

Brine and sediment chemistry of the Holocene coastal sabkha at Ras Shukeir, Gulf of Suez, Egypt

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ABSTRACT

The coastal sabkha at Ras Shukeir is an elongated, almost flat and low-lying area with a semi-arid climate. It is biologically barren and encloses eastern and western saline and hyper-saline pools.

Both western and eastern pools are slightly alkaline (pH range 6.8–8.0), and groundwater has a pH higher than that of both sea water and saline pools. The eastern pools have lower salinity than the western pools, and seepage from the sea is believed to have had a greater effect on the nearer, eastern pools.

Gypsum is the only sulphate mineral present and halite represents the highest evaporative rank in the sequence. Celestite is a minor constituent. Evaporative pumping is believed to be the hydrodynamic process responsible for formation of the sabkha evaporites.

INTRODUCTION

The Holocene coastal sabkha at Ras Shukeir area is located on the western side of the Gulf of Suez, between Latitudes 28° 6' and 33° 20' N and Longitudes 33° 6' and 33° 15' E (Fig. 1). It lies between Ras Gharib to the north and Ras Shukeir to the south, occupying an area of about 78 km². It is nearly oval in shape, 19.5 km long and 4 km wide.

Drainage enters from the west bringing rain runoff through six main wadies (see Fig. 1). The general dip is towards the east, which helps trap this water in the sabkha.

Meteorological data from the Egyptian Meteorological Authority for the years 1970–1985 show that the area is semi-arid. Mean annual temperature is 23.2°C (maximum is 27.5°C and minimum = 17.8°C), relative humidity varies between 43% and 55%, and annual mean evaporation rate is 13.9 mm/month along the coast. The mean annual rainfall is 30 mm and is concentrated into a few showers which fall in the winter.

Morphologically, the coastal area is flat. It is flanked by the Red Sea mountains, which form a series of parallel N–S chains cut by E–W wadies. The supratidal zone is located inland, 1 km from the shore, so it is not affected by tidal events or even by strong storms.

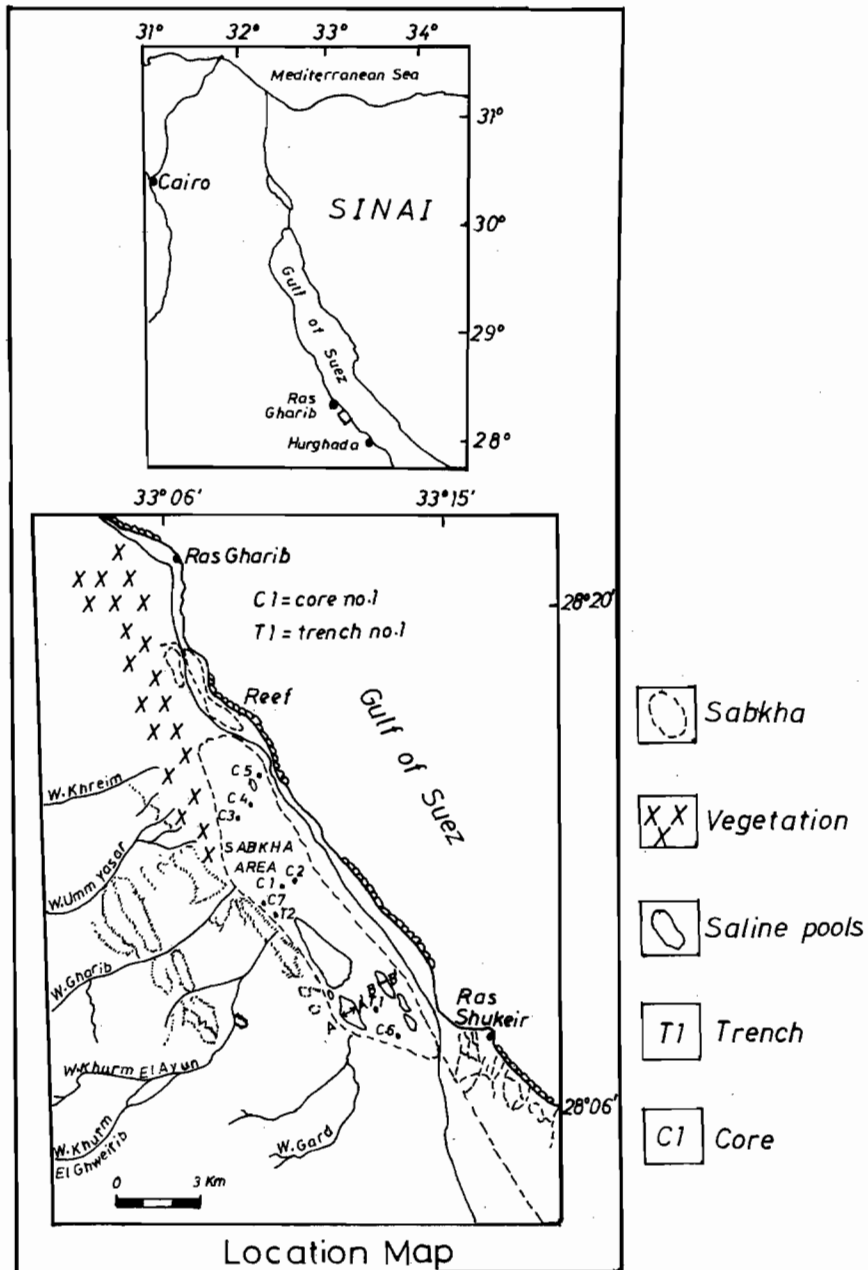


Fig. 1. Location map.

Vegetation on the slopes of the Red Sea mountains varies with elevation. The foothills, which receive more water than the higher slopes, have a thicker vegetation cover. The supratidal zone is more or less barren except for scattered halophytes, of which the most common is *Tamarix* sp. Species such as *Suaeda* sp., *Nitraria retusa*,

Aeluropus lagopoides, and *Anabasis articulata* have also been recorded (Abu Aisha, personal communication). These plants occur as small bushes around the salt marshes.

In 1980, during the widening of the road between Hurgada and Ras Gharib, waste materials from construction were pushed aside towards the sabkha, forming a barrier with an average height of 5 m. This barrier must have caused changes in the hydrological system of the area by helping fresh water runoff within the sabkha. Since the completion of the road in 1983, the sabkha area has become more restricted.

This paper discusses the mechanisms involved in the formation of the sabkha evaporites through a study of brines in different seasons, and of the geochemical characteristics of the sediments.

METHODOLOGY

Sixteen water samples were collected from the saline pools in two traverses from west to east (Fig. 1, A-A' and B-B'), using sodium-free plastic bottles. In addition, two groundwater samples were analyzed, and one water sample collected from the Gulf of Suez close to the studied sabkha was analyzed for comparison.

The water samples were analyzed for the major cations and anions: Na^+ , Ca^{2+} , Mg^{2+} , SO_4^{2-} , Cl^- and HCO_3^- . Sodium was determined by flame photometry, calcium determined complexometrically using a murexide indicator, while magnesium was determined by subtracting the calcium value after determining both calcium and magnesium complexometrically using eriochrome black T as indicator. Results are given in grams per liter and equivalent grams per liter. The term "groundwater", as used here, refers to the phreatic water level beneath the water table.

Thirty-two sediment samples were selected for the geochemical study, chosen from a trench (T_2) and surface sediments (Fig. 1). The trench samples represent 10 zones from bottom upwards. The surface samples were collected in order to identify the mineralogical constituents of the siliciclastic sediments in the sabkha. All samples were analyzed for the following major ions: Ca^{2+} , Mg^{2+} , Na^+ , Cl^- and SO_4^{2-} ; and Sr^{2+} as a trace element. Results are given in weight percent in Tables 5 and 6. Some of the major elements are expressed in these tables as weight percent oxides, while their equivalent concentrations (wt%) were calculated. The mineralogical composition was calculated and confirmed by XRD patterns.

BRINE CHEMISTRY

Diagenetic changes involving precipitation from concentrated brines, or reaction between brines and original sediments are reflected in brine chemistry (Kinsman 1965). Thus, chemical analysis of brines and groundwater should help to detect changes due to dissolution and precipitation.

Generally, in the absence of significant rainfall, groundwater of marine sabkhas are fed from the highly saline marine water of coastal lagoons, which percolate through the sediments and later concentrate by evaporation at the surface of the sabkha. The development of evaporite minerals in supratidal zones and marginal

pool sediments occurs by the upward movement of brine water and ions, with precipitation at or near the surface (Watson 1979). Thus, according to Curtis *et al.* (1963), the brines within the capillary zone above the groundwater level of Abu Dhabi sabkha have a strong concentration gradient.

Climatic factors, such as high rates of evaporation, high temperatures, rare precipitation and the absence of significant fresh water supply entering the Ras Shukeir sabkha pools, have led to concentration of the brines. The subsequent equilibrium between brines and host sediments results in precipitation of evaporite minerals.

Kinsman (1974) has shown that the potash facies minerals of marine evaporites are precipitated from brines with water vapour pressure less than 0.67. The mean relative humidity in the area (43%–55%) prevents precipitation of potash facies minerals. Low mean relative humidities only occur where marine areas are surrounded by large expanses of land. Thus only marine basins with a high continentality are likely to precipitate potash facies evaporites.

1. pH measurements:

The pH value is a sensitive measure of salinity of the medium, and variation in pH may reflect such processes as the decomposition of organic matter and the mixing of sabkha water with less saline water. In the Ras Shukeir sabkha, pH values of water in the saline pools range from 6.8 to 8.0 (Table 1a and b) indicating a weakly alkaline state with narrow pH range. Red Sea water gave a pH of 8.25, while that of groundwater in the sabkha is 8.57.

Amit & Bentor (1971) studied the effect of salt on pH in northern Sinai and suggested that low pH values were due to deficiency of bicarbonate ion caused by a high salt content of the medium. They also found that alkalinity increases by dilution. Bodenheimer & Neev (1963) termed this phenomenon "hidden alkalinity" and indicated that concentrated sea water shows a decrease in pH.

2. Total dissolved solids (salinity):

Two east–west traverses were made across the eastern and western pools. Results are given in Tables 1a and 1b, using sea water salinity as a standard for comparison. A minimum value of 160.0 g/l is recorded at the western end of the eastern pools, and the maximum for these pools is 200.0 g/l (close to the eastern end). Mean value

Table 1a. pH and salinity values of brines along a W–E traverse in the eastern saline pools

Sample No.	E1	E2	E3	E3a	E4	E5	E6	E7	E8
pH	7.07	7.04	7.59	7.02	7.59	7.55	7.49	7.67	7.55
Salinity (g/l)	160.0	180.0	190.0	170.0	190.0	180.0	200.0	190.0	180.0

Table 1b. pH and salinity values of brines along a W–E traverse in the western saline pools

Sample No.	W1	W2	W3	W4	W5
pH	7.83	7.63	8.00	7.74	7.98
Salinity (g/l)	197.2	207.0	214.9	203.2	190.7

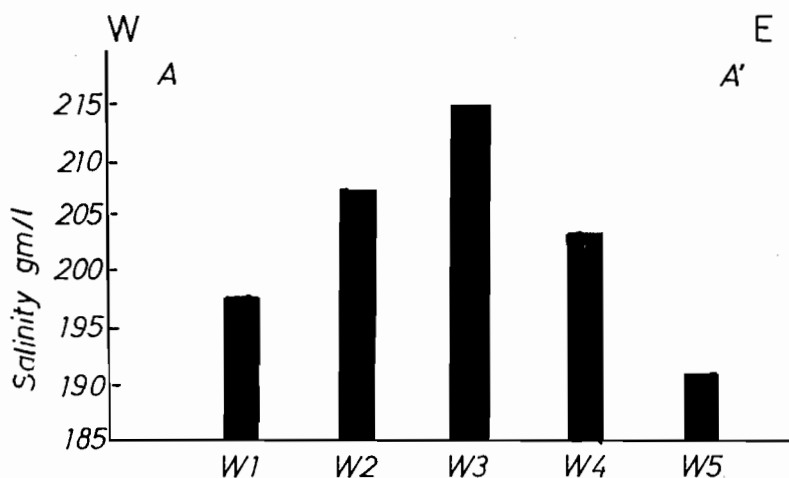


Fig. 2a. Salinity in the western saline pools along a traverse running from W to E.

is 182.2 g/l (Table 1a, Fig. 2b). In the western pools the minimum salinity is 190.7 g/l and the maximum 214.9 g/l, with a mean of 202.6 g/l (Table 1b, Fig. 2a). In general, both eastern and western pools have higher salinity than that of sea water (47.24 g/l). The lower salinity values of the eastern pools are probably due to seepage of sea water through the sabkha sediments. The western saline pools can be considered as part of an evaporative microbasin, in which salinity increases from the margin, where carbonates and sulphates precipitate, to the center where halides precipitate (Wali *et al.* 1986).

Groundwater salinity was determined as 104.6 and 217.0 g/l at two localities near the eastern and western saline pools respectively, the lower value being more than double that of sea water (47.24 g/l). Salinity values for the majority of brines in the pools are less than that of groundwater. Downward seepage of the brines may account for high salinity of the groundwater. Hsü & Siegenthaler (1969) came to the conclusion that either capillary action or evaporative pumping cause changes in density or salinity with depth.

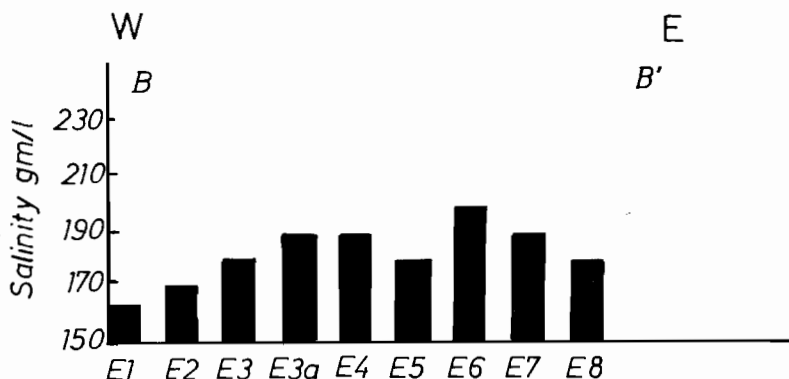


Fig. 2b. Salinity in the eastern saline pools along a traverse running from W to E.

Table 2. Ion concentrations of brines in the western saline pools

Sample No.	Units	Na ⁺	Ca ²⁺	Mg ²⁺	Cl ⁻	SO ₄ ²⁻	HCO ₃ ⁻
Sea water	g/l	14.91	0.57	1.42	25.45	3.51	0.18
	eq.g/l	0.65	0.03	0.12	0.72	0.07	0.01
Ground water (T ₁)	g/l	70.82	1.75	7.78	128.52	8.45	0.41
	eq.g/l	3.08	0.09	0.64	3.63	0.18	0.01
(T ₂)	g/l	36.31	2.80	2.43	56.00	6.71	1.83
	eq.g/l	1.58	0.14	0.20	1.58	0.14	0.03
W1	g/l	72.70	1.80	9.12	135.60	8.45	0.19
	eq.g/l	0.04	0.09	0.75	7.66	0.09	0.01
W2	g/l	63.94	1.65	7.11	116.10	8.15	0.23
	eq.g/l	2.78	0.08	0.58	3.32	0.17	0.01
W3	g/l	66.60	1.70	7.87	122.67	7.90	0.29
	eq.g/l	2.89	0.08	0.65	3.50	0.16	0.02
W4	g/l	71.48	1.90	6.59	126.74	8.06	0.21
	eq.g/l	3.11	0.09	0.54	3.62	0.17	0.01
W5	g/l	57.41	4.09	11.16	122.31	7.90	0.28
	eq.g/l	2.49	0.20	0.92	3.49	0.16	0.01
W6	g/l	62.71	2.01	5.90	110.79	8.49	0.74
	eq.g/l	2.73	0.10	0.49	3.17	0.18	0.01

Sr²⁺ not determined.

3. Ion relationships of the brines within the saline pools:

Sodium, calcium, magnesium, chloride, sulphate and bicarbonate were determined for brine in the saline pools, as well as for groundwater and sea water samples, and ion ratios were calculated (Tables 2, 3 and 4).

The calcium ion concentration ranges from 1.65 to 4.09 g/l in the western pools and from 0.72 to 1.36 g/l in the eastern pools. The concentration in groundwater ranges from 1.75 to 2.80 g/l while that in sea water is 0.57 g/l (Tables 2 and 4). The concentration of calcium in the saline pools is at least twice that of standard sea water. Calcium concentration decreases with depth due to precipitation of carbonate as supported by the presence of algal stromatolites, especially in the western hypersaline pools (Wali *et al.* 1986).

Table 3. Ion ratios of brines in the western saline pools

Sample No.	mMg ²⁺ /mCa ²⁺	Na ⁺ /Mg ²⁺	Na ⁺ /Ca ²⁺	Na ⁺ /Cl ⁻	Cl ⁻ /SO ₄ ²⁻	Mg ²⁺ :Ca ²⁺
Sea water	4.05	10.50	25.93	0.59	7.24	2.50:1
Ground water (T ₁)	7.62	9.10	40.38	0.55	15.21	4.43:1
	(T ₂)	1.42	14.94	12.97	0.65	8.34
W1	8.28	7.98	40.39	0.54	16.04	5.07:1
W2	7.05	8.99	38.68	0.55	14.25	4.30:1
W3	7.58	7.46	39.11	0.54	15.53	4.60:1
W4	5.67	10.84	37.54	0.56	15.73	3.60:1
W5	4.48	5.14	14.04	0.47	15.46	2.70:1
W6	4.82	10.64	31.29	0.57	13.05	2.90:1
Mean	6.31	8.51	33.51	0.54	15.01	

Table 4a. Ion concentration of brines in the eastern saline pools

Sample No.	Units	Na ⁺	Ca ²⁺	Mg ²⁺	Cl ⁻	SO ₄ ²⁻	HCO ₃ ⁻
E1	g/l	19.50	0.72	1.95	30.00	1.73	0.32
	eq.g/l	0.85	0.04	0.16	0.85	0.02	0.01
E2	g/l	20.80	1.00	2.07	32.00	2.40	1.22
	eq.g/l	0.90	0.05	0.17	0.90	0.03	0.02
E3	g/l	20.80	1.28	1.36	32.00	3.07	0.24
	eq.g/l	0.90	0.06	0.12	0.90	0.03	0.01
E4	g/l	20.10	1.36	1.60	31.00	3.26	0.15
	eq.g/l	0.87	0.07	0.13	0.88	0.03	0.01

Sr²⁺ not determined.

Table 4b. Ion ratios of brines in the eastern saline pools

Sample No.	mMg ²⁺ /mCa ²⁺	Na ⁺ /Mg ²⁺	Na ⁺ /Ca ²⁺	Na ⁺ /Cl ⁻	Cl ⁻ /SO ₄ ²⁻	Mg ²⁺ :Ca ²⁺
Sea water	4.05	10.50	25.93	0.59	7.24	2.50:1
E1	4.43	10.02	27.08	0.65	17.34	2.70:1
E2	3.39	10.06	20.80	0.65	13.33	2.06:1
E3	1.74	15.28	16.25	0.65	10.42	1.06:1
E4	1.93	12.52	14.78	0.65	9.51	1.18:1
Mean	2.87	11.97	19.73	0.65	12.65	

Concentration of sulphates is more or less uniform within the same saline pool. In the western hypersaline pools, the maximum values range from 7.90 to 8.49 g/l, while in the eastern saline pools the range is from 1.73 to 3.26 g/l. Groundwater samples gave a sulphate concentration of 6.71 and 8.45 g/l, while that of sea water is 3.51 g/l (Tables 2 and 4b). The sulphate concentration in the western saline pools is at least twice that of sea water. Moreover, the groundwater brines have sulphate concentrations much higher than that of sea water. The concentration of Ca²⁺ and SO₄²⁻ depends on the solubility product of gypsum, in addition to the expected depletion of Ca²⁺ due to precipitation of carbonate in algal stromatolites of the western pools.

Kinsman (1966) showed, by plotting specific gravity against chlorinity of some pool and groundwater brines, that gypsum is the stable calcium sulphate mineral in contact with brines in which chlorinity is less than 145‰, while anhydrite is the major mineral at chlorinity greater than 145‰ (Fig. 3). The gypsum-anhydrite equilibrium boundary was plotted using the solubility measurements, temperatures and concentration of lagoon brines, groundwater and interstitial brines. It can be seen that the equilibrium relationships derived from the brines cluster very closely within the field of gypsum precipitation (Fig. 3, dashed line). The data indicate that gypsum is the primary calcium sulphate mineral to precipitate from the brines (Fig. 3, solid line), in agreement with Kinsman (1966), and anhydrite has not been found in Ras Shukeir sabkha. Equilibrium data from the United Arab Emirates coastal sabkha

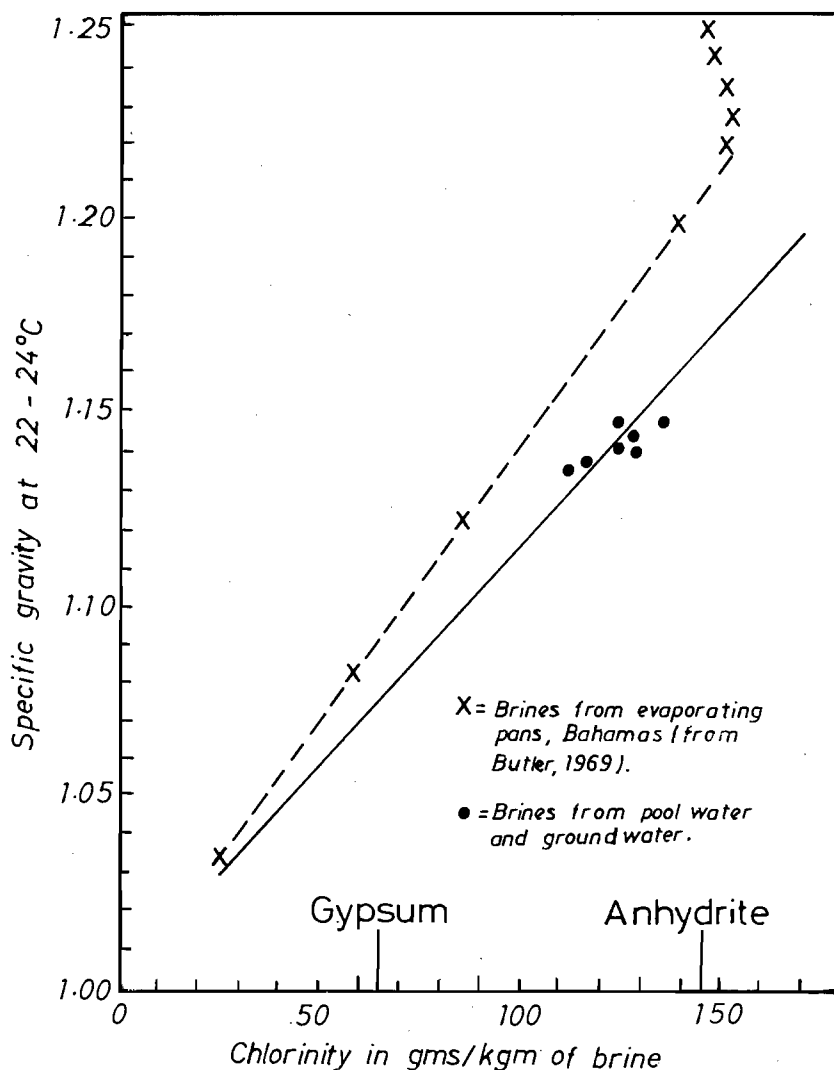


Fig. 3. Change in brine specific gravity with increasing brine concentration.

indicate that sea water-derived brines would have to exceed a mean annual temperature of 50°C for anhydrite to precipitate, and this temperature is not reached along the Gulf of Suez coast.

Concentration of magnesium in the western pools ranges between 5.90 and 11.16 g/l, while in the eastern pools it ranges between 1.36 and 2.07 g/l. The concentration of magnesium in groundwater samples ranges between 2.43 and 7.78 g/l and that of sea water is 1.42 g/l (Tables 2 and 4b). Both saline pools have much higher magnesium than sea water. Molecular $m \text{Mg}^{2+}/\text{Ca}^{2+}$ ratios in the saline pools range between 4.48 and 8.28 in the western saline pools (Table 3) and between 1.74 to 4.43 in the eastern pools (Table 4). Groundwater has $m \text{Mg}^{2+}/\text{Ca}^{2+}$ between 1.42 and 7.62 and that of sea water is 4.05 (Table 3). Magnesium concentration is

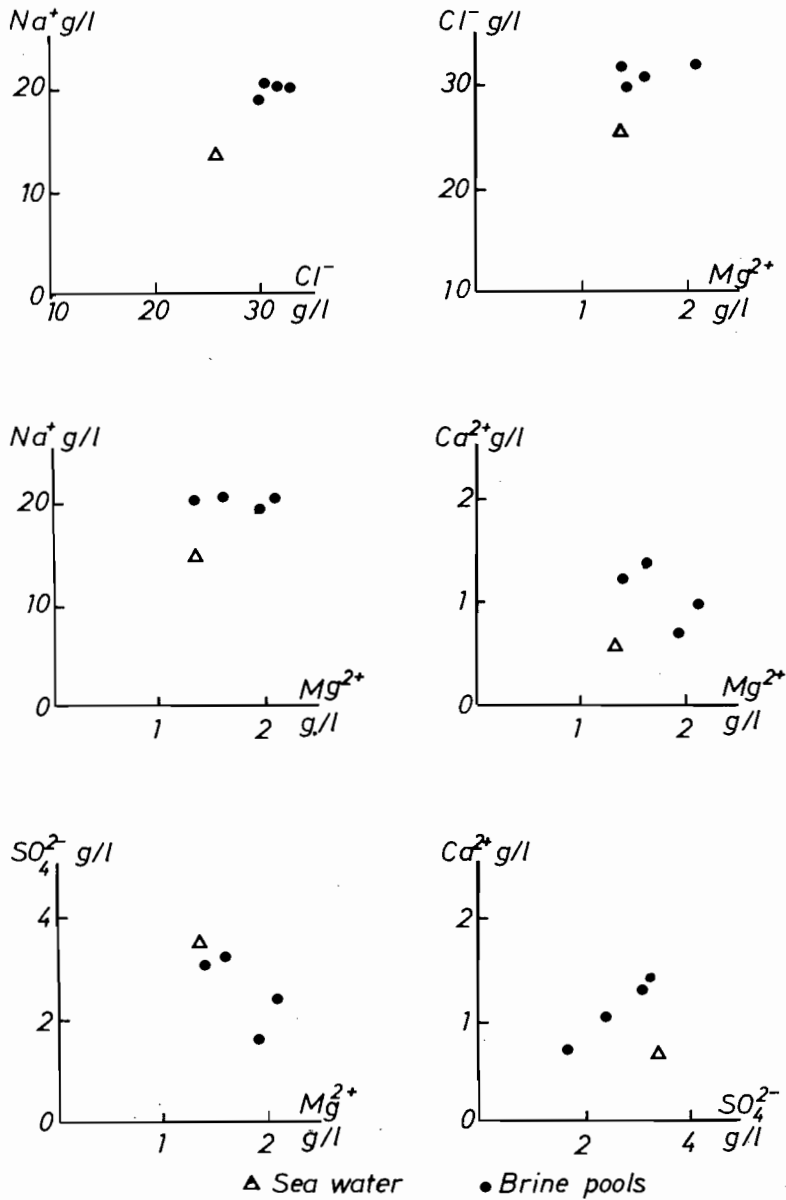


Fig. 4. Relationship between major ion concentrations in the eastern saline pools.

inversely proportional to that of calcium (Figs 4 and 5). The Mg^{2+}/Ca^{2+} ratio in both saline pools is higher than that of sea water, which reflects progressive depletion of calcium with increasing concentration, due to precipitation of gypsum. Dolomite is not recorded in the area, and the Mg^{2+}/Ca^{2+} ratio is between 2:1 and 4:1 (Tables 3 and 4), not high enough for dolomite to precipitate. Kinsman (1965) found that hypersaline dolomite begins to crystallize when the Mg^{2+}/Ca^{2+} ratio exceeds 5:1 to 10:1.

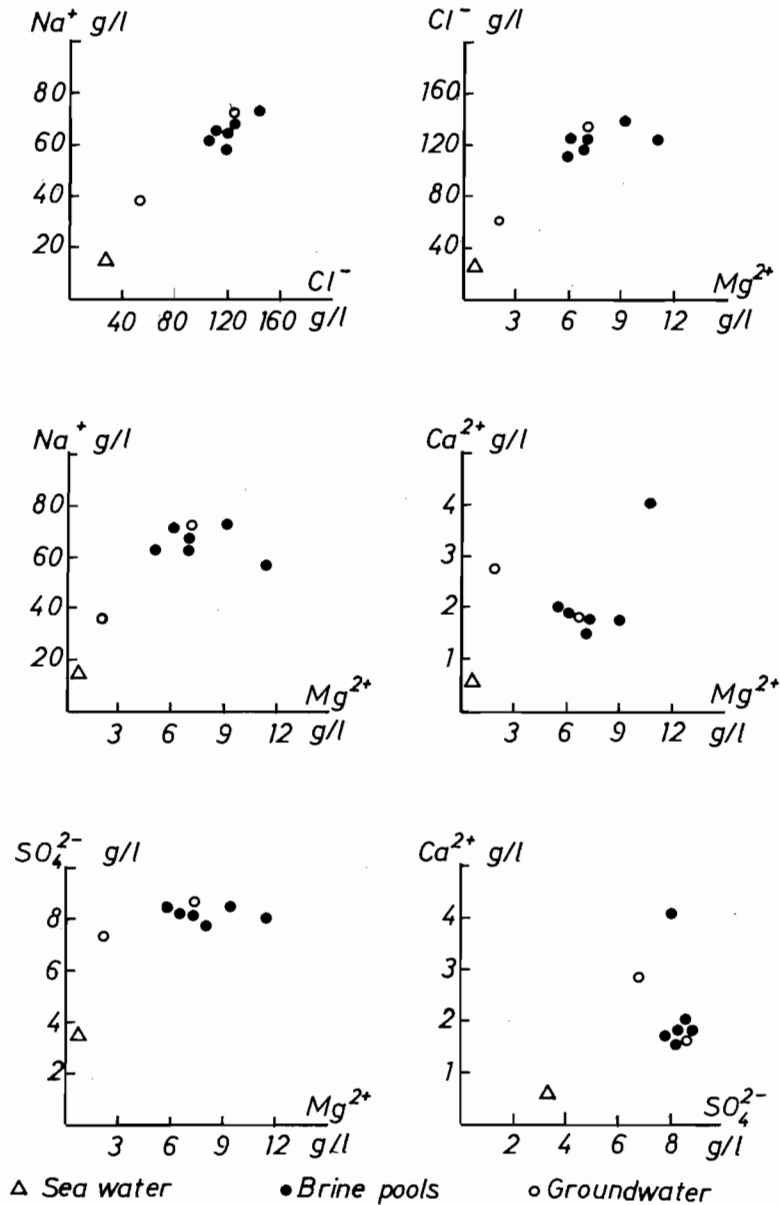


Fig. 5. Relationship between major ion concentrations in the western saline pools.

Concentration of chloride ions in the western pools ranges between 110.79 and 135.60 g/l and in the eastern pools between 30.00 and 32.00 g/l (Tables 2 and 4). Chloride ion concentration in the groundwater ranges between 56.00 and 128.52 g/l and that of sea water is 25.45 g/l (Table 2). Sodium and chloride values show the same pattern, being higher at shallow depths (Figs 6 and 7). The sodium to chlorine ratio of the saline pools is close to that of sea water, and sodium always has a linear

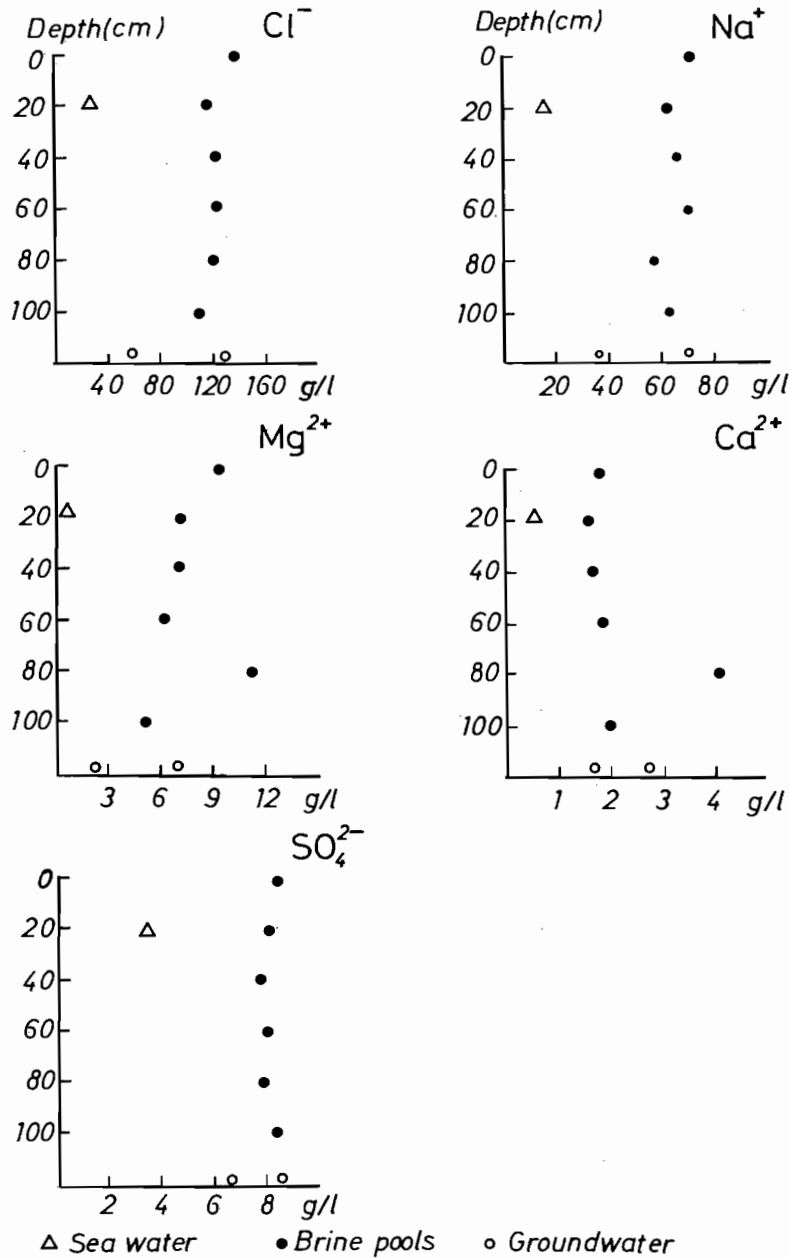


Fig. 6. Changes of major ion concentrations with depth in the western saline pools.

relationship with chlorine. This is paralleled by field observations which show halite as the only chloride present.

Seepage from the sea is the process which may be responsible for lower concentration of brines in the eastern pools (close to the sea) compared with the western pools. The ratios Na⁺/Mg²⁺, Na⁺/Ca²⁺, Cl⁻/SO₄²⁻, Cl⁻/Mg²⁺ and SO₄²⁻/Mg²⁺

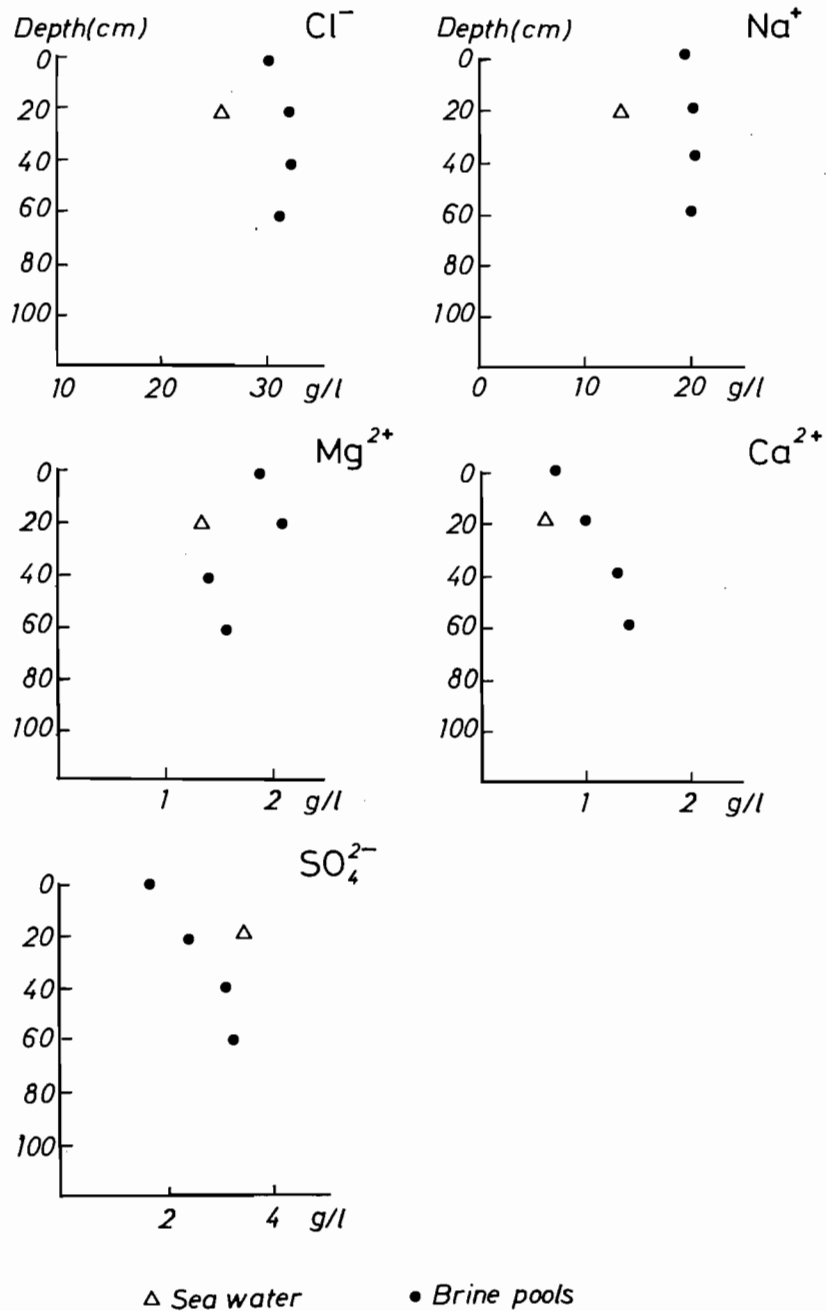


Fig. 7. Changes of major ion concentrations with depth in the eastern saline pools.

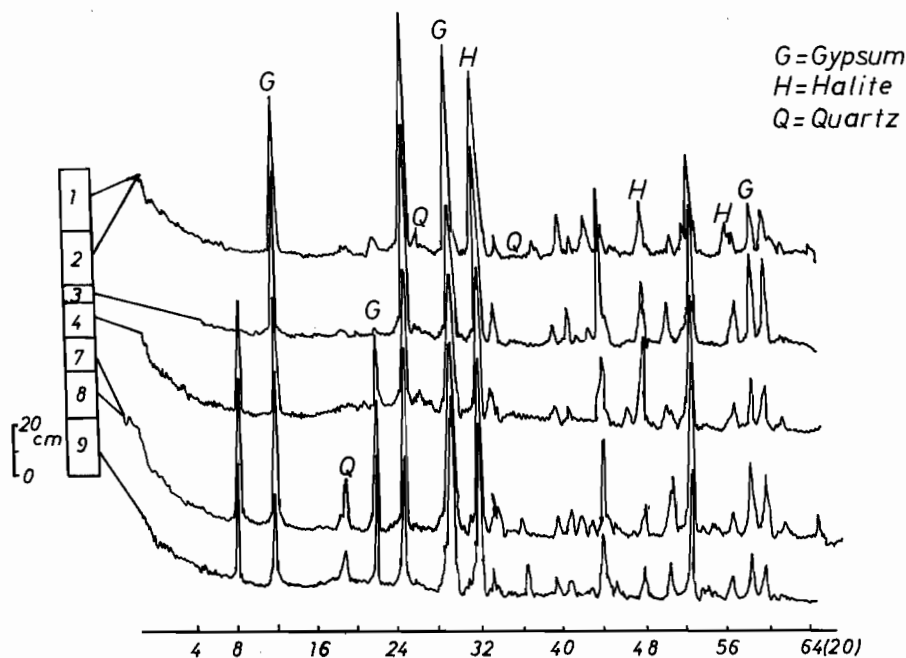


Fig. 8. X-ray diffraction patterns of the trench T2 sediments.

bear no relation to each other, probably because these substances do not form minerals of their own (Fig. 8).

GEOCHEMISTRY OF SEDIMENTS

There is extensive literature on laboratory studies of equilibria between calcium sulphate minerals (Gay 1965; Zen 1965; Kinsman 1966, 1967; Hardie 1967). Gay (1965) recognized four discrete solid phases in the system $\text{CaSO}_4\text{-CaSO}_4 \cdot 2\text{H}_2\text{O}$: gypsum, bassanite (hemihydrate), insoluble anhydrite and soluble anhydrite. As long as no intermediate compounds are formed (such as soluble salts), the equilibria between mineral phases are a function of the activity of water in solution of mineral reactions and of the relative humidity in the vapour-mineral reactions. This is true irrespective of whether the equilibria are stable or metastable (Kinsman 1974). Using the data of Kinsman qualitatively, it can be shown that gypsum and anhydrite can be stable minerals within the near surface environment, whereas bassanite will always be metastable.

Data for the 32 analysed samples are given in Tables 5 and 6, and are shown as distribution profiles of the elements in the trench samples (Fig. 9).

Concentration of calcium in the trench sediments varies between 17.46 and 22.95 wt% (Table 5), and generally, the higher concentration corresponds to the pure gypsum samples (Fig. 9). Calcium in the surface sediments varies between 1.86 and 11.88 wt% (Table 6), the low concentration being due to the fact that the dominating host sediments are siliciclastic (Wali *et al.* 1986).

Concentration of sulphates in the sabkha sediments varies between 32.73 and 54.00 wt% (Table 5), the highest value corresponding to zone 2, where gypsum pre-

Table 5. Chemical composition of the oxides and their equivalent element concentration (wt%) of the trench T₂ sediments

Sample No.	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	K ₂ O	Na ₂ O	SO ₃ ²⁻	Ca ²⁺	Mg ²⁺	K ⁺	Na ⁺	Cl ⁻	SO ₄ ²⁻
1a/1	0.01	0.01	—	31.34	0.61	0.03	0.27	50.66	22.39	0.0015	0.02	0.20	0.31	42.22
1a/2	0.43	0.06	0.05	30.72	0.55	0.04	1.55	49.55	21.96	0.0017	0.03	1.15	1.77	41.28
1a/3	0.59	0.19	0.05	31.41	0.35	0.04	1.25	46.72	22.45	0.0011	0.03	0.93	1.43	38.94
1/1	3.74	0.62	0.40	30.64	2.29	0.10	8.13	46.91	21.90	0.0070	0.08	6.03	9.30	39.09
1/2	1.25	0.11	0.03	31.60	0.90	0.03	4.89	50.61	22.58	0.0028	0.03	3.63	5.60	42.18
1/3	1.46	0.23	3.16	30.95	3.45	0.03	1.89	46.15	22.12	0.0107	0.03	1.41	2.17	38.46
1/5	6.77	1.04	3.64	27.13	5.15	0.17	2.99	34.61	19.39	0.0160	0.14	2.22	3.43	28.84
1/6	0.01	1.35	0.66	27.21	7.96	0.35	4.28	24.22	19.45	0.0247	0.29	3.18	4.90	20.18
1/7	1.11	0.12	0.30	30.69	0.35	0.06	0.90	43.29	21.93	0.0012	0.05	0.67	1.03	36.08
1/8	4.60	0.59	0.30	29.92	3.53	0.36	2.40	40.10	21.38	0.0109	0.30	1.78	2.75	33.42
1/9	4.20	0.62	3.54	29.94	2.50	0.12	1.49	41.21	21.40	0.0077	0.10	1.20	1.71	34.34
1/10	4.12	0.59	0.31	30.11	2.45	0.13	1.84	39.50	21.52	0.0076	0.11	1.37	2.11	32.92

dominates, while the minimum is in zone 4 where gypsum is scarce (Fig. 9). The sulphate concentration in the surface sediments varies between 3.18 and 20.94 wt% (Table 6), the higher concentration being found in old gypsum mounds. Dean (1978) reported that sulphate concentration is controlled by a number of factors as:

A. Evaporation may uniformly increase sulphate concentration.

B. Normal precipitation of gypsum and anhydrite takes up some sulphate but still allows it to increase in the brines, as shown by data from both artificial (Grabau 1920; Harmon *et al.* 1973) and their natural equivalent (Morris & Dickey 1957; Holser, unpublished data).

Sodium and chlorine profiles are concordant, showing continuous increase from zone 4 to zone 10, and a slight decrease from zone 4 to zone 2 as a result of halide precipitation at the top. In the surface samples, sodium concentration varies from 12.46 to 35.89 wt% and chlorine from 19.21 to 55.34 wt% (Table 6).

The concentration of magnesium in the sediments varies from 0.0 to 2.63 wt% (Table 5), attaining its maximum value in zone 4 (Fig. 9). Magnesium is not recorded in the surface samples which also show the lowest concentration of Ca²⁺. This may be the result of the prevailing acidic affinity during the precipitation of sulphates which aids the solubility of magnesium in the medium.

Table 6. Chemical composition of the oxides and their equivalent element concentration (wt%) of the surface sediments

Sample No.	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	K ₂ O	Na ₂ O	SO ₃ ²⁻	Ca ²⁺	Mg ²⁺	K ⁺	Na ⁺	Cl ⁻	SO ₄ ²⁺
1	11.10	1.76	1.89	11.82	4.30	0.27	17.08	21.77	8.45	0.0133	0.22	12.67	19.54	18.14
2	10.70	1.73	1.89	11.79	4.33	0.27	16.79	21.37	8.43	0.0134	0.22	12.46	19.21	17.81
3	16.00	1.51	1.61	3.82	1.51	0.07	37.48	4.35	2.73	0.0046	0.06	27.81	42.88	3.62
4	16.73	1.43	1.51	3.86	1.49	0.06	36.99	4.29	2.76	0.0046	0.05	27.45	42.33	3.57
5	2.10	0.74	1.51	2.61	1.71	0.16	48.37	3.88	1.86	0.0053	0.13	35.89	55.34	3.23
6	2.04	0.75	1.51	2.74	1.67	0.13	44.61	3.82	1.96	0.0052	0.11	33.10	51.04	3.18
7	1.93	1.98	1.94	3.37	3.61	0.31	31.94	6.93	2.41	0.0111	0.26	23.70	36.55	5.77
8	1.30	1.99	1.94	3.41	3.61	0.30	32.08	6.93	2.44	0.0111	0.25	23.80	36.70	5.77
9	6.30	1.30	0.75	16.16	3.02	0.15	41.28	5.46	11.55	0.0094	0.12	30.63	37.23	4.55
10	11.15	1.84	1.20	16.63	4.30	0.26	33.14	6.03	11.88	0.0133	0.21	26.07	40.20	5.02
11	11.01	1.63	1.86	16.63	3.87	0.25	34.84	6.77	11.88	0.0119	0.21	25.85	39.86	5.64
12	11.33	1.32	1.37	12.75	1.17	0.16	22.32	25.13	9.11	0.0036	0.13	16.56	25.54	20.94

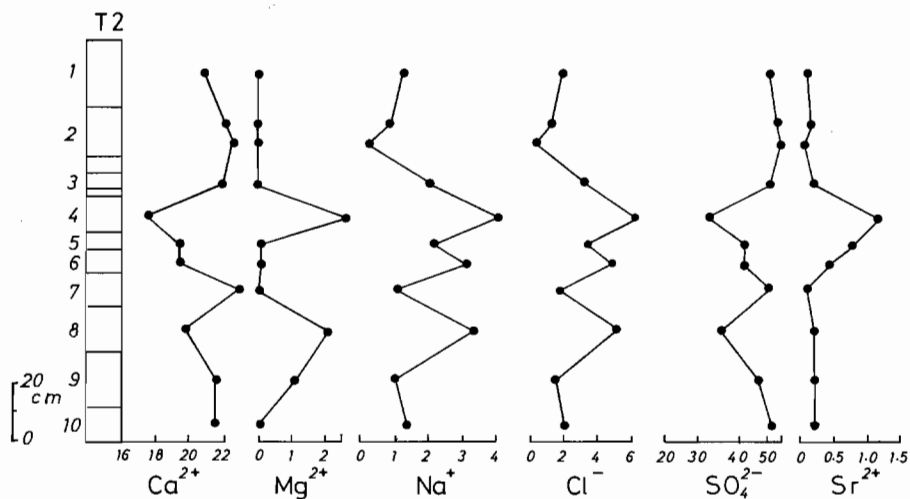


Fig. 9. Chemical composition of the major and trace elements of the trench T2 sediments.

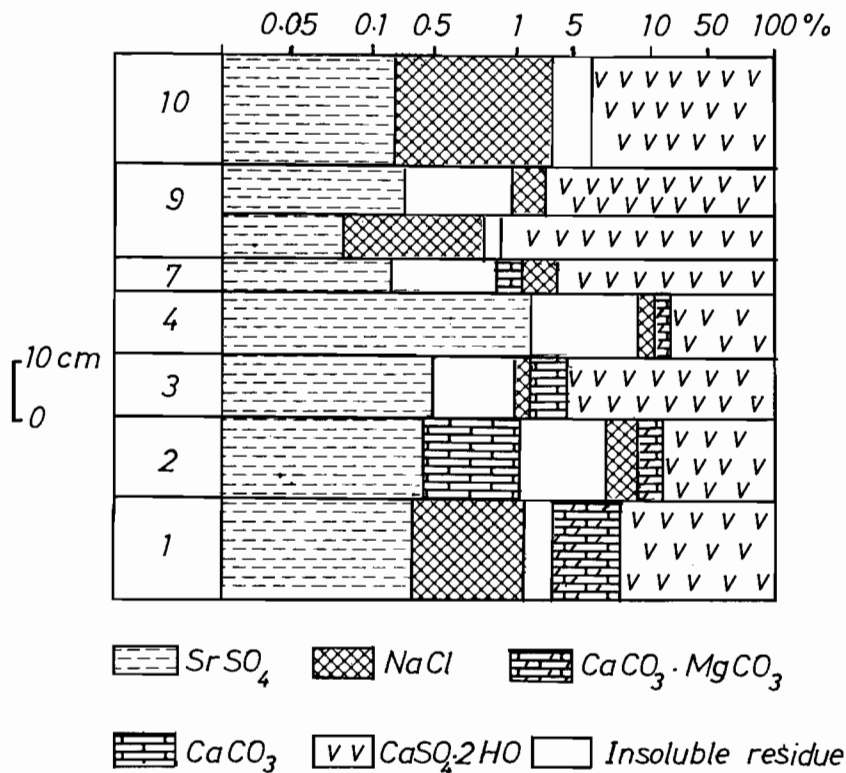


Fig. 10. Petrochemical diagram of the trench T2 sediments.

The concentration of potassium in the samples is generally low and varies between 0.02 and 0.30 wt% (Table 5). Primary potassium mineral phases are not recorded. The concentration of potassium in the surface sediments is also low and varies between 0.05 and 0.26 wt% (Table 6).

A petrochemical diagram (Fig. 10) was constructed for the trench and shows that the mineral phases are in accord with the above geochemical interpretation. Gypsum is the predominant sulphate mineral, while halite is also common and increases upwards. The insoluble residue increases with the increase of halite, especially in zones 1, 4 and 8. Field observations show the precipitation of halite within clayey sediments. Celestite is also recorded, but in minor amounts.

STRONTIUM VARIATION

Trace elements may be incorporated into an evaporite mineral by any one or a combination of: (a) solid solution, (b) adsorption and (c) occlusion (McIntire 1963).

Sr^{2+} is considered as a paleosalinity parameter in sulphate and carbonate minerals as is Br^- in halite. The role of Sr^{2+} in sulphates has been of prime interest since results from studies in the sabkha of United Arab Emirates and Baja California suggest it may be important (Philips 1947; Muller 1962). More recent work (Curtis *et al.* 1963; Kinsman 1969; Butler 1970) takes into consideration the partition coefficient of Sr^{2+} in both gypsum and anhydrite and considers the factors that control the $\text{Sr}^{2+}/\text{Ca}^{2+}$ ratio in evaporite-forming settings. The concentration of Sr^{2+} in brines is controlled by the balance between solubility of celestite and sulphate concentration. The latter is in turn controlled by a number of factors (Butler 1970):

- A. Evaporation may uniformly increase sulphate concentration.
- B. Dolomitization releases Ca^{2+} , which precipitates additional anhydrite (or gypsum) thus decreasing SO_4^{2-} practically to zero. This allows Sr^{2+} concentration to rise in the brine (Kinsman 1966, 1969; Butler 1970). Also Sr^{2+} may come from dolomitization of strontium-rich aragonite.
- C. Normal precipitation of gypsum and anhydrite takes up some sulphate, but still allows it to increase in the brines; consequently, Sr^{2+} relatively decreases in the brines.
- D. Biological reduction of sulphate to sulphur leads to a deficiency in common sulphate and will have an effect similar to dolomitization.
- E. Organisms may segregate highly variable amounts of Sr^{2+} in shells or skeletal growths.
- F. Strontium may be taken up by clays (Bausch 1965).

Dean (1978) believed that most trace Sr^{2+} in evaporite rocks is in solid solution. He considered that concentration of strontium in calcium sulphate minerals does not vary greatly and is usually in the range of 1,000 to 2,000 ppm, and suggested that most strontium is probably substituting for Ca^{2+} in sulphate and carbonate minerals. However, Ham (1952), in his work on the Permian Blaine Formation of Oklahoma, found the mean strontium concentration in 38 gypsum samples to be around 970 ppm.

Strontium concentration in the samples analyzed from the zones of our vertical profile (Fig. 9) ranges from 0.04 to 1.14% (400–1,140 ppm, Table 5). The highest concentration is in zone 4 which is depleted in SO_4^{2-} and has the lowest concentration of gypsum. Accordingly, Sr^{2+} is incorporated with Ca^{2+} to form celestite. In the lower zones (10–8) celestite is present in minor amounts. It also decreases in zones 3–1 at the top of the section with an increase of Ca^{2+} and SO_4^{2-} .

SUMMARY AND CONCLUSIONS

The area studied is located to the north of Ras Gharib town and covers about 78 km². The coastal area is flat, flanked by the Red Sea mountains on the west and the sea coast on the east.

The area is semi-arid, with a mean annual temperature of 23.2°C. Relative humidity varies between 43 and 55%. Annual mean evaporation rates along the coast are estimated to be 13.9 mm/month. The annual mean rainfall is 3 cm. These conditions allow the formation of sabkha along the coast.

Saline pools in the eastern part of the sabkha are small in size and shallow. Salinity ranges between 16% and 24% with the concentration increasing from the shore to the center. The bottom sediments in these pools are characterized by a high biological activity.

In the western part of the sabkha, hypersaline pools are larger in size and have an average salinity of 25.25%. The western pools can be differentiated into deep pools in the north and solar ponds to the south (Wali *et al.* 1986).

The eastern saline pools are close to the sea and seepage is responsible for the dilution of the brines, a condition which does not occur in the western pools. In contrast, the western pools contain brines with higher ion concentration and show the classical sequence of evaporite minerals from aragonite at the margin through gypsum to halite at the center.

The brines of the saline pools are slightly alkaline, with a pH from 6.8 to 8.0. Groundwater brines have pH higher than that of the sea water and saline pools. Gypsum is the only calcium sulphate mineral recorded, and anhydrite does not form in the Ras Shukeir sabkha for the reasons: (a) the brine chlorinities are within the field of gypsum precipitation (below 145‰), and (b) the temperature is not high enough. Dolomite is not recorded in the area since the $\text{Mg}^{2+}/\text{Ca}^{2+}$ ratio is not high enough to cause its precipitation. Celestite is recorded, but in only minor amounts, and is most probably formed due to the high evaporation rate of the brines.

Geochemical studies favour evaporative pumping as the hydrodynamic process most likely responsible for evaporite precipitation, for the reasons: (a) the analysed trench samples show an upward gradient of salinity content of Cl^- and Na^+ ; their deficiency at the top is the result of halite precipitation; (b) evaporitic minerals are almost completely absent below 50 cm and down to the water table, which is 70–100 cm deep. This is because the brines become more concentrated upwards.

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الخصائص الكيميائية للمحاليل الملحية ورواسب سيخة
شاطئية حديثة في منطقة رأس شقير، خليج السويس ، مصر

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جمهورية مصر العربية

خلاصة

تمثل السيخة الساحلية الحديثة بمنطقة رأس شقير امتدادا طويلا لمنطقة ضحلة واقعة في الحزام
شبة القاري ، وتشتمل المنطقة على بحيرات ملحية جهة الشرق ، وبحيرات عالية الملوحة على
الجانب الغربي .

تراوحت قيم الأس الأيدوجيني للمياه بين ٦,٨ و ٨,٠ ، كما دلت القياسات على أن المياه
الأرضية أكثر قلووية نسبيا من مياه البحر ومياه البحيرات . ويتسبب الرشح من مياه البحر في
تخفيض ملوحة البحيرات الشرقية لقرنها من البحر عن البحيرات الغربية .

دلت الدراسة المعدنية على أن معادن الكبريتات ممثلة في الجبس فقط ، بينما يمثل معدن الهاليت
نهاية مرحلة التبلور ، كما يتواجد معدن السيلستيت بنسب قليلة . واستنتج المؤلفون أن طريقة
صعود المحاليل الملحية نتيجة التبخير من السطح هي المسئولة عن ترسيب معادن المتبخرات في
السيخة .

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