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Gypsum Crystals Formation and Habits, Dukhan Sabkha, Qatar

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Abstract

This is the first study of the gypsum crystals habits in the famous, large, inland Dukhan Sabkha in the Qatar Peninsula. The study seeks to identify the various habits and vertical and horizontal distribution of the crystals in the sediments of the Sabkha. Forty four sediment samples rich in crystals, six shallow cores and twenty two brine samples were collected for the study. The factors that affected the crystals formation and shape are discussed in the study. Crystal formation speed and the reasons for the increase or decrease the growth rate identified.

Gypsum crystals of various habits and sizes are formed in the surface crust and at shallow depths in the Sabkha sediments. The crystals are of acicular, prismatic, lenticular and sub-lenticular, inter-grown sub-lenticular, pyramidal, elliptical and semi-elliptical, and pseudo-tetragonal shapes.

The proportion and habits of fine gypsum crystals in the Sabkha is large. Lenticular and Sub-lenticular crystals are dominant in the sediments, especially in the northeastern part of the Sabkha.

The proportion of sandy desert rose crystals (about 5 cm length) is rare and only found in the northeastern part of the Sabkha, to the west from the salt lake area; the crystals formed above groundwater level and at shallow depth, few centimeters from the surface.

Shallow groundwater level, saturated of sediments by brines, high temperature, high evaporation and saturated of brines by SO_4^{-2} and CaO_3^{2-} are provide suitable condition for formation of gypsum crystals in the Dukhan Sabkha sediments. In addition, the general elevation of Dukhan Sabkha below sea level (-1) is lead to greater rates of evaporation over groundwater recharge in the Sabkha. The crystals are formed either as a result of evaporation of sewage brines within the Sabkha or as a result of dissolved previous gypsum in the rocks bed within the Sabkha and re- concentrated $SO4^{-2}$ and Ca^{2+} in the Sabkha brines. In some locations, where anhydrite dominant, gypsum crystals could also formed as a result of anhydrite dehydration.

The main conclusion of this study are: (1) The conditions for formation of gypsum in the Dukhan Sabkha are available and accordingly various shapes of gypsum crystals formed in the surface and at various depths in the Sabkha deposits; (2) This Sabkha is suitable place for establishing a project for cultivation of this important mineral and exploiting it economically; and (3) This work can be used as model for the study and utilization of the inland Sabkha in Qatar and neighboring countries.

Keywords: Gypsum crystals; Habits; Fluid loss; Dukhan sabkha; Brine chemistry

Introduction

Although evaporite minerals in the Arabian Gulf Sabkhas have been investigated by several workers, gypsum crystal habits are not studied. Only, limited information about the crystals in the Sabkhas is available in some previous reports. Such as these studies found in: Cavelier [1], Illing et al. [2], Al-Hitmi [3], Ragab et al. [4], Curtis et al. [5], Evans et al. [6], Kinsman [7-9], Shearman et al. [10], Shearman [11], Park [12], Butler [13] and [14], Butler et al. [15], Gunatilaka and Mwango [16], Behairy et al. [17], Mougenot [18], Hurlbert et al. [19], Antia [20], Xavier and Klemm [21] and Corselli and Aghib [22].

This is the first study of the gypsum crystals shapes in the famous, large, inland Dukhan Sabkha in the Qatar Peninsula. The study seeks to identify the various habits and vertical and horizontal distribution of the crystals in the sediments of the Sabkha. The factors that affected the crystals formation and shape are discussed in the study. Forty four sediment samples rich in crystals, six shallow cores and twenty two brine samples were collected for the study. The binocular microscope, polarizing microscope and scanning electronic microscope were used in the study of the sediments samples, gypsum crystals, smear slides and thin sections. Chemical analyses were completed for brine samples to define pH, conductivity, cations and anions.

Important series of science questions are answered in the study, such as:

1. What is controlling the creation, formation and development of the crystals?
2. Why are some shapes of gypsum crystals dominant in some locations and disappeared in others locations within the Sabkha.
3. What is the relation between the chemical properties of the brines within the Sabkha and the formation of gypsum crystals in the Sabkha?
4. What is the role of sediment types in the formation and in the shape of gypsum crystals within the Sabkha?
5. Are gypsum crystals primary or secondary, and what is the relation between anhydrite and gypsum formation in the Sabkha?

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General Setting of the Studied Area

Dukhan Sabkha is the largest inland Sabkha in the Qatar Peninsula, covers about 73 km^2 and located in the west adjacent to the Jabal Dukhan hills, and occupies a synclinal area between the Dukhan anticline in the west and the Qatar anticline in the east. It is situated in a depression shaped like an inverted L, one of its arms extends north-south and the second one northeast-southwest (Figure 1). The length of the north-south arm is about 20 km. Its width is 3 km in the north, 2 km in the middle and 4km in the south, decreasing to 1km at its southern edges. The length of the second arm is 8.5 km and its width is about 4 km. The surface of the Sabkha is flat, about one meter below sea level (Figure 2), except near the edges, is more than 1m above sea level due to the development of nebkhas (plants trapping sand). The lowest part of the Sabkha is in the south (25°20'E, 50°50'N), where it reaches -6 m below sea level [23]. There are small hills of bedrock within the sabkha along its margin to the northeast, northwest and southeast. These hills range in height from 1 to 7 m and consist of dolomitic limestone of the Upper Dammam Formation. The western side of the Sabkha is straighter than the other side, as it is constrained by the Dukhan anticline [24].

Figure 1: Landsat image mosaic, showing Dukhan Sabkha on the western part of Qatar (After Centre for GIS in cooperation with Geomatics Canada. Scale 1:200,000).

Figure 2: Detailed topographic contour map of Dukhan Sabkha (After Hunting Surveys Limited, 1982 with additions and modifications).

The deposits of Dukhan Sabkha consists of a compact, dry crust of halite (3 mm-2 cm thick), above brown or grey sand deposits, or brown sand intercalated with grey gypsum-rich layers [25]. Deposits of sand, clay and silt are present at the edges of the Sabkha, while a gypsum bed about 2 m thick is found in the central region. Anhydrite and halite are mainly dominant in the northeastern part of the Sabkha. Anhydrite presents at shallow depth (about 20 cm) as nodules and as fine grains (similar to gruel) mixed with halite, silt and dark black and grey deposits of microbial mats [25]. The thickness of anhydrite deposits in the northeastern part of the Sabkha is 2 to 3 cm; where it is mixed with mud and quartz sand. Accumulation of sand sheets and small sand dunes are found in the south and southeastern part of the Sabkha. Recent eolian sand sheets are also present in various positions in the western part of the Sabkha.

The groundwater level in Dukhan Sabkha is between a few centimeters and 120 cm below the surface. The sources of groundwater in the Sabkha include both the sea to the north, and the freshwater of the main northern aquifer. Rainwater and runoff also form a third source of freshwater in the Sabkha, especially after heavy storms. In the Dukhan Sabkha the movement of groundwater takes place as follows. (1) Vertical movement, both towards the surface due to capillary action, affected by the high rates of evaporation, and downwards during rainy periods, under the influence of gravity. Because of the shallow groundwater level, high rates of evaporation and low rainfall the movement of groundwater towards the surface is dominant. (2) Horizontal movement, affected by high tides and by the amount of freshwater drainage inside the Sabkha [25].

Methodology

Field study and sample collection

Field studies were carried out in Dukhan Sabkha during April, May and July 2010. Observations were made for gypsum crystals dominant on the surface and at shallow depths in the sediments of the Sabkha. Information about the groundwater level, type and size of the sediments, microbial mats dominant in the Sabkha were recorded. Gypsum crystals and sediment samples (44 samples) rich in crystals in addition to shallow core samples (6 cores) were collected from 41 locations (Figure 3 and Table 1) and photographs for the crystals and the locations rich in crystals were taken in the field. Twenty two brine samples were also collected from pit stations in various locations within the Sabkha.

Manually testing and microscopic study

The core samples were described and their length and colour defined. Photographs were taken of these cores and their important sediment features (Figure 4). After that the core samples and other studied samples were dried in the laboratory by leaving them uncovered and exposed to the atmosphere for three days. A sieving process was undertaken for the core and pit samples. Gypsum crystals, fragments and grains were picked out. The colour of the sediments was defined by using a rock-colour chart and the size and the shape of the crystals and fragments were defined under the binocular microscope by using

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a grain size scale. Photographs of the various crystals and fragments were taken under a polarizing microscope. Tables were drawn up to include a summary of the major characteristics of the studied samples in relation to depth and to graphic logs.

Scanning electron microscopy

Gypsum crystals and gypsum fragments were studied by using scanning electron microscope (Jeol/JSM-6400). For the study, the samples were fixed on the surface of stage with double sided sticky tape and thinly coated with gold. The samples were positioned in the SEM, viewed, studied and photographed.

Smear slides and thin sections study

Thin-section and smear slides were made for about 44 sediment samples rich in gypsum from the Sabkha. The samples for this study were chosen according to variations of color and appearance at various depths (following the hand specimen and binocular microscopic studies). Various habits of gypsum crystals and fragments were determined. Photographs were taken of the components under the polarizing microscope to show the various shapes of gypsum crystals and important characteristics.

Analyses of brine

Chemical analyses of 22 brine samples from Dukhan Sabkha were studied. The temperature range for the brine was 21C-23C. The analysis of these was completed to define the pH, conductivity, cations Na^+, Mg^{2+}, Ca^{2+}, Sr^{+2} and anions Cl^-, SO_4^{2-}, HCO_3^- of the samples.

A simple statistical approach was used to establish relationships between the different elements measured.

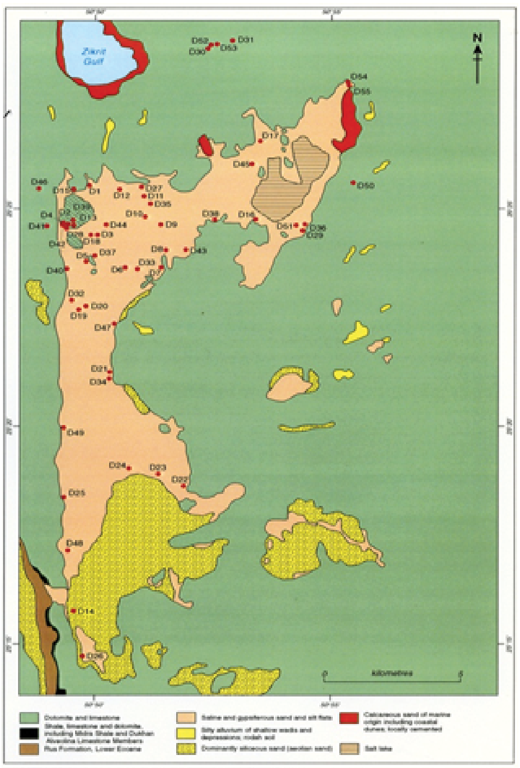

Figure 3: Locations of the study stations in Dukhan Sabkha (Base map after Hunting Geology and Geophysics Limited, 1980).

Stations	Location		Sample types
	Longitude	Latitude	P=pit, C=core, B=brine.
D1	N=25˚ 25′48″	E=50˚ 49′ 99″	P, B
D2	N=25˚ 24″ 54″	E=50˚ 49′50″	P
D3	N=25˚ 24′ 33″	E=50˚ 50′ 14″	P
D4	N=25˚ 24′54″	E=50˚ 49′ 41″	P
D5	N=25˚ 23′76″	E=50˚ 49″ 88″	P, B,
D6	N=25˚ 23′ 56″	E=50˚ 50′70″	P, B,
D7	N=25˚ 23′ 57″	E=50˚ 51′48″	P, B,
D8	N=25˚ 23′ 99″	E=50˚ 51′ 51″	P, B,
D9	N=25˚ 24′ 54″	E=50˚ 51′43″	P
D10	N=25˚ 24′78″	E=50˚ 51″ 16″	P, B,
D11	N=25˚ 25′ 20″	E=50′ 51′ 10″	P, B,
D12	N=25˚ 25′33″	E=50˚ 50′ 58″	P, B,
D13	N=25˚ 24′ 53″	E=50˚ 49′ 58″	P
D14	N=25˚ 15′ 85″	E=50˚ 49′58″	P, B,
D15	N=25˚ 25′32″	E=50˚ 49′ 63″	P
D16	N=5˚ 24′ 65″	E=50˚ 53′ 40″	P, B,
D17	N=25˚ 26′ 69″	E=50˚ 53′ 69″	P, B,
D18	N=25˚ 24′34″	E=50˚ 50′ 0″	P
D19	N=25˚ 22′ 87″	E=50˚ 40′ 48″	P
D20	N=25˚ 22′ 73″	E=50˚ 49′86″	P, B,
D21	N=25˚ 21′26″	E=50˚ 50′48″	P, B,
D22	N=25˚ 18′ 67″	E=50˚ 51′ 91″	P, B,
D23	N=25˚ 18′ 95″	E=50˚ 51′ 38″	P, B,
D24	N=25˚ 19′ 07″	E=50˚ 50′78″	P, B,
D25	N=25˚ 18′ 41″	E=50′ 49′ 42″	P
D26	N=25˚ 14′84″	E=50˚ 49′ 79″	P
D27	N=25˚ 25′ 40″	E=50˚ 51˚ 06″	P, B,
D28	N=25˚ 24′ 49″	E=50˚ 49′ 40″	P
D29	N=25˚ 24′46″	E=50˚ 54′ 44″	P
D30	N=25˚ 28′ 53″	E50˚ 52′ 47″	P
D31	N=25˚ 28′64″	E=50˚ 52′99″	P
D32	N=25˚ 22′ 88″	E=50˚ 49/ 66″	P
D33	N=25˚ 23′ 62″	E=50˚ 50′ 93″	P, B,
D34	N=25˚ 21′ 28″	E =50˚ 50′ 35″	P, B,
D35	N=25˚ 25′ 0″	E=50˚ 51′24″	P
D36	N=25˚ 24′ 54″	E=50˚ 54′ 51″	C,
D37	N=25˚ 23′ 73″	E=50˚ 49′69″	P, B,
D38	N=25˚ 24′ 58″	E=50˚ 52′ 64″	P, B,
D39	N=25˚ 24′43″	E=50˚ 49′31″	P
D40	N=25˚ 23′ 77″	E=50˚ 49′ 36″	P
D41	N=25˚ 24′ 55″	E=50˚ 49′12″	P
D42	N=25˚ 24′ 50″	E=50˚ 49′ 40″	P
D43	N= 25˚ 23′ 97″	E=50˚ 51′99″	P
D44	N=25˚ 24′ 52″	E=50˚ 50′ 32″	P
D45	N=25˚ 25′ 94″	E=50˚ 53′ 31″	P
D46	N=25˚ 52′ 49″	E= 50˚ 49′92″	P
D47	N=25˚ 22′32″	E=50˚ 50′41″	P
D48	N=25˚ 17′ 11″	E=50˚ 49′ 44″	P, B,
D49	N= 25˚ 27′51″	E=50˚ 50′49″	P
D50	N=25˚ 25′53″	E=50˚ 55′40″	P
D51	N=25˚24′ 55″	E=50˚ 54′ 28″	C, B,
D52	N=25˚ 28′53″	E=50˚ 52′ 49″	P
D53	N= 25˚ 28′ 56″	E=50˚ 52′ 50″	P
D54	N=25˚ 27′ 77″	E=50˚ 55′ 46″	P
D55	N=25˚ 27′66″	E=50˚ 55′46″	P
D56	N=25˚ 33′ 66″	E=50˚ 50′ 40″	P

Table 1: Names and locations of the studied stations in Dukhan Sabkha.

The methods that were applied for determining seawater salinity and pH were those of Grasshoff [26] and Strickland and Parsons [27]. For trace metals in seawater found in Kremling et al. [28] and for major constituents in seawater in Kremling (1983a). Methods for analyses of seawater for anions and cations were found in Crompton [29].

Result of the Study

Field study

Most of the Surface of the Sabkha is covered by compact crust of fine deposits of sand, clay mud, halite and very fine grains of gypsum (a, b, and c in Figure 5). The color of the crust is various between beige to light beige and light gray, and the thickness is various from few millimeter and reach to 2 cm in some location.

Brown and white patches of circular and elongated shape (over 2 m^2 in size) in the middle of the northern part of the Dukhan Sabkha and in the western part of the Sabkha. These patches probably areas of dead nebkhas (d, e and f in Figure 5). The amount of halite on the surface of the white patches is high and the deposits are dry and less compact, while the brown patches contain a large probation of small crystals of gypsum and their deposits are saturated by water. Accumulation of sand sheets and small sand dunes are found in the south and southeastern part of the Sabkha. Recent eolian sand sheets are also present in various positions in the western part of the Sabkha. Large numbers of shallow surface drainage, varies in their length connected with the edges of the Sabkha, especially the northeastern and northwestern edges. These drainage are feeding the Sabkha by rainwater, especially during rainy periods, also bring the fine deposits from the land to these parts of the Sabkha. Shallow salt lake covering about 12 km is located in the northeastern part of the Sabkha. The surface of the Sabkha in this area

Figure 5: General view of Dukhan Sabkha (**a** and **b** is brown compact surface crust in the northern part of the Sabkha, **c** is light gray crust in the northeastern part, **d**, **e** and **f** brown and white patches in the western and middle of the northern part of the Sabkha).

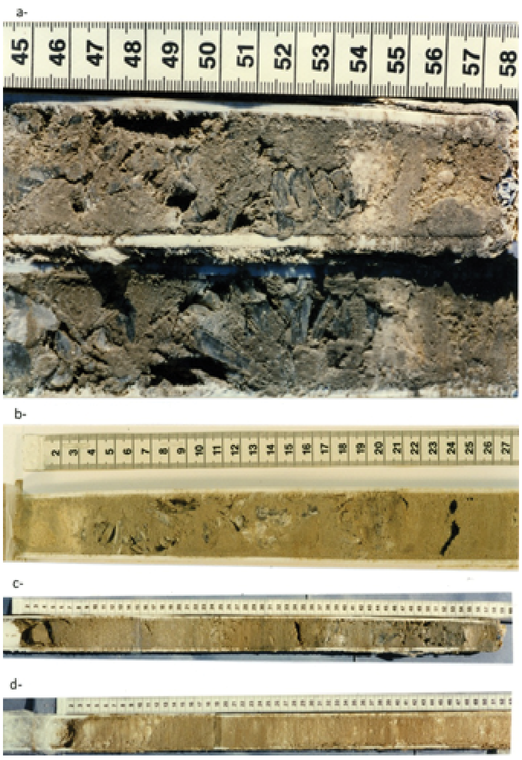

Figure 4: Core samples from Dukhan Sabkha (Note that gypsum fragments And anhydrite abundance in the sediments).

is covered by a thin crust of halite and in some locations, thin brown crust (rubber texture) consists of mud, clays and microbial mat covers the surface. At the margin of the lake, anhydrite nodules are present at a depth of about 20 cm from the surface and towards the land, the anhydrite nodules become finer (similar to gruel) mixed with halite, silt and dark black and grey deposits of algae mats (a and b in Figure 6).

Nebkhas and salt resistant plants are quite common, especially along its northwestern edges of the Sabkha (c in Figure 6). Species include Halocnomum stobiolaceum, Halopeplis perfoliate, Halogeton alopecuroides and Arthrocnemum glaucum.

Gypsum crystals of various habits and different sizes were recorded in the sediments. The crystals are common in the surface crust and at shallow depths (few cm from the surface), especially in the north and in the middle part of the Sabkha and decreases in the south and along the margins of the Sabkha. In some locations, in the southern and eastern part of the Sabkha, the crystals are present down to about half a meter.

Large numbers of very fine of acicular gypsum crystals were found on the surface crust of the Sabkha. Crystals of lenticular and sub-lenticular, and inter-grown sub-lenticular habit are present on the surface and at a few centimetres from the surface within the sediments of the brown and white patches, especially in the northeastern part of the Sabkha. Abundant gypsum crystals of prismatic and acicular shapes, of various lengths and thickness, are found within and beside small artificial pit, in the northern part of the Sabkha (d in Figure 6). The crystals increase in size under the brines inside the pit. Large crystals of desert rose shape (about 5 cm length) were only found on the surface in the northeastern part of the Sabkha, to the west from the salt lake area. The crystals formed above groundwater level and at shallow depth, few centimeters from the surface. In general, the proportion of gypsum crystals at the edges within the Sabkha is very small and disappear in most the samples from these locations.

Laboratory study

Sediments samples: The laboratory study showed that gypsum found through Dukhan Sabkha deposits as crystal fragments and as crystals of various habits and sizes (a, b, c, d, e and f in Figures 7-9). The crystals are acicular, lenticular and sub-lenticular, inter-grown sub-lenticular, prismatic, pyramidal, and elliptical and semielliptical. Twining appeared in large numbers of small, colorless gypsum crystals. In some samples gypsum crystals dissolved as a result of heating. Most the sediments samples included more than one habit of crystals and the acicular, lenticular and sub-lenticular, inter-grown sub-lenticular and pyramidal are the dominant habits of gypsum crystals in the Sabkha. The lenticular and sub-lenticular crystals vary in length between 0.2 mm-6 mm and in diameter between 0.1-5 mm. The acicular crystals are between 0.2-8 mm in length and their widths are between 0.1-3.1 mm. In the artificial pit in the northern part of the Sabkha, acicular crystals reach about 2.5 cm in length. For inter-grown sub-lenticular crystals, the length varies between 1-2.2 mm and the width is between 0.3-4 mm. The pyramidal crystals range in length from 0.3-4.2 mm and in width from 0.1-2 mm. For the prismatic crystals, the length is from 0.2-8 mm and the width from 0.2- 4.2 mm. Swallow-tail twinning is found in some of prismatic habits. The pseudo-tetragonal habits vary in length from 1.5-2.5 mm and in their width from 1-3mm.

In the northern and northeastern part of the Sabkha**,** the sediments include gypsum crystals and fragments of broken crystals. The crystals are lenticular and sub-lenticular, prismatic, pyramidal, acicular and inter-grown-sub-lenticular. The lenticular and sub-lenticular crystals vary in their length from 1-3.4 mm and in their width from 0.3-2.6 mm. The length of the prismatic crystals varies from 0.5-8 mm and in width from 0.3-2 mm. For pyramidal crystals the length is in the range from 0.3-4 mm and width from 0.1-1.2 mm. The acicular crystals vary in length from 2.2-4.3 mm and in their thickness from 0.5-3.1 mm. The

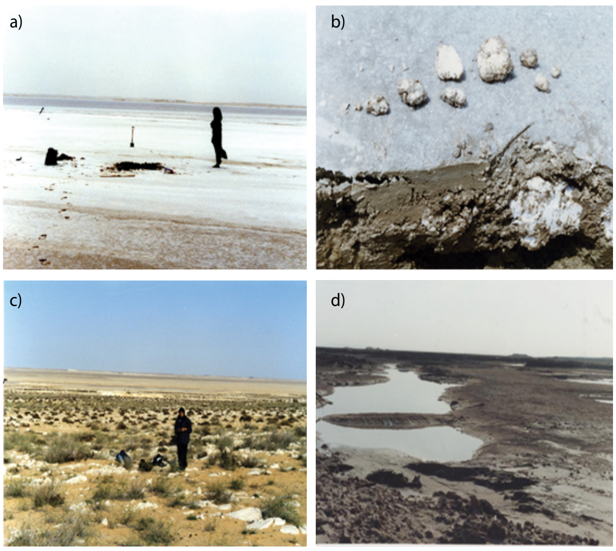

Figure 6: Dukhan Sabkha: **a** and **b** is area of shallow salt lake in the northeastern part of the Sabkha, **c** is Nebkhas and salt resistant plants dominant at the northwestern edges of the Sabkha, **d** is artificial lake for extracting water in the northern part of the Sabkha. (Note that halite cover the surface of the area in **a**, and anhydrite appears as nodules and gruel in **b**).

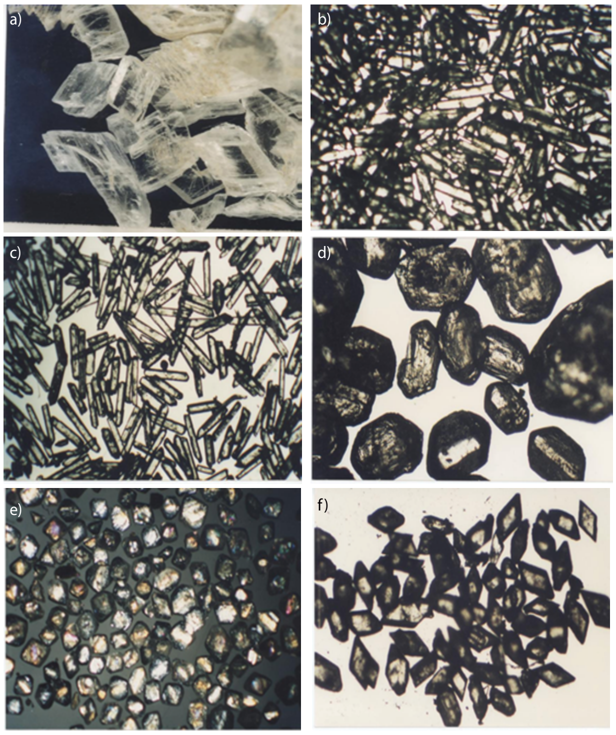

Figure 7: Gypsum crystals of various shapes and sizes in the sediment samples, Dukhan Sabkha. (**a** gypsum fragments off broken crystals, **b** and **c** thin gypsum crystals of acicular shape, d short, thick acicular crystals, **e** and **f** pyramidal shapes) – lenses power is 2.5 and field view is 3.4 mm.

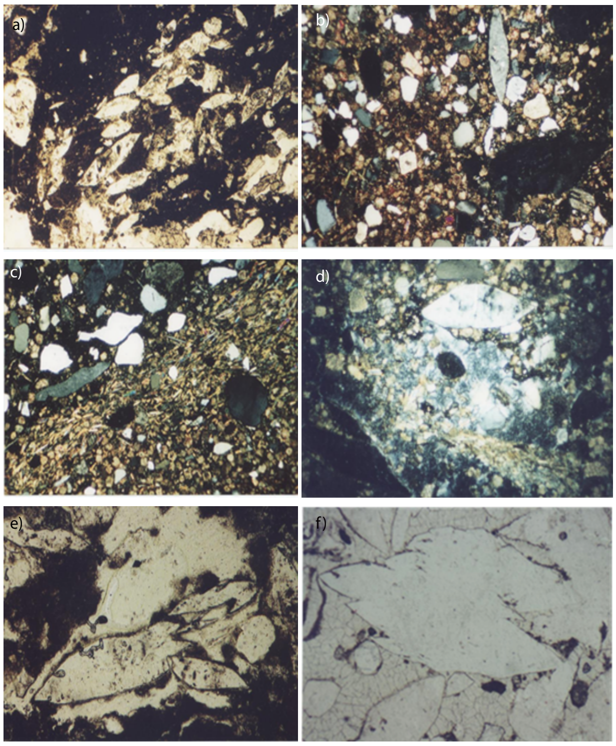

Figure 8: Gypsum crystals of elongated lenticular shapes dominant in the sediments, northeastern part of Dukhan Sabkha. (Note that anhydrite is dominant in **a**, **b**, **c** and **d**, and the crystals with jagged edges). Lenses power is 2.5 and field view is 3.4 m; for **e** and **f** magnification is 40x.

length for inter-grown sub-lenticular crystals varies from 0.6-4 mm and the width from 0.2-1 mm. The crystal fragments vary in length from 0.8 -16 mm and width from 0.5-8 mm.

In some locations in the northwestern part of the Sabkha, gypsum is only found as prismatic crystals and as fragments of broken crystals. The length of the crystals is up to 4 mm and the width is 0.2 mm. The crystal fragments are larger and of about 6 mm length. More habits of crystals were found in other stations in the same part of the Sabkha. Gypsum crystals of lenticular and sub-lenticular, prismatic and pyramidal shapes were found in the sediments. The length of the lenticular and sub-lenticular habits is from 1-4 mm and from 1.5-4 mm for the prismatic crystals, and <1 mm for the pyramidal crystals. The prismatic crystals vary in their length from 0.5-2.5 mm.

In the middle part of the Sabkha, gypsum fragments of broken crystals were found in some samples. The fragments vary in their length from 2-8 mm.

In the eastern part of the Sabkha, the crystals are of acicular, prismatic, lenticular and sub-lenticular, pyramidal and inter-grown sub-lenticular habits. The length of the prismatic crystals varies from 0.8-5 mm and the width from 0.2-3.8 mm. The acicular crystals vary in their length from 0.6-8 mm and in their thickness from 0.3 -1.3 mm. For pyramidal crystals the length varies from 2-8 mm and the width is from 1.4-2 mm. The inter-grown sub-lenticular crystals vary in their length from 1.3-6 mm. The broken fragments attain up to 21 mm length.

In the western part of the Sabkha, the sediments include gypsum crystals of inter-grown sub-lenticular, prismatic and pyramidal habits. The crystals vary in length from 1-5 mm and in width up to about 1 mm. Fragments of broken gypsum crystals were also found in the samples. The length of the fragments is about 10 mm and the width about 4 mm.

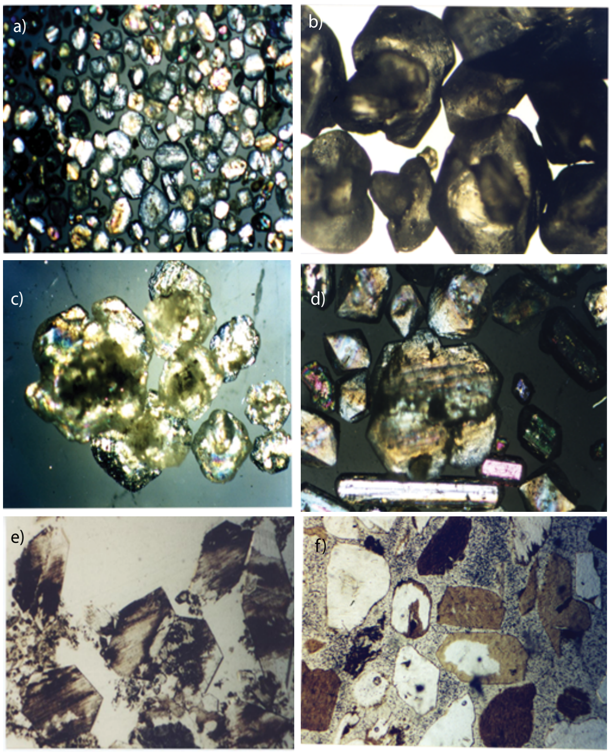

Figure 9: Various habits of gypsum crystals, Dukhan Sabkha (**a** various shapes of gypsum crystals different in their sizes, **b**, **c** and **d** twining appears in lenticular and sub-lenticular crystals, **e** and **f** gypsum crystals dissolved as a result of heating). Lenses power is 2.5 and field view is 3.4mm; for e and f magnification is 40.

In the southern part of the Sabkha, gypsum found as complete crystals and as fragments of broken crystals. The crystals are of pyramidal, prismatic, lenticular and sub-lenticular and inter-grown sub-lenticular habits. The pyramidal crystals are more dominant and they vary in their length from 0.3-1 mm, width is about 0.4 mm. The length of the prismatic crystals varies from 0.6-3 mm and their thickness from 0.2-0.8 mm. The length of the lenticular and sub-lenticular is mostly from 2.3-6 mm and their width from 1.4-5 mm. The inter-grown sub-lenticular crystals vary in their length from 0.5 -5 mm.

In the southwestern part of the Sabkha, the situation is different than in the southern part, as the sediments include only small proportion of gypsum crystals and fragments. The crystals are of inter-grown sub-lenticular habit and the fragments vary in their length from 0.4-2.2 mm. In some stations most of the crystals are pyramidal, some are roughly hexagonal. The crystals vary in their length from 2-4 mm and in their width from 1-1.2 mm.

In the southeastern part of the Sabkha, such as in station D32 and D38, the sediments include gypsum crystals and fragments of broken crystals. The crystals are lenticular and sub-lenticular, prismatic, pyramidal and inter-grown sub-lenticular. The lenticular and sub-lenticular, and prismatic crystals vary in their length from 1-5 mm. The length of the pyramidal crystals is usually about 2 mm; it is up to 6 mm for inter-grown crystals. The length of prismatic crystals is 3.8 mm and the thickness varies from 1-2 mm. The fragments attain up to 8 mm in length. In the sediments of station D22 from the same part of the Sabkha, the sediments only include gypsum fragments of about 8 mm thickness.

Brine chemistry

The chemical characteristics and mean of 22 brines from various locations of Dukhan Sabkha and one seawater sample from the northern coast of Qatar are summarized in Table 2 and Figure 10. In the brine samples the mean of pH is 6.8, with a range between 6.4 and 7.3. The highest value was recorded in station D27 from an artificial pit in the northern part of the Sabkha. The lowest value was recorded in stations D6 and D16 from the northeastern extension of the Sabkha, at depth 30 cm and 50 cm successively.

The mean for Na^+ is 38.6 ppt (range 11.3 to 91.1 ppt) and it is 62.1 ppt for Cl^- (range 20.2 to 146.8 ppt). The highest values of Na^+ and Cl^- were recorded in a sample from the station D27. The lowest amounts for the two elements were recorded in a sample from station D21 beside the eastern edge of the middle part of the Sabkha (at a depth of 50 cm).

In general, the proportion of Na^+ and Cl^- gradually decreases from north to the south, and is mainly high in the northeastern part of the Sabkha.

The mean for Ca^{2+} is 1.5 ppt (range 0.8-2 ppt) and for SO_4^{2-} 6.6 ppt (range 2.8-12.5 ppt). The highest proportion Ca^{2+} was recorded in shallow subsurface brine samples (at depth 0.5 and 1 m) from southeastern and western part of the Sabkha. The lowest Ca^{2+} was recorded in the southeastern part of the Sabkha at depth of about 90 cm. The highest proportion for SO_4^{2-} was recorded in brine from the station D27, while the lowest proportion for this ion was recorded in a sample from station D48 in the southern part of the Sabkha, at a depth of about 50 cm.

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Location													
Station	Longitude	Latitude	Dep. (Cm)	pH	Cond.	Na^+ (ppt.)	Cl^- (ppt)	Ca^{2+} (ppt)	SO_4^{2-} (ppt)	Mg^{2+} (ppt)	Sr^{2+} (ppt)	HCO_3^{2-} (ppt)	TDS (ppt)
D1	N=25° 25′48″	E=50° 49′97″	110	7.1	121.5	33.4	55.8	1.6	9.4	3.6	0.03	0.08	103.9
D5	N=25° 23′76″	E=50° 49′88″	100	6.5	131.3	36.5	58.6	2	4.7	3.1	0.04	0.07	104.9
D6	N=25° 23′56‴	E=50° 50′70″	30	6.4	155.8	47	82	1.6	8.1	4.4	0.04	0.07	143.2
D7	N=25° 23′57″	E=50° 51′48″	30	6.6	127.2	34.9	58.6	1.6	7.4	3.8	0.03	0.07	106.5
D8	N=25° 23′99″	E=50°51′51″	25	6.9	167.9	53.3	84.1	1.6	8.3	5.4	0.03	0.08	152.7
D10	N=25°24′78″	E=50° 51′16″	80	6.8	138.1	39.7	60.7	1.7	5.2	3.9	0.03	0.08	111.3
D11	N=25° 25′20″	E=50° 51′10″	120	6.9	131.4	36.9	58	1.8	6.5	3.6	0.03	0.04	106.9
D12	N=25° 25′33″	E=50° 50′58″	60	6.8	151.4	46.5	67.3	1.7	6.9	4.6	0.04	0.06	127.1
D14	N=25° 15′85″	E=50° 49′58″	60	7.2	58.8	12.3	22.6	1.6	3.3	1.3	0.04	0.14	41.1
D16	N=25° 24′65″	E=50° 53′40″	50	6.4	192.8	67.5	99	1.4	6.9	6.3	0.03	0.06	181.3
D17	N=25° 26′69″	E=50° 53′69″	50	7.3	141.8	46.3	69.4	1.7	7.7	4.6	0.03	0.13	129.7
D20	N=25° 22′73″	E=50° 49′86″	120	6.9	139.9	39.9	57.8	1.6	5.3	4	0.03	0.1	108.7
D21	N=25° 21′26″	E=50° 50′48″	50	7.1	55.7	11.3	20.2	1.4	6.5	1.5	0.03	0.11	41
D22	N=25°18′67″	E=50° 51′90″	90	7.2	81.3	19	31.8	0.8	3.9	2.3	0.04	0.08	57.9
D23	N=5° 18′ 95″	E=50° 51′38″	50	6.7	148.8	44.5	67.1	1.5	7.7	3.8	0.03	0.11	124.7
D24	N=25° 19′07″	E=50° 50′78″	60	6.8	129.1	36.1	54.7	1.6	5.6	3.1	0.04	0.08	101.8
D33	N=25° 23′62″	E=50° 50′93″	30	6.6	185.1	61.5	112.9	1.4	10.8	6.2	0.03	0.06	192.9
D34	N=25° 21′28″	E=50° 50′58″	80	6.7	145.7	42.7	74.3	1.6	8.7	4.3	0.04	0.07	131.7
D37	N=25° 23′72″	E=50° 49′69″	50	6.8	128.1	36	57.8	1.1	6.6	3.7	0.02	0.1	105.4
D38	N=25° 24′58″	E=50° 52/64″	50	6.8	143.1	41	70.9	1.2	5.8	4.2	0.02	0.1	123.2
D48	N=25° 17′11″	E=50° 49′44″	50	7.2	98.9	25.2	40.7	2	2.8	2.1	0.05	0.01	72.8
D27	N=25° 25′40″	E=50° 51′06″	Art. Pit.	7.2	220	91.1	146.8	0.9	12.5	9.7	0.07	0.17	261.1
Mean				6.8	132.1	38.6	62.1	1.5	6.6	3.8	0.03	0.1	112.8
Standard sea water in gram/litre				___	____	10.56	18.98	0.40	2.65	1.27	0.008	____	34.3

Table 2: Results of chemical analyses of 22 water samples from Dukan Sabkha.

The mean of Mg^{2+} is 3.8 ppt (range 1.3-9.7 ppt). The highest proportion was recorded in the northern part of the Sabkha and the lowest proportion was recorded in a sample from station D14 in the southern part of the Sabkha, at a depth of about 60 cm. In general Mg^{2+} concentrated in the northeastern part of the Sabkha and it decreases to the south.

The mean of Sr^{2+} is 0.03 ppt (range from 0.02-0.07 ppt). There is no difference in the mean of Sr^{2+} in the selected samples within the Sabkha. The high concentration within the Sabkha brines is in the northeastern part of the Sabkha.

The mean of HCO_3^{2-} in the brines is 0.1 ppt (range 0.01 to 0.17 ppt). The concentration of HCO_3^{2-} increases to the northeast and to the south within the Sabkha.

The mean of TDS is 112.8 ppt (range 41 to 261.1 ppt). The highest proportion was recorded in sample from station D27 in the northern part of the Sabkha (at a depth of about 50 cm). The lowest proportion was recorded from station D21 in the southern part of the Sabkha at a depth of about 50 cm. The TDS mainly concentrated in the northeastern part of the Sabkha and decreases in the south.

The statistical study showed that there is good relationship between Na^+ and Cl^-, and between Cl^- and Mg^{2+} in Dukhan Sabkha brines, R^2=0.97 and 0.96 respectively (Figures 11a and 11b). There is no apparent relationship between Ca^{2+} and SO_4^{2-} and Ca^{2+} and Cl^-, Cl^- and Ca^{2+}, Mg^{2+} and Ca^{2+}, but SO_4^{2-} makes relatively good relationships with Mg^{2+}, gives R^2=0.63 (Figure 11c).

There is a good relationship between TDS and Na^+, Cl^- and TDS and Mg^{2+}, R^2=0.99, 1 and 0.98 respectively (Figures 11d-11f). Good relationship was also found between TDS and SO_4^{2-} and TDS with Mg^{2+}/Ca^{2+}; R^2=0.6 and 0.7 respectively (Figure 11g and 11h), but there is no apparent relationship between TDS and Ca^{2+}.

Discussions

Sediment samples

Most of the Surface of the Sabkha is covered by hard compact crust of fine deposits of sand, clay mud, halite and rich in very fine crystals of acicular shape of gypsum. At the edges of the Sabkha the surface drainage feeds the Sabkha by rainwater, especially during rainy period and sand deposits are dominating in these positions, accordingly the compact crust is not present at the edges of the Sabkha.

Various habits of gypsum crystals, of different sizes are present in Dukhan Sabkha sediments. The crystals are mainly formed on the surface and at shallow depths. Suitable conditions such as high ground water level, high temperature, saturation of Sabkha sediments by brines and a high rate of evaporation are probably reasons for formation of these crystals. The main reasons for variation in the amount and habit of gypsum crystals in the Dukhan Sabkha are:

(1) The surface of the Sabkha is flat, about one meter below sea level. This lead to feeding Sabkha basin by greater rate of groundwater and this water exposed to high evaporation processes during the year. (2) The principal sediment type is the second important reason. In Dukhan Sabkha, silt, clay and fine carbonate sediments are common than sand deposits. This is the main reason for the dominant of the fine acicular crystals in the Sabkha sediments. (3) Dukhan Sabkha is an inland Sabkha, accordingly the evaporation process in the Sabkha is very active leading to a greater proportion of gypsum in the former.

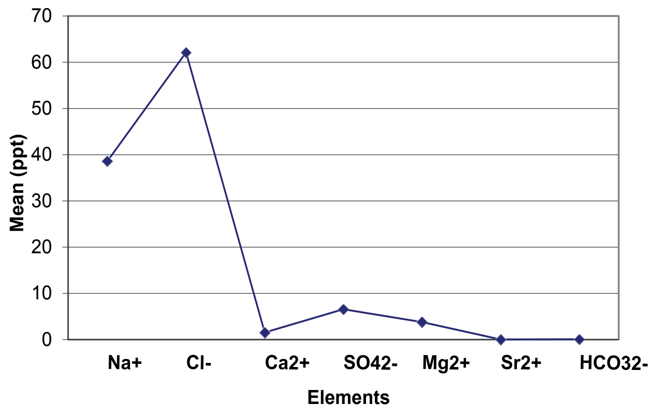

Figure 10: Mean of brine elements in 22 samples from the Dukhan Sabkha.

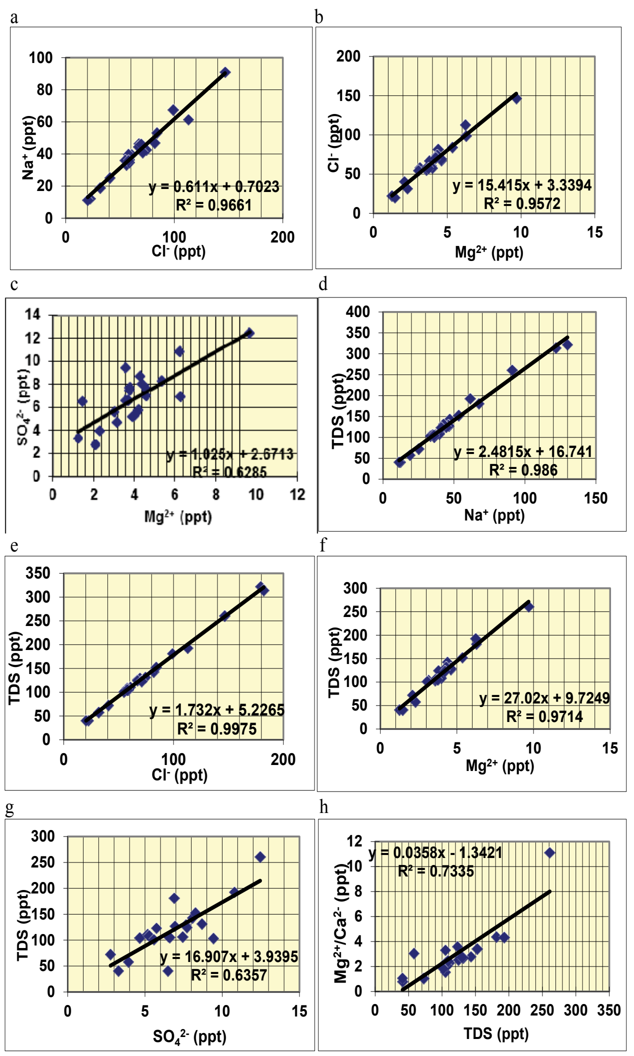

Figure 11: Correlation statistics of relationship of cations and anions in 22 brine samples, Dukhan Sabkha (**a** and **b** showed good relationship between Na^+ and Cl, and between Cl^- and Mg.$^{2+}$ TDS gives good relationship with Na^+,Cl^- and Mg^+ as in **d, e** and **f**. Relatively good relationship found between SO_4^{2-} with Mg^+ and TDS with SO_4^{2-} and with Mg^{2+}/Ca^{2-}as in **c**, **g** and **h** respectively).

The proportion of gypsum crystals in Dukhan Sabkha increases in the location of fine sediments. It seems that fine grained sediments allows more than one habit of the crystals to grow in the Sabkha. The evaporation process in fine sediments is slower than that in coarser sediments, allowing the brine to be retained in the sediments for enough to form more than one shape of the crystals. The more rapid evaporation process through coarse deposits not give enough time for such a wide range of crystals shapes to form. Large numbers of small lenticular and sub-lenticular crystals are present at shallow depths, in the northeastern part of Dukhan Sabkha, above groundwater level, beneath and between the anhydrite deposits and bellow microbial mats. Some of the crystals show swallowtail twins. The saturation of sediments by brine of high salinity and the dominance of fine sediments (silt and clay) in addition to the thin surface cover of clays and microbial mats (of rubber-like texture) are important factors in the formation of these crystals in this part of the Sabkha. Because a high porosity and low permeability in the fine sediments and a surface cover of rubbery texture, capillarity plays an important role in formation of gypsum crystals of various habits at shallow depths in this part of the Sabkha. The evaporation process of groundwater is slowed down in these conditions so that water near the surface has time to become saturated. This situation gives gypsum a good chance to form at shallow depths. Cody [30] believed that organic matter is a major factor for growth of lenticular habit, under alkaline rather than acidic conditions.

In the northeastern part of Dukhan Sabkha, where lenticular and sub-lenticular crystals are dominant, microbial mats are also present in the sediments. It clear that the fine sediments and microbial mats play an important in forming the crystals of lenticular and sub-lenticular shape. The crystals, however, are also found in other locations of the Sabkha, and are of large size, although there is no organic material in the sediments. Raup suggested that gypsum could be precipitated by the mixing of seawater brines of different composition and density at various stages of evaporation, either as crystallization at the brine surface or at depth as a result of temperature changes. Edinger believed that the relative degree of super-saturation of brines has major role in determining the relative growth rate of gypsum crystals habit faces and the particle size. The ions present in the solution (Sr^{2+}, Ag^+, OH^-, H^+, NO_3^-, Na^+ and HSO_4^-) modify the influence of the super saturation on these processes. Curtis et al. [5] reported that, in Abu Dhabi Sabkha, lenticular and sub-lenticular crystals are dominant within the algal mats as a result of hydration of anhydrite caused by the influx of less saline groundwater from inland. In the northeastern part of Dukhan Sabkha beside the salt lake area the salinity is high and the crystals are present beneath and between the anhydrite, but mainly beneath. This means that, the crystals have been formed before anhydrite and the situation in this part of the Dukhan Sabkha is similar to that in Abu Dhabi Sabkha. The crystals found between the anhydrite layers could have been formed as a result of hydration of anhydrite.

Prismatic crystals abundant in Dukhan Sabkha sediments. Cody [30] believed that elongate prismatic gypsum formed in acid conditions, whether or not organic material is present. This agrees with the situation of the dominant of prismatic crystals in the studied Sabkha. The total dissolved solid (TDS) of Dukhan Sabkha brines averages about 113 ppt. This amount of TDS in the brines of the Sabkha is probably another reason for the present of prismatic crystals in Dukhan Sabkha.

The presence of pyramidal crystals in Dukhan Sabkha sediments and their dominance in the northeastern part of Dukhan Sabkha is probably because fine sediments are abundant in these locations. Cody suggested that organic matter associated with clay stops the growth of the 111 face of the crystals, accordingly the pyramidal gypsum habits are usually dominant in clay-rich organic deposits. In the present study, pyramidal crystals are found in fine carbonate sediments lacking organic material. The size of the sediments probably controls the formation of this type of gypsum habit in Dukhan Sabkha.

Masson [31] believed that the type of sediments affected the size of gypsum crystals of southern Texas. High porosity and permeability of the sediments caused rapid migration of brine ions and accordingly large crystals of gypsum formed in the area. For the same reason large gypsum crystals of desert rose habit are dominant beside the western edge of Dukhan Sabkha, where quartz sand is dominant, but such as these crystals are not found in other parts of the Sabkha.

Brine chemistry

The chemical characteristics and mean of brine elements in the Dukhan Sabkha are summarized in Table 2 and Figure 10. In the brine the values of pH are almost the same in all the samples and there is no relation was found between the depth and pH of the studied samples. The pH value of the Sabkha brines is less than that of the normal seawater. It varied between 6.4 to7.3 and the mean was 6.8. For sea water pH is around 8.2 and it can decrease to 6.3 with increased CO_2 as during photosynthesis, but it does not normally exceed 8.4 [32]. The decrease of pH in the brines of the studied Sabkha was probably not caused by phytoplankton and algal mat, because the proportion of organic carbons recorded in the sediments from Sabkha was low. It found that the brines of high salinity have low pH (e.g. samples from northeastern part). The brine samples from the southern part of the Sabkha, also include high value of pH because their salinity is low (Table 2). Krumgalz [33] from his studies of salt effect on the pH of hypersaline solution found similar results. However, the salinity is affect in the value of pH in Dukhan Sabkha brine, although the range of pH in the brines is narrow; between 6.4 and 7.3.

The mean concentration for Na^+ and Cl^- in the brine samples is high (41 ppt and 62.1 ppt respectively). This is not what was initially expected. It was thought that the proportion of halite in Dukhan Sabkha should be high, as Dukhan Sabkha is an inland Sabkha, is present in a shallow basin, and there is no surface channels joining the Sabkha to seawater. Possible reasons for this are: (1) The main fresh ground water aquifer of Qatar is in the middle of the northern part and the freshwater drains to the sea across Dukhan Sabkha. The freshwater mixes with the groundwater of the Sabkha and decreases its salinity. (2) The presence of the Dukhan anticline to the west of Dukhan Sabkha probably decreases the run of the freshwater to the sea. (3) The main farms are found in the northern part of Qatar. Some of these farms are located not far from Dukhan Sabkha. Parts of the fresh water irrigation could reach Dukhan Sabkha and this decrease its salinity. (4) The annual rainfall, during rainy periods is higher in the northern part of Qatar than in the south. This rainwater probably decreases the groundwater salinity of Dukhan Sabkha. (5) Dukhan Sabkha is more likely to be supplied with surface drainage water as it is inland and thus receives surface drainage from all directions.

However, the main factors causing the high concentration of Na^+ and Cl^- in the brines of Dukhan Sabkhas are: (1) The evaporation processes from the surface and from shallow subsurface water within the Sabkhas (2) A high percentage of sodium chloride in the Sabkhas sediments; about 46%. Halite in the sediments could be easily dissolved by water, accordingly the brines of Sabkha became saturated in Na^+ and $Cl.^-$

The mean for Ca^{2+} is 1.5ppt and mostly less than 2ppt but approximately three times higher than that of the seawater sample. SO_4^{2-} in brines is 6.6 ppt. It is about two and halves time higher than in the seawater sample. Gypsum in the Sabkha sediments is probably an important source for Ca^{2+} and SO_4^{2-} in the brines. It is a dominant evaporite mineral in the Sabkha sediments.

Because gypsum percentage in Dukhan Sabkha sediments is high, it was thought that SO_4^{2-} in the Sabkha brines would be high; but the situation is opposite to what was expected. The reason is probably because: (1) Dukhan Sabkha is fed by fresh groundwater (2) The mean probation of SO_4^{2-} in the brines of Dukhan Sabkha was lost in the formation of gypsum, and this is why the proportion of SO_4^{2-} in Dukhan Sabkha brines is small and the percentage of gypsum in its sediments is high. Illing et al. [2] suggested that Ca^{2+} and SO_4^{2-} in the Faishak Sabkha in the western part of Qatar are utilized in the formation of gypsum, accordingly their proportion in the Sabkha brine is small. This situation is similar to the state in the studied Sabkhas.

The two brine samples (stations D5 and D48) included about 2 ppt Ca^{2+} probably because of dissolution of gypsum and calcite in nearby rocks. The proportion of gypsum crystals in the sediments of these two locations is high. This gypsum in the sediments probably source for Ca^{2+} and SO_4^{2-} in the Sabkhas brines. For same reason, the brine sample D27 from the northern part of Dukhan Sabkha included the highest proportion of SO_4^{2-} (12.5 ppt).

The mean for Mg^{2+} is high, about 3.8 ppt. Kinsman [34] reported that high salinity reduces the activity of pH in the H_2O and with a decrease the salinity the activity of pH increases. This situation is similar to the cases in our studied Sabkha. In Dukhan Sabkha the TDS in the brines was 112.8 ppt, and it was 41 for Na^+ and 66 for Cl^-. The low salinity in the brines probably increase the activity of H_2O, thus the activity of formation of gypsum and anhydrite in the Sabkha became high, resulting in the Mg^{2+} percentage in the Sabkha becoming low. In the brines of the Sabkha, Mg^{2+} simply increases with salinity and Cl^-. For example, the highest proportion for Mg^{2+} (9.7 ppt) was recorded in sample D17 from the northern part of the Sabkha. The sample also included a high proportion of Cl^- (146.8 ppt) and this means that magnesium chloride is the reason for the high proportion of Mg^{2+} in this sample. For the same reason, most of the brine samples from the Sabkha included a high proportion of Mg^{2+} whilst including a high proportion of Cl^- (Table 2).

The good relationship between Mg^{2+} and Cl^- in Sabkha brines probably results from the low salinity and the high pH activity. This gives a good chance for the concentration of Cl^- in the brines to form magnesium chloride and so leads to low Mg^{2+}. No good relationship was found between $Mg^{2+}$and Ca^{2+}in the brines, probably because the balance was affected by utilized Ca^{2+} in gypsum formation. Since Mg^{2+} is affected by the salinity, this reflected on the relationship between $Mg^{2+}$and TDS and for this reason, a good relationship was found between $Mg^{2+}$and TDS in the brines of Dukhan Sabkha.

The relationship of SO_4^{2-} with Mg^{2+} became significant, only after excluding the samples from the anhydrite area. This is probably because the brines of the anhydrite area are distinguished by different chemical characteristics than the brines in the other locations of Dukhan Sabkha and are as a result of the difference of geology, sediments and brines level.

The proportion of Sr^{2+} in the brines from Dukhan Sabkha is small. It is twice the proportion of this element found in the seawater. Gypsum is probably the main source for Sr^{2+} in the brines, because it is dominant in its sediments. The highest concentration of Sr^{2+} was found in the northeastern part of Dukhan Sabkha and gypsum is dominant in the northern part of the Sabkha.

The concentration of HCO_3^{2-} in the brines is small, but it is higher than that of seawater. The minor concentration of HCO_3^{2-} in the brines is probably because the proportion of microbial mat in the Sabkha is small. Microbial mats are mainly dominant in the northeastern part of the Sabkha and this probably lead to a high concentration of HCO_3^{2-} The remains of dead plants in the southern part of the Sabkha probably increase the proportion of HCO_3^{2-} in the sediments of this part of the Sabkha. Later HCO_3^{2-} could be concentrated in rainwater and penetrate inside the Sabkha and mix with brines at shallow depths.

The mean of the TDS of the brine samples is 112.8 ppt. The main reason being because Dukhan Sabkha receives fresh water from the land and from rains, during rainy seasons. The total of TDS in the brines of the northeastern extension of the Sabkha is higher than that in the other parts and in the southern part is lower than in the other parts. In general, the TDS decreases from north to south and increases from east to west.

The TDS decreases from east to west because the eastern part of the Sabkha is receiving fresh groundwater as drainage from the main northern aquifer and from small ground lenses located to the east. For this reason the salinity (11.3 ppt) in the brine sample from station D21 beside the eastern edge of the Sabkha is low. The western part of the Sabkha is more affected by seawater.

Conclusion

Dukhan Sabkha is the largest inland Sabkha located on the western part of Qatar and occupies a synclinal area. The surface of the Sabkha is flat, about one meter below sea level, except near the edges is more than 1m above sea level because the accumulation of blown sand.

Most of the Surface of the Sabkha is covered by compact crust of fine deposits of sand, clay mud, halite and very fine grains of gypsum of various color between white and beige to light gray. The thickness of the crust varies from few millimeters and reach to one centimeter in some location.

Brown and white patches of circular and elongated shape (over $2m^2$ in size) in the middle of the northern part and in the western part of the Sabkha. The amount of halite on the surface of the white patches is high and the deposits are dry and less compact, while the brown patches contain a large probation of small crystals of gypsum and their deposits are saturated by water.

The type of the sediments at the edges of the Dukhan Sabkha is different from those in other parts of the Sabkha and mainly consists of sand, silt, and clay. Gypsum and halite also decrease in abundance near the edges.

Various habits of gypsum crystals of different sizes and shapes are abundant in the sediments of Dukhan Sabkha on the surface and at shallow depths (few centimeters from the surface). In most locations more than one shape of gypsum crystals grown at same depth. The crystals are common in the middle and in the northeastern part of the Sabkha and decreases in the south and along its margins. In some locations, in the southern and eastern part of the Sabkha, the crystals are present down to about half a meter. The opportunity of forming gypsum is high away from the internal border of the Sabkha. This is due to the presence of sandy sediments, which decrease the depth of the land in these locations, accordingly, saturation of sediments by penetrating water at shallow depth decreased in these parts of the Sabkha. The surface drainage connected with the edges of the Sabkha and supplied this part of the Sabkha by water and fine sediments from areas outside the Sabkha, especially during rainy periods, probably is an another important reason.

The crystals in the sediments are include acicular, elliptical, semi-elliptical, prism-shaped, pyramidal, lenticular, sub-lenticular, hexagonal, pseudo-tetragonal and inter-grown crystal shapes. In general, the size of gypsum crystals in the sediments is less than 1 cm, but for acicular crystals those present in the artificial pit in the northern part of the Sabkha it reaches about 2.5 cm in length. The acicular, lenticular and sub-lenticular crystals are the most abundant habit. Some of these lenticular and sub-lenticular crystals have elongated, thin edges or distinguished with jagged edges. The proportion of sandy desert rose crystals in Dukhan Sabkha (about 5 cm length) is rare and only found in the northeastern part of the Sabkha, to the west from the salt lake area. The crystals formed above groundwater level and at shallow depth, few centimeters from the surface. Broken gypsum crystals (varying in length from0.8-16 mm) are also abundant, probably due to natural breakage (due to temperature extremes) as well as to breakage during sampling and transport.

The variation of gypsum crystals in the shape and size are, at least in some parts, related to the various types of sediments. It seems that fine grained sediment allows more than one habit of the crystals to form in comparison with coarse grained sediment. The evaporation process from fine sediments is slower than that from coarser sediments and this retains the brines in the sediments for long enough to form more than one shape of crystal. The more rapid evaporation process through coarse sand does not give enough time for such a wide range of crystal shapes to form.

The fine sediments, rich in microbial mats in the northeastern part of the Sabkha is reason for dominant the fine lenticular and sub-lenticular gypsum crystals at shallow depth in this part of the Sabkha. The crystals found between the anhydrite layers could have been formed as a result of hydration of anhydrite. The prismatic crystals abundant in Dukhan Sabkha sediments, whether or not organic material is present. The acid conditions is the main reason for the abundant of prismatic crystals within the Sabkha sediments.

Suitable conditions such as high ground water level, high temperature, saturation of Sabkha sediments by brines and a high rate of evaporation are probably reasons for formation of these crystals. The main reasons for variation in the amount and habit of gypsum crystals in the Sabkha sediments are: (1) The surface of the Sabkha is flat, about one meter below sea level. This lead to feeding Sabkha basin by greater rate of groundwater and this water exposed to high evaporation processes during the year. (2) The principal sediment type is the second important reason. In Dukhan Sabkha, silt, clay and fine carbonate sediments are common than sand deposits. This is the main reason for the dominant of the fine acicular crystals in the Sabkha sediments. (3) Dukhan Sabkha is an inland, covers large area, accordingly the evaporation process in the Sabkha is very active leading to a greater proportion of gypsum in the former.

The mean of pH in the brines of Dukhan Sabkha is 6.8, less than that of the normal seawater which is 7.47. The mean of pH is same in all the brine samples and there is no relation was found between the depth and pH of the studied samples. The salinity of the brines of the Sabkha probably affects the value of pH; the brines of high salinity have low pH and the brines of low salinity have high pH. The effect of salinity on pH is due to the effect of salt concentration on hydrogen ion activity in natural marine and geochemical systems. Changing the hydrogen ion activity will affect the solubility of number of elements and minerals and also the equilibrium kinetics of many processes.

Na^+ and Cl^- in the brine samples is 38.6 ppt and 62.1 ppt respectively. The salinity is gradually decreases from north to south. It is highest in the northeastern part of the Sabkha. The mean salinity in the brines is about half than the salinity of the brines of Sea water. This is not what was initially expected, because Dukhan Sabkha is inland Sabkha, present in shallow basin, affected by high evaporation. Possible reasons for this are: (1) The main fresh ground water aquifer of Qatar is in the middle of the northern part and the freshwater drains to the sea across Dukhan Sabkha. The freshwater mixes with the groundwater of the Sabkha and decreases its salinity. (2) The presence of the Dukhan anticline to the west of Dukhan Sabkha probably decreases the run of the freshwater to the sea. (3) The main farms are found in the northern part of Qatar. Some of these farms are located not far from Dukhan Sabkha. Parts of the fresh water irrigation could reach Dukhan Sabkha and this decrease its salinity. (4) The annual rainfall, during rainy periods is higher in the northern part of Qatar than in the south. This rainwater probably decreases the groundwater salinity of Dukhan Sabkha. (5) Dukhan Sabkha is more likely to be supplied with surface drainage water as it is inland and thus receives surface drainage from all directions.

However, the main factors causing the concentration of Na^+ and Cl^- in the brines of Dukhan Sabkhas are: (1) The evaporation processes from the surface and from shallow subsurface water within the Sabkhas (2) Halite in the sediments is high, especially in the northern part of the Sabkha and this could be easily dissolved by water, accordingly the brines of Sabkha became saturated in Na^+ and Cl^-.

The mean for Ca^{2+} is 1.5 ppt and mostly less than 2 ppt but approximately three times higher than that of the seawater sample. SO_4^{2-} in brines is 6.6 ppt. It is about two and halves time higher than in the seawater sample. Gypsum in the Sabkha sediments is probably an important source for Ca^{2+} and SO_4^{2-} in the brines. Because gypsum is a dominant evaporite mineral in the Sabkha sediments it was thought that SO_4^{2-} in the Sabkha brines would be high; but the situation is opposite to what was expected. The reason is probably because: (1) Dukhan Sabkha is fed by fresh groundwater (2) The mean probation of SO_4^{2-} in the brines of Dukhan Sabkha was lost in the formation of gypsum, and this is why the proportion of SO_4^{2-} in Dukhan Sabkha brines is small and the percentage of gypsum in its sediments is high.

The mean for Mg^{2+} is high, about 3.8 ppt. The concentration of Mg^{2+} in the brines increases in the northeastern part of the Sabkha and it decreases to the south. The low salinity in the brines probably increase the activity of H_2O, thus the activity of formation of gypsum and anhydrite in the Sabkha became high, resulting in the Mg^{2+} percentage in the Sabkha becoming low. In the brines of the Sabkha, Mg^{2+}simply increases with salinity and Cl^-, most of the brine samples that included high proportion of Mg^{2+} included a high proportion of Cl^-.The good relationship between Mg^{2+} and Cl^- in Sabkha brines probably results from the low salinity and the high pH activity. This gives a good chance for the concentration of Cl^- in the brines to form magnesium chloride and so leads to low Mg^{2+}.

The mean of Sr^{2+} is 0.03 ppt and there is no difference in the mean of Sr^{2+} in the selected samples within the Sabkha. The high concentration within the Sabkha brines is in the northeastern part of the Sabkha.

The concentration of HCO_3^{2-} in the brines is small, but it is higher than that of seawater. The minor concentration of HCO_3^{2-} in the brines is probably because the proportion of microbial mat in the Sabkha is small.

The mean of the TDS of the brine samples is 112.8 ppt. The main reason being because Dukhan Sabkha receives fresh water from the land and from rains, during rainy seasons. The total of TDS in the brines of the northeastern extension of the Sabkha is higher than that in the other parts and in the southern part is lower than in the other parts. In general, the TDS decreases from north to south and increases from east to west.

However, the general situation in Dukhan Sabkha is that the brine samples of low TDS are distinguished by high pH and the brine sample samples of high TDS are distinguished by low pH. The effect of organic carbon in the pH values in the Sabkha is not clear.

The statistical study showed that there is good relationship between Na^+ and Cl^-, and between Cl^- and Mg^{2+} in Dukhan Sabkha brines, R^2=0.97 and 0.96 respectively. Because the salinity of Dukhan Sabkha is low, the relationship between Mg^{2+} and Cl^- in the brines is good. No good relationship was found between $Mg^{2+}$and Ca^{2+} in the brines of Dukhan Sabkhas, probably because the balance was affected by utilized Ca^{2+} in gypsum formation. Since Mg^{2+} is affected by the salinity, this reflected on the relationship between $Mg^{2+}$and TDS and for this reason, a good relationship was found in the brines of Dukhan Sabkha.

There is a good relationship between TDS and Na^+, Cl^- and TDS and Mg^{2+}/Ca^{2+}; R^2=0.99, 1 and 0.73 respectively. Good relationship was also found between TDS and SO_4^{2-} and TDS with Mg^{2+}; R^2=0.6 and 0.97 respectively. This is a normal situation; Dukhan Sabkha is a wide inland Sabkha fed by seawater and affected by high evaporation process; in addition, the formation of the evaporates deposits, especially gypsum, is active.

There is no apparent relationship between Ca^{2+} and TDS, Ca^{2+}, SO_4^{2-}, and Cl^-, and between Cl^- and Ca^{2+}, Mg^{2+} and Ca^{2+}, but SO_4^{2-} makes relatively good relationships with Mg^{2+}, gives R^2=0.63.

The low salinity and high pH activity of the Sabkha brines reflected on the relationship between the elements of brines within the Sabkha.

Recommendations

a. This study presented here is a good example of gypsum crystals growing in inland Sabkha. The nature and distribution of sediment facies and the influence of climate, together with the groundwater source and movement as documented in this study, can be used as model to study the inland Sabkhas worldwide.

b. Because the conditions are suitable for formation of gypsum crystals in the Dukhan Sabkha, this study recommends to exploiting the area of Dukhan Sabkha for cultivation gypsum.

c. Allocate area from the Sabkha to use as a scientific station for study gypsum growth and crystals types. Scientific publications about the growth and shapes of gypsum within the Sabkha will be published periodically by researchers and those interested in this mineral.

d. Dukhan Sabkha can be used as a model for study the growth of the different shapes of gypsum in nature. Schools students can visit the Sabkha to study gypsum mineral in its natural environment.

e. Large desert roses (3.5-23 m) are only grow in the northern part of Dukhan Sabkha. The factors which affect in growing and development the crystals, only in this part of the Sabkha need more study.

f. Although Dukhan Sabkha is only about 3 km from the Arabian Gulf (to the north) and about 5 km from the sea in the west, it is not clear how much seawater contributes to the Sabkha brines by seepage from these coastal zones. For this reason the connection of the Sabkha with the sea needs study. It is still not obvious if there are underground waterways (channels) connecting the Sabkha with the sea, and if these tubes formed as a result of folding or dissolution process of evaporite rocks in the area.

g. In relation to water geochemistry characteristic, isotopic studies need to be completed for groundwater in Dukhan Sabkha. The importance of the study is to identify the geochemistry of water and the rate of strontium.

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