

Pedo-Chemical Studies on Saline Playas in the Arabian Shelf

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دراسات بيدو كيميائية على بعض البلايا الملحية (السبخات) في الرصيف (الساحلي) العربي

المخلص: يهدف هذا البحث إلى دراسة بعض الصفات البيدوكيميائية للبلايا الداخلية والساحلية الموجودة في تكوينات الرصيف (الساحلي) العربي. لقد أوضحت نتائج الدراسة أن معظم البلايا ذات اسطح مستوية إلى شبه مستوية مع تواجد قشور ملحية متباينة السمك. كما أظهرت النتائج أن القطاعات الممثلة للسبخات ذات ملوحة مرتفعة مقارنة بالمناطق المحيطة بها مع سيادة أملاح الكلوريدات والكبريتات الذائبة للصدويوم متبوعا بالكالسيوم أو المغنيسيوم. ويتشابه تركيب ملوحة الطبقات المختلفة لقطاعات السبخات الساحلية مع تركيب مياه الخليج بينهما يكون تركيب ملوحة الطبقات المختلفة لقطاعات السبخات الداخلية أكثر تأثرا بالصرف من المناطق المجاورة لها والظروف البيئية المحيطة بها. وكان ذلك واضحا من نسب بعض الكاتيونات إلى بعضها الآخر وكذلك معامل الارتباط بين درجة التوصيل الكهربائي (ملوحة التربة) وكلامن البورون والمغنيسيوم الذائب وكان معامل الارتباط كبيرا في حالة السبخات الساحلية مقارنة بمثلتها في السبخات الداخلية. ولذلك نجد أن من أكثر العمليات البيولوجية تأثيرا على تكوين السبخات الساحلية هي حركة المياه الجوفية الغنية بالأملاح والمتأثرة بمياه الخليج بصورة مباشرة أو غير مباشرة، بينما يتأثر تكوين السبخات الداخلية بالعمليات السائدة بها مثل عمليات الغسيل وتراكم الرواسب وتركيز الأملاح نتيجة للتبخر. وأوضحت نتائج تحليل القشرة الملحية سيادة أملاح الكلوريدات والكبريتات الذائبة للصدويوم والمغنيسيوم والكالسيوم ثم البوتاسيوم. لقد أكدت التحليلات باستخدام الأشعة السينية تواجد معادن السهاليت والجبس والكربونات بالإضافة إلى معدني الألبومائيت والبلودايت. وتعزى الاختلافات الرئيسية بين السبخات الساحلية والداخلية إلى مصدرها وتكوينها وعمق الماء الأرضي وبالتالي التركيب الكيميائي للقشرة الملحية لكل منهما.

ABSTRACT: This research was undertaken to study the pedo-chemical characteristics of selected playas (sabkhas) in the Arabian Shelf. Results indicated that most of the sabkhas are flat to almost flat having salt crusts with variable thickness. Profiles representing the sabkha surface are extremely saline compared with that of the surrounding landscapes. The dominant soluble salts are Cl^- and SO_4^{2-} of Na^+ followed by Ca^{2+} or Mg^{2+} . The compositions of the coastal sabkhas profile layers are closely related to the Gulf water composition while the inland playas are more associated with local conditions. This was confirmed from the similarity in salt levels, ion molar ratios and relatively high correlation coefficients between the electrical conductivity of soluble salts (EC_e) and either soluble B^{3+} ($r^2=0.80$) or soluble Mg^{2+} ($r^2=0.60$) in coastal compared with that of the inland sabkhas ($r^2=0.17$) and ($r^2=0.37$), respectively. The main pedological process affecting the formation of coastal sabkhas is the upward movement of the water table which is rich in salts originating from the Gulf waters either directly or through wind action. Leaching, accumulation of sediments and evaporative concentrations of the solutes are the processes prevailing in the inland sabkhas. Salt crusts are dominated by Cl^- and SO_4^{2-} of Na^+ , Mg^{2+} and Ca^{2+} salts while K^+ salts are relatively low. X-ray diffraction patterns confirm the presence of halite, gypsum and carbonate minerals. Epsomite and bloedite minerals were identified in both coastal and inland sabkhas. Specific minerals and relative abundance was quite variable between the salt crusts due to the characteristic conditions of each sabkha. The major differences between the inland and coastal sabkhas are related to the source, composition and depth of the water table and consequently the composition and mineralogy of the surface salt crusts.

Playa is the geological term for the flat and generally barren lower portions of arid basins of internal drainage that periodically flood and accumulate sediments (Neal, 1965). This is an important characteristic that makes playa the flattest of all land forms. Sabkha is the term applied to playas in many Middle East countries. Moreover, Al-Sayari and Zotl (1978) reported that sabkhas are saline flats underlain

by clay, silt and sand, and often encrusted with salt. The Arabian Shelf is one of the two major land masses forming the Arabian Peninsula. This shelf lies to the east of the Arabian shield, where it forms about two thirds of the peninsula and is composed mainly of sedimentary rocks among which scattered dry lakes are present in depressional areas. A common feature of the deserts in this region is the topographic depressions

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known as playa lakes, which usually have no drainage outlets for runoff. When the lakes dry up, mineral salts are left behind. There are two types of sabkhas. The first type is the coastal sabkha which is a super tidal surface produced by depositional overlap of marine sediments. In some cases, eolin deposits are also present. The associated brines are derived primarily from sea water. The second type is the inland sabkha, which lies away from the coast, and represents areas of equilibrium between eolian deposits and deflation, controlled by the local water table. Evaporation through the surface causes the formation of brine and the precipitation of evaporite minerals (Al-Sayari and Zotl, 1978). Saudi Arabia has large numbers of both coastal and inland sabkhas. These sabkhas result from the varying influences of geological structure, surface features, climatological conditions and the location from the saline water sources. Sabkhas are common features along the shoreline from Kuwait to the southern end of the Arabian Gulf. Sabkhat Matti, southeast of Qatar, is the largest of these with an area of about 6,000 km² (Al-Sayari and Zotl, 1978). El-Farra (1978) reported on the number of sabkhas existing in the different regions of the Arabian shelf,

focusing mainly on the eastern, western and Najd regions. The eastern regions include sabkhas identified in the Gulf coast, Al-Hofuf and east Al-Rubh Alkhali. El-Farra reported that there were 150 sabkhas along the Arabian Gulf (i.e. Sikak, 800 km²; ar Riyas, 900 km²; Salwah and Mashakhil sabkhas) and about 30 sabkhas east of Al-Hofuf. It was clear after reviewing the literature that there is insufficient data published on the chemical and mineralogical characteristics of the sabkhas in the Arabian Shelf.

The main objective of our study was to examine the pedo-chemical characteristics of selected inland and coastal sabkhas formed under the Arabian Shelf formations. A second objective was to evaluate the effect of saline conditions on the mineralogical composition of selected surface salt crusts of sabkhas.

Materials and Methods

DESCRIPTION OF THE STUDIED SABKHAHS: Six sabkhas were selected for this study to represent the coastal and inland sabkhas in eastern and central regions of the Arabian Shelf (Figure 1). Ramadan sabkha is located in the eastern region near

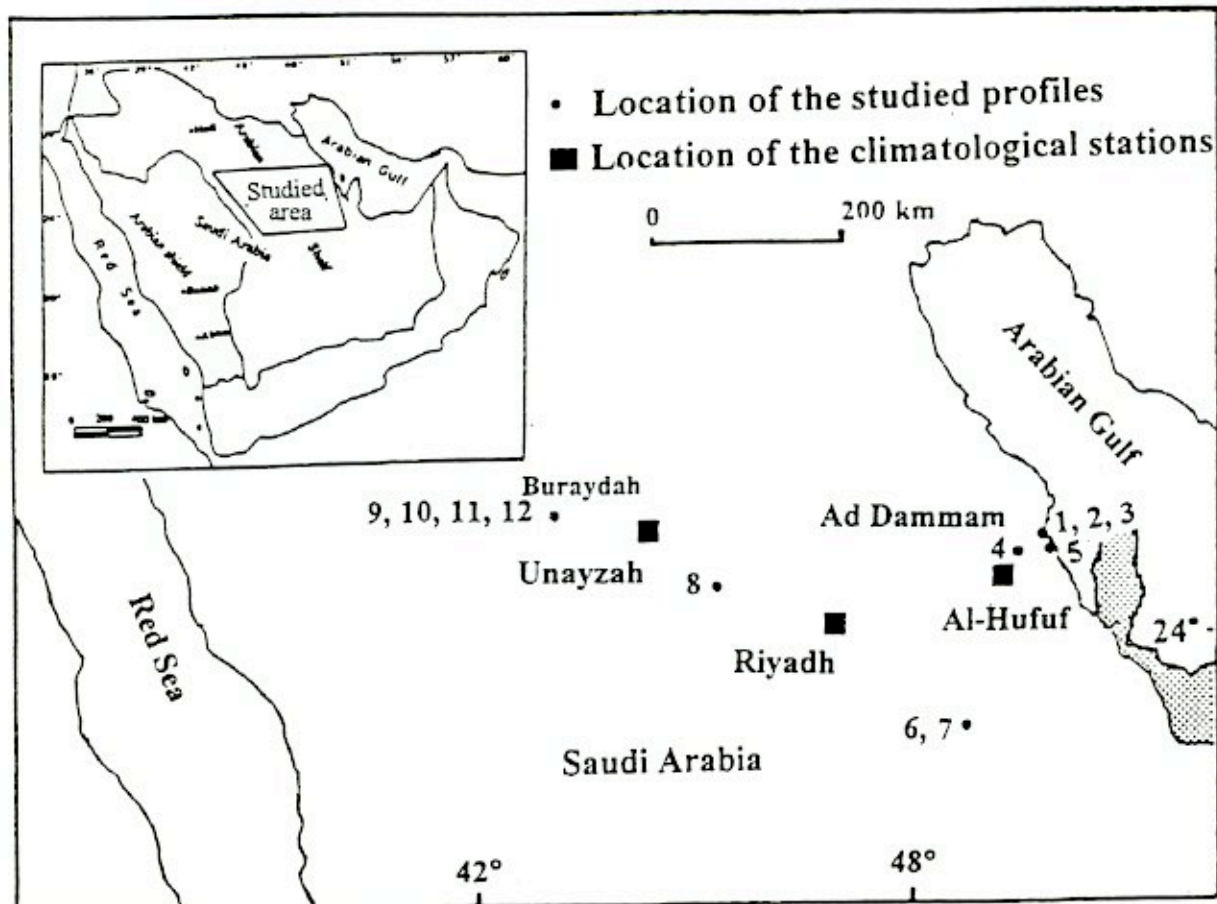


Figure 1. Location map

Abqaiq and is connected to the Arabian Gulf through sabkhat Dannan. It is one of the coastal and dry sabkhas and lies at an elevation of 100 m above sea level (asl). The water table level was found at 45 to 60 cm below the surface. Profiles 1, 2 and 3 were taken from the sabkha surface, the foot slope and the top of a surrounding sand dune, respectively. The dominant natural vegetation in the sabkha surfaces are *Zygophyllum qattarensis*, *Zygophyllum Coccineum* and *Halopeplis Perfoliata*, while *Hammada elegans* Sp dominates higher on the sand dune.

Sihat sabkha is located near the coast of the Arabian Gulf. It is considered to be a wet coastal sabkha and lies at 20 m asl. The dominant natural vegetation is mainly extensive shrubs. Profile 4 was taken from the sabkha surface.

Ad-Dammam sabkha is located on the Gulf near the Dammam-Riyadh road 20 km from Dammam and is considered as one of the coastal sabkhas. It lies at 20 m asl. Profile 5 was collected from the sabkha surface sediments. The profile depth is limited by the presence of a very hard layer at 80 cm deep.

Yibrin sabkha is located 7.5 km west of Yibrin. It is one of the dry inland sabkhas and lies at 160 m asl. Many Wadis are associated with this sabkha (e.g. Wadi Wabzah). Profiles 6 and 7 were collected from the sabkha surfaces.

Al-Milh "Mamlahat Al-Qasab" sabkha is located in the central region 60 km Northwest of Riyadh. It lies at an elevation of 600 m asl. The sabkha is surrounded by the Twaiq mountains from the north and east, elevation 1022 m asl, and sand dunes of Uraq Al-Buldan from south and west, 700 m asl. This sabkha is connected with Wadi Bu'aythiran and Wadi Wirat through a drainage system. Scattered natural vegetation such as *Halopeplis perf* is present. Profile 8 was collected from the sabkha surface.

Al-Awasjiah sabkha is located in the central region 5 km from Al-Awasjiah. It lies at 600 m asl and is surrounded by sand dunes from east Nafud ath Thuwayrat and from west Naas Sirr. These lie at 800 m asl. Scattered farms exist in the area at elevations higher than the sabkha level. Profiles 9, 10 and 12 were taken from the sabkha surface, while profile 11 was collected to represent the surrounding dunes.

SAMPLING AND ANALYSIS: The location of the profiles was selected to represent the surface features dominant in each of the sabkhas (i.e. the physiographic position, wetness conditions, slope and presence or absence of natural vegetation). Profiles were dug, deep, morphologically described and then representative samples were collected from the surface salt crust when present. Various analyses were carried out as follows: calcium carbonate (CaCO_3) content was determined by

calcimeter according to US Salinity Laboratory Staff (1954). Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) content was determined according to Berigari and Al-Any (1994). Soluble salts (EC_s) were assessed in the saturation paste extract using an electrical conductivity meter capable of measuring a relatively wide range of salt levels. Soluble cations and anions were determined in the saturation paste extracts, after the appropriate dilutions, according to the standard methods outlined by Page *et al.* (1982). Na^+ and K^+ were measured by flame photometry, Ca^{2+} and Mg^{2+} by titration with versenate, Cl^- by titration with a standard silver nitrate solution, CO_3^{2-} and HCO_3^- by titration with HCl and SO_4^{2-} by turbidimetry. Water soluble B^{3+} was measured in the saturation paste extract using the Azomethen-H method (Bingham, 1982). Water samples were collected from the standing water table in the auger hole of each profile followed by chemical analysis according to the standard methods (Page *et al.*, 1982).

Mineralogical analysis of the salt crust was carried out on the collected samples by X-ray diffraction, following grinding and powder mounting of the fine materials (<2.0 mm) on aluminum holders. Selected samples were heated in an oven at 105°C for 2 h before examining by X-ray diffraction. A Philips diffractometer equipped with a Cu tube was used to obtain the X-ray diffraction data. Scans were run at 2 degrees theta per minute from 6 to 50. Identification of the evaporite minerals was carried out according to Braitsch (1971), Gumuzzio *et al.* (1982), Whittig *et al.* (1982) and Doner and Lynn (1989).

Results and Discussions

The relief of sabkha surfaces was level. The texture of the Rumadan sabkha surface profile and the surrounding dunes was sandy. Sihat and Ad-Dammam sabkhas had sandy clay loam and loamy sand texture throughout their profiles, respectively. Yibrin sabkha had a loamy texture below the surface crust and a sandy loam texture in the underlying layers. The texture of Al-Malh sabkha was clay loam in the surface layer underlain by sandy loam and clay in the deep layers. Al-Awasjiah sabkha had sandy to sandy loam texture in the layers. The observed variations in texture within and between the studied sabkhas were due to the sediment sources and sedimentation pattern of each sabkha. Salt crusts having variable thickness were present in both inland (2-15 cm) and coastal (2-3 cm) sabkhas. They had slight to strong effervescence and similar soft to hard fine crystals. Water table levels were shallow in most of the studied profiles, particularly those representing the sabkha surfaces. There were very hard layers close to the surface in the Sihat and Ad-Dammam sabkhas.

Climatic data for the coastal sabkhahs were collected from the nearest meteorological station in Al-Hassa for which the mean annual precipitation was 78.9 mm. The highest monthly evaporation occurs in June and July with values of about 450 mm. The Riyadh meteorological station was the nearest station to Al-Malh inland sabkhah. The mean annual precipitation was 83.3 mm while the monthly evaporation ranged from 102.7 mm in January to 354 mm in June. The Unayzah meteorological station was the nearest to the Al-Awasjiah inland sabkhah where the mean annual precipitation was 69.5 mm. Accordingly, long periods of moisture deficit occur. The upward movement of water and accumulation of surface salt crusts was abundant throughout most of the year. Under such climatic conditions certain mineralogical species are likely to be found in the surface salt crust (Gumuzzio *et al.*, 1982).

COASTAL SABKHAHS: Data of profiles 1, 2 and 3 show relatively low saturation percentage, SP, values reflecting the sandy texture of all layers, except the deepest layer of profile 3 (Table 1). Calcium carbonate contents were quite low, while the pH values ranged from 7.14 to 8.25. Relatively low gypsum contents were present in the different profile layers with the highest amount occurring at the surface. Variable E_c values were detected with the highest values appearing in the sabkhah surface profile. These variations could be due to downward movement of soluble salts from the higher elevation (profile 3) and their accumulation in the lower elevation (sabkhah surface, profile 1). This was also clear from the level of salinity and its distribution within and between profiles 2 and 3. Salt crust was present only in the sabkhah surface profile reflecting the higher salinity level and the upward movements of salts and their accumulation on the surface. Sodium ions were the dominant cation in the saturation extracts, followed by Mg^{2+} in the higher salinity samples and Ca^{2+} in the relatively low salinity samples. Further, the Mg^{2+}/Ca^{2+} ratios increased with an increase in salinity values. This trend may have been due to the existence of saline water rich in Mg^{2+} from the Gulf. Analysis of the water table samples of profile 1 (Table 2) supports this trend since the salinity level was quite high and Mg^{2+} was the second dominant cation. In addition, the values of Na^+/Mg^{2+} and Na^+/Cl^- ratios were quite similar in both water table and Gulf water samples. Chloride ions were the dominant anions followed by SO_4^{2-} with HCO_3^- being the lowest. Accordingly, the dominant soluble salts could be in the form of chlorides and sulfates of Na^+ , Mg^{2+} and or Ca^{2+} . Water-soluble B^{3+} was relatively high in the sabkhah surface profile. Chemical analysis of the surface salt crust (Table 3) indicated the

dominance of chloride and sulfate salts of Na^+ followed by Mg^{2+} and Ca^{2+} , while K^+ was relatively low. Salt distribution and compositions which resulted from the upward movements through the profile can be explained by the chemical solubility, particularly in the sabkhah surface profile (Hardie and Eugster, 1970). Precipitation of Ca^{2+} in the form of calcite or gypsum depletes the solution in Ca^{2+} ions. Next calcite-gypsum and mixed Na-Mg- (SO_4) minerals may occur as saline water migrates upward through the profile (Timpson *et al.*, 1986). Similar patterns were found by Butler (1969) who reported constant Mg^{2+}/Ca^{2+} values with increasing Mg^{2+} concentrations for the Trucial Coast near Abu Dhabi. This suggested equilibrium conditions between brines and evaporite-carbonate minerals. Data for Sihat Sabkhah (profile 4) showed that the calcium carbonate content was quite high whereas the gypsum was relatively low. Levels of salinity and water-soluble B were particularly high in the surface layers. This trend may reflect the long term accumulation of salts in the surface layers via evaporation. Sodium is the dominant cation followed by Mg^{2+} and Ca^{2+} ions. Considerable concentration of K^+ ions were also present. Chloride was the dominant anion followed by SO_4^{2-} and HCO_3^- . The dominance of Na^+ and Mg^{2+} cations and Cl^- anions indicated that the main source of salinity was the sea water coming from the Gulf through direct seepage and wind action. This trend agreed well with the analysis of Gulf water and the water table samples (Table 2) which were closely similar in salinity levels, ion compositions and Na^+/Mg^{2+} and Na^+/Cl^- molar ratios. Data of profile 1, which represent the Ad-Dammam sabkhah (Table 1), show that gypsum was present in appreciable amounts in the deepest two layers of the profile whereas $CaCO_3$ contents were quite low with no trend in distribution with depth. Salinity levels were quite high and decreased with depth. Salts were dominated by Na^+ , followed by Ca^{2+} in the salt crust, whereas Mg^{2+} was the second dominant ion in the other layers. Regarding the anions, Cl^- dominated followed by SO_4^{2-} then HCO_3^- . Therefore, the dominant salts were chlorides and sulfates of Na^+ followed by Ca^{2+} or Mg^{2+} and K^+ .

It appears that the chemical composition of the coastal sabkhahs was affected mainly by the salt water of the Gulf either through direct seepage or through wind action which carried the saline water droplets to the sabkhah or the surrounding dunes and then to the sabkhah surface through leaching. This finding was consistent with the ion ratios Na^+/Mg^{2+} and Na^+/Cl^- of the Gulf water and the water table of the coastal sabkhahs. Further, the values of water soluble B^{3+} increased with the increase in salinity of the different layers. Therefore, the main pedo-chemical process taking place in the coastal sabkhah was the upward

TABLE 1

Profile No.	Depth cm	SP %	pH	EC ds m ⁻¹	Soluble ions cmol.kg ⁻¹										CaCO ₃ g.kg ⁻¹	CaSO ₄ .2H ₂ O g.kg ⁻¹	B ⁺⁺ mg.kg ⁻¹
					Ca ⁺⁺	Mg ⁺⁺	Na ⁺	K ⁺	HCO ₃ ⁻	Cl ⁻	SO ₄ ²⁻	Na ⁺ /Mg ⁺⁺	Na ⁺ /Cl ⁻	Mg ⁺⁺ /Ca ⁺⁺			
1	2-10	22.5	7.14	27.9	0.98	1.40	5.87	0.22	0.21	6.20	1.18	8.4	0.95	1.43	47	44.6	1.34
	10-25	20.4	7.73	28.1	1.09	1.73	5.45	0.21	0.24	5.59	1.49	6.3	0.97	1.59	35	12.9	0.79
	25-45	20.5	7.47	25.8	1.00	1.48	5.60	0.17	0.19	5.15	1.41	7.6	1.09	1.48	44	11.2	0.47
2	0-15	17.5	7.29	28.7	1.24	1.27	4.26	0.14	0.19	5.23	0.95	6.7	0.82	1.02	38	15.9	1.10
	15-30	19.0	7.52	9.8	0.73	0.40	1.36	0.07	0.19	1.62	0.82	6.8	0.84	0.55	35	3.0	0.39
	30-45	20.5	7.44	9.9	0.70	0.40	1.65	0.07	0.22	1.70	0.81	8.3	0.97	0.57	29	10.8	0.55
3	45-60	19.5	7.68	13.8	0.77	0.50	2.37	0.08	0.13	2.47	0.87	9.5	0.96	0.65	36	7.5	0.55
	0-15	18.3	8.25	2.9	0.40	0.09	0.19	0.02	0.08	0.28	0.31	4.2	0.68	0.20	57	1.5	0.06
	15-30	19.5	7.65	3.6	0.34	0.11	0.26	0.02	0.04	0.49	0.33	4.7	0.53	0.32	41	1.8	0.04
4	30-45	19.0	7.94	6.57	0.59	0.16	0.83	0.06	0.06	0.82	0.51	10.4	1.01	0.27	39	3.0	0.28
	45-60	20.1	7.54	7.0	0.54	0.25	1.03	0.05	0.05	0.98	0.59	8.2	1.05	0.46	28	3.0	0.32
	60-110	28.5	7.47	17.3	1.38	0.76	4.71	0.13	0.33	5.70	1.68	12.4	0.83	0.55	34	11.2	0.74
5	2-7	32.5	7.17	160.0	2.57	29.30	61.90	2.23	0.94	94.30	2.97	4.2	0.66	11.40	308	124.0	5.39
	7-12	33.1	7.47	133.0	3.38	25.90	44.30	2.00	0.63	67.10	3.64	3.4	0.66	7.65	400	20.2	2.91
	12+	32.0	7.28	103.0	3.46	12.30	20.50	0.96	0.67	37.40	3.10	3.3	0.55	3.54	300	32.9	1.13
60-80	3-15	19.8	7.09	200.0	2.26	2.62	74.20	0.29	0.49	72.30	1.98	56.7	1.03	1.16	77	8.0	2.78
	15-40	18.4	6.75	180.0	3.16	20.40	37.60	2.91	0.44	60.00	1.20	3.7	0.63	6.46	64	16.2	3.71
	40-60	19.2	6.94	157.0	2.76	13.20	39.50	1.02	0.40	53.80	1.56	6.0	0.73	4.79	34	194.0	3.45
60-80	37.5	6.21	117.0	4.58	13.10	54.00	1.18	0.66	67.50	2.79	8.2	0.80	2.87	61	129.0	3.55	

TABLE 2

Chemical analysis of water table samples collected from the studied profiles

Sample No.	Depth cm	pH	T.S.S.* % w/v	Soluble ions mmol.L ⁻¹						Na ⁺ /Mg ⁺⁺	Mg ⁺⁺ /Ca ⁺⁺	Na ⁺ /Cl ⁻	
				Ca ⁺⁺	Mg ⁺⁺	Na ⁺	K ⁺	HCO ₃ ⁻	Cl ⁻				SO ₄ ²⁻
A.G. ^b	--	7.77	4.90	14.5	71.0	648	0.53	5.25	7.3	44.0	9.13	4.90	0.89
Prof. 1	45+	7.28	2.90	30.0	40.3	351	0.55	5.00	385.0	50.0	8.71	1.34	0.91
Prof. 4	12+	7.76	4.84	19.0	72.8	629	0.35	5.75	705.0	48.5	8.64	3.83	0.89
Prof. 8	100+	7.72	20.30	62.0	315.0	2150	1.70	3.50	2800.0	45.0	6.83	5.08	0.77
Prof. 9	30+	6.90	36.50	11.0	1070.0	3724	1.90	11.0	5250.0	314.0	3.48	97.30	0.71
Prof. 10	50+	6.95	36.10	11.0	1023.0	3628	1.80	11.5	5110.0	284.0	3.55	93.00	0.71
Prof. 12	150+	6.83	21.50	21.0	750.0	1959	1.30	9.25	3080.0	205.0	2.61	35.70	0.64

* T.S.S. : Total soluble salts ^b A.G. : Arabian Gulf

movement of saline water through the profile and accumulation of salts at the sabkha surface as a result of evaporation. At higher elevations, particularly in the surrounding dunes, downward movement of solutes was an effective process in leaching accumulated salts. Periodic flooding of the sabkha surfaces could also disturb the chemical balance in the profile thus affecting the salt level, composition and distribution within the profiles and the crust (Butler 1969). The difference in salinity between the sabkha surface profiles may have been due to the periodic flooding or other processes which reduced the salt levels of Rumadan (100 m asl) relative to those of Ad-Dammam (20 m asl) and Sihat (20 m asl) sabkhas. In addition, the surrounding dunes of Rumadan sabkha, which had very low salinity levels, constitute an important land resource for agricultural development, provided that irrigation water can be secured.

INLAND SABKHAHS: Data in Table 4 indicate that relatively high contents of gypsum were present in Yiprin sabkha (profiles 6 and 7) with an increasing content with depth as in profile 6. Levels of soluble salts were quite high in the surface layers but decreased drastically with depth in both profiles. Soluble Na^+ and Cl^- were the dominant ions followed by Mg^{2+} in the very high salinity samples and Ca^{2+} in the relatively low salinity counterparts. Relatively high contents of soluble K^+ were present in the upper layers of profile 6. Therefore, NaCl was the main soluble salt followed by Mg^{2+} or Ca^{2+} chlorides. Sulfate anion was relatively low and may be controlled by the presence of gypsum. Ratios of $\text{Na}^+/\text{Mg}^{2+}$ and Na^+/Cl^- showed no specific distribution trend with depth, while the $\text{Mg}^{2+}/\text{Ca}^{2+}$ ratio increased with increasing salinity. The rise in the $\text{Mg}^{2+}/\text{Ca}^{2+}$ ratio can be attributed to the precipitation of Ca^{2+} ions as carbonate and sulfate minerals. On the other hand, relatively low salinity levels were present in the dunes surrounding Yibrin sabkha (profile 7), even though it had a thick surface salt crust rich in gypsum and depleted in CaCO_3 . Therefore, the main process affecting the formation of the Yibrin sabkha was the accumulation of salts and gypsum through evaporative concentration as well as accumulation of gypsum and salt-rich sediments from the surrounding wadis. Data from the Al-Milh "Mamlahat Al-Qasab" sabkha show that CaCO_3 and $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ contents were relatively high in the different layers of the profile (profile 8). The amounts of soluble salts were quite high particularly in the surface layers and were dominated by NaCl followed by Ca^{2+} or Mg^{2+} chlorides. Relatively low levels of sulfate ions were present which could be controlled by the presence of gypsum. Similarly, no specific trend was observed for $\text{Na}^+/\text{Mg}^{2+}$ ratios in the different

layers. Data from Al-Awasjiah sabkha showed high salinity levels and variable gypsum contents in the profiles representing the sabkha surface, whereas contents in the surrounding dunes were very low. Relatively high quantities of CaCO_3 were present in the wet sabkhas of profiles 9 and 10. The surrounding dunes generally had sandy textures throughout the studied layers. The variation in texture of profiles and layers could be due to the lack of homogeneity amongst the parent materials from which the sabkha surface was formed. Sodium chloride was the dominant soluble salt followed by Mg^{2+} or Ca^{2+} salts in the higher and lower salinity samples respectively. Salinity of the surrounding dunes was low with high Ca^{2+} concentrations relative to Na^+ and Mg^{2+} . Relatively high $\text{Na}^+/\text{Mg}^{2+}$ and Na^+/Cl^- ratios were present in the dry sabkha (profile 12) as compared with those of the wet sabkha (profiles 9 and 10). This could be related to the existing conditions of drying which may have precipitated Mg^{2+} in slightly soluble forms. A similar trend was observed for the $\text{Mg}^{2+}/\text{Ca}^{2+}$ ratios, which showed relatively higher values in the wet sabkha compared to that of the dry one. Concentrations of the total soluble salts were extremely high in the water table samples of the inland sabkha (profiles 8, 9, 10 and 12). Dominant salts were mainly Cl^- followed by SO_4^{2-} of Na^+ and Mg^{2+} .

Correlation coefficients (r^2) between EC_e values and saturation paste extract compositions were B^{3+} (0.17), Na^+ (0.91), Cl^- (0.88), and Mg^{2+} (0.37). Values of (r^2) indicated that Na^+ and Cl^- contributed more to EC_e values than B and Mg^{2+} . The ion ratios $\text{Na}^+/\text{Mg}^{2+}$, $\text{Mg}^{2+}/\text{Ca}^{2+}$ and Na^+/Cl^- of the water table (Table 2) were quite similar to profiles 9 and 10 while profiles 8 and 12 were different. Under the existing conditions of high salinity, evaporation will cause precipitation of slightly soluble compounds in the profile and at the surface. This process will deplete the solution in some ions and change the concentration of ions, ion ratios and chemical composition of the profile layers. The high values of the $\text{Mg}^{2+}/\text{Ca}^{2+}$ ratio of the water table samples and the profile layers of Al-Awasjiah sabkha could have been due to the precipitation of calcite and gypsum and the depletion of the solution in Ca^{2+} ions. This process is consistent with the presence of relatively high gypsum and calcite contents. Further, the content of water-soluble B^{3+} in the studied inland sabkhas was relatively low compared with that of the coastal sabkhas. This was due mainly to the source of the sabkha sediments as well as the source and composition of the water table and salts.

CHEMICAL COMPOSITION AND MINERALOGY OF SALT CRUSTS: Analysis of salt crusts samples was carried out

TABLE 3

Chemical analysis and mineralogical compositions of salt crust samples

Profile No.	Depth cm	pH	EC dS m ⁻¹	Soluble ions g·kg ⁻¹					SO ₄ ²⁻	CaCO ₃ g·kg ⁻¹	CaSO ₄ ·2H ₂ O g·kg ⁻¹	Na ⁺ /Mg ²⁺	Mineralogy ^{a,b}	
				Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	HCO ₃ ⁻						Cl ⁻
Coastal Sabkhhah														
1	0-2	7.30	0.39	6.0	3.6	29.4	1.4	19.8	53.3	11.1	29	47.9	16.3	Q, H, D, B, G, E, C
4	0-2	7.10	1.15	17.5	7.5	94.0	1.2	38.1	169.0	36.0	35	52.5	25.1	Q, H, G, E, B
5	0-30	7.10	0.35	5.0	1.8	29.4	0.2	19.8	47.9	7.6	61	4.0	32.7	Q, H, G, E, B
Inland Sabkhhah														
6	0-3	6.60	1.90	65.0	1.5	130.0	2.1	30.5	222.0	132.0	91	257.0	174.0	H, G, A, D, B, T, C, An
7	0-10	8.20	1.35	168.0	3.0	0.5	0.1	30.5	26.6	396.0	47	500.0	0.3	G, B, E, D
8	0-2	0.11	1.50	17.5	16.5	120.0	2.7	41.9	229.0	9.0	25	9.3	14.5	H, B, A
9	0-15	7.10	3.60	10.0	6.0	371.0	0.9	26.7	577	31.2	27	37.0	129.0	H, T, E, G
10	0-3	7.20	3.20	25.0	3.0	307.0	0.7	30.5	488	55.2	57	199.0	205.0	H, G, B, E
12	0-5	7.09	2.20	30.2	7.3	312.0	0.7	22.5	298	29.2	32	177.0	85.5	H, G, B, E

^a Mineralogy: Q: Quartz; H: Halite; G: Gypsum; D: Dolomite; C: Calcite; E: Epsomite; B: Bloedite; T: Thenardite; A: Anhydrite and An: Analcime.
^b Minerals present in sequences (descending order).

TABLE 4

Chemical properties of profiles in inland sabkhhahs

Profile No.	Depth cm	SP %	pH	EC dS m ⁻¹	Soluble ions cmol·kg ⁻¹					Na ⁺ /Mg ²⁺	Na ⁺ /Cl	Mg ²⁺ /Ca ²⁺	CaCO ₃ g·kg ⁻¹	CaSO ₄ ·2H ₂ O g·kg ⁻¹	B ⁺ mg·kg ⁻¹		
					Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	HCO ₃ ⁻							Cl ⁻	SO ₄ ²⁻
6	3-15	27.4	7.10	214.0	6.60	20.40	102.9	4.44	0.34	118.0	0.38	10.1	0.87	3.09	105.0	242	0.75
	15-25	24.5	7.20	199.0	2.87	8.72	78.2	2.58	0.49	94.3	1.32	17.9	0.83	3.04	89.0	486	0.46
	25-40	25.0	8.10	51.8	2.15	1.60	14.5	0.79	0.29	18.0	0.43	18.1	0.81	0.74	160.0	552	0.28
	40-50	35.0	8.20	19.7	1.75	0.84	6.31	0.30	0.40	6.5	1.87	15.0	1.02	0.48	128.0	592	0.18
	10-30	22.1	7.65	7.2	2.06	0.28	0.91	0.03	0.23	1.2	1.12	6.5	0.76	0.14	69.0	500	0.60
7	2-10	29.4	6.50	220.0	29.0	5.50	118.5	0.04	0.10	153.0	0.40	43.1	0.78	1.09	368.0	8	0.47
	10-25	27.5	6.74	99.5	9.63	10.50	23.9	0.93	0.52	41.3	0.96	4.6	0.58	0.53	297.0	806	0.85
	25-40	27.2	7.52	36.6	2.90	1.55	9.82	0.26	0.11	11.2	1.43	12.7	0.88	0.52	201.0	285	0.35
	40-70	29.4	7.50	38.2	3.16	1.65	10.9	0.22	0.88	12.8	1.66	13.2	0.85	0.52	216.0	260	0.66
	70-85	34.6	7.20	41.9	7.29	6.39	11.2	0.30	0.83	20.8	1.31	3.5	0.54	0.88	273.0	170	0.37
9	85-100	47.2	7.02	34.7	2.93	2.56	16.0	0.31	0.42	16.9	2.34	12.5	0.95	0.87	314.0	82	0.34
	15-30	35.8	6.86	185.0	1.36	40.20	101	2.53	0.82	137.8	8.48	5.0	0.74	29.50	367.0	104	1.50
	3-10	33.0	7.48	165.0	7.26	48.80	67.4	3.05	0.79	113.5	10.40	2.8	0.59	6.72	168.0	387	6.12
	10-25	33.0	7.24	168.0	1.32	51.40	67.4	2.74	1.16	118.8	7.39	2.6	0.57	38.90	254.0	312	2.46
	25-50	37.1	7.11	117.0	2.45	27.20	40.3	1.66	1.19	68.6	4.01	3.0	0.59	11.09	296.0	286	1.04
10	0-50	18.5	8.35	1.6	0.20	0.07	0.13	0.02	0.07	0.1	0.16	3.7	0.93	0.35	4.9	39	0.05
	50-100	19.0	8.13	2.1	0.23	0.11	0.16	0.01	0.05	0.2	0.19	2.9	0.70	0.48	3.7	38	0.04
	100-150	18.5	7.90	398.0	0.46	0.39	0.38	0.03	0.05	0.6	0.08	2.0	0.60	0.85	6.3	31	0.04
	5-15	22.3	6.58	145.0	2.38	10.30	43.8	1.24	0.79	51.3	3.03	8.5	0.85	4.31	19.5	23	0.54
	15-50	22.0	6.73	140.0	1.98	5.89	39.6	0.98	0.42	47.3	3.34	13.5	0.84	2.97	18.1	26	0.55
12	50-70	28.7	7.05	116.0	2.35	5.27	39.9	0.84	0.60	47.4	4.08	15.2	0.84	2.24	15.6	28	0.67
	70-100	22.6	7.49	86.0	1.24	2.40	21.7	0.41	0.43	26.0	3.01	18.1	0.84	1.94	18.1	23	0.50
	100-150	23.5	7.22	106.0	2.54	6.80	29.8	0.55	0.52	35.3	3.29	8.78	0.85	2.68	15.6	41	0.46

using sample water ratios ranging from 1:100 to 1:1000. Data are presented only for the 1:500 ratio (Table 3). Results indicated that the effect of increasing the dilution of the suspension was to reduce the EC values. No significant change in the ion content ($\text{g}\cdot\text{kg}^{-1}$) of samples was found as a result of dilution except for Ca^{2+} and sulfate ions in the high gypsum samples, e.g. at Yibrin. Soluble Na^+ was the dominant cation followed by Ca^{2+} , Mg^{2+} and K^+ in all salt crust samples but one, namely, the Yibrin sabkha (profile 7). Here Ca^{2+} dominated followed by Mg^{2+} , Na^+ and K^+ . Besides the Yibrin sabkha profiles which were rich in sulfates, anions were dominated by Cl^- . Therefore, with the exception of the sabkha of Yibrin, the dominant soluble salts in salt crust samples were mainly Cl^- and SO_4^{2-} of Na^+ , Ca^{2+} and Mg^{2+} . The former, however, was dominated by Ca^{2+} and SO_4^{2-} in the surrounding dunes (profile 7) and SO_4^{2-} of Na^+ and Ca^{2+} in the dry sabkha surface (profile 6). X-ray diffraction patterns of the different salt crust samples (Figure 2) confirmed the presence of halite (NaCl) mineral as a major salt constituent in the coastal sabkhas. Gypsum, epsomite ($\text{MgSO}_4\cdot 7\text{H}_2\text{O}$), bloedite ($\text{Na}_2\text{MgSO}_4\cdot 4\text{H}_2\text{O}$) and dolomite ($\text{CaMg}(\text{CO}_3)_2$) were also present in relatively low contents (Table 3). Quartz was detected in almost all samples particularly in the coastal sabkha sample which undoubtedly was

due to eolian action. The salt crust of Yibrin sabkha showed different mineralogy. The dry crust contained almost entirely pure gypsum (profile 6) with the surrounding dunes being rich in gypsum and halite (profile 7). Other minerals were detected in both profiles e.g. calcite, bloedite, epsomite, dolomite and anhydrite (CaSO_4). Traces of the mineral analcime were detected in profile 6 from the characteristic peaks (d-spacing) at 0.342, 0.292 and 0.558 nm (Gude, 1981). Variations in mineralogy are undoubtedly related to the composition of the solution and sediments which appeared to be rich in gypsum and other sedimentary rocks. Surface crusts of Al-Awasjah sabkha were dominated by halite with minor quantities of gypsum, bloedite, thenardite (Na_2SO_4), epsomite and calcite minerals. It is worth mentioning that the identified minerals and in particular gypsum and the Na^+ and Mg^{2+} sulfates were subject to seasonal changes due to temperature variation and to other prevailing climatic factors. Timpson *et al.* (1986) concluded from their study on the evaporite mineralogy that hydration state, mineral occurrences, and mineral solubility were seasonally dependent. Further, Driessen and Schoorl (1973) reported on the temperature stability of mirabilite and thenardite with respect to hydration states. Similarly, heating the samples at 105°C followed by examination using X-ray diffraction

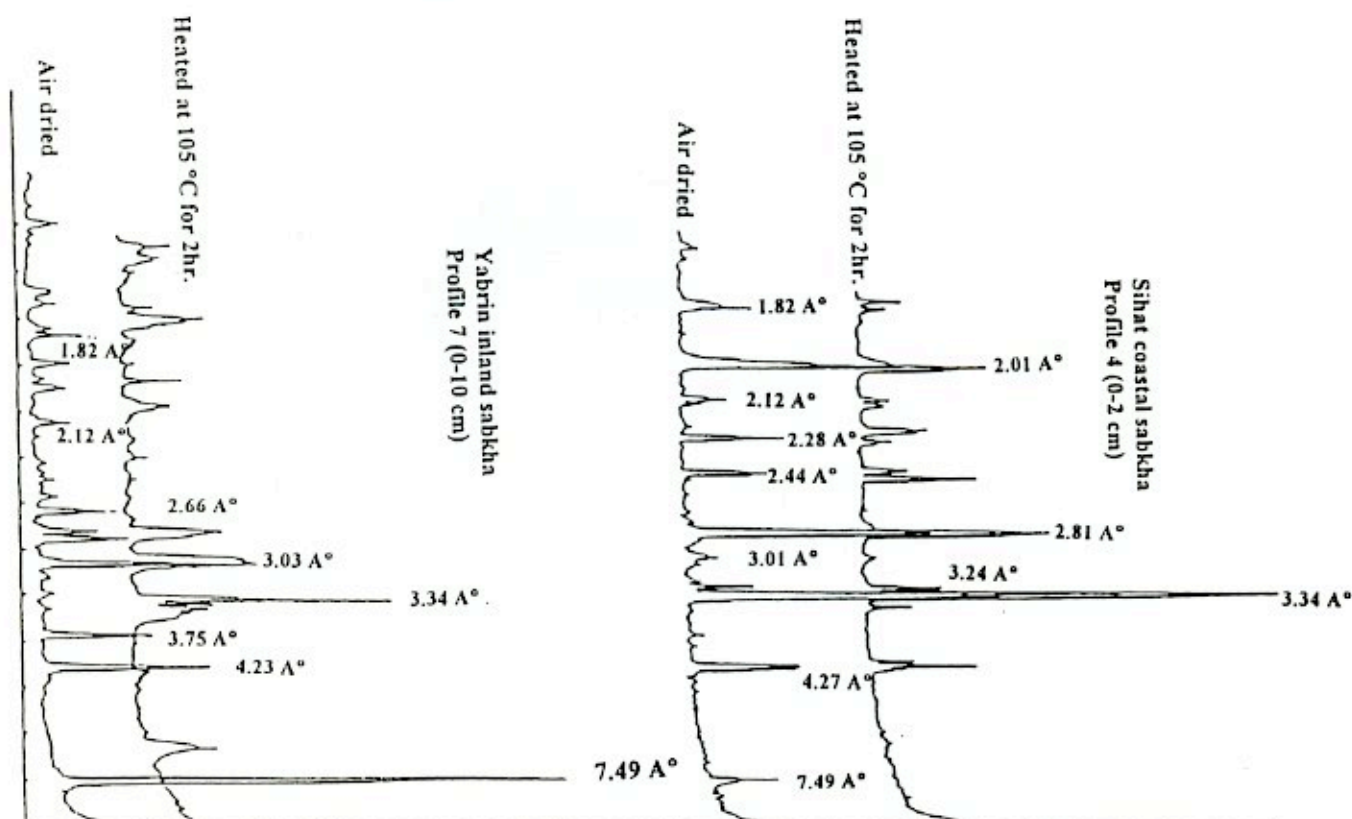


Figure 2. X-ray diffraction pattern of selected salt crust samples

indicated the elimination of gypsum peaks and the appearance of new diagnostic peaks for bassanite ($\text{CaSO}_4 \cdot 1/2\text{H}_2\text{O}$), (Figure 2). Therefore, the absence of gypsum peaks on heating confirms the conversion of gypsum crystals to bassanite in all gypsum containing samples. This mechanism might partially occur under the prevailing arid climate.

Conclusions

Very high quantities of water soluble salts were present in the sabkha surfaces. The composition of the coastal sabkhas was closely related to the composition of the Gulf water whereas inland sabkhas were associated to local environmental conditions and seeps. This was confirmed from the similarity in salt levels, ion ratios and the relatively high correlation coefficients between EC_e and water soluble B^{3+} ($r^2=0.8$) or Mg^{2+} ($r^2=0.6$) in coastal sabkhas as compared with the inland sabkhas ($r^2=0.17$ and 0.37) respectively. The main pedological process affecting formation of the coastal sabkhas were the upward movement of the water tables rich in salts originating mainly from Gulf waters either directly or through wind action. Leaching, accumulation of sediments, and evaporative concentration of the solutes were the processes prevailing in the inland sabkhas. Salt crusts were dominated by Cl^- and SO_4^{2-} of Na^+ , Mg^{2+} and Ca^{2+} salts where K^+ salts were present in low concentrations. X-ray diffraction patterns confirmed the presence of halite, gypsum and carbonate minerals associated with various other minerals. Epsomite and bloedite were identified in the coastal and inland playas. Specific minerals and relative abundance was quite variable between the evaporites and the characteristic conditions of each sabkha. The major differences between the inland and coastal sabkhas were related to the sources, composition, and depth of the water tables. This, of course, reflects the composition and mineralogy of the profile and the surface salt crusts.

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