both rule the local abundance of major microbial taxa and, thus, biofacies. Local decrease in brine depth usually correlates with broader environmental fluctuations which select for the increasing abundance of eurytopic major taxa that produce characteristic biogenic fabrics. The shallower the setting, the less the eurytopic community type is limited by increasing salinity. Both increasing depth and extreme salinities select for the increasing abundance of specialists (stenotopic taxa) tolerating only narrower ranges of environmental factors. The following first three sections summarize biofacies characteristics of eurytopic mat communities. The fourth is related to the dominance of stenotopic groups. Although using the Solar Lake example, these biofacies may contribute to deposits in brines of far greater depths.

5.1
Brine Table Below the Surface

In this case, biofacies characteristics are intrasedimentary biolaminites dominated by the L_h-lamina type, associated with gypsum. Deformation of the biofilm-stabilized surface is common, including cracks, doming and folding. Evaporative pumping is active, also providing moisture to the growth sites of microbial sediments. The mats are additions to clastic sediments (mud, sand; carbonate or non-carbonate) imported into the area by wind, episodic sheet floods or washover from the sea. Environmental settings are sabkhas.

5.2
Ephemeral Surface Brine

Biofacies characteristics include biolaminoid structures and initial biogenic varvites (Fig. 4). In metahaline conditions, cerithid gastropods meeting the growth areas of the biolaminoid facies leave shells behind. Biogenic varvites commonly occur at increasing salinities that exclude the gastropods. The biolaminites are frequently wrinkled due to net-like structures and pinnacles on the one hand (growth-related), and cracking, folding and doming on the other (related to physical stress; Fig. 7). The mat community shows increasing abundance of coccoid species. Sulfate crystals still occur. Coating of sulfate particles by carbonates indicates partial solution/reduction of the sulfate by microbes. Environmental settings are the rims and lower supratidal flats of playa lakes, salinas and peritidal lagoons. The hydrological regime is still variable, with moisture being supplied to the growth sites of microbial sediments by seepage and capillary action.

5.3
Perennial Surface Brine

Biofacies characteristics include regularly spaced biogenic varvites (Fig. 4A,B) and sedimentary augen structures. The biolaminites commonly are wrinkled due to pinnacle formation. Folding and doming is still common due to gas production in the subsurface sediments. The mat community is relatively the most diverse and productive of the depth zones compared. Due to high rates of sulfate reduction, there is almost no gypsum preserved. Carbonate minerals form in situ due to microbial conversion of organic matter, internal diffusion controls, microbial mineral solution by gypsum reduction, increase in dissolved HCO_3^-, and precipitation of secondary calcite (Fig. 5). Associated features may include burial by clastics brought in by occasional sheet floods. Environmental settings are shallow, permanently water-filled saline basins like the Gavish Sabkha lagoon, man-made salinas and the deeper Solar Lake shelf.

5.4
Stratified Basins Several Meters Deep (e.g., Solar Lake)

In the anoxic hypolimnion, soft flocculent fabrics of microbial mats occur, composed of halophilic filamentous cyanobacteria (e.g. *Oscillatoria limnetica*) and unicelluar species (*Aphanothece halophytica*). Below the pycnocline, sulfur-dependent anoxy-photobacteria and anaerobic bacteria increase in number. The flocculent mats undergo rapid anaerobic decay. The bottom sediments are marked by faint interlamination of microbial mats in and between large gypsum crystals that precipitate subaquatically at the lake bottom.

6
Summary

1. The harsh conditions of evaporite environments exclude many groups of organisms, but those that thrive in hypersaline areas maintain high reproduction rates. Among these are cyanobacteria, other phototrophic bacteria, and halophilic green algae.
2. Primary production creates the organic material upon which biogeochemical cycles are based that produce a variety of authigenic minerals.
3. Evaporite settings vary from widely fluctuating to fairly uniform environmental conditions. Local decrease of brine depth usually correlates with broader environmental fluctuations, including salinity shifts. These conditions select for increasing abundance of eurytopic taxa, mainly benthic cyanobacteria.
4. Cyanobacteria initiate highly productive microbial mat ecosystems in which externally fluctuating conditions of the shallow evaporite environment are moderated due to the capacity of these organisms to produce water-retaining slime, to store energy by light-harvesting systems, to transform and transfer nutrients in biogeochemical cycles, and to establish vertically stratified benthic systems that withstand periods of dryness.
5. Increasing depth and extreme salinity both select for increased abundance of specialists (stenotopic taxa) tolerating only narrower ranges of environmental factors.
6. Communities dominated by benthic eurytopic cyanobacteria produce characteristic microbial sediments including stromatolitic laminae, biolaminoid facies, sedimentary augen structures, and pinnacle structures. Communities dominated by stenotopic major taxa often contribute less unambiguous structures, e.g. flocculent organics, to the sedimentary record.
7. In nutrient-enriched hypersaline basins, plankton dominance may outcompete benthic microbial mats, but also contribute to organic-rich strata.

References

Assereto RLAM, Kendall CGStC (1977) Nature, origin and classification of peritidal tepee structures and related breccias. Sedimentology 24:153–210

Bernier P, Gaillard C, Gall JC, Barale G, Bourseau JP, Buffetaut E, Wenz S (1991) Morphogenetic impact of microbial mats on surface structures of Kimmeridgian micritic limestones (Cerin, France). Sedimentology 38:127–136

Brongersma-Sanders M (1992) On the association of ore deposits with stromatolites. In: Schidlowski M et al. (eds) Early organic evolution: Implications for mineral and energy resources. Springer, Berlin Heidelberg New York, pp 478–482

Cohen Y, Krumbein WE, Goldberg M, Shilo M (1977) Solar Lake (Sinai). 1. Physical and chemical limnology. Limnol Oceanogr 22:597–608

Cornée A, Dickman M, Busson G (1992) Laminated cyanobacterial mats in sediments of solar salt works: some sedimentological implications. Sedimentology 39:599–612

Dahanayake K, Krumbein WE (1985) Ultrastructure of a microbial mat generated phosphorite. Miner Deposita 20:260–265

Dahanayake K, Krumbein WE (1986) Microbial structures in oolitic iron formations. Miner Deposita 21:85–94

Dahanayake K, Gerdes G, Krumbein WE (1985) Stromatolites, oncolites and oolites biogenically formed in situ. Naturwissenschaften 72:513–518

Decima A, McKenzie JA, Schreiber BC (1988) The origin of "evaporative" limestones: an example from the Messinian of Sicily (Italy). J Sed Petrol 58:256–272

Dor I, Paz N (1989) Temporal and spatial distribution of mat microalgae in the experimental Solar ponds, Dead Sea area, Israel. In: Cohen Y, Rosenberg E (eds) Microbial mats, physiological ecology of benthic microbial communities. ASM, Washington, DC, pp 114–122

Dyer BD, Krumbein WE, Mossman DJ (1994) Accumulation of gold in the sheath of *Plectonema terebrans* (filamentous marine cyanobacteria). Geomicrobiology J 12:91–98

Ehrlich HL (1990) Geomicrobiology. Dekker, New York

Fan P, Li J, Meng Q, Ju X, Li Z (1992) Biomarkers and other hydrocarbon in Upper Sinian stromatolitic dolostones from southwest China. In: Schidlowski M et al. (eds) Early organic evolution: Implications for mineral and energy resources. Springer, Berlin Heidelberg New York, pp 308–316

Folk RL (1973) Carbonate petrography in the post-Sorbian age. In: Ginsburg RN (ed) Evolving concepts in sedimentology. John Hopkins University, Baltimore, pp 118–158

Friedman GM (1978) "Solar Lake": a sea-marginal pond of the Red Sea (Gulf of Aqaba or Elat) in which algal mats generate carbonate particles and laminites. In: Krumbein WE (ed) Environmental biogeochemistry and geomicrobiology 1. The aquatic environment. Ann Arbor, pp 227–235

Friedman GM (1980) Dolomite is an evaporite mineral: Evidence from the rock record and from sea-marginal pond of the Red Sea. SEPM Spec Publ 28:69–80

Friedman GM, Sneh A, Owen RW (1985) The Ras Muhammad Pool: Implications for the Gavish Sabkha. In: Friedman GM, Krumbein WE (eds) Hypersaline ecosystems: the Gavish Sabkha. Ecological Studies 53. Springer, Berlin Heidelberg New York, pp 218–237

Friedman GM, Sanders JE, Kopaska-Merkel D (1992) Principles of sedimentary deposits. MacMillan, New York

Gavish E, Krumbein WE, Halevy J (1985) Geomorphology, mineralogy and groundwater geochemistry as factors of the hydrodynamic system of the Gavish Sabkha. In: Friedman GM, Krumbein WE (eds) Hypersaline ecosystems: the Gavish Sabkha. Ecological studies 53. Springer, Berlin Heidelberg New York, pp 186–217

Gerdes G, Krumbein WE (1987) Biolaminated deposits. In: Bhattacharya S, Friedman GM, Neugebauer HJ, Seilacher A (eds) Lecture Notes in Earth Sciences 9. Springer, Berlin Heidelberg New York

Gerdes G, Krumbein WE, Holtkamp EM (1985) Salinity and water activity related zonation of microbial communities and potential stromatolites of the Gavish Sabkha. In: Friedman GM, Krumbein WE (eds) Hypersaline Ecosystems – The Gavish Sabkha. Ecological Studies 53. Springer, Berlin Heidelberg New York, pp 238 – 266

Gerdes G, Krumbein WE, Reineck HE (1991) Biolaminations – ecological versus depositional dynamics. In: Einsele G, Ricken W, Seilacher A (eds) Cycles and events in stratigraphy. Springer, Berlin Heidelberg New York, pp 592 – 607

Gerdes G, Dunajtschik-Piewak K, Riege H, Taher AG, Krumbein, WE., Reineck HE (1995) Structural diversity of biogenic carbonate particles in microbial mats. Sedimentology 41:1273 – 1294

Golubic S (1980) Halophily and halotolerance in cyanophytes. Origins Life 10:169 – 183

Guerrero R, Mas J (1989) Multilayered microbial communities in aquatic ecosystems: Growth and loss factors. In: Cohen Y, Rosenberg E (eds) Microbial mats, physiological ecology of benthic microbial communities. ASM, Washington, DC, pp 37 – 51

Hardie LA (1984) Evaporites: marine or non-marine? Am J Sci 284:193 – 240

Hardie LA (1987) Dolomitization: a critical view of some current views. J Sed Petrol 57:166 – 183

Imhoff JF (1988) Halophilic phototrophic bacteria. In: Rodriguez-Valera F (ed) Halophilic bacteria. CRC Press, Boca Raton, pp 85 – 108

Javor B (1989) Hypersaline environments. Springer, Berlin Heidelberg New York

Kendall AC (1992) Evaporites. In: Walker RG, James NP (eds) Facies models. Geol Assoc Can, pp 375 – 409

Kiene RP, Oremland RS, Catena A, Miller LG, Capone D (1986) Metabolism of reduced methylated sulfur compounds by anaerobic sediments and a pure culture of an estuarine methanogen. Appl Environ Microbiol 52:1037 – 1045

Kinsmann DJJ (1969) Modes of formation, sedimentary associations, and diagnostic features of shallow-water and supratidal evaporites. Am Assoc Petrol Geol Bull 53:830 – 840

Krumbein WE (1979) Calcification by bacteria and algae. In: Trudinger PA, Swaine DJ (eds) Biogeochemical cycling of mineral-forming elements. Elsevier, Amsterdam, pp 47 – 67

Krumbein WE (1985) Applied and economic aspects of sabkha systems – genesis of salt, ore and hydrocarbon deposits and biotechnology. In: Friedman GM, Krumbein WE (eds) Hypersaline ecosystems: the Gavish Sabkha. Ecological studies 53. Springer, Berlin Heidelberg New York, pp 426 – 436

Krumbein WE, Cohen Y, Shilo M (1977) Solar Lake (Sinai) 4. Stromatolitic cyanobacterial mats. Limnol Oceanogr 22:635 – 656

Lopez-Cortes A, Ochoa JL, Vazquez-Duhalt R. (1994) Participation of halobacteria in crystal formation and the crystallization rate of NaCl. Geomicrobiol J 12:69 – 80

Norton C, Grant WD (1988) Survival of halobacteria within fluid inclusions in salt crystals. J Gen Microbiol 134:1365 – 1373

Park RK (1977) The preservation potential of some recent stromatolites. Sedimentology 24:485 – 506

Por FD (1985) Anchialine pools – comparative hydrobiology. In: Friedman GM, Krumbein WE (eds) Hypersaline ecosystems: the Gavish Sabkha, Ecological studies 53. Springer, Berlin Heidelberg New York, pp 136 – 145

Purser BH (1985) Coastal evaporite systems. In: Friedman GM, Krumbein WE (eds) Hypersaline ecosystems: the Gavish Sabkha. Ecological studies 53. Springer, Berlin Heidelberg, New York, pp 72 – 102

Reineck HE, Gerdes G, Claes M., Dunajtschik-Piewak K, Riege H, Krumbein WE (1990) Microbial modification of sedimentary surface structures. In: Heling D, Rothe P, Förstner U, Stoffers P (eds) Sediments and environmental geochemistry. Springer, Berlin Heidelberg New York, pp 254 – 276

Renfro AR (1974) Genesis of evaporite-associated stratiform metalliferous deposits – a sabkha process. Econ Geol 69:33 – 45

Schreiber BC, Kinsman DJJ (1975) New observations on the Pleistocene evaporites of Montallegro, Sicily and a modern analog. J Sed Petrol 45:469 – 479

Shinn E (1986) Modern carbonate tidal flats: their diagnostic features. In: Hardie LA, Shinn EA (eds) Carbonate depositional environments modern and ancient, part 3. Tidal flats. Colorado School of Mines Quarterly 81:7 – 35

Soudry D, Champetier Y (1983) Microbial processes in the Negev phosphorites (southern Israel). Sedimentology 30:411 – 423

Taher AG (1988) Sedimentology and geochemistry of the coastal sabkha, Ras Shukheir, Gulf of Suez, Egypt. MSc Thesis, Cairo University, Egypt

Taher AG, Wahab Abd el, Philip G, Krumbein WE, Wali AM (1995) Evaporitic sedimentation and microbial mats in a salina system (Port Fouad, Egypt). Int J Salt Lake Res 4:117 – 131

Warren JK (1982) The hydrological setting, occurrence and significance of gypsum in late Quaternary salt lakes in south Australia. Sedimentology 29:609 – 637

Wood A, Burke Ch, Knott B (1991) Chemolithotrophic surfur bacteria in sediments, mats, and stromatolites of Western Australian saline lakes. Geomicrobiol J 9:41 – 49