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Lithostratigraphy, Facies Interpretation and Depositional Environment of the Lower Miocene Gypsified Stromatolites and Microbial Laminates, Rabigh and Ubhur Areas, Red Sea Coast, Saudi Arabia

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*Abstract***.** The Lower Miocene evaporites in Rabigh and Ubhur areas belong to the Gehfa Member, Dafin Formation and Ubhur Formation, respectively. In Rabigh area, the evaporite sequence is composed of gypsified rhizocretion (formed in supratidal sabkha) and a thick sequence composed of gypsified stromatolites and microbial laminites, and skeletal gypsum (formed in upper subtidal and intertidal environments). This sequence is conformably overlying the fluvial siliciclastics of Al-Hakkak Member, Dafin Formation. In Ubhur area, the evaporite sequence is composed of gypsified microbial laminites, highly enriched in fine silt-sized quartz grains that may form nodular mosaic structure. The Ubhur evaporites are formed dominantly in supratidal sabkha environment, that intermittently submerged to the intertidal environment.

Microscopic investigation of the Rabigh and Ubhur evaporites indicate the dominance of secondary gypsum rocks that mantled with 20-30 cm thick powdery anhydrite crust. Relics of primary prismatic, lenticular and rosette gypsum crystals are observed in areas highly enriched in microbial micrite.

The dominance of stromatolites and microbial laminites structures indicate their formation in low salinity brine (60-150 g/l), absence of grazer and burrowers, and sufficient oxygenation in supratidal and shallow depositional environment. On the other hand, the gypsum laminae indicate a relatively higher salinity of the brine (> 150 g/l) and their deposition in permanent shallow subaqueous environment. Periodic exposure of the subaqueous evaporites is evidenced by the presence of gypsified rhizocretion and displacive nodular mosaic structure.

Keywords: Lithostratigraphy, Miocene, gypsified, stromatolites, microbial laminites, Saudi Arabia.

Introduction

Facies analysis is a key tool for the reconstruction of the palaeogeography and depositional history of sedimentary basins. However, application of the method to ancient evaporite basins is limited by the common, often complete, diagenetic transformation of the evaporites (Babel, 2005). This obliterates the primary features required for analysis of the original depositional facies. Primary gypsum deposits are particularly sensitive to dehydration and rehydration processes, which operate both during the deep burial-exhumation cycle and in the original depositional setting (Warren, 1999 and 2006; and Babel, 2005).

The syn-rift Miocene evaporites of the Red Sea coastal plain of Saudi Arabia occur sporadically from Midyan Peninsula (at north) to Jizan (at south). These evaporites are usually affected by sever diagenetic obliteration of the primary depositional structures during burial and uplift. The same diagenetic overprint is also observed in the syn-rift Miocene evaporites of the Egyptian Red Sea coast by Aref (2003A), and Aref *et al.* (2003).

The exposed syn-rift Miocene evaporites are studied in Rabigh area (between latitudes 22° 41´ and 22° 43´, and longitudes 39° 08´ and 39° 12´) and Ubhur area (between latitudes 21° 50´ and 21° 53´ and longitudes 39° 08´ and 39° 09´), Fig. 1. Three stratigraphic sections are measured and sampled; two of them are in Rabigh area; at Wadi Gehfa (Lat. N 22° 44´ 182, Long. E 39° 09´ 046) and Miqat Al-Gehfa (Lat. 22° 43´ 562, Long. E 39° 08´ 463). The third is in Ubhur area near Al Kura (Lat. N 21° 50´ 786, Long. E 39° 08´ 162); (Fig. 1 and 2), 57 thin sections of the evaporite rocks are made with epoxy cement under dry cool condition. These evaporites are composed dominantly of secondary gypsum that encrusted with 20-30 cm anhydrite crust. The origin and significance of these diagenetic evaporitic minerals (gypsum and anhydrite) have been published by Mandurah and Aref (2010), and are out of the scope of the present work. Fortunately, the dominance of stromatolites and microbial laminites structures in the studied evaporites of Rabigh and Ubhur areas still preserve primary depositional textures and structures. These help in facies interpretation and reconstruction of the depositional environment of the evaporites.

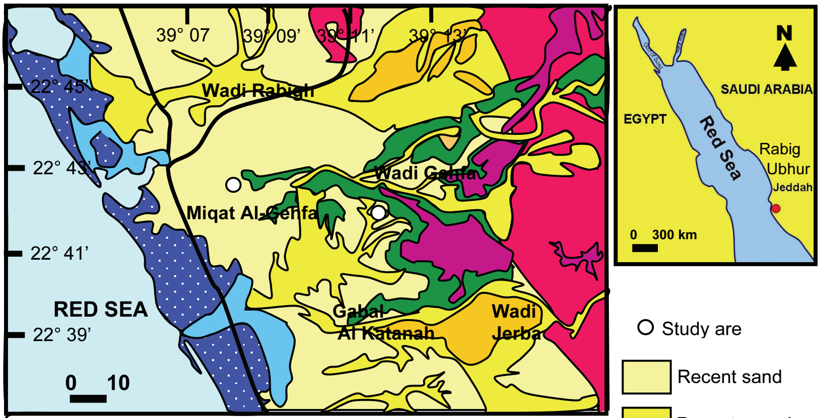
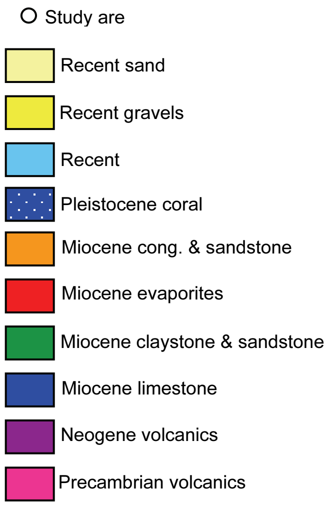


Fig. 1-1. Geologic map and location of the composite sections in Rabigh area, Red Sea, Saudi Arabia. (Modified after Ramsey, 1986).



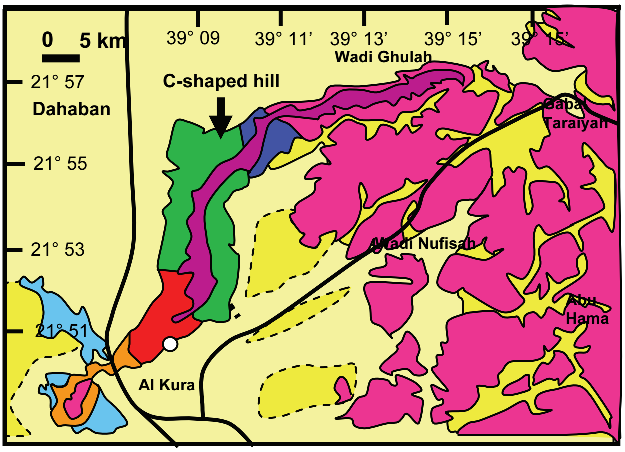


Fig. 1-2. Geologic map and location of the composite sections in Ubhur area, Red Sea, Saudi Arabia. (Modified after Moore and Al-Rehaili, 1989; Mandurah and Aref, 2010).

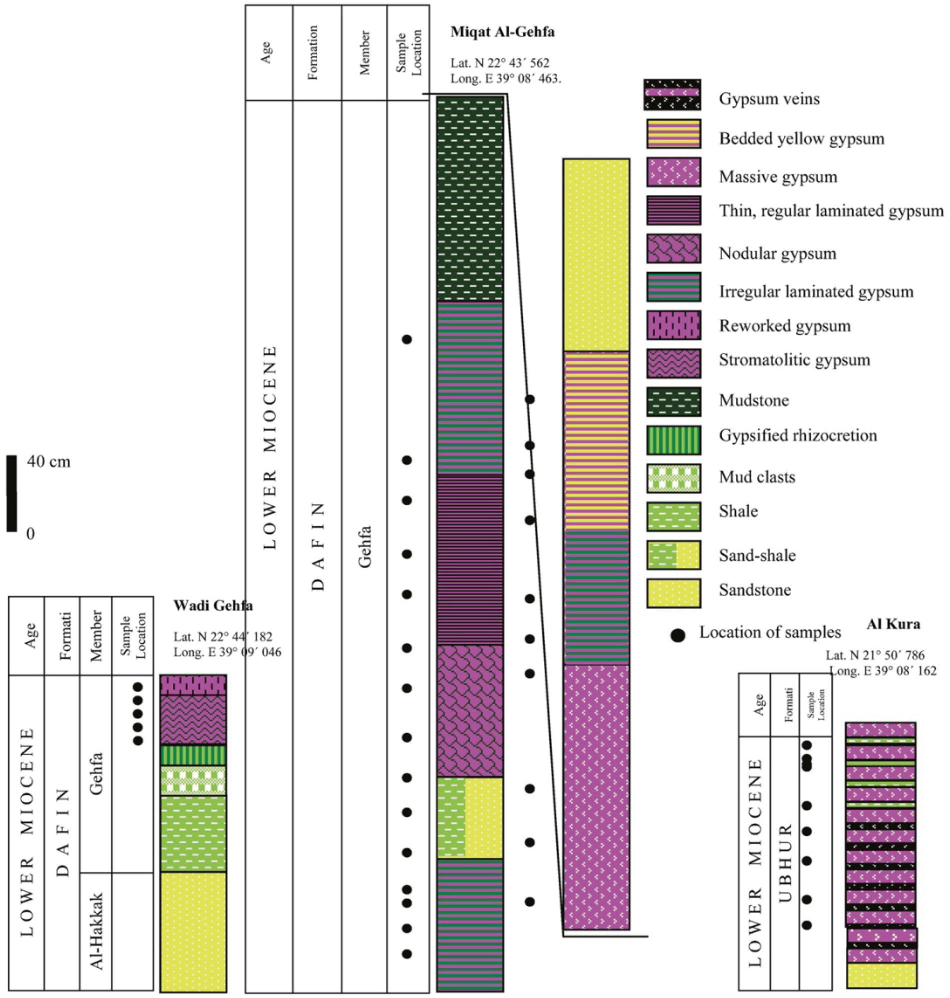


Fig. 2. The lithostratigraphic sections of the exposed evaporites in Rabigh and Ubhur areas, Red Sea, Saudi Arabia. (Modified after Mandurah and Aref, 2010).

Lithostratigraphy

The stratigraphic setting and facies composition of the syn-rift Miocene evaporites of the Red Sea coastal plain of Saudi Arabia were assigned with different formation names of varied ages. They are represented by: (1) The thick Lower Miocene submarine evaporites of the Yanbu Formation of the Tayran Group (Hughes and Filatoff, 1995), which consists of halite, anhydrite and minor shale. The Yanbu Formation is not exposed along the Red Sea coast, and it is penetrated in exploration wells in the Yanbu Basin and to the north in Midyan (Cocker and Hughes, 1993). (2) The latest Early Miocene evaporites of Jabal Kibrit Formation (An Numan Member) and the earliest Middle Miocene mudstones and submarine evaporites of Kial Formation, Maqna Group (Hughes and Filatoff, 1995). The Jabal Kibrit Formation consists of anhydrite-carbonate facies. The Kial Formation is typified by interbedded anhydrites, calcareous siltstones and carbonates. In Midyan peninsula, thick evaporites of the Mansiyah Formation were deposited extensively during the Middle Miocene, and are overlain by poorly exposed sands, shales and thin anhydrite beds of the Middle to Upper Miocene Ghawwas Formation.

North of Jeddah area, the Precambrian basement rocks form the eastern shoulder of the Red Sea coastal plain of Saudi Arabia (Fig. 1). They are unconformably overlain by Cretaceous to Miocene sedimentary rocks (Shumaysi, Usfan, Dafin and Ubhur formations) in the west and by Miocene to Pliocene lavas in the north (Ramsay, 1986; Moore and Al-Rehaili, 1989). Extensive areas of Quaternary surficial deposits (sand and gravel) are extended on the coastal plain and in the major wadies.

In Rabigh area, the Miocene Dafin Formation of Ramsay (1986) is composed of three lithofacies, these are siliciclastics, carbonates and evaporites. Taj and Hegab (2005) assigned Al-Hakkak Member for the siliciclastics sequence, the Jerba Member for the carbonates sequence, and the Gehfa Member for the evaporites sequence. The siliciclastic lithofacies facies is widely exposed in most of the eastern part of Rabigh area at Wadi Al Haqqaq, Wadi Al Hajar and Wadi Al Jerba (Taj and Hegab, 2005). The carbonate facies outcrops at the southeastern part of the sedimentary cover (Wadi Al Jerba) and consists of dolomitic, oolitic, intraclastic, foraminiferal packstone and wackestone, and dolomitic mudstone (Mandurah *et al*., 2009). The evaporites facies outcrops at the most northwestern part of the sedimentary cover (Miqat Al-Gehfa), and increases in thickness towards north and northwest. The evaporites of Gehfa Member are conformably overlain the siliciclastics of Al-Hakkak Member, and is laterally equivalent to the carbonates of Jerba Member (Mandurah *et al.,* 2009).

Because the Lower Miocene Al Wajh and Yanbu formations have regional distribution from Al Wajh and Yanbu basins at north to Jeddah at south (Hughes and Johnson, 2005). In turn, the siliciclastics of Al-

Hakkak Member can be raised to the formation rank and is equivalent to the siliciclastics of Al-Wajh Formation. The carbonate of Jerba Member is also raised to the formation rank, and is equivalent to the carbonate of the Musayr Formation. The evaporite of the Gehfa Member is also raised to the formation rank and is equivalent to the evaporite of Yanbu Formation.

In Ubhur area, the Lower Miocene Ubhur Formation (Andreieff, 1983) consists of green sandy clay, siltstone and soft, white bioclastic limestone with gypsum bed interbedded with the clay. Spencer and Vincent (1984) believed that the exposed part of the Ubhur Formation at Al Harrat represents a small part of thick evaporitic sequence, attaining 77 meters in thickness, deposited in Tihama beneath the coastal plain north and south of Jeddah. Hughes and Johnson (2005) declared that the Musayer Formation which consists of basal calcareous sandstone, overlain by skeletal grainstone and pack/wackestone carbonates rich in macro- and micro-fauna is equivalent to the Early Miocene Ubhur Formation of Spencer (1987).

Description and Interpretation of the Evaporite Lithofacies

In Rabigh area, at outcrops and in the active quarries near Miqat Al-Gehfa, the evaporite sequence is composed dominantly of secondary gypsum with abundant microbial laminated and stromatolitic structures (Fig. 2). The evaporite sequence conformably overlies a succession of green, brown sandstone, siltstone and mudstone layers. The lower part of the evaporite sequence shows numerous gypsified rootlets (rhizocretion) at its contact with the underlying mudstone layer (Fig. 3). In Ubhur area, the evaporites have a limited exposure because they have been extensively excavated during the last decade. They are composed of 50 to 70 cm thick, interbedded gypsum-dominated layers and clastic-dominated layers (Fig. 4).

Microscopic examination of the evaporite lithofacies in Rabigh and Ubhur indicates that they are composed of secondary porphyrotopic, granular, alabastrine and satin spar gypsum, and stair-step and felted anhydrite (Mandurah and Aref, 2010). Most of these textures are partially to completely mask the primary morphology of the evaporite minerals, unless if microbial micritic carbonate laminae are existed. The latter preserves the original morphology and fabrics of the deposited primary gypsum or halite crystals which makes possible reconstruction of the sedimentary environments.

Fig. 3. Gypsified rhizolithes at the base of the gypsum sequence at Wadi Gehfa, Rabigh area.

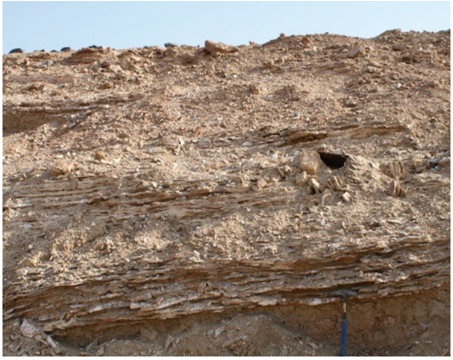


Fig. 4. Alternation of thin bedded gypsum dominated layers and clastic dominated layers in Ubhur area.

To interpret the depositional environments of the evaporite lithofacies, the results of the abovementioned diagenetic overprinting during burial and uplift are not taken into consideration. The primary depositional structures and textures that are preserved within microbial laminites and stromatolites structures are dealt with in this work. The interplay of the microbial structures (laminites and/or stromatolites) and gypsum deposition led to the subdivision of the evaporite lithofacies into four facies; these are: (1) Stromatolitic gypsum, (2) Skeletal gypsum, (3) Microbial laminated gypsum (irregular and regular), and (4) Nodular laminated gypsum. These facies variations point to minor changes in the physicochemical environmental conditions (such as water depth, salinity, agitation and the methods of emplacement of the gypsum crystals …*etc*.). It is important to note that the common association in all of the abovementioned facies is the microbial carbonate laminae which point to a very shallow salina or sabkha setting. The following is a description of the characteristics of these facies followed by the interpretation of their environmental conditions.

1. *Stromatolitic Gypsum*

This facies is recorded near the base of the gypsum sequence at Rabigh area. It is composed of wavy microbial carbonate laminae that form laterally linkage head of stromatolite type (Fig. 5). The stromatolite is formed of thick (3-5 cm) white gypsum layer that is interlayered with thinner (< 1 cm) greenish to brownish carbonate laminae (Fig. 5). On the bedding surface, the stromatolitic gypsum forms ripple-like morphology of irregular, non-bifurcated or bifurcated crests (Fig. 6). Close examination of the bedding surface shows the presence of concentric, elliptical to irregular white gypsum laminae surround the central green, domal patches of the microbial carbonate (Fig. 7).

Fig. 5. Laterally, close linked stromatolites type composed of white gypsum and greenish microbial carbonate laminae, Wadi Gehfa, Rabigh area.

Fig. 6. Surface exposure of ripple-like morphology of stromatolite type, Wadi Gehfa, Rabigh area.

Fig. 7. Truncation of the stromatolite layer into irregular, spherical isolated structure, Wadi Gehfa, Rabigh area.

Microscopic examination of this facies indicate the presence of clear zone composed of secondary gypsum and dark zone composed of dense microbial micrite. The secondary gypsum obscures completely the primary fabrics of the evaporites, unless microbial micritic filaments are existed. The microbial micrite is composed of dense micrite grains, sometimes with black organic materials that aggregated to form dense laminae (Fig. 8). The laminae may be continuous for a long distance or dissected into short parallel lamination. The microbial micrite laminae are relatively thin (< 200 µm), in contrast to the thicker (> 500 µm) gypsum laminae (Fig. 9). The growth of the porphyrotopic and granular gypsum usually intersect and enclose several areas of the former gypsum-microbial micrite lamination (Fig. 9).

The microbial micrite may preserve the lenticular and prismatic gypsum crystals structure within the thick micrite lamination (Fig. 10), or entrap and bind gypsum crystals by free floating of microbial filaments (Fig. 11). A pyramidal shape of successive microbial micrite laminae (Fig. 12), most probably point to a former crust composed of upward pointing chevron halite crystals.

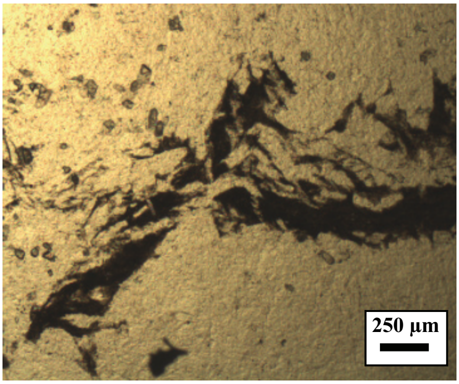


Fig. 8. Dense microbial micrite with displacive growth of prismatic gypsum crystals, Plane Light.

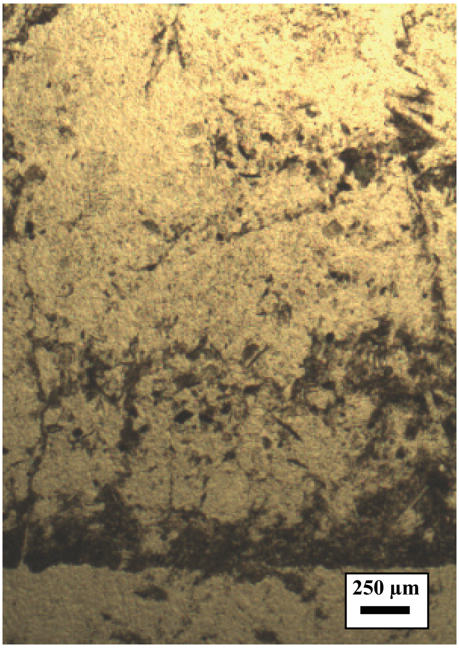


Fig. 9. Thin microbial micrite laminae entrap prismatic gypsum crystals, and thicker gypsum laminae without any morphology of the primary crystals, Plane Light.

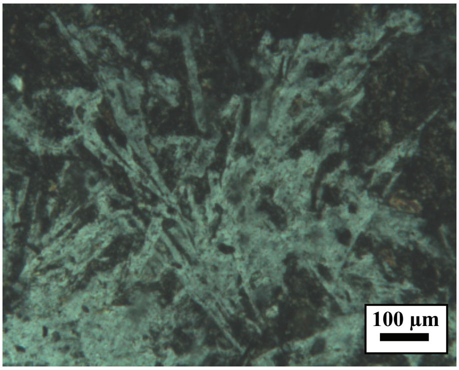


Fig. 10. Ghosts of prismatic and rosette gypsum in microbial micrite, Polars Crossed.

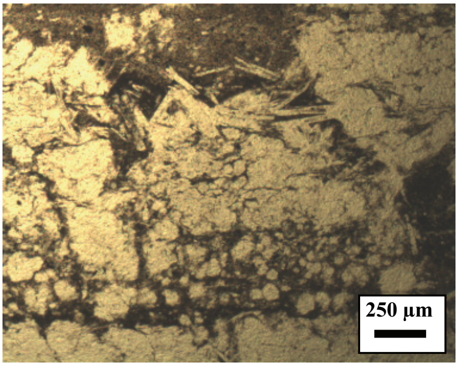


Fig. 11. Microbial micrite laminae preserve the nodular displacive structure at bottom and the morphology of sunken prismatic gypsum crystals, Plane Light.

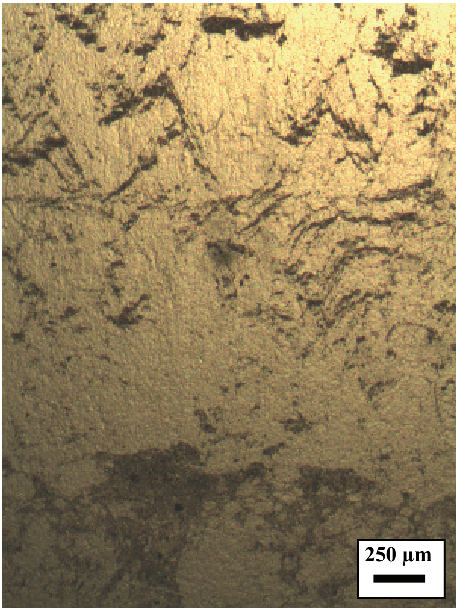


Fig. 12. Thin dark microbial lamina and thick gypsum lamina that encloses ghosts of pyramidal chevron of former halite crystals, Plane Light.

Environmental Interpretation

The sedimentary structures and textures in the gypsified stromatolite facies belong to the category of biologically induced physical structures, similar to that described from the peritidal environment of Mellum Island of the southern North Sea (Gerdes *et al.,* 1993; Noffke *et al.,* 1996; 1997; and Noffke, 1998). The existence of interlaminated gypsum and microbial micrite in a rippled structure is controlled by two dominant factors, namely depositional dynamics (hydrodynamic energy, water depth, wind speed, light intensity, salinity), and the activity of phototrophic microorganisms colonizing the sediment (Noffke *et al*., 1996).

The gypsum laminae indicate a relatively higher saline condition where initial deposition of coarser prismatic gypsum crystals from suspension in a relatively higher flow regime occurred. These coarse gypsum crystals sink on the surface of microbial mats, or are entrapped by microbial filaments (Fig. 8-11). In a response to a following phase of decreasing salinities and flow velocities, the grain size of the gypsum crystals decrease gradually to fine gypsum. The latter forms the major part of the gypsum laminae where microbial filaments are absent. After the hydrological energy has approached the minimum, and the salinity are suitable for microbial growth. Microphotobenthos colonize the freshly sedimented gypsum layer, initially forming biofilms, which after longer period of non- or low-rate of deposition reach a mat like condensation of organic matter (Fig. 10), similar to the observation of Noffke *et al*. (1997). Each microbial mat essentially represents a stage of low-rate deposition. During its development, grains still fall down on the mat and become glued together by the microbial slime (Fig. 8). The microbial mats are capable of a rapid gliding mobility, probably via gel excretion, which allows them to escape burial (Gerdes *et al*., 1993). By this means, the microbial filaments migrate from the buried mats during sedimentation of the coarse gypsum crystals to the freshly deposited new surface, where they grow and multiply to form a new mat. Noffke *et al.* (1997) gave another explanation for the silt sized crystals within the mats, and related them to the characteristic behavior of the mat forming filamentous cyanobacteria *Microcoleus cotonoplastes* to erect tufts perpendicular to the mat surface into the supernatant fluid. This functions as bafflers that may trap silt sized grains even during periods of moving water (Noffke *et al.,* 1997).

Increase in the hydrodynamic energy and salinity favors sedimentation of coarser gypsum crystals, which cover the microbial laminae. Reduced availability of light induced by burial of the microbial laminites serves as a trigger mechanism for their continuous growth. Concomitant with deposition of the coarse gypsum crystals is the slight agitation of the water by currents or waves, which favor the formation of rippled, non-cohesive sedimentary surface (Fig. 5). As a result of low sedimentation rates and low physical agitation, a microbial biomass accumulates on the sediment-surface of ripples favoring a cohesive, biostabilized surface. This biostabilized surface lamina leads to the conservation of the former physically induced rippled surface and prevents the destruction of the underlying ripples from subsequent higher flow condition.

2. Skeletal Gypsum

This facies is recorded overlying (with gradational contact) the stromatolitic gypsum (Fig. 13). It is composed of slightly reworked white prismatic and saber-like gypsum crystals (< 3 cm long) dispersed in greenish microbial carbonate mud (Fig. 14). Traces of dissected microbial carbonate laminae are partially observed between the skeletal gypsum and carbonate mud (Fig. 14). On the bedding surface, white scattered gypsum crystals are existed due to their perforation of the dark microbial carbonate laminae (Fig. 15).

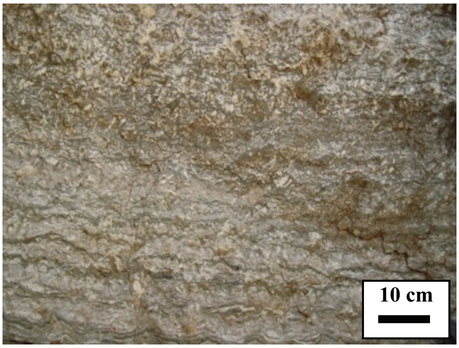


Fig. 13. Gradational contact between stromatolite laminae at bottom, and skeletal gypsum at top, Wadi Gehfa, Rabigh area.

Fig. 15. Scattered white gypsum crystals, surrounded with greenish microbial carbonate from the skeletal gypsum layer, Wadi Gehfa, Rabigh area.

Fig. 14. Random orientation of prismatic and saber-like white gypsum crystals in greenish microbial carbonate. Note the remains of microbial lamination (arrow), Wadi Gehfa, Rabigh area.

Environmental Interpretation

The small size of the prismatic and saber-like gypsum crystals may suggest rapid precipitation in a subaqueous environment and/or fluctuating environmental conditions (Warren, 1982), or it may be due to slight supersaturation of the bottom brines. The slightly inclined position of the gypsum crystals (Fig. 14) may be due to compaction of the gypsum crystals which were rotated, possibly because of mass movements, from an original horizontal position, where they grow mostly normal to the depositional surface. Such gypsum crystals may be also subjected to slight reworking, as described from the recent coastal salina of South Australia (Warren, 1982).

The dissected and disrupted nature of some microbial gypsum laminae within the skeletal gypsum facies is interpreted as a result of the physical forces generated from displacive crystallization of the gypsum crystals which lead to the disturbance of the rippled structure that was formerly stabilized by microbial mats. Very early displacive growth of such large gypsum crystals leads to the ductile upheaval of the soft microbial mats and disturbance of the rippled structure (Fig. 14).

3. *Microbial Laminated Gypsum (Irregular and Regular)*

This facies is recorded overlying the massive gypsum and forms the major parts of the gypsum quarries (Fig. 2). Two types are distinguished in the field; irregular laminated gypsum (Fig. 16) and regular laminated gypsum (Fig. 17) that may laterally grade to each other. No differences in the composition of both types are existed. They consist of slightly irregular or regular thin, yellowish, brownish or greenish microbial carbonate laminae and thicker white to pale grey, dark grey or pale yellow gypsum laminae (Fig. 16 and 17). The only difference between them is the common occurrence of horizontal satin-spar gypsum veins in the regular microbial laminated gypsum (Fig. 18). The gypsum veins occur in discontinuity surfaces between the microbial carbonate laminae and gypsum laminae. This is most probably took place during uplift of the evaporite sequence, where unloading result in the formation of open spaces (discontinuity surfaces) between the relatively hard carbonate laminae, and the relatively soft gypsum laminae (Warren, 1999; 2006). During formation of the secondary gypsum, the excess sulfate fills these discontinuity surfaces as satin-spar gypsum veins (Holliday, 1970).

Environmental Interpretation.

Microbial mats are often formed in shallow water evaporitic environments, as shown by their presence in many modern hypersaline lagoons and lakes (Walter, 1976; Bauld, 1981, 1984; Cohen et al., 1984; Friedman and Krumbein, 1985; and Gerdes and Krumbein, 1987), marine intertidal and supratidal areas (Fisk, 1959; Logan, 1961; Kendall and

Skipwith, 1968; Basyoni and Aref, 2009; and Taj and Aref, 2009), and large tide-free solar salt works (Schneider and Herrmann, 1980; Orti Cabo et al., 1984; Reineck et al., 1990; Cornée et al., 1992; and Aref, 2000 and 2008). Microbial mats are also identified in many ancient evaporitic stromatolites including the Archean of Western Australia (Lowe, 1983), the Permian of northern Poland (Gasiewicz et al., 1987), the Messinian of Cyprus (Rouchy and Monty, 1981), the Messinian of northern Egypt (Aref, 2003B), and the Miocene of Rabigh and Ubhur areas (Mandurah and Aref, 2010).

Fig. 16. Irregular intercalation of thicker grey gypsum beds and thinner yellow microbial laminae, Miqat Al-Gehfa, Rabigh area.

Fig. 17. Intercalations of regular grey and white gypsum and yellowish microbial carbonate laminae, Miqat Al-Gehfa, Rabigh area.

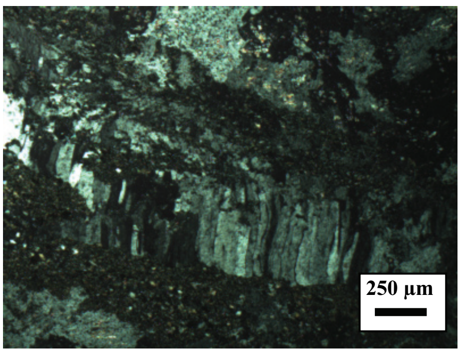


Fig. 18. Vertical arrangement of gypsum crystals in satin spar vein between microbial carbonate laminae, Polars Crossed.

In a semi-restricted coastal area behind a barrier, the supply of seawater led to the formation of a shallow coastal salina. When the salinity of the coastal salina ranges from 60 to 150 g/l, microbial mats can grow extensively on the bottom sediment. During higher salinity value (> 150 g/l), gypsum crystals nucleate from the brine and sink on the surface of the microbial mats. During burial of the microbial mats below the sunken gypsum crystals, they are inhibited to grow because of the higher salinity value. Replenishment of the brine with normal marine water decreases the salinity to 60-150 g/l, where microbial mats escape from burial and form new microbial laminae.

4. ***Nodular Laminated Gypsum***

This microfacies is recorded only in Ubhur area. Macroscopically, it is similar to the microbial laminated gypsum facies. It consists of interlamination of white gypsum laminae and yellow to pale red microbial carbonate laminae that are rich in fine siliciclastics (Fig. 19). Microscopically, the microbial carbonate laminae are composed of microbial micritic filaments that surround numerous small gypsum nodules (Fig. 20). The gypsum laminae are mostly composed of random prismatic gypsum crystals that are partially entrapped within microbial filaments (Fig. 21).

Environmental Interpretation

The interlamination of gypsum and microbial carbonate laminae, the dominance of gypsum nodules and the existence of reddish silt-sized materials, are factors that point to very shallow salina and supratidal sabkha environment of deposition. Similar to the microbial laminated gypsum facies, the microbial mats are formed in a shallow salina with low salinity value (60-150 g/l), and the gypsum crystals are precipitated from the brine at higher salinity value (> 150 g/l). Change of the shallow salina to supratidal sabkha condition is probably due to the decrease in marine water inflow relative to evaporation which favors lowering of the brine below the sediment surface of the sabkha. Resurgence of this brine that is saturated with respect to gypsum, through the microbial carbonate laminae led to displacive growth of gypsum nodules (Fig. 20). Similar features are described by Rosen and Warren (1990) from Bristol Dry Lake. Return of the supratidal sabkha environment to shallow salina as a result of the increase in marine water inflows favor free settling of prismatic gypsum crystals on the surface of microbial mats (Fig. 21).

Fig. 19. Intercalation of white gypsum laminae and reddish microbial carbonate laminae rich in silt-sized siliciclastics, Ubhur area.

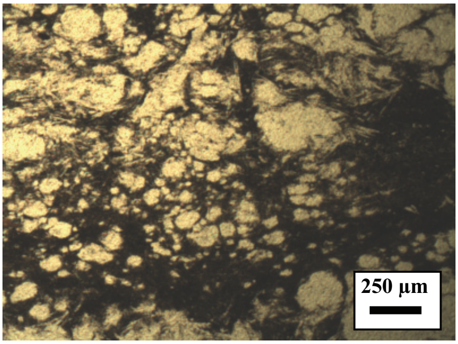


Fig. 20. Numerous displacive gypsum nodules in dark microbial micrite, Plane Light.

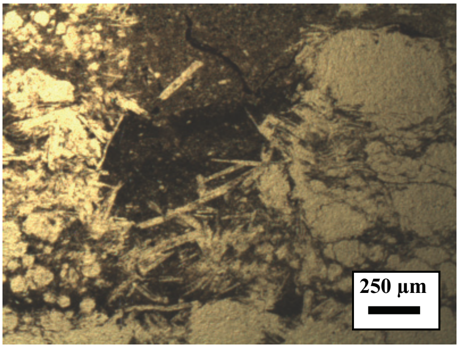


Fig. 21. Long prismatic and rosette gypsum crystals between displacive gypsum nodules in microbial micrite, Plane Light.

Depositional Environment of the Evaporites

The geological setting and sedimentological characteristics of the Miocene evaporites in Rabigh and Ubhur areas suggest that microbial mat growth and gypsum precipitation occurred dominantly in a marginal marine salina. Periodic subaerial exposure of the sediments to the supratidal sabkha setting may occur intermittently in Ubhur area, as evidenced by the common occurrence of displacive nodular structure.

The continuous supply of seawater to a shallow coastal salina led to extensive microbial mat growth at the salinity range of 60 - 150 g/l. The microbes grew subaqueously and formed mats on the bottom sediment. The decrease of water inflow with respect to evaporation result into restriction of the shallow coastal salina and the increase in salinity to over 150 g/l, where cyanobacteria could not survive and ceased to grow. At this condition, subaqueous precipitation of free falling gypsum crystals over the growing microbial mats is dominated.

Continued sediment accumulation (gypsum and microbial carbonate laminae) in the coastal salina, or uplift of the salina bottom, led to a change from salina to sabkha, where the sediment was perennially moistened by evaporative pumping or capillary water supply. This led to extensive growth of laminated microbial mats on the sediment surface. Gypsum nucleated displacively within and between microbial mats from saline groundwater.

The internal lamination of microbial stromatolites and laminites resulted from seasonally oscillating water depth and changes in salinity. During winter, with the increase in water depth and decrease in salinity, microbial mats became dominant. The reverse conditions occurred during summer, leading to displacive growth of gypsum nodules from saturated groundwater within the microbial mats (Fig. 20).

Cornée *et al.,* (1992) and Noffke *et al., (*1997) pointed out that the maximum production of microbial mats occurs in extremely shallow waters (2-12 cm depth) in the upper intertidal zone. The effects of currents and waves led to the formation of ripples in the non-cohesive deposited gypsum crystals. Decrease in flow velocity favors growth of microbial mats on top of the ripples, which lead to their biostablization from subsequent higher flow regime. Gerdes *et al.*, (1993) found that sediment stabilization by microbial mats starts in the upper intertidal zone and increases towards the supratidal zone. Pope *et al.*, (2000) found that the lack of subaerial exposure surfaces, mud cracks, flat pebble conglomerates and troughs filled with clastic carbonates, in addition to evenly laminated stromatolites suggest that the deposition of stromatolites was shallow enough to be influenced by wave-generated or wind-generated currents. Therefore the stromatolite facies in Rabigh area was formed in the marginal marine part of very shallow salina (upper intertidal and lower supratidal zone), without a prolonged period of desiccation. Subsequently after deposition of the stromatolitic gypsum in the marginal evaporite flat, the skeletal gypsum crystals were formed in a brine pan characterized by deeper water and higher salinity.

Summary and Conclusions

The Lower Miocene evaporites of Dafin and Ubhur formations outcrop in Rabigh and Ubhur areas, respectively. They are composed of secondary gypsum rocks that are mantled with thin anhydrite crust. The existence of microbial carbonate laminae help in preservation of the primary structures and textures of the evaporites which help in interpretation of their depositional environment. Four evaporite facies are distinguished, which are: (1) Stromatolitic gypsum, (2) skeletal gypsum, (3) microbial laminated gypsum, and (4) nodular laminated gypsum. The first three facies are formed in shallow coastal salina, whereas the last facies is formed in a supratidal sabkha.

The prevalence of microbial mats in laminated, stromatolitic and nodular forms suggests: (1) Sufficient oxygenation; (2) continuous supply of nutrients from seawater influx; (3) good light penetration in very shallow waters, and (4) the absence of grazers and burrowers (Kendall and Skipwith, 1968; Warren, 1982; Cornée *et a1.,* 1992*).*

Precipitation of gypsum is either through free settling of prismatic crystals from the saline water body, or by displacive growth from resurgent groundwater. These gypsum crystals are usually entrapped by microbial filaments, which lead finally to the formation of interlaminated gypsum-rich laminae and microbial carbonate-rich laminae.

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الطباقية الصخرية، التفسير ألسحني وبيئة الترسيب لجبس الميوسين السفلى الاستروماتوليتي والصفائح الميكروبية، مناطق أبحر ورابغ، شاطئ البحر الأحمر، المملكة العربية السعودية

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المستخلص. تتبع متبخرات الميوسين السفلي في مناطق رابغ وأبحر عضو الجحفة لمتكون رابغ ومتكون أبحر، على التوالي. يتكون تتابع المتبخرات في منطقة رابغ من جذور نباتية متجبسة (تكونت في بيئة سبخة شاطئية) وتتابع سميك من الاستروماتولايت الجبسي والصفائح الميكروبية والجبس الهيكلي (تكون في بيئة بحرية ضحلة). وهذا التتابع يعلو متوافقًا الفتاتيات النهرية لعضو الحكاك التابع لمتكون دافن. أما في منطقة أبحر، فإن تتابع المتبخرات يتكون من الصفائح الميكروبية الجبسية والتي تكون غنية بالغرين، والتي تكون شكل العناقيد الملتحمة. تكونت متبخرات أبحر في بيئة سبخة شاطئية، والتي أنغمرت لفترات بسيطة في منطقة المد والجزر.

تشير الدراسات المجهرية لمتبخرات رابغ وأبحر إلى شيوع الجبس الثانوي المغطي بقشرة من الأنهيدرايت. توجد بقايا من بلورات أولية من الجبس ألمنشوري والعدسي والوردي في المناطق الغنية بالصفائح الميكروبية.

يشير انتشار أشكال الاستروماتولايت والصفائح الميكروبية على تكونها في أجاج قليل الملوحة (٦٠–١٥٠ جرام/لتر)، غياب الكائنات الآكلة والمثقبات، وتوافر الأكسجين في بيئة ترسيب فوق مدية وشاطئية ضحلة. أما صفائح الجبس فإنها تشير إلى ملوحة عالية نسبياً للأجاج (> ١٥٠ جرام/لتر) وترسيبها دائمًا في بيئة بحرية ضحلة. يستدل على الانكشاف المتقطع للمتبخرات البحرية بوجود جذور نباتية متجبسة ونمو بالإزاحة لعنقوديات جبسية ملتحمة.