Classification and depositional environments of Quaternary pedogenic gypsum crusts (gypcrete) from east of the Fayum Depression, Egypt

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Abstract

The eastern boundary of the Fayum Depression (45 m below sea level) is bounded by a 99-m-high hill (inselberg of Girza) that slopes gently eastward towards the Nile Valley. The inselberg and the surrounding plain are encrusted with 50–130-cm-thick gypsum crusts that exhibit well-defined pedogenic horizons. Also, east of the Nile Valley, the Qattamia plateau is encrusted with gypsum crusts that form 50-m-wide ‘pavements’ that are scattered at different levels. The gypsum crusts range in thickness from 20 to 50 cm, and do not form characteristic vertical horizons. The individual gypcrete pavements exhibit massive mottled or powdery structure. Using structural, fabric and textural criteria, three main types of crusts are distinguished: (1) Eluvial horizon—massive to spongy-like powdery gypsum crusts, found at the land surface and consisting of gravels and sands cemented with gypsum; (2) Illuvial horizon A—massive indurated gypsum crusts that consist dominantly of white gypsum with horizontal and sub-vertical black gypsum veinlets; (3) Illuvial horizon B—massive mottled gypsum crusts that consist of carbonate or shale fragments floating in gypsum cement. Petrographically, the gypsum crusts in the Girza and Qattamia areas comprise a varying abundance of microcrystalline, fine lenticular, coarse lenticular, porphyroblastic, prismatic or poikilotopic gypsum. Lenticular and microcrystalline gypsum crystals are usually observed filling rhizotubules in all crusts. The origin of the gypsum crusts is related to pedogenic processes which involved the leaching of gypsum from the underlying, or adjoining, gypsiferous shale or marl layers and the subsequent displacive crystallization of gypsum in the upper soil horizon. Cycles of wetting (rainfall) and drying are believed to account for the dissolution and translocation of gypsum from the upper eluvial horizon and its recrystallization as microcrystalline and fine lenticular gypsum in the illuvial horizon A. The poikilotopic gypsum crystals in the illuvial horizon B reflect the abundance of gypsum-enriched groundwater in the phreatic zone. The dominant processes of gypsum growth are by displacive and/or inclusive crystallization, reflecting formation in pedogenic setting. The existence of gypsum crusts capping the inselberg and the surrounding plain of Girza area resist eastward deepening of the Fayum Depression. On the other hand, the gypsum crusts on the surface of the Qattamia plateau favor the development of relief inversion due to the removal of the surrounding soft materials. Therefore, the gypsum crusts provide useful paleoclimatic and geomorphic indicators to the study areas.

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1. Introduction

Gypsum crusts have been reported from all the continents, including Antarctica and are found in many arid regions, generally where throughout the year mean monthly potential evaporation exceeds mean monthly precipitation (Watson, 1985). Gypsum crusts and soils are defined as surficial and penesurfacial accumulations that have the following specification (Watson, 1985): (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. Watson (1985) also grouped the consolidated gypsum, together with weakly cemented and powdery gypsum accumulations under the term gypsum crusts.

In Egypt, there are extensive literatures on duricrusts composed of calcite (calcrete), e.g. the Red Sea region (El Aref et al., 1985, 1986); 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) (El Aref and Lotfy, 1985; El Aref et al., 1987; El-Sayed, 2002), and iron oxides (laterite, ferricrete) (El Aref et al., 1990). However, nothing was mentioned on surface crusts of pedogenic origin composed of gypsum (gypcrete, gypsite or crouˆte gypseuse zonée). This in spite of the fact that gypseous soils and gypsiferous beds are widespread in the semiarid and arid climate of Egypt.

In the present study, a clear distinction between chemical evaporite sediments and weathering residue is needed. The familiar evaporite is that produced by brines concentration of marine, meteoric, groundwater or thermal water due to heating or cooling and is accumulated by chemical, biological or physical processes. On the other hand, 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). Processes of dissolution and recrystallization in the gypsum crusts usually produce gypsum textures that are very similar to that in the chemical evaporite sediments. However, the gypsum crusts may exist at different topographic elevations and slopes and have distinctive vertical horizons that are absent in the chemical evaporite sediments.

The purpose of the present work is to investigate gypsum crusts (gypcrete) in two locations in the north central part of Egypt; Girza area and Qattamia area (Fig. 1). This work is based on stratigraphic, geomorphic and micropetrographic criteria of the gypsum crusts, which helped in interpretation of the processes involved in the evolution and diagenesis of the various gypsum crusts. Finally, genetic and depositional models of gypcrete formation are achieved which provide valuable paleotopographic, paleoclimatic and paleoenvironmental information on the Quaternary epoch in the study areas.

2. Geologic setting and geomorphology

In spite of the fact that the carbonate rocks (Cretaceous and later sediments) constitute about 450,000 km², about one-half the total surface area of Egypt (Fig. 1), the gypsum crusts are recorded only capping the Middle Eocene carbonate rocks that are interbedded with thick gypsiferous shale beds in the north central part of Egypt. In Girza area, the gypsum crusts are capping different stratigraphic formations (Fig. 2), the oldest of which is the Middle Eocene Ravine beds (Gehannam Formation) that consist of gypsiferous shale, marl, limestone and sandstone (Strougo and Haggag, 1984). The Ravine beds form the inselberg of Girza (Gebel Gerzah) that reach a height of 99 m and overlooking the Fayum Depression that reach a depth up to 45 m below sea level at Lake Qarun. Near the top part of the inselberg of Girza, the gypcrete is recorded capping the early late Pleistocene polygenetic gravels of the Abbasia Formation (Fig. 2) that are mainly derived from the basement rocks of the Red Sea region (Said, 1981).
Said (1981) point to the occurrence of gypseous paleosol on top of the Abbasia Formation in the western bank of the Nile Valley and termed it as ‘Gerza Formation’. According to Said (1981), the gypseous soil is of early late Pleistocene in age which indicate deposition at an interval of aridity that extends from the end of Acheulian to the Mousterian–Aterian times, an interval which extend for about 40,000 years. On the other hand Beadnell (1905) and Abdallah and El-Kadi (1974) believed that the gypseous deposits of Girza is post-Upper Pliocene in age.
Fig. 2. (A) Geologic map of Girza area, Nile Valley, Egypt (modified after Conoco Coral Egypt, 1989). (B) Distribution of the different gypsum crusts in Girza area.
Around the inselberg of Girza, the gypsum crusts are capping the plain surface of the Nile sediments from the height of 40 m to almost every rock types near the cultivated land of the Nile Valley (Fig. 2A). On the other hand, the Qattamia area forms an elevated plateau (<120 m in height), which is dissected by several steep-sided wadis. In the north and west the plateau slopes gently, whereas the southwestern part is dissected by the steep quarry cliffs of the cement companies. The Qattamia plateau consists of the highest formations of the Middle Eocene (Wadi Garaw Formation) and the Upper Eocene (Wadi Hof Formation). The Wadi Garaw Formation consists of variegated gypsiferous clay, marl and sandy marl with few shell banks near the top (Strougo and Abd-Allah, 1990). Wadi Hof Formation is lithologically similar to Wadi Garaw Formation, but contains much sandier layers with a common sandy dolomitic intervals. The gypsum crusts are recorded at different levels on the plateau surface as well as on the gentler slope sides of the wadis.

The precise age determination of the gypsum crusts in the Qattamia area are not treated before as most workers are directed to the stratigraphy and Paleontology of the Eocene in the Qattamia and Helwan areas. However, because the gypsum crusts are found as surficial deposits restricted only to the gypsiferous clay of the Middle Eocene Wadi Garaw Formation and are not recorded to the east, where the Oligocene and Miocene sediments are widespread, therefore they may be equated with the nearest gypsum crusts of Girza area, which cap the datable early late Pleistocene gravels of the Abbasia Formation. Here, a post early Late Pleistocene age is the most probable age of gypsum crusts in the Qattamia area.

3. Gypsum crusts (gypcrete)

3.1. Field occurrence and distribution

In Girza area, the gypsum crusts are continuously covering all the land area between the Fayum Depression and the Nile Valley (Fig. 2A), giving the surface the appearance of possessing an extensive pavement. The gypsum crusts rest directly upon soft gypsiferous shale beds interbedded with thin fractured limestone in the Girza inselberg, thus preserving the paleotopography from wind erosion and weathering. They also mantle the pediment slopes of the inselberg as well as the plain area between the Fayum Depression and the Nile Valley (Fig. 2). They rest over Pliocene carbonate and gravels as well as Pleistocene gravels. The gypsum crusts commonly create the mesa and butte landscapes around the Fayum Depression, where they cap the less durable, soft, thick (15 m) gypsiferous shale beds (Fig. 3A). The gypsum crusts are of not uniform thickness, they are thinner (<50 cm) at the summit of the inselberg and near the cultivated land of the Nile Valley, whereas they are thicker (130 cm) at the lower pediment slope of the inselberg (Fig. 2B). The gypsum crusts are whitish, grayish or brownish in color that are present as cementing materials to gravels, sands, shale or carbonate fragments. At the elevation of 40 m, small channels, of northward orientation, are cutting the gypsiferous shale layers. The channels are composed of fine laminated sand that enclose <30 cm in size locally derived fragments from the gypsum crusts (Fig. 3B and C). The channels as well as the surrounding gypsiferous shale are encrusted with a powdery gypsum crust rich in quartz pebbles.

In the Qattamia area, the gypsum crusts are sporadically distributed on the surface of the plateau. The gypsum crusts cap gypsiferous shale or marl or even limestone in either topographic highs or lows, thus preserving the old land surface from wind erosion and weathering. Sometimes, the land area that is covered with gypsum crusts form slightly higher relief, when erosion has preferentially removed the surrounding soft material. The gypsum crusts are generally of white or turbid color that is usually cement shale and/or carbonate fragments from the underlying bedrock. The top 10 cm of the gypsum crusts in Girza and Qattamia areas is composed of powdery soft materials, due to climatic dehydration, that may be mixed with lag gravels on the top of the inselberg of Girza or covered with windblown sandy materials elsewhere. The bed exposures of the crusts on the inselberg are persistently covered with a few millimeters encrustation of black desert varnish.

3.2. Classification

On the basis of stratigraphic, structural and textural criteria, three main types of gypsum crusts have been
identified, these are from top to base: (1) massive powdery gypcrete; (2) massive indurated gypcrete, and (3) massive mottled gypcrete. The first type is a surface gypsum crusts that are persistently found on the top part of all land areas in Girza either covering the massive indurated gypcrete, or the massive mottled
gypcrete or even over the bedrock directly (Fig. 2B). The second type is recorded only at and near the lower pediment slope of the Girza inselberg. The third type is recorded in a wide plain in Girza and Qattamia areas directly over the thick (15 m) gypsiferous shale or marl beds, that may be separated with brecciated limestone fragments (Fig. 2B). It is worth to mention that the contacts between these gypsum crusts or between the gypsum crusts and the underlying bedrock are usually gradational, with about 10 cm transitional zone.

3.2.1. Massive powdery gypcrete

This horizons range from 15 to 40 cm thick crusts, which contain 30% to 60% (by weight) gypsum. The gypsum is white in color, massive or porous, powdery that cement polygenetic gravels and sands to form a matrix supported conglomerate (Fig. 3D). Probably due to weathering process and the removal of some of gypsum from this horizon to subsurface crusts, the crust is vuggy and loose. Further weathering of this crust leads to the concentration of lag gravels at the surface that indicate an original thicker crust than that is present today. Similar scattered gravely material on hilltops or on broad plains of surface crusts has been previously described by Cooke (1970) and Watson (1988). They interpreted their occurrence as upward migration of pebbles and cobbles through surficial materials as a result of either volumetric changes in the deposits during wetting and drying cycles or due to erosion of finer materials.

Fig. 4. (A) Gypsum cement carbonate and shale fragments and forming a mottled pattern. (B) The massive mottled gypcrete horizon mantle brecciated and uncracked carbonate bedrock. The breccia fragments increase in size downwards and have their longest dimension parallel to the bedding. Note the scattered lag gravels on top of the gypsum crust. (C) Gypsum vein composed of dark brown and white laminae that has a sharp contact with carbonate rock. (D) Irregularly shaped gypsum nodules scattered within marl layer and may result from filling of rootlet hollows. GC: gypsum cement, Cr: carbonate or shale fragments.
3.2.2. Massive indurated gypcrete

This horizon is much thicker than the surface crust; it is 30–70 cm thick crust, very hard, and resist to erosion. It has a gypsum content varying from 60% to 90% (by weight). It ranges in color from white, gray, dark gray to light brown, without any apparent sedimentary structures. The crust is usually cut with 0.1–7-cm-thick, black to dark gray gypsum veins that take a horizontal, vertical or even oblique orientation (Fig. 3E). Upon quarrying, this horizon is cracked at the weak planes of the gypsum veins into 20–50 cm spheroidal masses.

3.2.3. Massive mottled gypcrete

This horizon ranges from 15- to 50-cm-thick crusts, with gypsum content ranging from 50% to
60% (by weight). The gypsum is white in color that cement brick-like carbonate or shale fragments (Fig. 4A), ranging in size from a few millimeters near the top to several centimeters near the bottom (Fig. 4B), that render the whole crust a yellowish or greenish coloration. The carbonate and shale fragments are oriented with their long dimension parallel to the bedding and may be densely aggregated or are widely scattered. Therefore, the thickness of the gypsum cement varies widely within the same crust. Dark brown to black gypsum veins are also distributed in this horizon (Fig. 4C).

The bedrock below the massive mottled gypcrete is either gypsiferous shale or marl that is soft without any apparent structures, or is composed of brecciated carbonate. The shale or marl layers contain irregularly
shaped, <2 cm gypsum nodules (Fig. 4D). The carbonate fragments range from few centimeters below the gypsum crusts to large (about 70 cm) fragments to uncracked bedrock towards the bottom (Fig. 4B). Sometimes, the cracks are filled with satin-spar gypsum veins with a thickness up to 2 cm.

3.3. Petrography

Examination of thin sections from the different gypsum crusts reveals that there are several types of gypsum crystals. The petrographic terminology employed to describe the micromorphology of gypsum crystals is that provided by Watson (1985), which is later accepted by Watson (1988), El-Sayed (1993, 2000) and Hartley and May (1998). The observed forms of gypsum are microcrystalline gypsum, fine and coarse lenticular gypsum, prismatic gypsum, porphyroblastic gypsum, poikilotopic gypsum and fibrous gypsum. It is important to point out that these terms are solely descriptive without any genetic implication as that made in the familiar evaporites (e.g. Holliday, 1980).

Fig. 7. (A) Displacive growth of large lenticular gypsum between floating quartz grains that are surrounded with thin clay coat, Crossed Nicols. (B) A thin clay coating to quartz and displacive gypsum crystals on the right hand side and a clear zone without clay coating on the left hand side is most probably related to infiltrating meteoric water carrying clayey materials, Crossed Nicols. (C) A closely packed random prismatic gypsum that are forming granular texture, with a scattered carbonate material, Crossed Nicols. (D) Porphyroblastic gypsum with interpenetrating boundaries probably due to preferential growth of gypsum, Crossed Nicols. (E) Aggressive replacement of the large lenticular gypsum along one side of the crystals with fine lenticular gypsum, Crossed Nicols. (F) A nodular structure of microcrystalline gypsum within coarse lenticular gypsum most probably resulted from filling of rootlet hollows, Crossed Nicols. (G) Replacement of the porphyroblastic gypsum with prismatic anhydrite due to climatic dehydration, Crossed Nicols. GL: large lenticular gypsum, GP: porphyroblastic gypsum, qz: quartz grains, Cl: clay coating, gl: fine lenticular gypsum, gm: microcrystalline gypsum, An: prismatic anhydrite, GR: granular gypsum.
1970). Also, the presence of these forms of gypsum crystals is not restricted to a certain gypsum crust, but varies widely from horizon to horizon (Figs. 5 and 6). Exception to this is the occurrence of poikilotopic gypsum, which is restricted only to the lower massive mottled gypcrete horizon.

Regardless of the extent of mineralogical and textural alterations due to diagenesis, the main components of the gypcrete horizons may be conventionally described in two categories: the host sediments and the cementing gypsum materials.

3.3.1. Massive powdery gypcrete

In a decreasing order of abundance, the gypsum crystals are represented by the following morphologies: lenticular, prismatic, porphyroblastic and microcrystalline. The non-evaporite component is represented only with quartz (Figs. 5 and 6). The lenticular gypsum crystals are coarse in size (600 × 2400 μm) and displacively grown with random orientation between quartz grains (Fig. 7A). Sometimes the lenticular gypsum crystals as well as the host (detrital) quartz grains are lined with thin coat of clay (Fig. 7B) that may be related to soil process. The granular gypsum is composed of euhedral to anhedral crystals, 400–800 μm in size, which are scattered between quartz grains (Fig. 7C). The porphyroblasts of gypsum have a size ranging from 700 to 2000 μm. They have irregular interpenetrated boundaries, sometimes with a smooth stylolitic pattern (Fig. 7D). All types of gypsum crystals are slightly corroded and engulfed with <10 μm in size microcrystalline and fine lenticular gypsum crystals, that are present as patches between the large crystals (Fig. 7E). Also, the fine gypsum crystals are forming circular to elliptical nodular structures between the large size gypsum crystals (Fig. 7F) and may result from filling of rootlet hollows after decay of the rootlet structure. Similar elongated nodular structure is described by Sanz-Rubio et al. (1999) and is interpreted as a product of pedogenic process. Due to climatic dehydation, the gypsum crystals in this horizon are usually

Fig. 7 (continued).
replaced with <30 µm long, felted and prismatic anhydrite crystals (Fig. 7G) that increase in intensity toward the bed exposure, forming 10-cm-thick white powdery anhydrite crust.

3.3.2. Massive indurated gypcrete

This horizon consists of higher gypsum content (60–90%) than the overlying and underlying horizons (Fig. 6). The overlying transitional boundary of this horizon contains few quartz from the overlying horizon and the underlying transitional boundary contains few to slightly dense amount of carbonate or shale fragments from the underlying horizon. The crystal forms of gypsum are represented in a decreasing abundance by microcrystalline gypsum, coarse lenticular gypsum, fine lenticular gypsum and porphyroblasts of gypsum with a few cross cutting gypsum veins. Some of the coarse lenticular gypsum and the porphyroblastic gypsum exist as floating crystals with highly corroded crystal boundaries within a ground mass composed of fine lenticular gypsum and/or microcrystalline gypsum (Fig. 8A). Corrosion of the coarse lenticular gypsum and the porphyroblasts of gypsum starts usually at crystal boundaries (Fig. 8A) or less commonly restricted to one margin of the crystals (Fig. 8B). The corrosion starts from minor

Fig. 8. (A) Preferential replacement of the large lenticular gypsum with microcrystalline and fine lenticular gypsum, Crossed Nicols. (B) Selective ingression of the coarse gypsum crystals with microcrystalline gypsum at certain crystal boundaries, Nicols Crossed. (C) Scattered vestiges of gypsum in fine lenticular gypsum due to high degree of replacement, Crossed Nicols. (D) Replacement of porphyroblastic gypsum with fine lenticular gypsum with uncorroded quartz grains due to clay coating (arrows), Crossed Nicols. (E) Thick laminae of microcrystalline gypsum interlaminated with thin laminae of fine lenticular gypsum, Crossed Nicols. (F) A slightly twisted vein filled with prismatic gypsum and showing a swollen end of the vein (arrows), Crossed Nicols. (G) Highly twisted gypsum veins filled with fibrous gypsum in a ground mass of alabastrine gypsum, Crossed Nicols. (H) Nodular structure filled with coarse lenticular gypsum in a ground mass composed of alabastrine gypsum probably due to filling of rootlet hollows, Crossed Nicols. GL: large lenticular gypsum, GP: porphyroblastic gypsum, qz: quartz grains, Cl: clay coating, gl: fine lenticular gypsum, gm: microcrystalline gypsum, gv: gypsum vein.
to high serrated crystal boundaries that still preserve their primary crystal forms (Fig. 8A) to the occurrence of small (<400 μm) vestiges of irregular gypsum scattered within fine lenticular and/or microcrystalline gypsum that form a floating pattern (Fig. 8C).

The microcrystalline gypsum (<10 μm in size) and the fine (16×80 μm) lenticular gypsum form small and large, circular, elliptical or irregular patches in this horizon or may form the whole thin sections (Fig. 8B and C). In all these occurrences, floating quartz grains and relics of clear gypsum crystals still existed (Fig. 8D). The fine gypsum crystals may form laminations due to either size differences or due to alternation of fine lenticular gypsum-rich laminae and microcrystalline gypsum-rich laminae (Fig. 8E).

Within the microcrystalline and the fine lenticular gypsum as well as the large gypsum crystals, up to 60 μm thick veins of granular and fibrous gypsum are widespread (Fig. 8F). Some of these gypsum veins have ambiguous morphology as they are irregularly twisted (Fig. 8G), of variable width (<100 μm) and length (<2 cm). Some parts of the veins are swollen either at the end of the veins (Fig. 8F) or throughout their extension. Probably, cross-section of these veins results into the circular or elliptical nodular structure (Fig. 8H).

3.3.3. Massive mottled gypcrete

The morphologic and petrographic similarities of this horizon in Girza and Qattamia areas are their abundance in carbonate and/or shale fragments, produced by mechanical disintegration of the underlying middle Eocene limestone and shale, and the presence of poikilotopic gypsum, a feature which is not recorded in the overlying horizons (Fig. 6). The abundance of the other crystal forms of gypsum in this horizon in Girza and Qattamia areas is varied. In Girza area, this horizon consists of equal amount of poikilotopic gypsum and coarse lenticular gypsum; both are followed by a smaller abundance of micro-
crystalline gypsum and prismatic gypsum (Fig. 6). Whereas in the Qattamia area, the gypsum crystals are represented in a decreasing abundance by microcrystalline gypsum, coarse lenticular gypsum, fine lenticular gypsum, porphyroblastic, poikilotopic and finally prismatic gypsum (Fig. 6).

The coarse lenticular gypsum in this facies is much thinner and longer (200×2800 μm) than that recorded in the overlying horizons (Fig. 9A). They grow displacively within carbonate or shale fragments (Fig. 9A), or may form smaller (100×400 μm) random lenticular crystals. When the lenticular gypsum grow between carbonate or shale fragments (Fig. 9B), they are easily corroded and replaced by microcrystalline or fine lenticular gypsum to form a preferential dissolution features (solutional pitting). The poikilotopic gypsum are widespread in this horizon as clear, coarse (up to 4000 μm) crystals, which encompass fine and coarse carbonate or shale fragments which may exhibit preferred or random orientation within the poikilotopic gypsum crystals (Fig. 9C). Sometimes in the Qattamia area, the gypsum crystals are aggregated to form circular or elliptical gypsum nodules that are scattered within the carbonate or shale fragments (Fig. 9D).

4. Discussion

4.1. Source of gypsum

Studies of the distribution of the evaporite deposits in Egypt show their close proximity to the present shores of the Mediterranean Sea, Gulf of Suez, Gulf of

Fig. 9. (A) Thin, elongated lenticular gypsum grow displacively in carbonate fragment, Crossed Nicols. (B) The displacively grown large lenticular gypsum is preferentially replaced with irregular patch of microcrystalline gypsum, Crossed Nicols. (C) Large poikilotopic gypsum crystals enclose inclusion of carbonate fragments that form preferred orientation, Crossed Nicols. (D) Nodular and elongated-like structures filled with fine lenticular gypsum in carbonate fragment, Crossed Nicols. GL: large lenticular gypsum, gl: fine lenticular gypsum, gm: microcrystalline gypsum, GK: poikilotopic gypsum, Cr: carbonate fragments.
Aqaba and Red Sea for the marine sourced evaporites, and in El Bahariya Oasis, Siwa Depression and Qattara Depression for the groundwater sourced evaporites. In Girza and Qattamia areas, either marine or groundwater origin for the gypsum crusts is abandoned because: (1) The nearest evaporite deposit is located beyond 120 km to the east. Therefore, an aeolian transport of gypseous materials eroded from these deposits is discounted. (2) The possibility that the Pliocene Sea in Egypt forms saline lakes (Abdallah and El-Kadi, 1974) is disagreed because the gypsum crusts cap rocks of Pleistocene age or capping rocks that are not overlaid with Pliocene sediments as on the plateau surface of the Qattamia area, and (3) groundwater seepage or surface flooding from the Nile (+20 m) or Lake Qarun (−45 m) is not accepted due to the elevation difference between their water surfaces and the highest gypsum crust (about 99 m in Girza). Therefore, it is impossible for the water to seep for 150 m to be evaporated and to form gypcrete. Despite the existence of gypsum in layers or horizons, their geomorphic, stratigraphic and petrographic characteristics ruled out deposition from permanent or ephemeral saline water body (e.g. lake, lagoon, saline pan, etc.). The arguments to rule out the subaqueous environment are: (1) The occurrence of the gypsum in horizons that mantle the pediment slope, plain, or topographic depression. (2) Gypsum crystals are displacive or inclusive, and grow in a near surface matrix. (3) The absence of bottom-nucleated crystals, or brine–air or brine column nucleated crystals. (4) The absence of a common nucleation surface for the growing gypsum crystals. (5) Inclusion of host rock materials between or within the gypsum crystals. (6) Gypsum layers are relatively thin when compared with subaqueous evaporites. In addition, another argument that rule out a coastal sabkha setting is the absence of peritidal to subtidal sediments such as fine grained to micritic or dolomicritic carbonate, as well as silty carbonate and carbonate siltstone (Butler, 1970; West et al., 1979) in the gypsum crusts.

The liable source of gypcrete in the study areas is the thick beds of the gypsiferous shale or marl, where the gypsum crusts are localized only either over or in close proximity to these deposits. Beyond the gypsiferous shale or marl beds, where the Cretaceous and Eocene carbonate crop out, the rocks are capped with calcrete, silcrete or ferricrete and show numerous karst features (Philip et al., 1990; El-Sayed, 2002 and reference therein).

4.2. Origin of the gypsum crusts

The origin of the different gypsum crusts is problematic. The morphology, textures and structures of the gypsum crystals in each crust are considered characteristics of eluvial, illuvial, hydromorphic, surface exhumation or diagenetic processes. Combination of field, stratigraphic and petrographic characteristics allowed the identification of the origin of each crust.

The massive powdery gypcrete horizon, the top most surficial horizon, consists of a mixture of coarse lenticular gypsum, prismatic gypsum and porphyroblasts of gypsum that are displacively grown within host sands and gravels. These crystal forms of gypsum are considered characteristics of illuvial subsurface crusts by Casten-Siedell and Hardie (1984), Watson (1985, 1988) and Hartley and May (1998). These gypsum crystals are primary grown by illuvial accretion within a lower soil horizon. Exposure of this illuvial crust through erosion of the overlying materials brings the gypsum crusts into the upper eluvial soil zone. During period of rainfall, all these crystals are subjected to preferential dissolution and are replaced by microcrystalline gypsum. During period of excess rainfall, the dissolved gypsum by rain water is translocated to a lower soil horizon, leaving the upper eluvial soil horizon slightly vuggy, and finally lead to clast-supported conglomeratic patches within the gypsum cemented conglomerate, and also lead to the concentration of lag gravels on the surface crust.

The massive, porous and powdery nature of the surface gypsum crust are considered as exhumed subsurface crust, which is formed by degradation of subsurface crusts to powdery residue, as a result of dissolution, leaching and climatic dehydration. Exhumation of the illuvial crusts is often brought by aeolian erosion of the unconsolidated materials (Watson and Nash, 1997).

The massive indurated gypcrete horizon consists mainly of microcrystalline gypsum and fine lenticular gypsum that are corroding and replacing coarse lenticular and prismatic gypsum crystals. In this subsurface gypsic crust, the gypsum crystals that deposited at or near the ground surface is dissolved and leached.
into this subsurface soil horizon, where it precipitated rapidly during subsequent desiccation. Concomitant with this process of illuviation is the degradation of the large gypsum crystals that are formed as primary crystals within this subsurface crust into fine gypsum crystals. Both mechanisms result in the development of a massive, clast-poor horizon between upper gravel-rich horizon and a lower carbonate or shale-rich horizon, similar to the B-horizon described from mature illuvial saline desert soils of Quaternary age (Amit and Gerson, 1986; Birkeland and Gerson, 1991), or Miocene age (Hartley and May, 1998). However, the presence of fibrous and granular gypsum veins of horizontal, oblique or vertical orientation, of variable widths (1–6 cm) in this horizon may be related to periodic surface exposure of gypsum crusts, similar to that interpreted by Hartley and May (1998). The gypsum veins are probably filled tensi- tional cracks caused by desiccation (Tucker, 1978), or thermal contraction (Coquek and Hunter, 1986) from infiltrating meteoric water highly enriched in gypsum from dissolution of the overlying gypsum crust. The gypsum veins are believed to be concomitant with the formation of the microcrystalline and fine lenticular gypsum formation, and therefore they are of similar origin. Therefore, as discussed above, a purely illuvial origin of this horizon is discounted based on the presence of gypsum veins due to periodic surface exposure of this crust.

The massive mottled gypcrete horizon consists of poikilotopic, coarse lenticular, porphyroblastic, fine lenticular and microcrystalline gypsum. These crystal forms suggest an origin as a subsurface gypsic crust formed by a combination of illuviation (coarse lenticular and porphyroblastic gypsum), hydromorphic (poikilotopic) and diagenetic (fine lenticular and microcrystalline gypsum) processes. The consequence of illuviation, hydromorphic accretion is enigmatic. It is probably during a lower level of the water table when coarse lenticular and prismatic gypsum is formed by illuvial accretion. During high level of the water table, poikilotopic gypsum is formed in the lower soil zone in a lower slope location (Watson and Nash, 1997) from evaporating groundwater, and are characteristics of hydromorphic subsurface crusts (Coque, 1962; Watson, 1985, 1988; Watson and Nash, 1997; Hartley and May, 1998). These are in-turn are followed by corrosion of both illuvial and hydromorphic gypsum crystals to microcrystalline and fine lenticular gypsum by their dissolution and rapid recrystallization during desiccation.

The nodular and elongated structures that consist of lenticular (Figs. 8H and 9D) or microcrystalline gypsum (Fig. 7F) may result from filling of rootlet hollows by infiltrating meteoric water after decay of the rootlets. Similar rhizotubes either filled with gypsum were described from coastal sabkha setting by Aref et al. (1997), or controlling the growth of nodular anhydrite has been described by Sanz-Rubio et al. (1999) from palustrine continental sabkha setting.

4.3. Origin of the gypsum crystals

Petrographic observation of the different gypsum crusts in Girza and Qattamia areas have shown that there are several micromorphological forms of gypsum, each of which is not pertinent to a specific horizon. Exception to this restriction is the occurrence of poikilotopic gypsum in the massive mottled gypcrete horizon. However, it is often difficult to identify the mode of origin of a particular crust by simply studying it in a profile. Therefore, it is appropriate to examine the micromorphological fabrics and crystallization textures, which can be attributed to genetic or diagenetic processes, which are specific to a certain environment. This idea is in agreement with Watson and Nash (1997), who mentioned that the micromorphology and chemistry of many crusts provide the best available information on their origins.

The coarse lenticular gypsum, porphyroblasts of gypsum and prismatic gypsum crystals which are dominant in all gypsum crusts (Figs. 5 and 6), with varying abundance, or that are present as vestiges within a ground mass composed of microcrystalline and fine lenticular gypsum (Fig. 8A, B and C) is an evidence to their precursor primary origin. These primary crystals are clear, with rarely host rock inclusion, and grew displacively within a host sediment composed of clastic or carbonate materials. The dominance of coarse lenticular gypsum over all crystal forms indicates: (1) a crystallization from water rich in organic compounds of terrestrial origin, and (2) the possible insufficient supply of $\text{SO}_4^{2-}$ relative to $\text{Ca}^{2+}$, which lead to more adsorption of organic matter and a low growth rate of the $C$-axis (Cody
The granular gypsum is composed of euhedral and subhedral prismatic crystals that are densely aggregated (Fig. 7C). It may form in water lacking such organic contaminant, or of a variable composition.

The origin of porphyroblastic gypsum is problematic, it is presented as large patchy crystals with interpenetration boundaries (Fig. 7D) that may represent the discoidal orientation of lenticular gypsum that has undergone preferential dissolution by infiltrating meteoric water or may represent the preferential growth of gypsum according to the available free spaces. The porphyroblastic gypsum is not an indicator to burial or uplift diagenetic environments after a precursor anhydrite because the gypsum crusts are in themselves a surficial feature and the absence of any anhydrite vestiges within gypsum.

The poikilotopic gypsum that incorporates particles from the host sediments is grown mainly by inclusive growth. Such poikilotopic crystals develop when the crystal growth rate exceeds the maximum rate of particle displacement (Kastner, 1970). The poikilotopic crystals usually precipitate from underground waters, 1–2 m below the land surface, that are concentrated by capillary evaporation within a desiccated surface of continental sabkha, similar to observation by Coque (1962), Watson (1985) and Rouchy et al. (1994).

The fine lenticular gypsum and the microcrystalline gypsum are produced by diagenetic processes from preferential dissolution and leaching of former gypsum crystals (Fig. 8A, B and C), and the subsequent rapid evaporation of these waters during subsequent desiccation resulting into the precipitation of a fine gypsum matrix. Experimentally, Zen (1965) found that the solubility of gypsum in pure water is about 2.0 g CaSO₄ l⁻¹, but in the presence of sodium chloride, gypsum solubility is raised to 8.0 g CaSO₄ l⁻¹. It is observed that the gypsum crusts of the Fayum area contain much Na⁺ and Cl⁻ ions when compared to the Miocene evaporites of the Red Sea and Mediterranean Sea (Aref et al., 2002). Therefore, under the influence of infiltrating meteoric water, which is slightly enriched in Na⁺ and Cl⁻ ions from leaching of salt from the gypsiferous shale, the former coarse gypsum crystals are subjected to dissolution and subsequent rapid crystallization of fine gypsum crystals during desiccation. The passageways of the infiltrating meteoric water is evidenced by the occurrence of dark brown to black veins in the middle indurated crusts (Fig. 3E) that are composed of fine gypsum crystals. This process of gypsum degradation from large to small crystals without anhydrite stage in-between is uncommon in the familiar evaporites and is similar to sparmicritization in calcrite (Kahle, 1977; Watson and Nash, 1997).

4.4. Age and paleoclimatic implication

It is generally accepted that since the Quaternary, the onset of arid conditions in the Egyptian Nile Valley started in 300 ka (Middle Pleistocene) by deposition of Dandara Formation (Dandara crisis) (Table 1). This phase was followed by a short wet phase, which, in turn, shifted to aridification from about 100 ka (Late Pleistocene) (Paulissen and Verrmeersch, 1987). El-Asmar (1994) found that at least four arid climatic phases are presently related to four groups of eolianites in northern Egypt that is following four major transgressive phases. The oldest two phases (300 and 125 ka) are conformable to the above-mentioned arid phases. The youngest two aridity phases is that at 90 ± 15 ka and 5000 years BP (Table 1). Fontes and Gasse (1989) studied the Holocene and Late Pleistocene phases in North Africa. They indicated the presence of a humid phase during the Holocene dated up to 6000 years BP. This phase was followed by an arid climatic condition that is characterized by the occurrence of gypsiferous deposits and shows two short wet climatic conditions at 3700 and 3100 years BP.

During the middle and early late Pleistocene, intense rainfall in Egypt results in the accumulation of thick locally derived gravels (Abbasia Formation) (Said, 1981). Because the gypsum crusts mantle the polygenetic gravels of the Abbasia Formation and also older Formations, it may be related to the early Late Pleistocene (125 ka), Late Pleistocene (90 ± 15 ka), or the Late Holocene (5000 years BP) arid episodes (Table 1). The presence of small channels at the elevation of 40 m filled with fine sands that enclose <30 cm locally derived fragments from all the gypsum crusts (Fig. 3B and C) indicate that the formation of the gypsum crusts during arid phase should have been followed by a pluvial period (Table 1). Also, the numerous dissolution features in the gypcrete horizon
indicate several cycles of wetting and drying. Therefore, the gypsum crusts may be dated probably to 125 or 90 ± 15 ka arid episodes, before the youngest (5000 years BP) aridity phase. The surficial powdery gypsum crust that mantle the channel and the surrounding rock is probably the youngest gypsum crust which may be related to the youngest aridity phase (5000 years BP). However, the formation of gypcrete should have been started by a wet period, where rainfalls are sufficient to leach the gypsum from the gypsiferous sediments to a lower soil zone. The presence of rhizotubules filled with gypsum (Figs. 7F, 8H and 9D) in the gypsum crusts suggests a relatively high rainfall.

### 4.5. Geomorphic implication

The Fayum Depression, about 33 m above sea level, slopes gently towards Lake (Birket) Qarun, 45 m below sea level at the northwestern side of the depression. This depression is formed in Plio–Pleistocene time by fluvial activity followed by wind deflation (Sandford and Arkell, 1929). Since the onset of aridity during the Late Pleistocene time, the development of gypsum crust over the highly gypsiferous shale and marl beds will protect the land surface from further wind deflation by consolidating surface layers. Therefore, the rate of excavation of the depression in the western side is greater than on the eastern side in...
that areas mantled by gypsum crusts. The existence of gypsum crusts east of the Fayum Depression plays a major role in the development of the present-day topography of the Nile–Fayum divide (Fig. 10).

In the Qattamia area, surface gypsum crusts also play an important role in limiting aeolian deflation of loose sediments by cementing their surface layers. When gypsum crusts develop over soft gypsiferous
shale or marl beds in a topographic depression, this surface layer contains more gypseous cement than the surrounding higher rock types. Over a period of time, consolidation of the surface gypsum crusts and removal of the surrounding loose materials lead to the development of relief inversion (Fig. 10), similar to that described by Watson (1985).

### 4.6. Depositional environments

The geologic setting, sedimentologic and petrographic criteria of the Quaternary evaporites in Girza and Qattamia areas suggest that gypsum deposition occurred in a pedogenic setting. It is suggested that during wet periods, meteoric water flushes the gypsiferous beds, moves down slope and become saturated with gypsum derived from the gypsiferous beds. During dry periods, the gypsum-rich meteoric water are drawn to the surface by capillarity (per ascensum model of Watson, 1985), which lead to gypsum crystallization and crust accretion on the lower slope (Fig. 10). During another wetter period, the surface gypsum crust is partially dissolved by meteoric water that moves downward and is mixed with laterally moving gypsum-rich meteoric water from the gypsiferous beds which lead to deposition of subsurface gypsic crust (per descensum model of Watson, 1985). Watson (1985) argues that the amount of infiltrating water should not exceed the soil moisture deficit because the soluble salts cannot be flushed out of the soil zone. If the amount of rainfall is exceedingly high, the soil moisture storage capacity is exceeded, where the dissolved gypsum will be carried into the groundwater zone. If the infiltration capacity is exceeded, gypsum dissolved at the surface will be removed in surface runoff (Watson, 1985). During dry period, when the evaporation rate of the groundwater exceeds the soil moisture storage capacity, illuvial gypsum will grow displacively (vadose gypsum), or inclusively (phreatic gypsum), below the sediment surface. The growing gypsum crystals lead to cementation of the host sediments (carbonate, shale, gravel or sand).

The absence of early diagenetic anhydrite crystals in the studied gypsum point to a semiarid climate as in northern Egypt (Ali and West, 1983; Aref, 2000), and ruled out either arid or hyperarid climate as what prevailed in the Arabian Gulf (Butler, 1970) or the Red Sea region (Orszag-Sperber et al., 2001). The observed epigenetic anhydrite crystals in the upper surficial gypsum crust usually form thin (<10 cm) white powdery crust, which is much thinner than the Miocene and Quaternary evaporites of the Gulf of Suez and Red Sea regions which may reach up to 3 m in thickness. The variable thicknesses of the anhydrite crusts may be due to: (1) the fact the gypsum crusts of the Fayum area are subjected to a shorter period of aridity relative to the older evaporites of the Gulf of Suez and Red Sea regions. (2) The existence of the gypsum crusts in the Fayum area nearer to the fresh water of the Nile River, where the air moisture is less saline when compared to the Gulf of Suez and Red Sea evaporites. The latter are located adjacent to seawaters where a relatively saline moisture are dominated, which help in the conversion of much gypsum to anhydrite. Similar effect of saline moisture is described from the Holocene evaporites of the Gulf of Aqaba where much epigenetic anhydrite is observed toward the seaward side than the landward side (Aref, 1998). (3) The existence of the Fayum area toward the north where the climate is less arid, with some periods of rainfall, whereas the Gulf of Suez and Red Sea evaporites are located to the south, where the climate is hyperarid, which favor a more conversion of gypsum to anhydrite.

### 5. Summary and conclusions

Gypsum crusts (gypcrete) have been recorded capping the Middle Eocene gypsiferous shale or marl in Girza and Qattamia areas, as well as on the Pliocene–early late Pleistocene sediments in Girza area. In areas devoid of gypsiferous sediments, karst features and karst facies with or without “Egyptian Alabaster; CaCO₃” are previously recorded in the Eocene and Cretaceous limestone (Philip et al., 1990 and reference therein). Three horizons of gypcrete have been identified from top to bottom: (1) massive powdery gypcrete, (2) massive indurated gypcrete, and (3) massive mottled gypcrete. The gypsum crusts are composed of variable abundance of gypsum crystals such as microcrystalline, fine and coarse lenticular gypsum, porphyroblastic, prismatic and fibrous gypsum. Stratigraphic and petrographic criteria indicate that the gypsum crusts are formed through complex processes of illuviation, hydromorphic, dia-
References


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El-Asmar, H., 1994. Eolianite deposition as an evidence for the Middle and Late Quaternary aridity, northwest of the Nile delta coast, Egypt. J. Geol. 38, 379–400.


