CLASSIFICATION AND INTERPRETATION OF THE QUATERNARY GYPSUM CRUSTS (GYPCRETE) IN AYUN MOUSA AREA, WEST SINAI, EGYPT.

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Abstract: A thick (< 25 m) Middle Miocene Globigerina marl bed that includes several gypsiferous layers is widespread in the area of Ayun Mousa that form scattered isolated hills (mesas and buttes). The top part of the marl bed and some of their steep slopes are mantled with less than 4 m thick gypsum crusts (gypcrete). Three gypsum crusts are recognized, they are: (1) Subsurface lenticular to rosette gypsum crust, (2) Microbial to stromatolitic gypsum crust, and (3) Non-bedded gypsum crust.

The subsurface lenticular and rosette gypsum crust is composed of single lenticular (1-3 cm in size) and coarse (10 cm) rosette gypsum that grow displacively at the upper 1.5 m of the marl layer. This layer is a hydromorphic crust that formed at or near the water table from groundwater saturated with gypsum. The microbial and stromatolitic gypsum crust has a thickness of ~40 cm that composed of interbedding slightly irregular microbial laminae, or composed of laterally linked stromatolite. They are formed in a shallow ephemeral saline pond. The non-bedded gypsum crust is composed of 3-15 cm in size gravel fragments cemented with cemented with microcrystalline and alabastrine gypsum. This crust is formed either through the dissolution and leaching of gypsum from the gypsiferous horizons by pedogenic process, or from accumulation of wind derived gypsum sand and silt and their redeposition by rainwater.

Therefore, the gypsum crusts that mantle the Middle Miocene Globigerina marl can be correlated with the Quaternary pedogenic gypsum crusts in the Nile Valley (Aref, 2003a), and in Jordan (Turner and Makhlouf, 2005) and of Quaternary age. The existence of the multiple gypsum crusts gives useful information on the paleotopography and paleoclimate of the study area.

INTRODUCTION

In Egypt, there are extensive literatures on duricrusts composed of calcite (calcrete) from the Red Sea (El Aref *et al.*, 1985), El Bahariya-El Farafra Oases (Abu Khadra *et al.*, 1987; El Sayed, 1995), and the coastal ridges of the Mediterranean Sea (El Shahat *et al.*, 1987, Rashed, 1998), silica (silcrete), Abdel-Wahab *et al.* (1998), El Sayed (2002), and iron oxides (ferricrete), El Aref *et al.* (1990); Abdou-Soliman, *et al.* (2001).

In spite of the widespread occurrence of gypsum crusts in the arid region of the Middle East such as in Libya (Mckee and Moiola, 1975), Tunisia (Watson, 1985 and 1988), Algeria (Horta, 1980), Jordan (Turner and Makhlouf, 2005), Saudi Arabia (Johnson, 1978), Bahrain (Brunsden *et al.*, 1976), Iraq (Tucker, 1978) and Kuwait (El sayed, 1993). The only record of gypsum crusts of pedogenic origin (gypcrete) is recently described by Aref (2003a) in the Nile Valley at Girza and Qattamia areas.

Gypsum crust is a significant pedologic and geomorphologic features that is produced by terrestrial processes within the zone of weathering in which gypsum has dominantly accumulated in and/or replaced a pre-existing soil, rock or weathered materials, to give a substance which may ultimately develop into an indurated mass (Goudie, 1973). Watson (1985) gave the following specification of gypsum crusts: (1) a minimum thickness of 0.1 m, (2) a minimum gypsum content of about 15% by weight (D'Hoore, 1964), and (3) a gypsum content at least 5% greater than the underlying rocks (Buringh, 1968). If the soil contains less than 15% gypsum it is classified as gypsiferous soil.

The purpose of the present work is to investigate and classify the gypsum crusts (gypcrete) in Ayun Mousa area, west Sinai. A genetic model for the gypsum crusts formation is useful to provide valuable information of the paleotopography, paleoclimate and paleoenvironment on the Quaternary epoch in the study area.

A. GEOLOGIC SETTING.

Ayun Mousa area is located west of Sinai Peninsula near the eastern side of the Gulf of Suez (Fig. 1). The area is generally peneplained that is dominated by flat topped hills (mesas and buttes). Toward the east, the area is bounded by Gebel Raha that stands at 300 m above the low ground to the west (Said, 1962). Gebel Raha is composed of Eocene bedrocks (Mokattam Formation) that unconformably overlies the Cretaceous rocks (Sadek, 1959). At the foot of Gebel Raha, flat gravel terraces cemented with gypsum form indurated gypsum crusts (gypcrete), about 30 m above sea level is widespread that slopes gradually to the sea shore. Below the gypsum crusts, is a thick layer of Middle Miocene green shale and marl with veins of halite and selenite and rich in shells of Globegerina (Sadek, 1959). Further west, raised beaches of Pleistocene age is also recorded by Sadek (op. cit). A clastic dominated sabkha is recently formed after the construction of the asphaltic road in 1976 (Wali *et al.*, 1991). The sabkha is covered by efflorescent gypsum and halite crusts, and contains at least two gypsum dominated layer at depth.

B. GYPSUM CRUSTS.

B. 1. Field Description.

The Sinai side against the Martyr Abdel Monem Reyad tunnel, is generally a monotonous flat area that extends to the north of Ayun Mousa, where the first appearance of flat topped hills is existed. The hills, 8-30 m in height, show serrated boundaries that outline numerous depressions which formed part of the defense of this outpost during the Egyptian-Israeli wars. The hills themselves have military importance

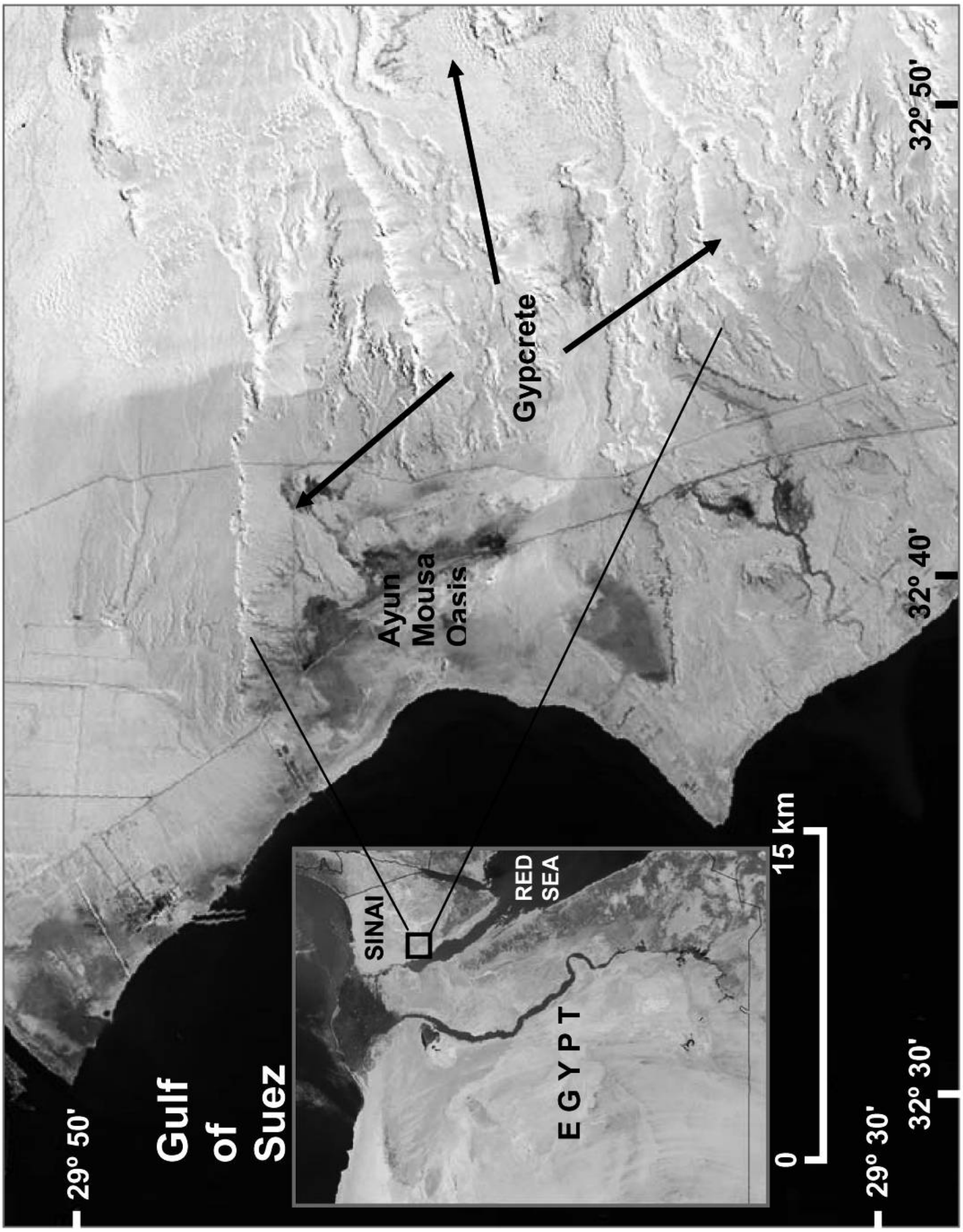


Fig. 1: Location of gypsum crusts (gypcrete) in Ayun Mousa area, west Sinai, Egypt.

as they are used by the Israeli occupation to build the famous Barleef Line (Fig. 2) that was damaged during the 1973 war.

The flat topped hills extend to the south of Ayun Mousa Oasis, and form some scattered hills near the foot of Gebel Raha to near the sea coast (Fig. 1). The hills are composed mainly from greenish marl that capped with 1.5 to 4.0 meters thick gypsum crusts. The hills show a characteristic gentle slope for the soft marl layer and steep slope or overhang for the more resistant gypsum crusts (Fig. 3). The lower marl unit encloses several layers of Globigerina of Middle Miocene age (Sadek, 1959).

The contact between the lower marl unit and the overlying gypsum crusts may be gradational from dominant marl with inclusions of lenticular, rosette, and nodular gypsum to dominant gypsum cement with inclusion of marl fragments.

The gypsum crusts are composed of up to 40 cm thick bedded gypsum that shows irregular microbial to stromatolitic structures. This layer is overlain by up to 4 m thick bed composed of gypsum cementing gravels.

B.2. Classification of gypsum crusts:

In the present work, the terms used to classify the gypsum crusts in Ayun Mousa area are those used by Watson (1985 and 1988), Watson and Nash (1997), with some modification. Three main types of gypsum crusts are differentiated, they are from base to top:

1. Subsurface lenticular to rosette gypsum crust.
2. Microbial to stromatolitic gypsum crust.
3. Non-bedded (massive) surface gypsum crust.

The following is a description of each type.

B.2.1. Subsurface lenticular to rosette gypsum crust:

This crust occurs at the top part of the green marl layer, with a thickness ranges from 70 cm to 150 cm. It is similar in composition, morphology and origin to the desert rose crust of Watson (1985). This crust is composed dominantly of interlocking aggregates of lenticular gypsum crystals that develop rosette pattern (Fig. 4), or composed of random single lenticular gypsum (Fig. 5). Rosette gypsum has size up to 10 cm that composed of random arrangement of 1-3 cm in size lenticular gypsum (Fig. 6), that enclose green marl material in-between, and within the growing lenticular gypsum crystals. These rosette aggregates may be fluted vertically along the boundaries due to dissolution by downward percolating meteoric water (Fig. 7). The distribution of the rosettes is characteristic that the fine crystals and small size of the rosettes occur at the top of the marl layer that increase to coarse gypsum crystals, and large rosette at depth of ~150 cm from the top of the marl layer.

B.2.2. Microbial to stromatolitic gypsum crust:

This crust is recorded sporadically over the rosette gypsum crust and below the non-bedded (massive) gypsum crust. The general bedding characteristic of this crust is similar to the horizontally bedded gypsum crusts of Watson (1985). This crust has irregular top boundary with the overlying non-bedded gypsum crust, and range in thickness from 20 cm to 40 cm. It is composed of either horizontal, slightly irregular gypsum beds (Fig. 8) similar to the microbial gypsum lamination in modern sabkha setting (Aref, 2004), or in Holocene (Aref, 1998) and Miocene (Aref, 2003B) sequences, or is composed of hemispheroidal layers that form laterally close linked hemispheroid stromatolite type (Fig. 9) of Logan *et al.* (1964) and Aref (1998).

The slightly irregular microbial and the hemispheroids are composed of 4-12 interbedded thick (<7 cm) white gypsum layer and thinner (<2 cm) green marl layer. The gypsum layer is composed of random to radial aggregate of rosette gypsum.

B.2.3. Non-bedded (massive) surface gypsum crust:

This gypsum crust is persistent all over the area of Ayun Mousa, capping directly the marl layer, or the rosette gypsum crust, or the stromatolitic gypsum crust. The thickness of this crust ranges from 90 cm to 4 m. it is composed mainly from gravel cemented with gypsum, and appear to be more resistant than the underlying gypsum crusts and marl layer (Fig. 10). Gravel fragments range in size from 7 cm up to 30 cm, composed mainly from dolostone, limestone, chert and minor chalk fragments. Some of the dolostone fragments show leaching of the nummulites, and other show casts of unidentified fossils. Some of the large fragments are encrusted with several concentric gypsum laminae (Fig. 11). Most of the distribution of the gravel fragments within gypsum is random, that mainly increase in density toward the top of the gypsum crust (Fig. 12).

The gypsum cementing the gravels is powdery to massive crystals that composed of either very fine gypsum crystals, or millimeter size lenticular aggregates. This gypsum crust may enclose vertical dissolution lines that are filled with aggregates of coarser single to lenticular gypsum (Fig. 13). This indicates the crystallization of gypsum in a pathway of downward percolating rainwater.

B.3. Interpretation.

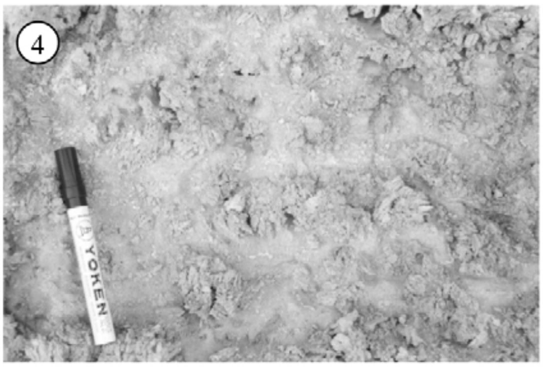
B.3.1.Subsurface lenticular to rosette gypsum crust

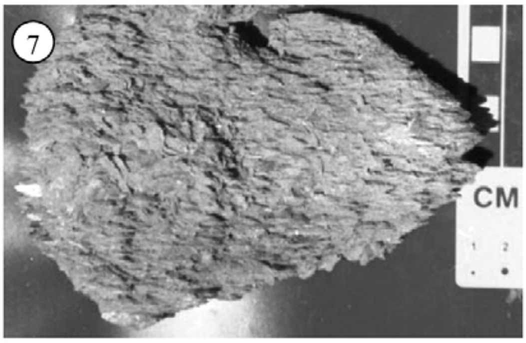
The single lenticular and rosettes of gypsum that enclosed within marl sediment are formed in continental or coastal evaporite basin (sabkha). Groundwater saturated with $CaSO_4$ invades the marl layer, and during increased phase of evaporation, gypsum precipitated as single lenticular crystals close to the sediment surface, and as aggregates of lenticular crystals that form rosette pattern at or near the water table, similar to the desert rose gypsum recorded in west Saudi Arabia (Basyoni *et al.*, 2006), and in Tunisia (Watson, 1985 and 1988). Watson (1985) interpret a similar desert rose crust as hydromorphic accretion, which precipitate in host sediments at or near surface water tables through evaporation of the groundwater.

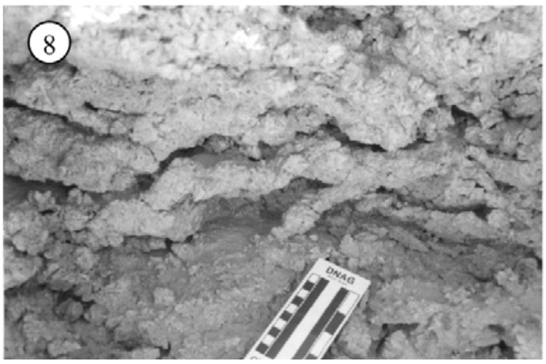
The dominant lenticular habit is due to the existence of humic acid derived from decayed terrestrial plant materials (Cody and Cody, 1988; Aref, 1998). The increase in crystal size of the gypsum is related to the long resident time and slow growth rate at or near the water table (Aref, 1998). Fluctuation of the groundwater is responsible for the occasional random distribution of coarse rosette gypsum through the top part of the marl layer.

B.3.2.Microbial to stromatolitic gypsum crust:

Following the groundwater saturated top part of the marl layer, is filling of some depressions on top part of the marl layer with much saline or brackish water that form shallow saline pond. The water may come from uprising of the groundwater, or surface runoff to fill the lowest part of a depression. When the pond is filled with ephemeral water, the increase in salinity to 80 g/l, favor the flourishing of microbial mats that cover the marl sediment surface. Increase in the salinity to 250 g/l favor growth of lenticular gypsum that encrusted, or enclosed within the microbial layer, similar to observation in modern sabkha setting by Cornee *et al.* (1990), Aref *et al.*







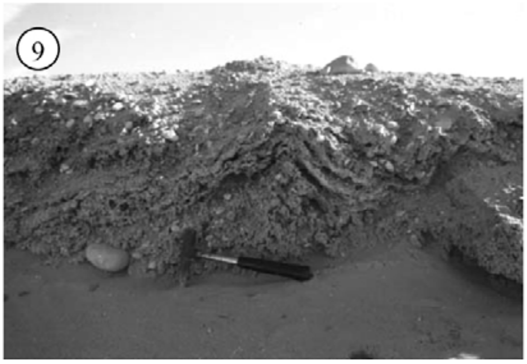


Fig. 2: Military towers and equipments of the Exhibition of the destructed Parleef Line on top of the hills encrusted with gypcrete.
Fig. 3: Hard indurated gypsum crusts (gypcrete) form cliff, on the gentle slope of the marl layer.
Fig. 4: Random distribution of rosette gypsum enclosed in marl that constitute the rosette gypsum crust.
Fig. 5: Single lenticular gypsum scattered and enclosed in the gypsum crust.
Fig. 6: Random distribution of lenticular gypsum that constitute the rosette structures.
Fig.7: Elongated dissolution lines (flutes) from percolated rain water in rosette gypsum.
Fig. 8: Slightly irregular microbial layer of white gypsum and partially eroded clay sediments that for the microbial gypsum crust.
Figure 9: Laterally close linked hemispheroid stromatolite type that form the stromatolite gypsum crust.

Fig. 10: Resistant gravel cemented with gypsum crust over the marl layer.
Fig. 11: Carbonate fragment surrounded with multiple concentric gypsum laminae in the non-bedded gypsum crust.
Fig. 12: Thick section of fluvial gravel cemented with gypsum that form resistant non-bedded gypsum crust.
Fig. 13: Filling of a downward dissolution pathway with fine gypsum rosettes from percolating rain water.

(1997) and Aref (2004).

When the depression is filled with permanent shallow saline water, laterally close linked hemispheroid stromatolite type is grew due to: (1) escape of organic gasses from decayed subsurface microbial mat (Noffke et al, 2001), (2) Entrapment of gypsum crystals by filamentous cyanobacteria, or nucleation of gypsum crystals at the apex of the hemispheroid is more rapid than that in depression, following by adaptation of the microbial mats on the new surface of the deposited gypsum crystals, and (3) Deposition of much fine clastic materials from suspension in depression between the hemispheroids. The sporadic distribution of this layer is controlled by the existence of depressions on top of the marl layer, and the pattern of the inflowing water that feed these depressions.

B.3.3 Non-bedded (massive) surface gypsum crust:

Unlike the rosette gypsum crust which is restricted to areas of groundwater saturated with gypsum, or the microbial to stromatolitic gypsum which is confined to ephemeral to perennial saline pond, the persistent distribution of the non-bedded gypsum crust all over the study area (marl layer at Ayun Mousa) point to a widespread source of $CaSO_4$. The derivation of the $CaSO_4$ is believed to come from the marl layer through pedogenesis as evidenced by: (1) The non-bedded gypsum crust occurs at the top of all marl hills with different elevations from 9 m to 30 m, and at the flanks of the marl hills, (2) The enrichment of the marl layer with gypsum veins, and (3) the occurrence of the gypsum cement below the fluvial gravel terraces.

During humid period of the Pleistocene, rainfall over the marl layer lead to dissolution and leaching of gypsum and form groundwater saturated with $CaSO_4$. During arid period, the $CaSO_4$ enriched groundwater is moved upward through the gravel terraces by the evaporative pumping mechanism of Hsü and Siegenthaler (1969) that lead to rapid precipitation of fine gypsum crystals between the gravel fragments.

Continued deposition of the evaporite crystals near the boundary of the marl layer and the overlying gravel terraces lead to the formation of massive gypsum horizon, with few scattered gravel fragments at bottom, and gypsum cemented open-work gravel structure near the top. The abandoned distribution and variable density of the gravel fragments within gypsum cement is related to the growth density of the gypsum crystals, that controlled by enrichment of $CaSO_4$ in the supplying groundwater.

A second possible source of some of the gypsum in the non-bedded gypsum crust may be derived from wind deflation of the Middle Miocene gypsum that may be totally eroded in the area of Ayun Mousa, or derived from the evaporite sequence close to Ras Sudr. The wind blown gypsum is deposited as gypsum sand and silt over the gravel terraces. After period of rainfall these sandy and silty gypsum are dissolved and infiltrate downward to form groundwater enriched in $CaSO_4$ at the top of the marl layer. During arid period, gypsum is precipitated rapidly as very fine crystals below and between the gravel fragments. The wind deflation source of the non-bedded gypsum crust is also described from Iraq (Tucker, 1978), Tunisia and Namibia (Watson, 1985 and 1988), and in Jordan (Turner and Makhlouf, 2005).

C. SUMMERY AND CONCLUSIONS

Gypsum crusts mantle the Middle Miocene Globigerina marl hills in Ayun Mousa area from the foot slope of Gebel Raha at east to near the Gulf of Suez coast to the west. These gypsum crusts play an important role in protecting the marl hills from subsequent erosion. Therefore, the marl hills which are mantled with gypsum crusts form high hills, 5-30 m in height, that surround local depressions. Surrounding the positive relief of the marl hills is a monotonous flat plain to the north of the entrance of the tunnel of the Martyr Abdel Monem Reyad.

Gypsum crusts are subdivided into three main types on the basis of structural criteria and depositional condition. Those formed by evaporation of groundwater at or near the water table by displacive mode of growth are characterized by the occurrence of single lenticular and rosette gypsum crystals that enclose marl material from the host sediment. Those formed in ephemeral saline ponds located in topographic depressions on top of the marl layer, and show changes in salinity, is characterized by the occurrence of slightly irregular microbial layering and laterally close linked hemispheroid stromatolite type. Those formed through pedogenic process is characterized by gravel fragments cemented with microcrystalline to alabastrine gypsum. The source of gypsum in the pedogenic gypsum crust is either the gypsiferous horizon in the marl layer, or wind deflation of gypsum sand and silt from the surrounding Miocene evaporites (now eroded). Percolation of meteoric water through the gypsiferous horizon in the marl layer or through the wind driven gypsum sand and silt, leads to dissolution and leaching of gypsum to the lower soil horizon. The gypsum enriched groundwater is held in the soil zone until subsequent evaporation, which favor rapid deposition of fine gypsum crystals around and below the gravel terraces. Repetition of these processes precipitates much gypsum cement to form a thick crust (~4 m) that encloses the gravel fragments. Watson (1985) argued to the inconsistence of the aeolian model in the case of the frequent presence of lag gravel on top of the surface crusts. The deposition of these coarse-grained materials cannot post-date gypsum accumulation. The size of some of these boulders preclude the possibility that they translocated upward through surface sediments by cycling wetting and drying causing volumetric changes in clay minerals or gypsum (Cooke, 1970).

The stratigraphic setting of the gypsum crusts and their lateral correlation with similar gypsum crusts in the Nile Valley by Aref (2003A), and in Jordan by Turner and Makhlouf (2005) argue for Late Pleistocene or Early Holocene age for the studied gypsum crusts in Ayun Mousa area.

In conclusion, the most likely source of gypsum in all crusts is the gypsiferous horizons in the Globigerina marl layer. The precise mechanisms involved in the formation of each type varies from rise of the groundwater for the rosette gypsum crusts, to formation of ephemeral shallow evaporite pond for the microbial to stromatolitic gypsum crust, to illuvial accumulation of gypsum by pedogenic process for the non-bedded gypsum crust.The recognition of these characteristic structural features in relict gypsum crust can provide information about the geomorphic history and paleoenvironment of this arid region during the Quaternary.

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