CHAPTER 8

Gypsum in desert soils, subsurface crusts and host sediments (Western Desert of Egypt)

Ashraf Mohamed & Konrad Rögner
Department of Geography, Ludwig-Maximilians-Universität, München, Germany

Sixten Bussemer
Institute of Geography and Geology, Ernst-Moritz-Arndt-Universität, Greifswald, Germany

ABSTRACT: The enrichment of gypsum in desert soils, subsurface crusts and host sediments—forming powder or solid, consolidated gypcretes—is related to an interaction of the following processes: 1) eolian transport from source areas, 2) temporary sedimentation at the land surface, 3) solution and displacement of gypsum by descending percolating water, 4) evaporation of water and precipitation of gypsum. These processes cannot be related to the environment of today, especially to the recent climatic conditions. There is a need of a more humid climate during the development of the gypcretes.

8.1 INTRODUCTION

8.1.1 Objectives and aims of the study

The area of Egypt and especially the margins of the Nile valley as well as of the Faiyum depression are confronted with a notable pressure by reclamation projects a result of the high population growth ratio (?). In a lot of these areas—foreseen for landuse projects—gypsum is outcropping in enriched or concentrated form at (surficial) or near to the surface (subsurficial). Usually the gypsum is hardened as a surface or subsurface duricrust, forming consolidated horizons, which are handicaps for the cultivation in land use projects. Especially the agricultural projects need urgently geomorphological studies with the aim of a detailed knowledge (i.e. distribution, thickness, matter) of the crusts.

The aims of our studies were: 1) Mapping and description of gypcretes und petrogypsic horizons with a geomorphological and sedimentological point of view, 2) laboratory analyses, 3) considerations concerning the kind of development and the environment during the formation of the crusts, 4) an attempt to reconstruct paleoclimatic conditions and their changes in a rough outline.

8.1.2 Previous work

Gypcretes and petrogypsic horizons (powder gypsum) are characteristic features in the area of our field studies (Figure 1). But these have been studied rarely in Egypt. Since

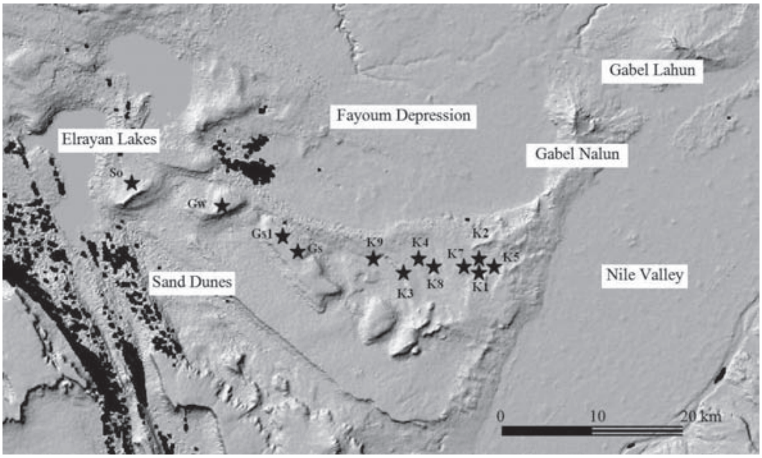

Figure 1. Location of the profiles (stars) and the Digital Elevation Model (DEM after SRTM data) of the study area (in black: sand dunes).

the early works of Beadnell (1905) and Blanckenhorn (1921) there exist only few studies concerning the formation and/or the distribution of gypcretes. And if studies have been carried out, they have dealt with the semiarid area of the Mediterranean Egypt (Ali and West, 1983). In the recent book of Embabi (2004) the description of crusts ("Surface crusts") reflects only on "calcretes, duricrust, caliche and ferricrete".

During the last few years studies of gypcretes in the hyperarid regions of Egypt have been published, dealing with the Gebel el Naalun area (Aref, 2003; Rögner *et al.,* 2006; Bussemer *et al.* 2009). The continuation of our studies as well as the presentation of the following paper has to be regarded as a continuation of our own work in a more extended area (the Gebel el Na'alun area is only a spot in the huge desert of Egypt).

8.1.3 Location

The area of field studies is situated close to the southern part of the oasis of Faiyum (Figure 1). The TPC-map (Tactical Pilot Chart, no. H-5 A, scale 1:500.000) showed for at least 20 years a small blue signature in this region, which was named 'aqueduct'. The construction of this irrigation channel (water source is the river Nil) started in 1946, but the "real" work has begun in 2004. Therefore the aqueduct has been a dry ditch for a period of more than 60 years.

In that dry channel we have carried out a major part of our field studies (profiles "Kanal" 1–9), because the deep outcrops enable to identify the crusts and the solid rocks over long distances under comfortable conditions. Therefore, the results presented below are representative ones, in no case they mirror singularities.

8.1.4 Methods

The different profiles were examined in the field by means of the normal spectrum (i.e. observation, drawing, photos, measurements, status of consolidation, sampling, etc.). During field work at the isolated hills and mesas some parts of sampling were executed by drilling.

The laboratory analyses (chapter 8.3) reflect merely a small part of the carried out investigations. The following paper is focused only on results concerning the ratios between Calcite ($CaCO_3$), Gypsum ($CaSO_4$), salts soluble in water (e.g. NaCl) and the left over (residual/remaining material, mostly called "rest"), which consists predominantly out of Quartz (SiO_2).

The calcite-content was measured by the SCHEIBLER-method (see Schlichting *et al.,* 1995), gypsum was detected by means of the sulphur content (CS-analyzer, Fa. Eltra), the dissolved salts by weight (Reeuwijk, 1995). Quartz was measured by RFA (PW 2404). The total amount of the left over/the remaining material/the "rest" was determined by weight after calcite, gypsum and soluble salts had been removed by solution.

8.2 PHYSICAL SETTING

8.2.1 Climate

From the matter and distribution of the gypcretes it can be concluded, that their formation must have occurred under climatic conditions differing significantly from the climate of today. That is the reason for the presentation of a few climatic data (Table 1). A short evaluation of meteorological and climatological conditions reveals that precipitation is very low. These very small amounts (Table 1) are confronted with very high values of transpiration (>3.000 mm) and evapotranspiration (>5.000 mm). According to the definition of the UNESCO (MAB, Technical Notes 7, 1977) the climate is "hyperarid", in an extraordinary manner.

The amounts of maximum rainfall during 24 h indicate that the annual mean can be reached or even exceeded during one single rainfall event with an extraordinary intensity. Some phenomena observed in the region—like erosion processes or the moving of soluble salts over distances of tens of centimeters—can be explained only by these high maximum rainfall values (with a high intensity, too) during 24 h.

8.2.2 Geomorphology and geology

The study area is a relative gentle landscape, which is interrupted by some escarpments and hills (see Figure 1). The differences in relative and absolute heights are moderate.

More in detail, the study area is characterized by the following different geomorphic landforms:

1. A gravelly plain which reaches a height of 75 m in the east and slopes gently down to the west to a height of approx. 30 m.
2. An area with mesas in the middle part of the study area, with a maximum height of ca. 100 m asl These mesas surround the Fayoum depression as an escarpment (especially in the northern part they form cuestas, but this is out of focus in this study).
3. The isolated hills at the western part of the study area, reaching heights between 40 m and 80 m (and sometimes more).

A lot of outcrops show an enrichment of gypsum at or near to the surface. The possible source areas are in a rough outline: (1) Veins or horizons of gypsum in the

Table 1. The mean annual precipitation of the Faiyum Region in mm and the maximum rainfall during 24 h. Data from Mohamed (2003) and Rögner (1998).

Station	Fayoum	Shakshuk	Kom Oshim	Beni Suef	Baharia
mm/year:	10,7	9,2	13,2	8,2	3,6
max. 24 h:	44	16	49,3	16,6	11,6

solid rock below or near the crusts (i.e. more or less autochthonous), (2) other sources more far away from the crusts (i.e. allochthonous).

Therefore it is vital to present a short outline of geology to decide, whether the gypsum can be derived from the outcropping rock or not. The outcropping solid rocks are marine in origin, carbonaceous and from Eocene (and Oligocene) age, sometimes superposed by Pliocene and often by Quaternary material.

The Eocene limestones of Egypt have been described as Mokattam Formation (lower and upper) by Zittel (1883) at first. According to the results of Swedan, (1986: 39) the Mokattam Formation is (again) subdivided in two members: (1) El Breig member (TemMb = Tertiary, Eocene, middle, Mokattam, Breig) and (2) Ravine member (TemMr, = Tertiary, Eocene, middle, Mokattam, Ravine).

Both members contain gypsum in very small amounts as small nodules and/or thin bands or veins. Both members could be a possible source for parts of the gypsum. But predominantly (in an overwhelming manner) they consist of limestone without any gypsum content.

For a colored version of the geological map of Swedan (1986) see Mohamed (2003) (http://edoc.ub.uni-muenchen.de/1012/), Rögner *et al.,* (2006), Bussemer *et al.,* (2006) (www.desertnet.de/proceedings/start.htm).

8.3 GYPSUM AND GYPCRETES

8.3.1 Gypsum crusts—a definition

Gypcretes are rarely studied compared to calcretes. Therefore, a common, obligatory, 'fixed' and accepted definition is lacking. In some papers scientists follow the definition of Watson, which is given below as a citation.

"Gypsum crusts have been defined as 'accumulations at or within 10 m of the land surface from 0,10 m to 5,0 m thick containing more than 15% by weight gypsum … and at least 5,0% by weight more gypsum than the underlying bedrock" (Watson, 1989, p. 28).

This definition is generally valid, even if the gypsum does not form consolidated crusts, e.g. if it appears as a nodule or as a powdery enrichment. We accept this definition and use it in its whole content. The Encyclopedia of Geomorphology (Vol. 1, pp. 507–509, author: Eckardt, G.) follows the above quoted definition.

Regarding the environment Watson (1989) states that the development of gypsum crusts takes place between 250 and 25 mm of annual precipitation. Gypsum crusts will be dissolved above the value of 250 mm, while below 25 mm only the solution of "common" salts like NaCl (Halite) is possible.

8.3.2 Profiles, distribution and description

12 different profiles were recorded in the study area (Figure 1) in detail. Profiles "Kanal" 1 to 9 are located in the gravelly desert plain south of the Faiyum depression.

The profiles “El Garaq S” and “El Garaq S1” represent a transition area between the gravelly plain and the mesas, which surround the Faiyum depression. Profile “El Garaq W” was taken at a mesa and profile “See O” at the top of a limestone hill in the Wadi El Raiyan depression.

All profiles named “Kanal” (numbers 1 to 9, taken in the long ditch, the “aqueduct” of the TPC map) show macroscopically nearly the same successions of horizons or sequences (from top to bottom):

– desert pavement (in most cases disturbed by human influence),
– gypcrete (usually developed as duricrust, with a higher sand content (e.g. the “rest”) in the uppermost part and a lower or nearly missing sand content in deeper situations,
– gypcrete (usually developed as duricrust),
– solid rock “swimming” in gypsum,
– limestone/shale penetrated by small bands or veins of gypsum,
– solid rock without cracks and fissures, no traces resp. very small traces of gypsum.

The other profiles seem to be not so well developed. The sequence of horizons is reduced (from top to bottom):

– desert pavement (undisturbed),
– gypcrete (usually developed as blister or scattered gypsum, with a higher sand content in the uppermost part),
– gypcrete (usually developed as duricrust),
– solid rock (no traces resp. very small traces of gypsum).

The description of the investigated profiles is given in Figure 2. A short comparison allows the following statements: 1) There is an increase in thickness of the gypsum crusts from East to West in the “Kanal-sections”. This could be related to a decrease in elevation above sea level (landscape dips gentle to the West). Deep positions in relief seem to promote the accumulation of gypsum. 2) The exposed positions “El Garaq S” to “See O” (top of mesas or hills) result in relatively thin gypcretes. Exposed positions do not favour the accumulation of gypsum.

1. Only in profiles “Kanal 5” and “Kanal 1” ascending groundwater could be the triggering factor in crust-formation. But the gypsum veins in the named profiles found in the shales—could be also regarded as a result of diagenetic processes (as in the other shale-profiles).
2. The gypsum veins in the profile “Kanal” 8, “Kanal” 4 and “El Garaq S1” are the result of descending water. This assumption could also explain the gypsum veins in the limestone sequence of “Kanal” 1.
3. The solid rock influences at most the lower part of the crusts. But in a lot of cases the crusts are superposed to the solid rock like a carpet.

Result: There exist good indications for a descending percolation-model of water (“per descensum”) enriched with gypsum, the evaporation of this water and the precipitation of gypsum. An ascending model does not fit with the field observations!

The top of the profiles consists normally of a desert pavement; therefore the profiles are truncated by processes of deflation (and sometimes by fluvial erosion). The thickness of the recent profiles is reduced compared to that of the time of formation. The fact that the desert pavement consists of hard and very resistant components like flint, petrified wood, quartz pebbles (sometimes nummulites) enables to think on distinct weathering processes. But horizons or materials indicating intensive chemical weathering cannot be proven by field and laboratory data.

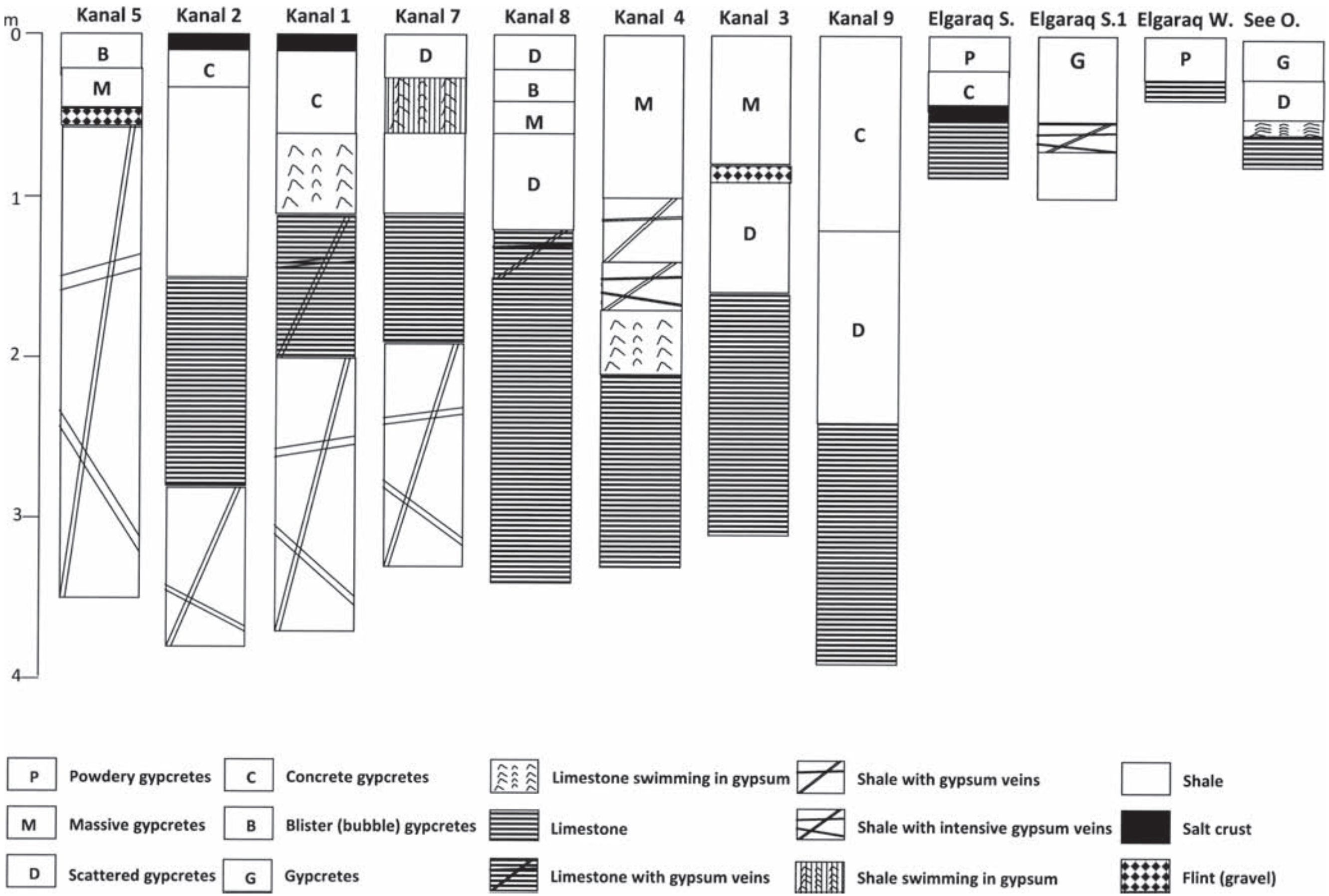

Figure 2. The 12 profiles according to the results of the field studies. Profile "Kanal 5" is situated in the East, "See O" in the West of the study area. Differentiation of the types of crusts according to Mohamed (2003).

8.3.3 Analyses, interpretation and classification

Gypsum is outcropping in enriched or concentrated form at or near to the surface of most of the studied landforms and in all studied profiles.

In previous studies dealing with the Gebel El Naalun Region (Rögner *et al.,* 2006) all profiles have displayed gypsum crusts/gypcretes according to the definition of Watson (1985, 1988, 1989, see chapter 8.2.1). Exceptions of that kind of distribution demonstrate only the recent wadi-sediments and the shoreline deposits of the historical Lake Moeris (mentioned by Herodotus 500 B.C.). These both geomorphological positions reveal no gypsum in the profiles, while the subrecent wadi sediments indicate the beginning of gypsum enrichment. In the region of the present study all landforms are proved by gypcretes, independent of the type of the underlaying rocks.

In a previous work Mohamed (2003) differentiated 5 types of gypcretes based on a textural description: powdery, massive, concreted, scattered and bubbly. This classification is used in Table 2.

The thickness of the gypcretes reaches up to 120 cm (profile "Kanal" 9), with an average of 40 cm. Related to textural types the thickness varies widely, but it is lower at the top of the mesas and isolated hills than in the gravely plains.

The laboratory analyses (Table 3) confirm the results of the field studies in distinct manner. All profiles show an enrichment of gypsum in the surficial and subsurficial parts, while in most cases the underlaying bedrock is free or nearly free of gypsum: Profile El Garaq W exposes a thin crust (25 cm) with an gypsum content of 20% while the solid rock below is free of gypsum (0,4%). In that small profile the crust is influenced by the solid rocks (high content of calcite) and even the desert pavement consists of nummulites gizehensis.

Location Kanal 7 shows an evident decrease in gypsum from the surface to deeper horizons (gypcrete: 83,6%; the transition zone: 33,0%; shale 6,6%; the solid limestone below: only 1,0%). In this profile a change between shale, limestone and shale (again) can be noticed. This superposition does not influence the gypsum content, but that of the other components.

The dissolved salts are enriched especially in a depth of 20–60 cm (samples 8–2 and 8–3), which could be caused by the infiltration of extraordinary rainfall amounts during 24 h (Table 1) to a depth, where water evaporates and the salts are precipitated. Distinct indicators for descending water are the described gypsum horizons (samples 8–1, 8–2

Table 2. Statistical data of the gypcretes. The number of the investigated crusts differs from the number of profiles, because most of the profiles show more than one type of gypsum crust.

type of gypcretes	number of gypcretes	in%	average thickness in cm	maximum thickness in cm	minimum thickness in cm
surface	11	44	36,4	120	5
subsurface	14	56	43,8	120	8
in sediments	21	84	36,45	120	5
in solid rocks	4	16	68,3	120	35
powdery	5	20	15	25	5
massive	6	24	53,7	100	22
concreted	5	20	48,8	120	10
scattered	7	28	38,5	120	8
blister/bubbly	2	8	15	20	10

Table 3. Geochemical data of the different profiles.

	"rest" (weight %)	calcite (weight %)	gypsum (weight %)	salts (weight %)
Kanal-1				
1-1	44,9	0,7	41,9	12,5
1-2	19,6	76,5	0,8	3,0
1-3	69,6	17,4	1,0	12,0
1-4	4,5	0,0	93,0	2,5
1-5	56,6	10,6	10,9	21,9
Kanal-2				
2-1	62,4	2,9	31,3	3,4
2-1a	76,5	11,3	5,9	6,3
2-2	81,8	14,3	0,8	3,1
2-3	10,8	84,2	0,6	4,4
2-4	59,5	39,5	0,9	0,0
Kanal-3				
3-1	44,0	5,8	47,5	2,7
3-2	17,0	5,5	74,3	3,1
3-3	6,6	26,2	66,2	1,0
3-4	9,2	27,8	61,8	1,2
3-5	5,3	50,9	42,3	1,4
3-6	1,5	95,2	2,3	1,1
Kanal-4				
4-1	18,6	3,3	77,2	0,8
4-4	62,6	6,9	12,9	17,5
4-3	22,6	2,2	62,0	13,2
4-4	37,9	2,5	44,6	15,0
4-5	7,2	89,8	1,2	1,8
4-6	2,7	93,4	3,3	0,6
Kanal-5				
5-1	50,8	1,2	46,0	1,9
5-2	68,0	0,5	24,4	7,2
5-3	4,7	0,0	85,9	9,4
5-5	71,9	0,0	3,6	24,6
5-6	89,2	0,0	0,7	10,1
Kanal-7				
7-1	14,5	0,2	83,6	1,7
7-2	56,7	2,0	33,0	8,3
7-3	46,6	29,2	6,6	17,7
7-4	8,0	88,5	1,1	2,4
7-5	8,2	30,4	1,0	10,3

(*Continued*)

Table 3. (*Continued*).

	"rest" (weight %)	calcite (weight %)	gypsum (weight %)	salts (weight %)
Kanal-8				
8-1	19,2	1,3	78,9	0,6
8-2	8,0	3,2	80,2	8,6
8-3	4,9	20,2	69,7	5,1
8-4	4,6	37,2	57,8	0,4
8-5	2,5	34,5	62,3	0,7
8-6	0,4z	98,9	0,1	0,6
Kanal-9				
9-1	13,6	3,2	74,3	9,0
9-2	5,5	34,1	56,0	4,5
9-3	1,4	96,2	0,5	1,8
9-4 ("salt-curtain")	8,6	60,8	2,3	28,3
El-Garaq-S				
S-1	17,2	47,2	35,5	0,1
S-2	3,8	49,2	25,3	21,7
S-3	3,4	51,0	3,6	42,1
S-4 (salt-crust)	4,9	91,9	1,8	1,3
El-Garaq-S1				
S1-1	67,2	15,8	16,4	0,6
S1-2	26,2	8,8	64,2	0,8
S1-3	32,4	5,0	61,2	1,4
S1-4	50,0	9,7	31,2	9,1
S1-5	57,3	14,1	23,6	5,0
S1-6	66,3	10,7	15,4	7,7
S1-7	62,6	12,7	14,9	9,8
El-Garaq-W				
W-1	7,8	71,4	20,4	0,5
W-2	2,3	96,4	0,4	0,8
See-O				
1-1	37,3	44,9	17,2	0,6
1-2	22,1	47,6	29,4	0,9
1-3	22,7	52,5	19,4	5,4
1-4	20,5	78,2	0,2	1,1

and 8–3), as well as the fact that gypsum penetrates into the top of the solid rocks (sample 8–4). As a result of this strong penetration of gypsum, the limestone particles seem to swim. The same information (of descending water with dissolved material) is given by the small bands of gypsum crystals (sample 8–5). These veins of gypsum crystals run down through the solid limestone (sample 8–5) and are ending after a few decimeters.

This evaluation of the laboratory analyses (result: descending water with dissolved gypsum) is supported by other field observations in the area of Gebel el

Na'alun, where bands/veins of gypsum crystals penetrate the solid limestone as well as the superposed gypcretes (Rögner *et al.*, 2006, Abb. 7, p. 98).

The results of laboratory analyses of another profile ("Kanal" 9) give answer to questions concerning the recent solution and precipitation processes. The gypcrete is forming a horizon with a thickness of 120 cm (Table 3, sample 9–1). At a depth of 120–240 cm, small veins of gypsum penetrate the solid limestone (sample 9–2) and between 240 and 390 cm the solid rock contains only 0,5% of gypsum (no veins!) and 1,8% of salts. But at some specific parts of the wall of the ditch the solid rock (below 240 cm depth) is covered by a curtain of material which consists to a high amount of salts (sample 9–4). The development of this curtain could have started not before 1946 (= beginning of the digging of the ditch) and is related to the (before mentioned) extraordinary rainfall during 24 h. This type of rainfall is able to infiltrate, to descend into the gypcretes and into the limestone. But the water is only able to solve salts and not gypsum or carbonates. The "rest", calcite and gypsum were transported as normal "bedload" of small particles while water was running along the wall of the ditch. The deep infiltration at this location is supported by fissures and desiccation cracks. By means of the "salt curtain" the recent processes of solution and precipitation can be limited to the solution of salts like NaCl (Halite), the solution of gypsum needs higher amounts of rainfall.

The recent enrichment of salt is also documented by the results of profile El Garaq S, which is situated in the center of a small and flat endorheic basin. In horizon S-3 the salt content culminates in 42,1% (Table 3), which is the highest value in all studied profiles. The salts are concentrated in a small horizon beneath the gypcrete. This coincides with the possibility of salt solution, movement by descending processes and precipitation under recent conditions, while today's rainfall is not able to solve and to move the gypsum.

Result: The formation of the gypcretes at the southern rim of the Faiyum depression took place under a more humid environment.

8.4 DISCUSSION

Other studies concerning the gypsum crusts/gypcretes (e.g. Goudie, 1973, p. 121; Eckardt, 2006) describe different possibilities for the sources of gypsum and different models of gypcrete formation. It is possible to group them as follows:

(1) Evaporation model from water bodies like marine environments, lakes, lagoons, saline pans, playas or sabkhas, and accumulation of gypsum as gypcretes. (2) In situ model: During the wet season the dissolution by percolating rain water takes place, during the dry season there is re-precipitation from water descending over a very limited distance towards the surface. (3) Fluvial model: The deposition of suitable materials and their precipitation in valleys or channels and those which involve the deposition or alteration of materials by sheet-flood action. (4) Groundwater model: The crust is a result of the upward capillary flow of gypsiferous water induced by constant and rapid evaporation at the surface in a comparatively rainless region ("per ascensum" model). (5) The "per descensum" model: The solutions containing gypsum might be leached from the upper soil horizons to accumulate at depth.

The models 1 to 4 can be excluded. In the area of field studies the gypcrete outcroppings are found in geomorphological positions which do not allow a reconstruction of evaporation basins (model 1). Model 2 cannot be proved because it needs gypsiferous rocks at the surface; they don't exist. The geomorphological position of the crusts denies the model 3. It is impossible, that ascending and evaporating groundwater (model 4) is responsible for the enrichment of gypsum at or near the surface, because in most cases the underlying rock is free or nearly free of gypsum. This is proven by means of the described sequences, analyses and the conclusions.

It is proved by field observations that gypsum—in some special situations—occurs in the solid shale as veins. But the volume of these veins is very small, compared to the mighty crusts. And it is also a result of our previous studies (Rögner *et al.*, 2006), that veins of gypsum penetrate not only the solid limestone or shale but the superposed gypcretes too. In this special case the veins are younger than the formation of the massive gypsum crusts! Vice versa, the massive crusts are the sources of the gypsum veins.

Desiccation cracks, filled with gypsum (and other eolian material), indicate, that ascending groundwater was not responsible for the enrichment of gypsum in the cracks; ascending water would destroy the cracks. Normally the formation of the crust is older than the genesis of the desiccation cracks and the filling of the cracks is the youngest element.

Based on the own studies we are able to propose the following model (Figure 3), which has clear relationship with the above described model 5. The arguments are given by field and laboratory analyses (chapter 8.3).

The main sources of the gypsum are situated in the marine surroundings (Mediterranean Sea, about 250 km to the North; the Gulf of Suez and the Red Sea, 130 km to the East) and especially the Qattara depression (–134 m below sea level and situated in the Northwest), in which gypsum is outcropping as gypsum dykes at the bottom of the depression (related to ascending groundwater).

The gypsum is deflated by wind action and is transported together with the (eolian) dust and sand to the sedimentation areas. Precipitation (rainfall, fog, dew) leads to a wash out and a temporary deposition at the surface (Figure 3a). Dry deposition (fall out) is also a possibility. The dust material is trapped by sparse vegetation and/or a wet surface. The precipitation events, especially the rainfall, cause infiltration, a solution of gypsum and soluble salts, followed by descending percolation (Figure 3b)

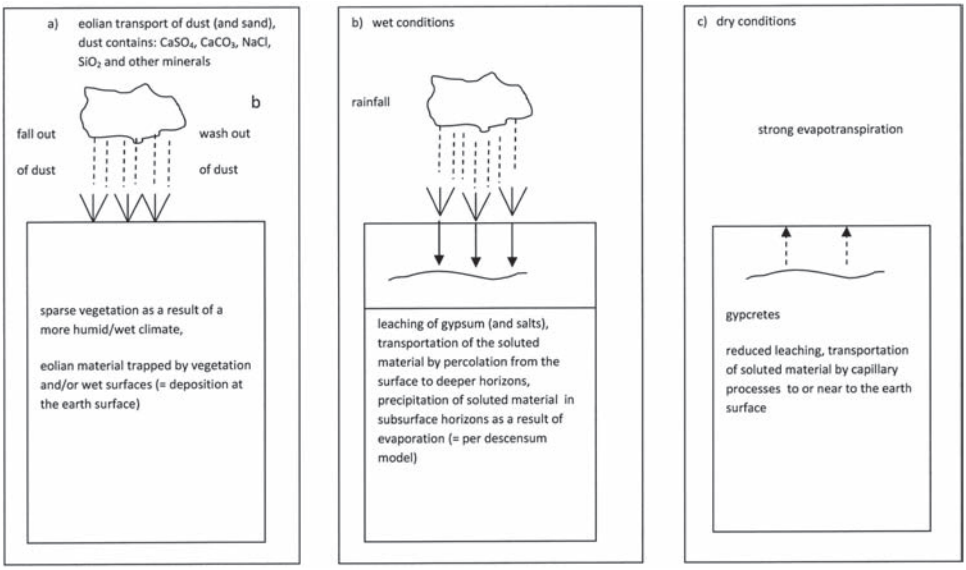

Figure 3. Suggested model for the development of the gypcretes in the study area.

and by precipitation of gypsum. The "rest", which could not soluted, is concentrated in the uppermost horizons, sometimes forming a vesicular layer. Dry conditions lead generally to evaporation and/or to the ascending percolation of water (caused by capillarity) to or near to the surface, resulting in deposition of gypsum by evaporation and other processes (Figure 3c).

Result: The development of the gypcretes has been caused by infiltrating and descending rainwater. The gypsum is of allochthonous origin, has been transported by winds (atmospherically), was washed out and/or accumulated in a relative dry (but not hyperarid!) environment as dust (or it is the product of chemical reactions). A descending water system led to the enrichment of the gypsum at or near the surface.

The age of the crust formation is young but not recent, a fact which is proven by the existence of gypcretes at all land surfaces, besides the recent wadi sediments and the shoreline sediments of the historical Lake Moeris.

The development of the crusts calls for a definitely moist climate compared with the hyperarid climate of today. According to the statement of Watson (1985, 1989) the annual rainfall must have been in the order of 250 mm as maximum and at least 50 mm in the minimum. The last threshold is derived from the interpretation of location "Kanal 9", because there was no mobilization of gypsum during rainfall events with a value of ca. 50 mm in 24 h.

During the time of the enrichment of gypsum and the formation of the crusts, the rainfall must have exceeded the values of today with a factor of 5 to 25. But the climate stayed arid; otherwise the crusts would have been destroyed by solution.

There has been no exact age dating of the crusts so far, but the time of formation could be assumed with young Pleistocene to Holocene (but not recent!). This assumption—derived from geomorphological results—is supported by the data of Said (1981), who reported an age of "early Late Pleistocene" for gypsum crusts in the area of the Nile valley. That is a contradiction to the papers, which have dealt with gypcretes in the Faiyum area: A Pliocene age for crust formation proposed by Beadnell (1905) is too old, a recent age proposed by Blanckenhorn (1921) is too young.

REFERENCES

Ali, Y.A. and West, I., 1983, Relationships of modern gypsum nodules in sabkhas of loess to compositions of brines and sediments in northern Egypt. *Journal of Sedimentary Petrology,* **53**, pp. 1151–1168.

Aref, M.A.M., 2003, Classification and depositional environments of Quaternary pedogenic gypsum crusts (gypcrete) from east of the Fayoum Depression, Egypt. *Sedimentary Geology,* **155**, pp. 87–108.

Ball, J., 1939, *Contributions to the Geography of Egypt.* Survey of Egypt, Cairo. (reprinted 1952).

Beadnell, H.J., 1905, *The topography and geology of the Fayoum Province of Egypt.* Survey Department, Cairo, Egypt.

Blanckenhorn, M., 1921, *Ägypten. Handbuch der Regionalen Geologie*, **VII**, **23**, Heidelberg.

Bussemer, S., Rögner, K., Mayer, Th. and Michel, J., 2009, Gypsum and gypsum crusts (Gypcretes) at the rims of the Faiyoum-Depression (Egypt). *Zentralblatt für Geologie und Paläontologie, Teil I*, **3** and **4**, pp. 169–179.

Embabi, N.S., 2004, *The geomorphology of Egypt. Volume I – The Nile Valley and the Western Desert*.

Goudie, A., 1973, *Duricrusts in tropical and subtropical landscapes.* Clarendon Press Oxford.

Mohamed, A.Y.A.H., 2003, Die Krusten der Ränder der Fayoum Depression—Geomorphologische Untersuchungen. *Ph.D. Thesis Faculty of Geosciences. LMU München*, http://edoc.ub.uni-muenchen.de/1012/. Unpublished.

Pfannenstiel, M., 1953, Das Quartär der Levante. Teil II: Die Entstehung der ägyptischen Oasendepressionen. In: *Abhandlungen der mathematisch-naturwissenschaftlichen Klasse*, **7**, Wiesbaden, pp. 337–411.

Rögner, K. and Müller-Koch, K., 1998, Rezente morphodynamische Prozesse in der Wadi Raiyan Region, Ägypten. *Paderborner Geographische Studien*, **11**, pp. 37–56.

Rögner, K., Bussemer, S., Meier, K., Mayer, Th., and Mohamed, A.Y.A.H., 2006, Die Gipskrusten der Gebel el Na'alun Region (Ägypten). *Mitteilungen der Geographischen Gesellschaft in München,* München, **88**, pp. 79–111.

Said, R., 1981, *The geological evolution of the river Nile*. Springer Verlag, New York.

Sandford, K.S. and Arkell, W.J. 1929, The origin of the Fayoum Depression. *Geographical Journal,* **24**, pp. 578–584.

Schlichting, E., Blume, HP. and Stahr, K., 1995, *Bodenkundliches Praktikum*. Berlin/Wien.

Swedan, A.H., 1986, Contributions to the Geology of Fayoum area. *Ph.D. Thesis, Faculty of Sciences, Cairo Univ., Egypt.* Unpublished.

UNESCO, 1977, Map of the world distribution of arid regions (MAB Technical Notes **7**, eplanatory note), Paris.

van Reeuwijk, L.P., 1995, Procedures for Soil Analysis, fifth edition, *ISRIC Technical Paper,* 9, (Wageningen, The Netherlands).

Watson, A., 1979, Gypsum crusts in deserts. *Journal of arid Environments*, **2**, pp. 3–20.

Watson, A., 1983, Gypsum crusts. In *Chemical sediments and Geomorphology*, edited by Goudie, A.S. and Pye, K. (Academic Press), pp. 133–161.

Watson, A., 1985, Structure, chemistry and origin of gypsum crusts in southern Tunisia and the central Namibia desert. *Sedimentology,* **32**, pp. 855–875.

Watson, A., 1988, Desert gypsum crusts as palaeoenvironmental indicators, a micropetrographic study of crusts from southern Tunisia and the central Namib desert. *Journal of arid Environments,* **15**, pp. 19–42.

Watson, A., 1989, Desert crusts and rock varnish. In *Arid Zone Geomorphology*, edited. by Thomas, D.S.G., (Belhaven Press, London), pp. 25–55.

Zittel, K.A., 1883, Beiträge zur Geologie und Paläontologie der Libyschen Wüste. *Paläontographica*, **8X**, Kassel.