Sedimentological and morphological characteristics of some nabkha deposits in the northern coastal plain of Kuwait, Arabia

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Nabkhas in the sabkha flat of the northern coastal plain of Kuwait are generally located in areas slightly higher than the evaporitic sabkha pans, and facing the alluvium fans descending from the bordering cliffs and slopes. They are developed by the deposition of wind-driven sediments around *Nitraria retusa* shrubs. The nabkhas vary in shape and size. However, they mostly have an elongated domal shape with an average height of 102 cm and an average length of 18 m. Three textural groups were recognized, namely, sandy nabkhas, silty sand nabkhas and sandy silt nabkhas. Detailed textural and mineralogical investigations of the nabkha deposits revealed that they are mainly derived from the sabkha flat sediments. Beach sands, desert aeolian deposits and dust fallout are considered as secondary sources. Morphometric parameters, mineralogic composition and textural characteristics of the studied sabkha are presented and are thoroughly discussed. It was concluded that *Nitraria retusa* shrubs are efficient horizontal sand traps for wind-driven sediments and, therefore, a thorough understanding of the development and aerodynamic behaviour of nabkha can provide useful information for the design of sustainable biological sand control measures in desert areas.

Keywords: nabkha; *Nitraria retusa*; sabkha; Kuwait; wind-driven sediments; biological sand control

Introduction

Cooke *et al.* (1993) have classified aeolian deposits into three main categories, namely: (a) mobile; (b) anchored; and (c) stabilized. Mobile deposits include sand sheets, zibar, network dunes, star dunes, linear dunes and transverse dunes. Anchored deposits comprise lee, flank, echo and climbing dunes. They divided the stabilized deposits into two groups, namely those stabilized by cementation, and those stabilized by vegetation. The first group includes clay dunes and aeolianites while the second one comprises vegetated parabolic dunes, dune ridges and nabkhas.

Nabka or nabkha is an Arabic word denoting a small sandy hillock. It was used in Arabic literature before Islam, more than 14 centuries ago (Ibn Manzur, undated). Gautier & Chudeau (1909) used the same term for a mound-like accumulation of wind-driven sediments around vegetation. Several terms have been used for this aeolian landform, such as bush-mounds, shrub-coppice dunes, knob dunes, phytogenetic hillocks, dune tumuli,

rebdou, nebbe, and takouit (Cooke *et al.*, 1993). Beheiry (1967) used the term knob dunes for some vegetated dunes in the Coachella valley in Southern California. Lancaster (1989) described nabkhas in the coastal margin of Namib Sand Sea as shrub coppice dunes formed by the deposition around the roots of actively growing plants of *Salsola sp.*

Nabkhas were also reported in Northern Chad (Worral, 1974), Lut Desert of Iran (Mahmoudi, 1977), Syrian Desert (Kosmowska-Suffcyuska, 1980), Qatar (Ashour *et al.*, 1991), Saudi Arabia (Al-Sayari & Zotl, 1978) and Egypt (Kassas & Zahran, 1967; Evenari *et al.*, 1985).

The term mega-nabkhas is used for large sand mounds that accumulate around clumps of trees which reach 10 m high and up to 1 km long. These were reported by Warren (1988) in Wahiba Sands, Cooper (1958) on the edges of Oregon coastal dunes, and Koster (1968) in Holland.

Cycles of nabkha deposition and erosion, functions controlling their size and density, and growth habit of its parent plant were described by several authors (Capot-Rey, 1957; Monod, 1961; Suslov, 1961; Coque, 1962; Gile, 1966; Mahmoudi, 1977; Gibbens *et al.*, 1983; Hesp, 1988, 1989).

The State of Kuwait is located in the north-eastern corner of the Arabian desert where it constitutes a part of the north-western coastal flat of the Arabian Gulf. Because of its dry, hot and windy climate, the detrital nature of its bedrock, and its location downwind of the high deflational area of the Mesopotamian flood plains, Kuwait witnesses remarkable aeolian activities (Khalaf, 1989; Khalaf & Al-Ajmi, 1993). Almost all types of erosional and depositional aeolian landforms are present within the desert of Kuwait (Khalaf *et al.*, 1984). Nabkhas are one of the most frequent aeolian deposits along the coastal plain of Kuwait. Several studies have examined the sedimentological aspects of the coastal area of Kuwait (Hilmy *et al.*, 1971; Saleh, 1975; Hayes, 1977; Khalaf, 1978, 1988; Picha, 1978; Gunatilaka *et al.*, 1980, 1984, 1985; Khalaf & Ala, 1980; Khalaf *et al.*, 1987; Al-Sarawi *et al.*, 1988; Al-Bakri & El-Sayed, 1991). However, the nabkha and sabkha sediments of the northern coastal area received little attention. Khalaf *et al.*, 1984 used the term sabkha drifts for nabkhas formed on the coastal sabkha flat of Kuwait. They described them as knob vegetated dunes. In their study on the coastal area of eastern Kuwait Bay, Kelio & Al Sheikh (1986), reported the occurrence of a nabkha field. Al-Hussaini (1988) investigated the nabkhas in the Al Khiran area, southern coastal plain of Kuwait.

This paper presents the geomorphology, textural characteristics, and mineralogical composition of the nabkha deposits developed on the sabkha flat along the northern coast of Kuwait. It also discusses their mode of occurrence and genesis.

Physiographic setting

Kuwait has a dry hot climate. The mean temperature in summer (July) is 37·4°C with a fairly large diurnal temperature range of about 17°C in January. Precipitation is scarce; the mean total is about 100 mm year. Wind blows from two main directions; the north-west and to a lesser extent, the south-east. Sand and duststorms are frequent in summer, especially during June and July when strong north-westerly winds blow over the dry lowlands of Southern Iraq.

Physiographically, Kuwait occupies the southern part of the Al-Dibdibba plain which is bounded to the north by the Mesopotamian flood plain of Iraq and to the west by the Al-Dahna sand sea of Saudi Arabia. The surface of Kuwait is generally flat to gently undulating desert plain, occasionally interrupted by low relief ridges, hills and escarpments. It slopes gradually north-eastward with an average gradient of about $2\,m\,km^{-1}$. The surface of Kuwait is carved in friable to partially cemented clastic deposits of Miocene to Pleistocene age, locally known as the Kuwait Group. The latter is divided into three formations in northern Kuwait. These are (from top to bottom): Al-Dibdibba,

Fars, and Ghor. Al-Dibdibba Formation is mostly formed of gravel sheet deposits which cover most of the northern desert of Kuwait (Owen & Nasr, 1958).

The desert of Kuwait is covered by several types of recent surface sediments including residual gravel, playas, desert washout and aeolian deposits. (Khalaf et al., 1984; Khalaf & Al-Ajmi, 1993). The following types of aeolian deposits were recognized: (1) rugged vegetated sand sheets; (2) smooth sand sheets; (3) active sand sheets; (4) aeolian *wadi* fill; (5) sand dunes and sand drifts. Coastal sand drifts vary in size and mode of occurrence. The present study deals with one type of these drifts — nabkhas.

Study area

On the basis of its morphology, the Kuwait coastal area can be broadly divided into northern and southern geomorphic provinces (Khalaf, 1970). The southern coastal province extends from the southern coast of Kuwait Bay to the southern border of the country. It is marked by a relatively steep beach profile and rocky intertidal flats.

The northern coastal province, which includes the coasts of Khor Al-Sabiyah and northern Kuwait Bay, is characterized by an extensive and gently inclined intertidal flat (Fig. 1). Khor Al-Subbiyah is a tidal channel separating Warba and Bubiyan Islands from the Kuwait mainland. Its western coastal flat is bounded landward by two sedimentomorphic units, namely, Umm Neqqa flat at the extreme north, and Al-Rukham slope which extends as far as Ras Al-Subbiyah in the extreme south.

Umm Neqqa flat is covered by extensive active sand sheets and a few scattered sand dunes and merges gradually within the coastal flat. Al-Rukham slope on the other hand is formed of Quaternary gravelly deposits covered with extensive pebbly gravel lag. It is extensively dissected by parallel drainage courses that debouch in the coastal flat. These courses are mostly filled with aeolian sand.

Three sedimentomorphic zones can be recognized in the coastal flat of Khor Al-Subbiyah, these are, from east to west: (a) intertidal mud flat; (b) supratidal flat; (c) sabkha flat. The intertidal mud flat is separated from the supratidal and sabkha flats by a flat terrace covered by elongated Oyster Banks. The supratidal flat is occasionally flooded by seawater during spring tides. Halophytes are sporadically scattered within the latter zone flat. A small accumulation of muddy sediments mixed with shell fragments occurs as wind shadows around these halophytes.

On the other hand, sabkha flats are relatively wide in the northern coastal area of Khor Al-Subbiyah and narrow towards the south. Their surfaces are covered with fluffy silty sediments, and scattered crystals of gypsum protrude from them. Shallow trenches in these sabkha flats showed that they are mostly formed of thin interlaminated layers of mud and sand. Mud layers are commonly very dense while sand layers are friable and contain a considerable amount of authigenic saccaroidal gypsum crystals. In the Ras Al-Subbiyah and Al-Maghasel areas, sabkha flats are partially covered with scattered patches of Molluscan shell lag.

The northern coast of Kuwait Bay is bounded landward by the Jal Az-Zor escarpment. It has a sedimentomorphic zonation similar to that of Khor Al-Subbiyah coastal area, in addition to a fourth zone, an alluvial fan plain which is located between the sabkha flat and the terraces of Jal Az-Zor escarpments.

Clusters of nabkhas occur as scattered fields on the inland side of the sabkha flat close to the alluvial fans (Fig. 2).

Materials and methods

The study area has been surveyed using aerial photos and topographic maps. The various types of surface sediments including nabkha deposits were investigated. The
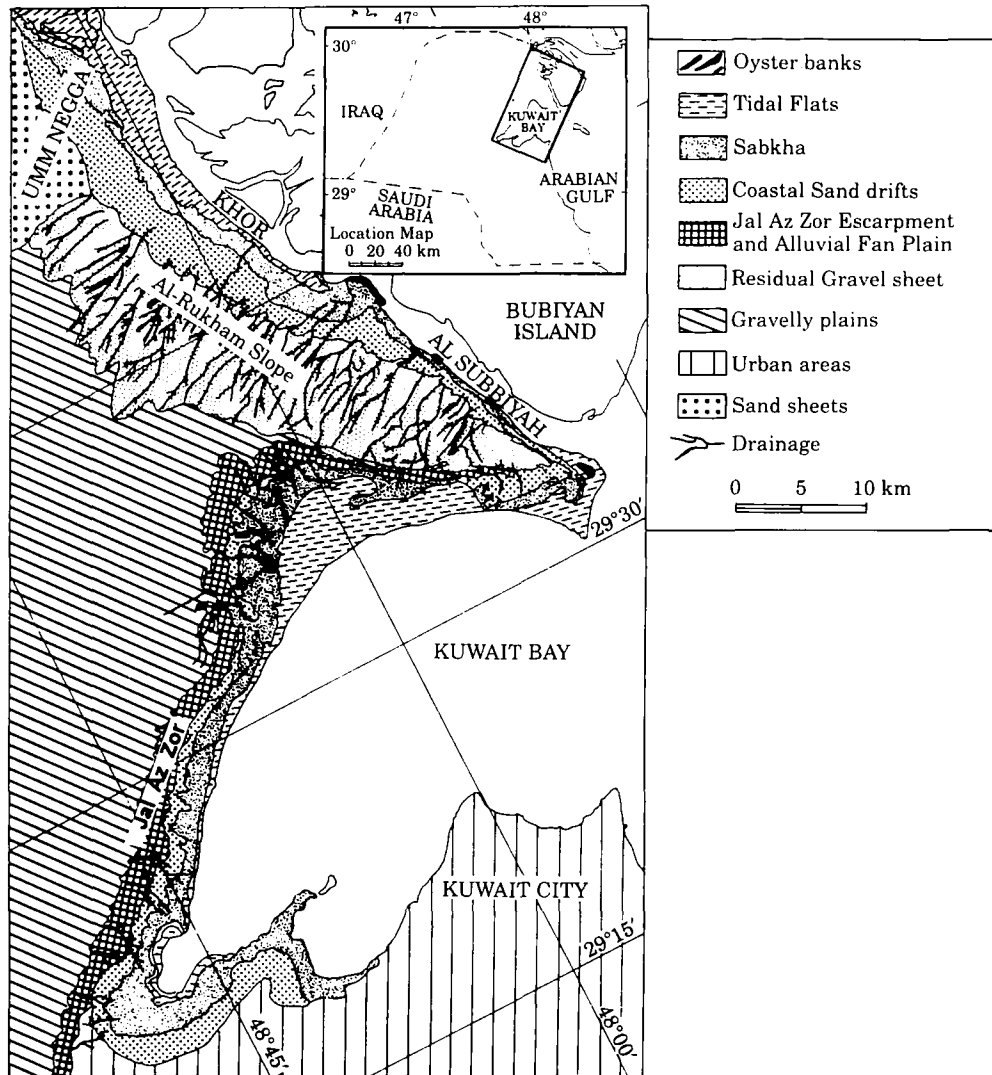
Figure 1. Simplified sedimentomorphic map of the northern coastal area of Kuwait.

morphological characteristics and mode of occurrence of the nabkha deposits were also studied and the various morphometric parameters of 18 nabkhas in the Kathma area were measured.

A total of 35 sediment samples were collected from the coastal area of Khor Al-Subbiyah and Kuwait Bay. These comprised 24 samples from the Nabkha deposits and 11 samples from the surface sabkha sediments (Fig. 3). Grain size analyses of all samples were carried out using standard sieving and sedimentation techniques (Folk, 1974). A sieve interval of 0.5ϕ was used. Statistical size parameters: Medium size (Md_{50}); Mean size ($M_z\phi$); Sorting (δ_I); Skewness (SK_i); and Kurtosis (K_G), were calculated according to Folk (1974). Eight samples were selected for the study of roundness and surface textures of quartz grains. Three sand size fractions were chosen for this study, medium, fine and very fine.

The roundness classes of about 200 grains in each size fraction were determined using Power's Visual Comparator (Powers, 1953). The logarithmic rho (ϱ) scale of Folk (1955)
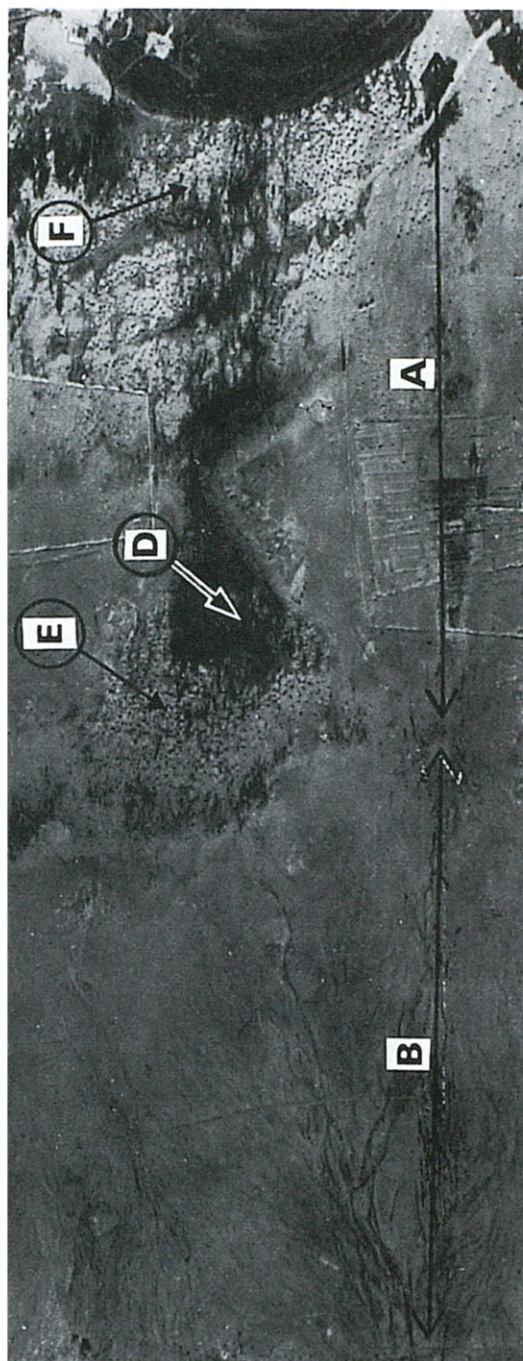
Figure 2. Aerial photograph of Kathma area showing the sabkha flat (A), alluvial fan plain at the foot-hills of Jal Az Zor (B), tidal flat (C), barren sabkha pans (D), landward nabkha (E), and Gulfward nabkhas (F).
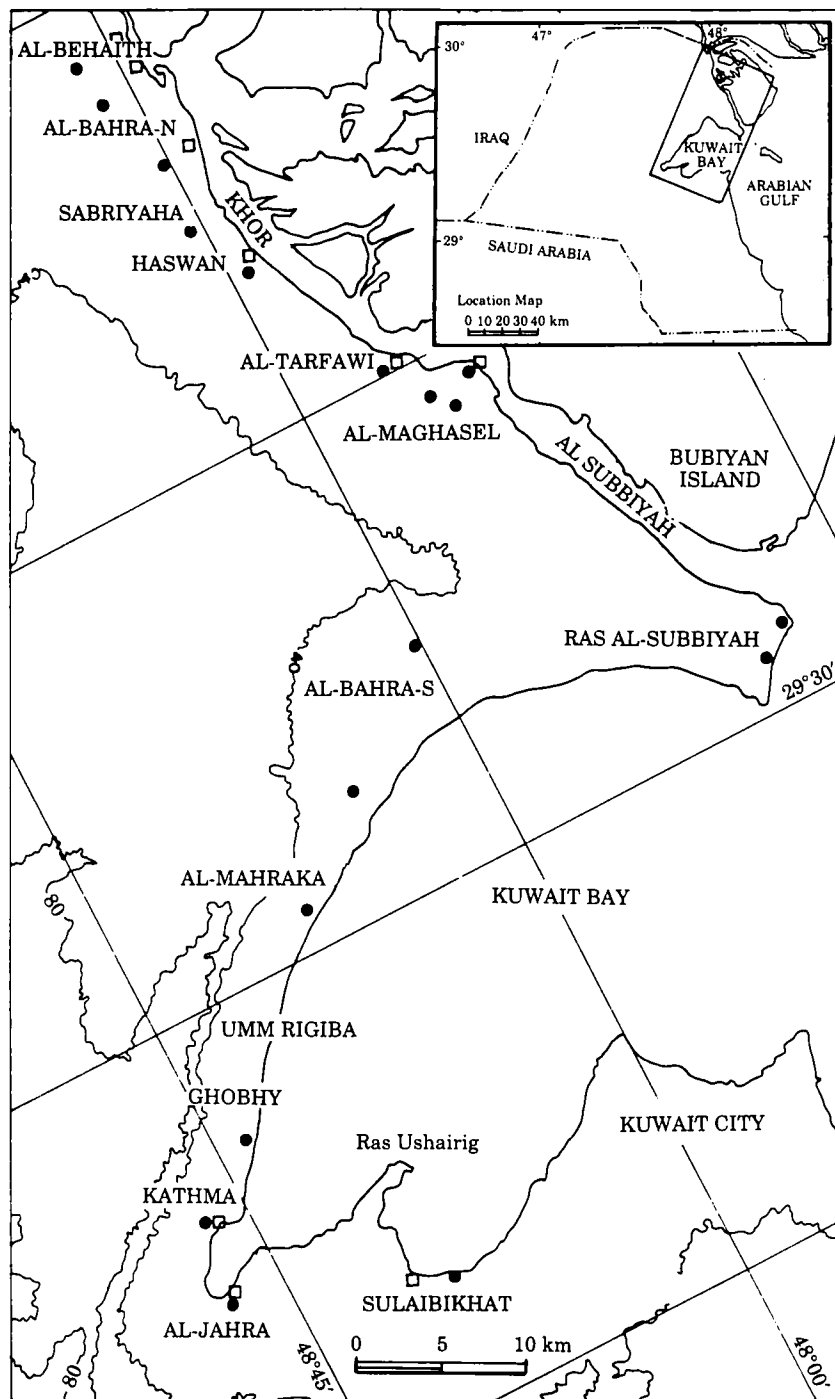
Figure 3. Sample location map (● = nabkha samples; □ = sabkha samples).

was used to define each roundness class. Mean roundness $(M\varrho)$ and roundness sorting $(\sigma\varrho)$ were determined for each size fraction. The relative frequency percentages of frosted and polished quartz grains were also determined.

The mineralogical composition of all samples was determined. The whole mineralogy of the coarse size fractions of each sample (very coarse, coarse and medium) was determined by grain counting using a binocular microscope. The fine size fractions which include fine sand, very fine sand and coarse silt of each sample, were separated into light and heavy mineral fractions using the standard bromoform method. The mineral composition of both light and heavy mineral fractions was determined using the standard counting technique.

The clay size fraction ($<4\ \mu$m) was separated from 10 samples by means of the sedimentation method. A suction-onto-ceramic-disc method (Shaw, 1971) was used for the preparation of oriented clay samples for x-ray diffraction analysis. The identification of clay minerals involved standard pretreatments of glyceration and heating at 550°C. The semi-quantitative estimates of the relative amounts of clay minerals were calculated as described by Schultz (1964).

Results

Occurrence and morphometric parameters

The northern sabkha flats of Kuwait are characterized by the occurrence of scattered fields of *Nitraria retusa* shrubs. They are distributed at the inland margins of the sabkha flats which are slightly higher than the shallow saline water table ($\pm$ 100 cm depth from sabkha surface). It was also noted that *Nitraria* fields commonly occur in the foreland of the alluvial fans of the Jal Az-Zor escarpments and Al-Rukham slope.

Low-lying areas in the sabkha flat are barren of *Nitraria* shrubs and occur as extensive flats covered by thin salt crust. Other halophytes shrubs occur within these saline pans, e.g. *Zygophyllum* sp. and *Salsola* sp.

The morphology and physiology of *Nitraria* shrubs favour the accumulation of wind-driven sediments. They are characterized by a wide porous crown and a strong root system that horizontally and vertically penetrates the sediment substrate. Moreover, the shrubs are capable of growing quickly over the accumulated wind-driven sediments.

The nabkhas observed around *Nitraria retusa* vary in size and shape. They generally have a mound shape (Fig. 4). However, those close to the inland fringes of the sabkha flat are elongated. On the other hand nabkhas within the Gulfward strip of the sabkha flat usually have a triangular shape due to the occurrence of a north-westerly downwind tail, and an almost vertical upwind nose.

In the Kathma area, elongated nabkhas occupy a zone of about 600 m wide and are bounded landward by small *Zygophyllum* nabkhas. They are arranged into parallel lines oriented between N30W and N40W. The spacing between the *Nitraria* shrubs along these lines averages at about 26 m. They usually have an elongated south-easterly tail and a shorter north-westerly nose. Several stages of nabkha development were noticed, i.e. small nabkhas, well developed nabkhas and eroded nabkhas. The most common are the well developed 'mature' nabkhas which reach up to 180 cm in height. Small nabkhas are more frequent in the Gulfward side of the sabkha. Their average height is about 87 cm.

Eroded nabkhas were noted in the inland side of the sabkha as well as along the coastline. The first type is present where low nabkhas occur within a wind corridor between two higher nabkhas. The second type is that eroded by the seawater during spring tidal flooding. Some nabkhas are completely eroded and the *Nitraria* shrubs are still surviving in spite of the partial exposure of their root system (Fig. 5).

The *Nitraria* crowns of some nabkhas are partially or completely dried up. The dry parts

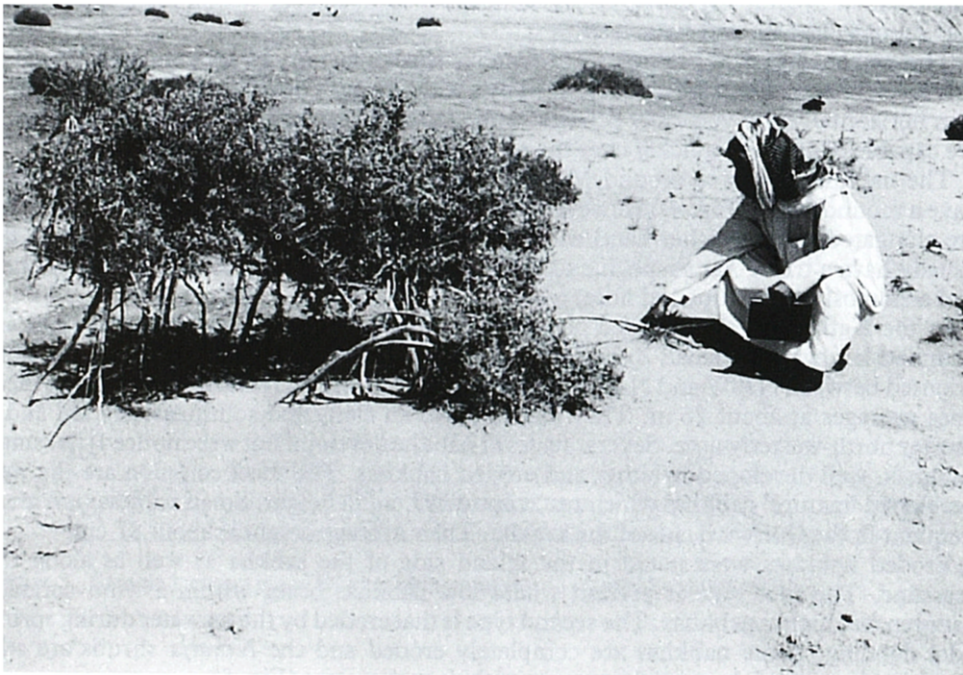**Figure 4.** The scattered nabkhas on the sabkha flat of Kathma area.

Figure 5. The complete erosion of nabkha.

usually occur on the windward side, specially in those nabkhas that are facing wind corridors.

For a better understanding of the pattern of aeolian sediment accumulation on *Nitraria* shrubs, the various morphometric parameters of about 18 nabkhas in Kathma area were measured. Figure 6 illustrates the measured parameters and Table 1 presents the morphometric measurements.

The height of *Nitraria* shrubs (H) varies between 220 cm and 72 cm within an average of 170·44 cm. The nabkha height (h) varies between 180 cm and 60 cm with an average of 102 cm. Therefore, the height of the shrub crown (H − h) varies from 140 cm to 12 cm within an average of 68·33 cm. The width of the shrub crown (w) ranges between 630 cm and 100 cm with an average of 369 cm. The total length of the nabkhas (W) ranges between 30 m and 4 m with an average of 18·34 m. The south-easterly nabkha tails (w₃) vary in length from 26·5 m to 2·0 m with an average of 14·4 m. The north-westerly noses, however, (w₂), vary in length between 0 and 10·7 m with an average of 4 m. In the partially damaged or dried up *Nitraria* crown, damaged parts vary from 50% to 12·5% with an average of 26·4%.

Fourteen combinations of the eight measured morphometric parameters were plotted as scatter diagrams to evaluate their inter-relationships. However, only five are significantly inter-related. The height of the nabkha is slightly related to the height of the shrub crown
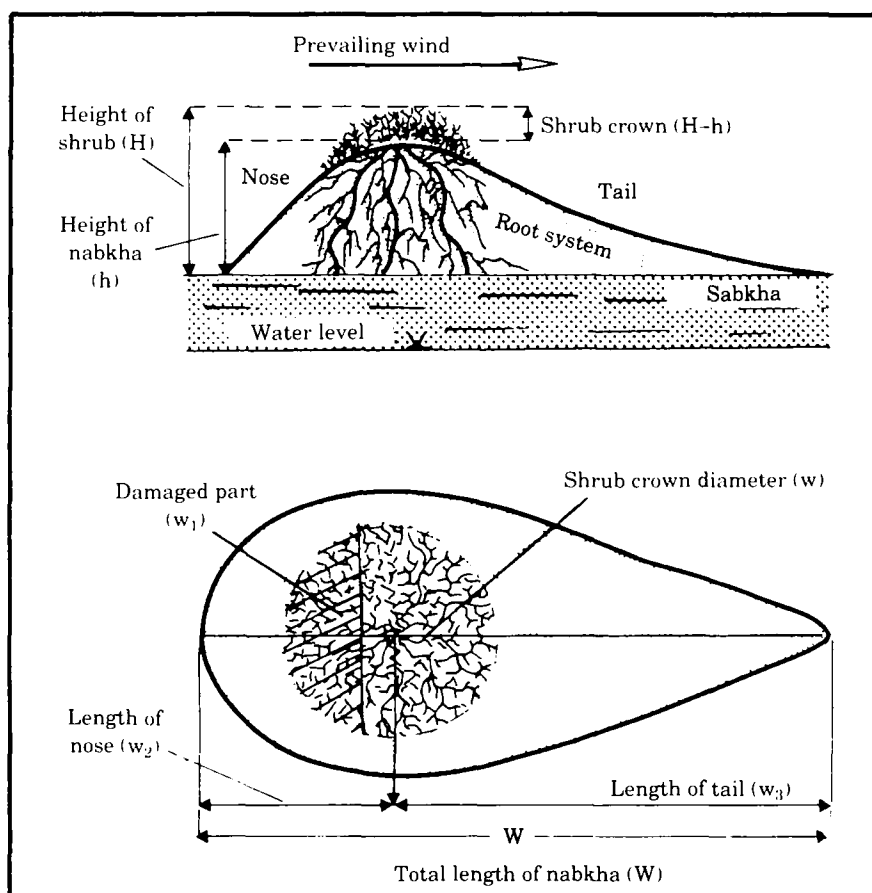

Figure 6. Schematic diagram illustrates the morphometric parameters of nabkhas.

Table 1. *Morphometric parameters of nabkha*

Sample No.	H*	h†	(H−h)‡	W§	w‖	w₁¶	w₂**	w₃††
KA-1	120	65	55	17·2	200	0	0	17·2
KA-2	137	78	59	26·5	300	0	0	26·5
KA-3	200	60	140	21·0	239	0	0	21·0
KA-4	160	65	95	24·8	320	0	0	24·8
KA-5	127	115	12	24·1	300	0	0	24·1
KA-6	170	140	30	17·0	370	0	0	17·0
KA-7	150	100	50	19	350	72	3·9	15·1
KA-8	170	65	105	4·1	180	85	2·1	2
KA-9	180	165	15	15·1	630	156	6·9	8·2
KA-10	167	105	62	17·3	590	95	7·4	9·9
KA-11	210	120	90	19·9	380	0	8·5	11·4
KA-12	170	105	65	24·8	470	65	10·7	14·1
KA-13	165	60	105	20	330	109	4·5	15·5
KA-14	220	130	90	14·4	405	90	3·5	10·9
KA-15	220	130	90	29·9	530	188	9·1	20·8
KA-16	72	0	72	0	100	50	0	0
KA-17	220	180	40	17·8	430	63	7·1	10·8
KA-18	210	155	55	18·9	520	65	8·8	10·1
Total average	170·44	102·11	68·33	18·43	369·11	56·67	4·03	14·41

* H = Height of Nitraria shrub (cm).
† h = Height of Nabkha (cm).
‡ H–h = Height of Nitraria shrub crown (cm).
§ W = Total length of Nabkha (m).
‖ w = Width of shrub crown (cm).
¶ w_1 = Width of dead part of the shrub crown (cm).
** w_2 = Length of windward side (Nabkha nose) (m).
†† w_3 = Length of leeward (Nabkha tail) (m).

with a correlation coefficient of 0·5 (Fig. 7(a)). The average ratio of shrub crown to nabkha height is about 0·66. The shorter the shrub crown the higher the nabkha crown. It was also found that the height of the nabkhas (h) increases with the increase of the shrub height (H) with a correlation coefficient of 0·7 (Fig. 7(b)). The average ratio of h/H is about 0·58. The total length of the nabkhas is related to their heights. The length increases with the increase in height (Fig. 7(c)). On average the total length of the nabkhas is about 18 times their height. The nabkha total length proportionally increases with the increase of the shrub height (Fig. 7(d)). In average the total length of the nabkha is about 11 times the shrub height. It was also noticed that the average length of the downwind tail is about 3·5 times the upwind nose. Figure 7(e) shows that the length of the upwind nose (w_2) is related to the shrub height (H), with a correlation coefficient of 0·6. The average ratio of w_2/H is about 3·35.

Grain size distribution

Relative frequency percentages of the various size classes and the values of size parameters of the studied nabkha and sabkha deposits are given in Tables 2 and 3. According to Folk's textural classification (Folk, 1974), nabkha deposits in northern Kuwait can be differentiated into three groups, namely: sandy, silty sand and sandy silt (Fig. 8). The majority of the studied nabkhas are formed of silty sand or sandy silt. Few nabkhas are
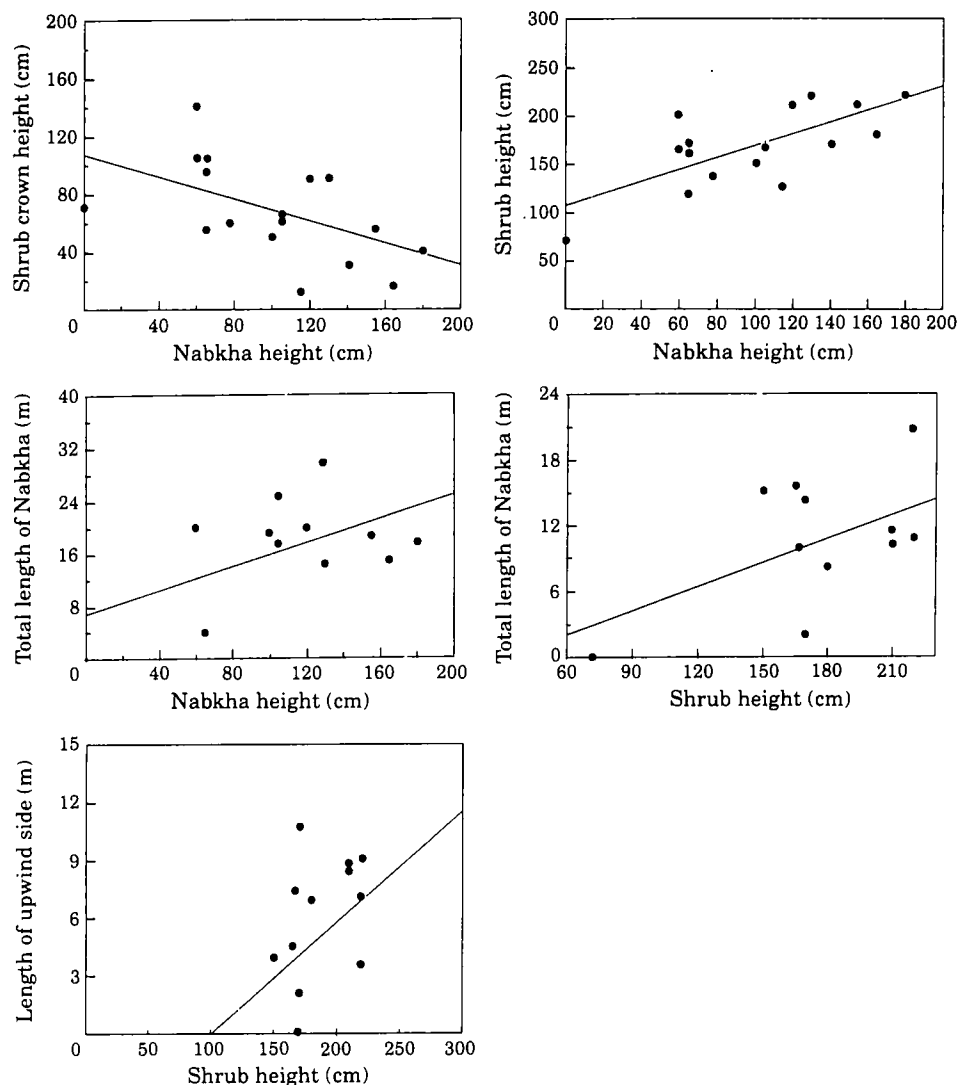
Figure 7. Interrelationships of some morphometric parameters of nabkhas in northern Kuwait sabkha flat.

formed of pure sand. These are mostly located close to the inland fringe of the sabkha flat. It was also noticed that sandy silt nabkhas occur in the areas where the sabkha flats are very wide and extensive, e.g. northern Bahra and southern Bahra. On the other hand, silty sand nabkhas, which are the most frequent, occur within the narrow sabkha flat.

Sandy nabkhas have up to 10% silt. Silty sand nabkhas and sandy silt nabkhas have an average sand : silt : clay ratio of 68·7%, 28·7% and 26%; and 40%, 55·5% and 4·4%, respectively. Figure 9 shows the simple frequency curves of the average grain size distribution of the three types of nabkhas. It is noticed that sandy nabkhas are generally unimodal with a modal class of fine sand size $(2·5\phi)$. The average size frequency distribution of the silty sand nabkhas is very platykurtic and has a plateau that covers the size classes from 2ϕ to $4·5\phi$, i.e. medium sand, fine sand, very fine sand and coarse silt. Such plateaux may be interpreted as being due to polymodality. Sandy silt nabkhas are

Table 2. *Grain size parameters and size fraction percentages of nabkha deposits in Northern Kuwait*

Sample No.	Area	Size parameters					Size fractions (%)		
		Md_{50}	$M_z\phi$	δ_I	SK_I	K_G	Sand	Silt	Clay
	Silty sand nabkha								
115	Al-Behaith	3·3	3·3	2·2	0·24	1.41	63·8	30·0	6·2
70	Al-Bahra N.	3·1	3·2	1·7	0·32	1.78	76·7	16·6	6·7
124	Al-Tarfawi	3·7	3·6	1·8	0·14	1.16	60·6	38·7	0·7
49(A)	Ras El-Sabbiyah	3·2	3·1	1·5	0·09	1.14	59·7	39·9	0·4
49(B)	Ras El-Sabbiyah	1·5	1·1	2·1	−0·15	0·98	86·1	13·4	0·5
47(A)	Ras El-Sabbiyah	2·9	2·9	1·7	0·11	1.02	64·5	34·0	1·5
47(B)	Ras El-Sabbiyah	2·9	2·6	2·2	−0·14	1.15	61·4	35·3	3·6
13	Al-Bahra S.	2·7	2·9	1·4	0·33	1.46	81·5	16·5	2·0
131	Al-Bahra S.	3·7	3·9	1·9	0·30	1.56	56·6	34·4	9·0
3(A)	Umm Rigiba	1·7	2·3	1·4	0·49	0.88	83·7	16·3	—
1(C)	Kathma	2·7	2·8	1·1	0·10	0.82	82·7	17·3	—
133	Al-Jahra	3·9	3·8	2·5	−0·14	0.75	50·8	47·8	1·4
87	Sulaibikhat	3·2	3·2	1·5	0·19	0.94	65·5	32·4	2·1
	Average	2·9	2·9	1·7	0·14	1.15	68·7	28·7	2·6
	Sandy silt nabkha								
119	Al-Bahra N.	4·4	5·0	1·7	0·41	1.03	30·7	67·0	2·3
122	Sabriyah	4·4	4·5	1·7	0·39	2.35	42·5	49·7	7·8
67	Haswan	4·1	4·2	1·7	−0·04	0.90	48·0	50·0	2·0
47(C)	Ras El-Sabbiyah	4·0	4·1	1·6	0·11	1.33	47·4	51·7	0·9
129	Al-Bahra S.	5·6	5·3	2·4	−0·15	0.78	31·6	59·3	9·1
	Average	4·5	4·6	1·8	0·09	1.27	40·0	55·5	4·4
	Sand nabkha								
30	Al-Maghasel	2·8	2·8	0·6	0·00	1.06	96·2	03·5	0·3
29	Al-Maghasel	2·7	2·7	0·9	0·00	0.92	93·6	05·3	1·1
27	Al-Maghasel	1·4	1·5	1·3	0·15	1.37	88·1	08·7	3·2
3(B)	Umm Rigiba	2·2	2·1	1·2	0·03	0.76	92·2	07·8	—
1(A)	Kathma	2·1	2·3	1·0	0·08	1·90	89·6	10·4	—
1(B)	Kathma	2·4	2·5	1·2	0·29	1·39	89·7	07·0	3·3
	Average	2·2	2·3	1·0	0·13	1·23	91·5	07·1	1·9
	Total average	3·2	3·3	1·5	0·12	1·21	66·7	30·4	2·9

generally unimodal to slightly polymodal. They have a primary mode of coarse silt fraction (4–5ϕ) and secondary modes of fine and very fine silt (7–8ϕ). The surface sabkha sediments have a wide range of grain sizes. However, silt and clay size fractions constitute about 60% in average. A wide spectrum of sand size classes occurs but also in small amounts (between 1 and 5%).

Cumulative curves of the average grain size distribution of the nabkha deposits show several size populations (Fig. 10). Sandy nabkhas have mainly one population, but divided into two sub-populations truncated very tangentially at about 2·5ϕ. The sandy silt nabkhas have one saltation population and two suspension sub-populations. The suspension population is truncated with the saltation population at about 5ϕ. While the two suspension sub-populations are truncated at 7ϕ. The silty sand nabkhas have two distinctive populations truncated at 4·5ϕ.

Table 3. *Grain size parameters, size fraction percentages, and textural classes of surface sabkha sediments in Northern Kuwait*

Sample No.	Area	Size parameters					Size fractions (%)			Textural classes
		Md_{50}	$M_z\phi$	δ	SK_I	K_G	Sand	Silt	Clay	
117	Al-Behaith	4·36	4·32	1·94	−0·05	0·66	40·2	58·3	1·5	Sandy silt
120	Al-Bahra N.	4·95	4·29	2·45	−0·41	0·74	37·4	60·4	2·2	Sandy silt
69	Al-Bahra N.	4·25	4·10	2·12	−0·17	0·69	45·2	52·3	2·5	Sandy silt
68	Haswan	6·90	5·90	2·09	−0·73	0·91	21·0	76·9	2·8	Sandy silt
125	Al-Tarfawi	4·17	4·22	2·33	0·06	1·12	42·5	49·7	7·8	Sandy silt
47	Ras El-Sabiyah	2·93	2·12	2·05	0·19	0·96	49·9	43·0	7·0	Sandy silt
134	Al Jahra	2·37	2·47	1·23	0·26	1·14	87·9	9·0	3·1	Sand
89	Sulaibikhat	3·87	3·91	2·06	−0·01	1·03	54·0	43·6	2·4	Silty sand
27	Al-Maghasel	5·93	5·54	2·38	−0·37	1·10	12·2	78·8	9·0	Silty sand
135	Ras Ushairig	5·00	4·50	2·45	−0·19	0·57	45·0	45·0	10·0	Sandy silt
136	Ras Ushairig	6·60	7·10	2·67	0·37	1·78	5·0	72·0	23·0	Silty sand
	Average	4·66	4·40	2·16	0·09	0·97	40·0	53·5	6·5	

Size parameters

The mean size of the sandy nabkhas ranges between $1·5\phi$ and $2·8\phi$ with an average of $2·3\phi$ (fine sand size). Silty sand nabkhas range in mean size between $1·1\phi$ and $3·9\phi$ with an average of $2·9\phi$ (fine sand size), while sandy silt nabkhas range in mean size between $4·1\phi$
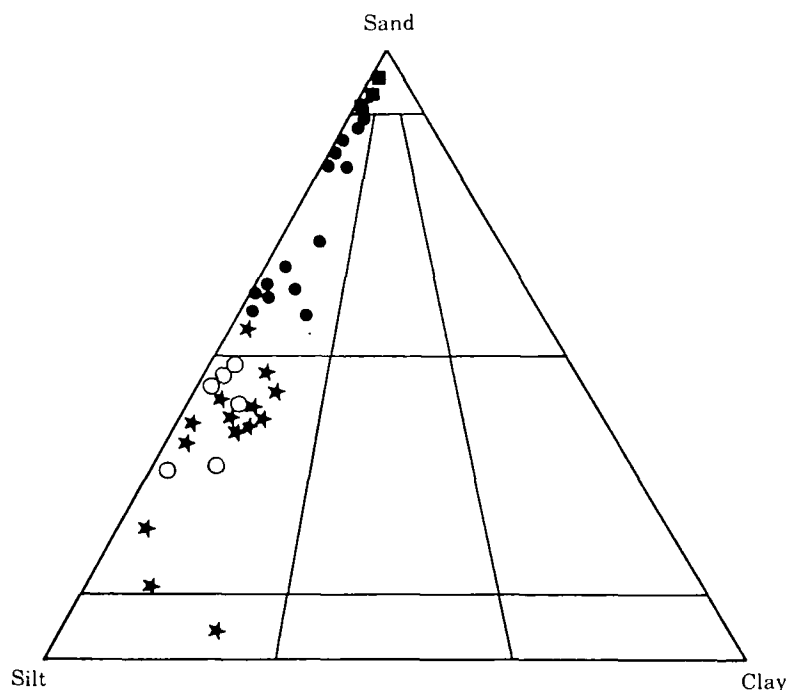

Figure 8. Textural classification of the nabkha deposits and sabkha sediments in northern Kuwait. (■ = sandy nabkhas; ● = silty sand nabkhas; ○ = sandy silt nabkhas; ★ = sabkha).
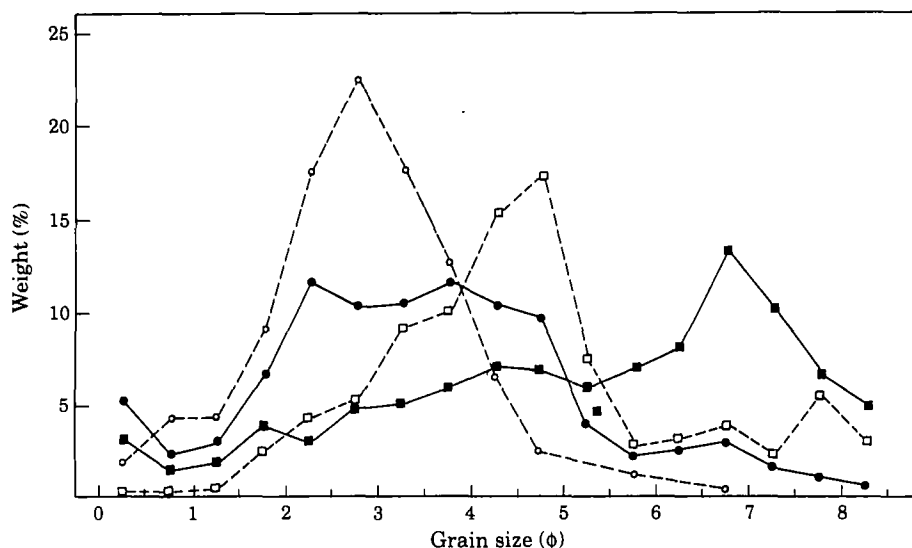
F. I. KHALAF *ET AL*.

Figure 9. Simple frequency curves of the average grain size distribution of the various types of nabkha and sabkha sediments. (--O-- = sandy nabkhas; —●— = silty sand nabkhas; ---□--- = sandy silt nabkhas; –■– = sabkha).

and 5·3ϕ with an average of 4·6ϕ (coarse silt). The surface sabkha sediments have a mean size that ranges between 2·1ϕ and 5·9ϕ with an average of 4·4ϕ (coarse silt).

The nabkha deposits studied are generally poorly sorted. However, sandy nabkhas are
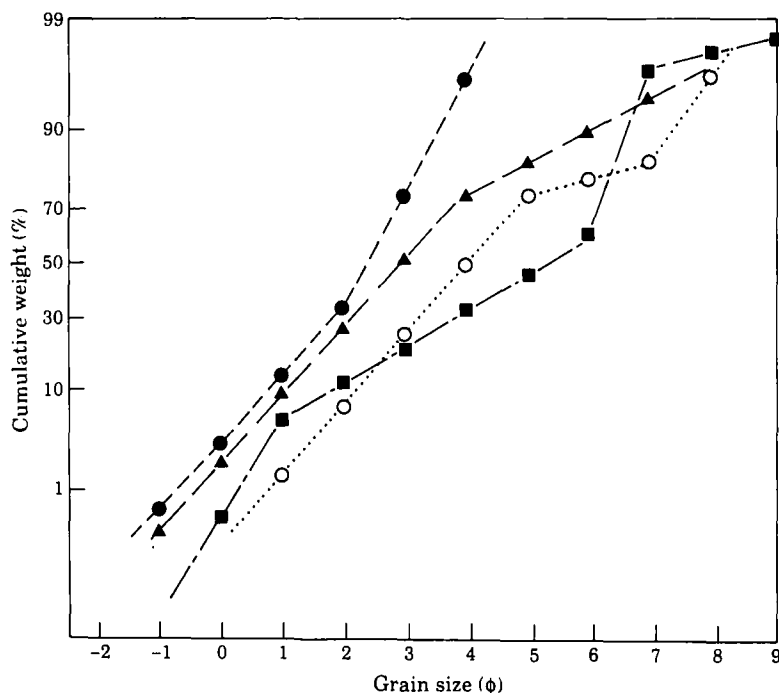

Figure 10. Cumulative curves of the average grain size distribution of nahkha and sabkha deposits. (--●-- = sandy nabkhas; –▲° = silty sand nabkhas; ···O··· = sandy silt nabkhas; –■– = sabkha).

relatively more sorted than the silty sand and sandy silt nabkhas. Sandy nabkhas range in sorting between $0 \cdot 65\phi$ (moderately well-sorted) and $1 \cdot 39\phi$ (poorly sorted) with an average sorting of $1 \cdot 07\phi$ (moderately sorted). Silty sand nabkhas range in sorting between $1 \cdot 12\phi$ (poorly sorted) to $2 \cdot 48\phi$ (very poorly sorted) with an average of $1 \cdot 77\phi$ (poorly sorted). The sandy silt nabkhas have an average sorting of $1 \cdot 82\phi$ (poorly sorted). The sabkha sediments are very poorly sorted. They range in sorting between $1 \cdot 23\phi$ and $2 \cdot 67\phi$ with an average of $2 \cdot 16\phi$. Poor sorting increases with the increase of silt fraction in the studied sediments (Fig. 11).

The size distribution of the sandy nabkhas is nearly skewed, with an average skewness of $+0 \cdot 09$. Silty sand nabkhas vary between negatively and positively skewed. However, the majority are fine skewed. Sandy silt nabkhas are generally strongly fine skewed, though some are coarse skewed. The sabkha sediments have a wide range of skewness, but they are generally coarsely skewed. Most of the studied nabkhas are mesokurtic to leptokurtic. However, the sandy nabkhas are platykurtic to mesokurtic. Sabkha sediments are generally mesokurtic.

Six combinations of the four size parameters were plotted as scatter diagrams to evaluate their inter-relationship and their effectiveness in characterizing the nabkha deposits (Fig. 12). A mean size *vs.* sorting diagram (Fig. 12(a)) shows that the best sorting was attained by sediments with a mean size between $2 \cdot 5\phi$ and $3 \cdot 0\phi$ (medium sand). This diagram clearly distinguishes the three types of nabkha deposits and the sabkha deposits. The sandy nabkhas occupy a small field in the area characterized by medium and coarse sand mean size and moderately to poorly sorted. This field is followed by the silty sand nabkha field in the direction of finer mean size and less sorting. The sandy silt nabkha field is located within the coarse silt mean size and poor to very poor sorting. Sabkha sediments are located within the silt size and very poorly sorted field.

Figure 12(b) shows the inter-relationship between mean size and skewness where a general trend can be noticed. The degree of positive skewness increases with the decrease in mean size. This diagram failed to distinguish between the various types of nabkhas. A mean size *vs.* kurtosis diagram (Fig. 12(c)) significantly differentiates sandy nabkhas from sandy silt nabkhas. The sorting *vs.* skewness diagram (Fig. 12(d)) shows a slight negative trend, i.e. coarse skewness increases with the decrease in sorting. The sorting *vs.* kurtosis
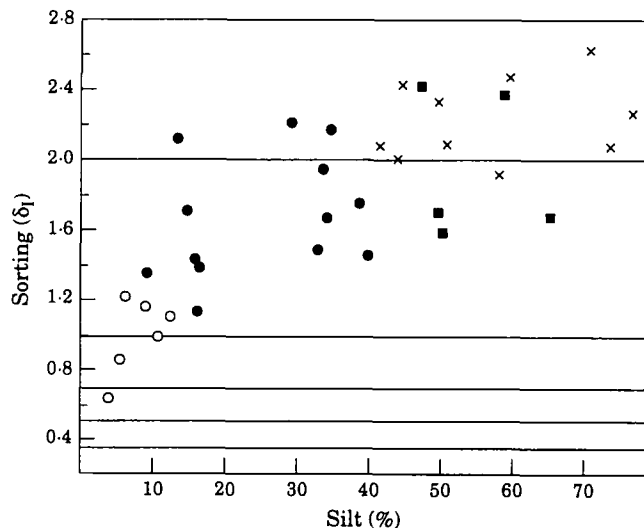

Figure 11. Relationship between sorting and silt frequency percentages in nabkha and sabkha deposits. ($\bigcirc$ = sandy nabkhas; $\bullet$ = silty sand nabkhas; $\blacksquare$ = sandy silt nabkhas; $\times$ = sabkha).
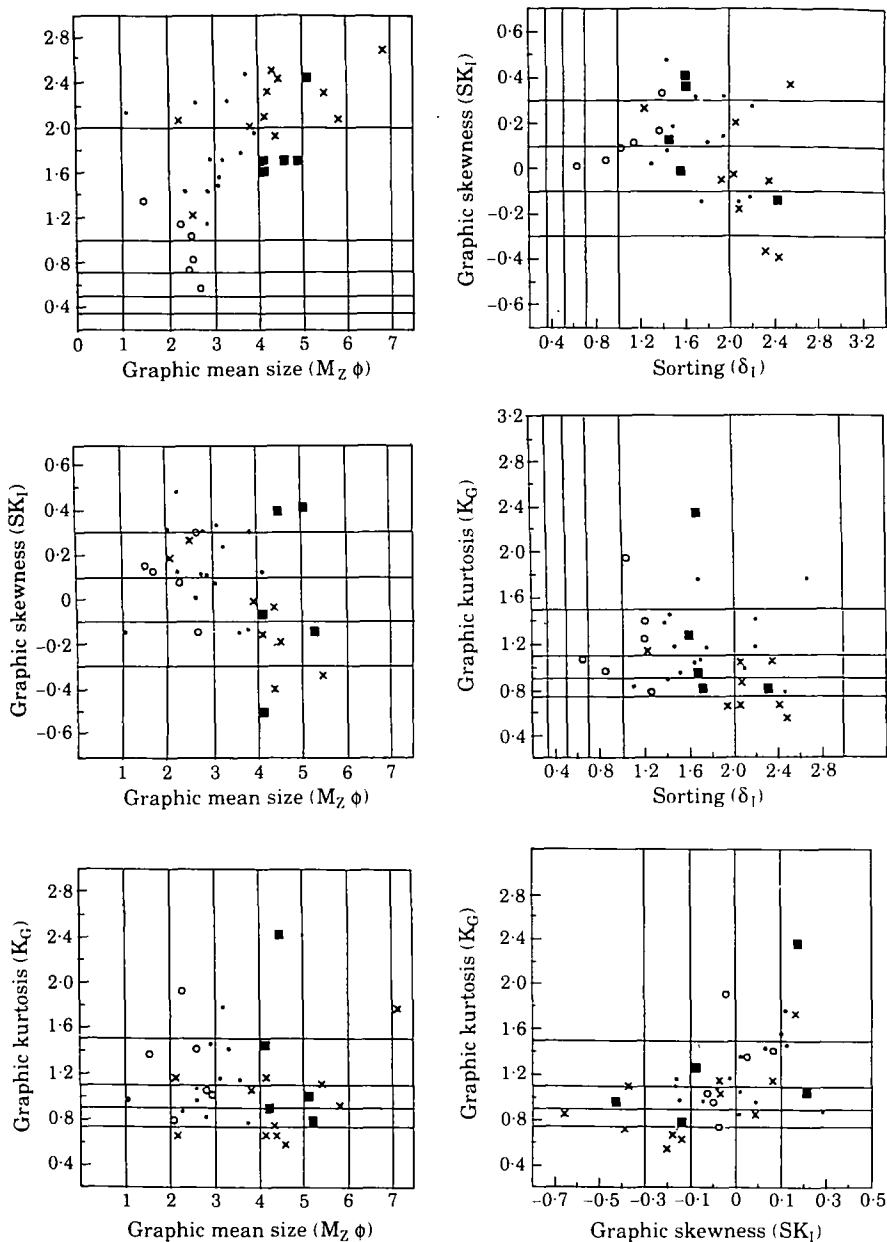
Figure 12. Scatter plot diagrams of the four size parameters of the nabkha deposits. (○ = sandy nabkhas; ● = silty sand nabkhas; ■ = sandy silt nabkhas; × = sabkha).

diagram (Fig. 12(e)) shows a very scattered pattern and no trend can be detected. A general trend can be noted in the scatter plot diagram of skewness *vs.* kurtosis (Fig. 12(f)). Positive skewness is generally attained by leptokurtic sediments.

Roundness and surface textures

The average relative frequency percentages of quartz grains in the various roundness classes of nabkha and sabkha deposits studied are presented in histograms (Fig. 13). The
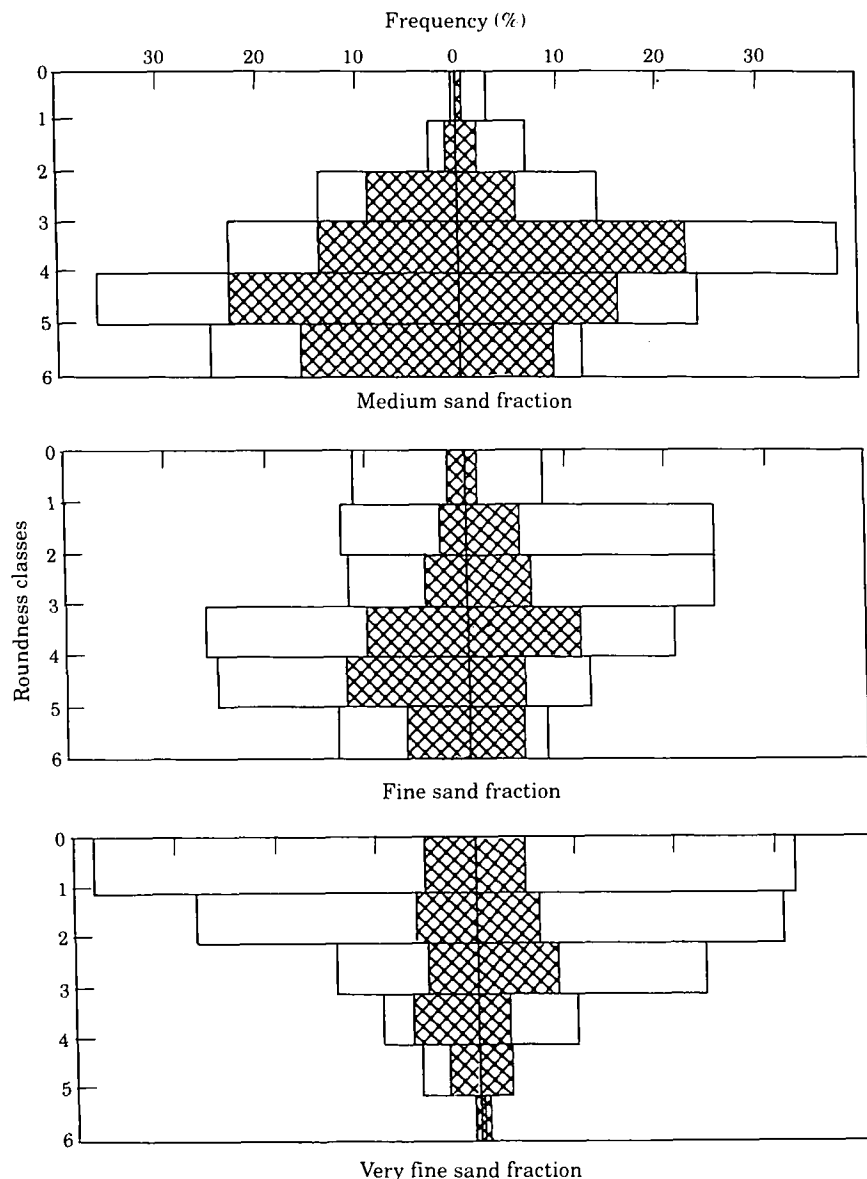
Figure 13. Histograms of frequency percentages of the roundness classes of both frosted ▨ and polished ☐ quartz grains in the medium sand, fine sand, very fine sand fraction of nabkha and sabkha sediments.

relative frequency percentages of both frosted and polished grains in each roundness class are also shown. All studied sediments have a unimodal distribution. In the medium sand fraction of nabkha deposits, 38·5% of the quartz grains are sub-rounded (modal class), 24% are angular, while 37·5% are rounded. The roundness modal class in the fine sand fraction is angular (ϱ = 1–2), with about 24% of the quartz grains sub-angular, 21% sub-rounded, 11% rounded, and 8% well-rounded. In the very fine sand fraction the roundness modal class is very angular (ϱ = 0–1) and constitutes about 32%. Angular and sub-angular classes form about 54%.

A similar distribution pattern was also found in the sabkha sediments. However, it was noticed that they are relatively more rounded than the nabkha deposits. The average mean

roundness ($M\varrho$) of quartz grains in nabkha deposits is 1·6 (angular), 2·7 (sub-angular) and 3·6 (sub-rounded) in the very fine sand, fine sand and medium sand fractions, respectively. On the other hand, the average $M\varrho$ of sabkha sediments is 1·4 (angular), 3·5 (sub-rounded) and 4·4 (rounded) in the very fine sand, fine sand and medium sand fractions, respectively. No relation was detected between the average roundness sorting values and the grain size. However, it was noticed that the medium sand fraction of the studied sediments has more roundness sorting than the other size fractions.

Two types of quartz grains were recognized in the studied sediments, namely, frosted grains and smooth or polished grains. Frosting of quartz grains is mainly due to the abundance of impact pits which are usually of small size (2–6 μm). Although the investigated grains were thoroughly cleaned, the impact pits have usually remnants of whitish clay material. Very few are filled with reddish material. Polished quartz grains are not pitted. However, they are characterized by the abundance of a irregular conchoidal breakage pattern.

A close relationship between surface texture, roundness and grain size was recognized in the studied sediments. Frosted or pitted grains are commonly well-rounded, while polished or smooth grains are mostly angular. Polished quartz grains are more frequent in the very fine sand fraction and decrease with the increase in the grain size (Fig. 13). No significant difference was noted between the frequency distribution of frosted and polished quartz grains in both nabkha and sabkha deposits.

Mineralogical composition

Coarse size fraction (>0·25 mm)

The coarse size fraction of the studied nabkha and sabkha deposits, namely, very coarse sand, coarse sand and medium sand, is composed mainly of quartz, feldspars, rock fragments and gypsum. Shell fragments and oolites occur in considerable amounts in some of the studied deposits (Table 4).

Feldspar is commonly present as equant subhedral grains that range in colour from milky-white, and buff to rosy. Perthite, which is a wormy intergrowth of albite in orthoclase or microcline, is the most abundant variety of feldspar. Textures and fabrics of feldspar grains indicate a granitic and pegmetitic source.

Two main types of rock fragments are present in the sediments studied, volcanic and calcretic. Volcanic rock fragments are present as well-rounded dark grains, while calcretic rock fragments are generally rounded and white. The latter are composed of fine-grained quartz grains cemented by micritic calcite cement.

Shell fragments are mostly present as fragmented chips or flakes of Molluscan shells. Calcareous oolites are present as whole ooids and oolitic fragments. Gypsum occurs as euhedral to subhedral, equant to elongated grains, of which some are cleavaged. The majority of gypsum grains are frosted, and some are partially or completely altered to anhydrite.

Mineralogical composition of the very coarse sand fraction of the nabkha deposits significantly varies from one place to another. In northern Khor Al-Sabbiyah area, it is mainly composed of quartz and feldspars with significant amounts of shell fragments and gypsum. In Ras Al-Sabbiyah, it is mostly formed of shell fragments and gypsum, where their average relative frequency percentages are 80 and 14, respectively. Quartz, calcite debris and shell fragments are the main constituents of the very coarse sand fractions of the North Kuwait Bay Nabkhas. Their average relative frequency percentages are 63, 17·5 and 11·2, respectively. Gypsum is also abundant (8%). In Southern Kuwait Bay the very coarse sand fraction is mostly formed of shell fragments, calcretic debris and gypsum. Their average percentages are 44, 28 and 28, respectively.

Table 4. Average relative frequency percentages of the various mineral grains in the sand fractions* (>250 μ) of nabkha and sabkha deposits

	N. Khor Al-Sabbiyah			Ras Al-Sabbiyah			N. Kuwait Bay			S. Kuwait Bay			Sabkha		
	VCS	CS	MS	VCS	CS	MS	VCS	CS	MS	VCS	CS	MS	VCS	CS	MS
Quartz	56·40	58·54	72·50	04·70	14·96	44·10	63·02	79·50	70·80	06·90	49·80	21·10	24·00	14·50	22·30
Feldspars	10·60	11·73	04·24	00·44	02·78	12·18	16·00	09·87	10·30	00·00	06·80	02·50	05·00	04·00	01·70
Shell fragment	18·85	05·77	02·98	79·22	57·38	30·03	11·20	00·25	00·08	44·10	08·60	00·35	14·50	03·00	01·50
Oolites	00·00	00·00	00·00	00·00	00·00	00·00	00·00	00·00	15·50	00·00	15·05	62·05	00·00	07·50	19·50
SRF†	01·80	03·58	00·38	01·40	02·34	00·94	17·50	03·41	03·13	27·90	05·95	04·10	10·00	03·50	01·30
VRF‡	03·27	01·38	01·45	00·62	01·18	01·22	03·14	03·40	03·86	00·00	00·50	00·45	00·90	01·00	00·30
Gypsum	09·47	11·22	12·64	13·52	21·12	16·56	08·06	04·41	07·10	27·90	11·15	09·50	45·50	61·70	53·40

* VCS = very coarse sand; CS = coarse sand; MS = medium sand.
† SRF = sedimentary rock fragments.
‡ VRF = volcanic rock fragments.

The distribution pattern of mineral grains of the coarse and medium sand fractions is similar to that of the very coarse sand fraction. However, certain mineral grains are preferentially concentrated in these size fractions. Quartz grains increase with the decrease of grain size, while shell fragments are generally concentrated in the very coarse sand fraction. Oolites occur in the coarse and medium sand fractions of the nabkhas in Kuwait Bay area, especially those in Jahra and Sulaibikhat.

The coarse size fractions of the sabkha sediments are mostly composed of gypsum, quartz and shell fragments, and oolites (Table 4). The latter occur only in Jahra and Sulaibikhat areas. Gypsum occurs as authigenic crystals that range in size from 3–0·3 mm.

Fine size fraction (250–30 μm)

The fine size fraction, which includes fine sand, very fine sand and coarse silt, constitutes a considerable portion of both the nabkhas and sabkhas deposits. Therefore, the study of their mineralogical composition is useful in understanding their genesis. Both light and heavy mineral fractions were studied. Average weight percentages of the heavy minerals are about 11, 14 and 16 in the fine sand, very fine sand and coarse silt fractions, respectively.

Light minerals

Light mineral fractions of both nabkha and sabkha deposits are mainly composed of quartz, feldspars, gypsum and calcite. Chert, mica and anhydrite are present in subordinate amounts (Table 5).

The term calcite grains is used here to denote detrital fragments composed of calcite or aragonite and where their fabric is not indicative to their origin, i.e. whether derived from calcretic debris or calcitic shell fragments.

Siliciclastic mineral grains (quartz and feldspars) are the most abundant in the fine size fraction of both nabkha and sabkha deposits. Quartz and feldspar grains constitute about 48·4%, 53·5% and 50·5% of the fine sand, very fine sand, coarse silt fractions of the nabkha deposits, respectively. Gypsum and calcite grains follow the siliciclastic grains in abundance. Gypsum forms 32% of the average composition of the fine sand fraction. It decreases to 11% in the coarse silt fraction. Calcite grains are less abundant in the fine sand fraction (13·2%) and more so in the coarse silt fraction (30·8%). A similar pattern of distribution was noted in the sabkha deposits.

Table 5. *Average relative frequency percentages of the light mineral grains in the fine size fraction* of nabkha and sabkha deposits in Kuwait*

	Nabkha			Sabkha		
	FS	VFS	CST	FS	VFS	CST
Quartz	30·4	27·3	30·2	21·0	34·6	38·7
Feldspars	18·4	26·2	20·3	32·0	27·2	16·5
Calcite	13·2	25·2	30·8	11·6	16·6	25·9
Gypsum	32·0	13·5	11·0	30·7	16·2	14·0
Chert	3·5	6·3	4·0	1·0	3·0	2·4
Mica	2·5	1·7	3·7	3·7	2·4	2·5

* FS = fine sand; VFS = very fine sand; CST = coarse silt.

Heavy minerals

Heavy minerals of the fine size fraction of both nabkha and sabkha deposits are composed mainly of pyroxenes, dolomite, opaque minerals and amphiboles. Garnet, biotite, epidote, zircon, topaz, tourmaline, sillimanite, kyanite, rutile, monazite, andalusite and staurolite are present in subordinate amounts (Table 6).

Opaque mineral grains are mainly represented by grains of iron oxide minerals (Khalaf, 1970). They have an average frequency of 19·6%, 20·0% and 19·0% in the fine sand, very fine sand and coarse silt fractions of the nabkha deposits, respectively. Pyroxenes are represented by augite, hypersthene, diopside and enstatite. They usually concentrate in the fine sand fraction. Amphiboles are represented mainly by green hornblende, basaltic hornblende, and actinolite with green hornblende as the most frequent variety.

Garnet is recorded from all samples as colourless, pinkish and violetish grains of angular to sub-angular shape, of which some are euhedral. It usually concentrates in the fine sand fraction where it has an average frequency percentage of about 9·1. Epidotes are represented mostly by pistachite and zoisite. Zircon occurs as traces and is present as well-rounded euhedral grains.

The heavy mineral suites of the fine size fraction of the sabkha sediments are similar to those of the nabkha deposits. One of the most pronounced characteristics of the heavy mineral fractions of both nabkha and sabkha deposits is the abundant occurrence of dolomite. It has an average frequency percentage of 24·8, 32·1 and 34·0 in the fine sand, very fine sand and coarse silt fractions of the nabkha deposits, respectively. Dolomite occurs as rounded to sub-rounded grains in the fine sand fraction, while euhedral rhombs are very frequent in the coarse silt fraction. It is generally concentrated in the coarse silt fraction of both nabkha and sabkha deposits.

Clay size (< 4 μm)

The clay size fraction is composed of clay minerals and non-clay minerals. Clay minerals are represented by illite, illite-montmorillonite mixed layer, palygorskite, kaolinite and chlorite. Non-clay minerals comprise quartz, dolomite, calcite and feldspars. The relative frequency percentages of the clay minerals were estimated using a semi-quantitative method (Table 7). In almost all samples, illite, and illite-montmorillonite were found to be the most frequent clay minerals. They form more than 60% of the clay minerals on average. Palygorskite is relatively abundant and comprises about one-third of the clay minerals.

Table 6. *Average relative frequency percentages of the heavy mineral grains in the fine size fraction (250–230 μm) of nabkha and sabkha deposits*

Heavy minerals	Nabkha			Sabkha		
	FS	VFS	CST	FS	VFS	CST
Pyroxenes	25·4	14·7	17·7	18·7	11·3	8·2
Dolomite	24·8	32·1	34·0	26·1	33·2	34·9
Opaques	19·6	20·0	19·0	14·8	28·6	36·4
Amphiboles	10·9	12·9	17·2	21·0	10·2	4·3
Garnet	9·1	4·0	2·0	14·0	2·8	3·1
Biotite	5·0	2·2	<1·0	1·5	1·0	<1·0
Epidotes	2·6	9·1	5·0	2·0	9·0	8·7
Others*	<3·0	<4·0	<5·0	<2·0	<4·0	<4·0

* Zircon, topaz, andalusite, staurolite, sillimanite and kyanite.

Table 7. *Relative frequency percentage of clay minerals in some selected nabkha deposits*

Sample No.	Area	Illite	Illite montmorillonite	Palygorskite	Chloritew	Kaolinite
115	Al-Behaith	25	30	30	5	10
70	Al-Bahra N.	30	40	25	5	0
47 (B)	Al-Subbiyah	35	35	25	5	0
13	Al-Bahra N.	35	25	30	10	0
131	Al-Bahra S.	30	35	25	5	5
87	Sulaibikhat	35	25	30	5	10
122	Sabriyaha	25	30	35	—	10
67	Haswan	25	35	30	—	10
129	Al-Bahra S.	40	35	20	5	0
1 (B)	Kathma	40	30	25	—	0
	Average	32	34	27	4	5

Discussion

The occurrence and geomorphometric characteristics of the *Nitraria retusa* nabkhas in the northern sabkha flat of Kuwait revealed that their development is controlled by the general sedimentomorphic and local hydrogeologic conditions of the northern coastal area of Kuwait. Their restricted occurrence in front of the alluvial fans of Jal Az Zor escarpments and Al Rukham slopes indicates favourable groundwater conditions, i.e. relatively low water salinity. This may be due to the replenishment of the shallow saline water table by the alluvium water. The notable increase in the size and densities of *Nitraria* shrubs in the inland fringe of the studied sabkha may also support this assumption. Gunatilaka and Mwango (1987) have noted that *Nitraria* nabkhas growing in the inland sabkha of southern Kuwait do not exist in areas where the water salinity exceeds 28%. They interpreted the lower salinity of the groundwater in the sabkha pans to the recharge from inland sources. This supports the aforementioned interpretation.

Deterioration of overgrown *Nitraria* shrubs (>220 cm in height) may be attributed to unavailability of the required water. This could happen due to the drop of water-table during summer, especially during spring low tide. The partial destruction of the windward side of the *Nitraria* shrubs is attributed to sand blasting during severe sandstorms. Their total or partial decay may eventually lead to the deflation of the nabkha deposits.

The morphometric parameters of the studied nabkhas indicate that the nabkhas' morphology is closely related to the dimensions of the *Nitraria* shrubs. It was found that the height of the shrub is the main factor controlling the shape and size of the nabkha deposits.

Variability in the shape of nabkha, in spite of their subjection to the same wind conditions, may be attributed to the variation in the nature of the sabkha flat, i.e. its moisture content, relief and types of surface sediments. The limited sediment accumulation on the north-west side of the Gulfward nabkhas could be attributed to shortage of non-cohesive surface mobile sediments, and the stabilization of the accumulated deposits on the south-easterly side by the wet sabkha surface.

Granulometrical analysis of the studied nabkhas revealed that they are formed of a well-graded mixture of sand and silt with a little amount of clay. Based on the relative frequency distribution of their size classes, they are grouped into three textural types, sandy, silty sand and sandy silt nabkhas. Sandy nabkhas occur in the inland fringe of the sabkha flat while the silty sand and sandy silt nabkhas are mostly located in the middle of the sabkha flat. On the other hand, the surface sabkha sediments in the study area are mostly sandy silt. The grain size distribution pattern of the various types of nabkha deposits as revealed

from their simple frequency curves and cumulative plots reflects, to a great extent, their mode of development as well as their genetic inter-relationship with the surrounding surface sediments.

Sandy nabkhas are formed of one main size population which is correlatable with the fine size population of the coastal sand drifts in the study area (Khalaf, 1989) which are located to the north and east of the sandy nabkhas.

The silty sand nabkhas have two size populations which are correlatable with the sabkha sediments' coarse and medium size populations. The bulk of the main size population, which is composed of a well-graded mixture of sands and silt, could be produced from the deflated sabkha sediments after partial reduction of the fine silt fraction. This could happen by the subjection of the deflated sabkha sediments to wind action during several cycles, i.e. successive transportation and sedimentation episodes. Some of the sand fraction could also be derived from the inland aeolian sand bodies.

The grain size distribution pattern of the sandy silt nabkhas is generally similar to that of the sabkha sediments. This suggests that sandy silt nabkhas are developed by the accumulation of unprocessed deflated sabkha sediments.

The statistical size parameters of the nabkha deposits studied can be closely correlated with their genetic development. Although they are of aeolian origin, their size parameters are significantly different from those of the other types of aeolian deposits in Kuwait with the exception of sandy nabkhas. Khalaf (1989) found that the average mean size of all aeolian sediments in Kuwait (excluding sabkha nabkhas) is medium sand $(1-2\phi)$. The studied silty sand and sandy silt nabkhas have an average mean size of fine sand size $(2 \cdot 9\phi)$ and coarse silt $(4 \cdot 6\phi)$. The same differences apply to sorting. While most of the inland aeolian deposits are sorted, the sabkha nabkhas have a graded grain size, i.e. poorly to very poorly sorted. Skewness and kurtosis of the studied nabkhas show no significant differences relative to those of the other aeolian deposits. It is suggested that the mean size and sorting of the sabkha nabkhas are greatly influenced by the silt and clay admixtures derived from the sabkha sediments.

Comparison between the scatter plots of different combinations of the statistical size parameters of the studied sabkha nabkhas and those of the other aeolian deposits in Kuwait presented by Khalaf (1989) revealed that such scatter plots are capable of differentiating between them. However, sorting vs. mean size and kurtosis vs. mean size diagrams were found to be the most effective, even in differentiating between the various textural types of nabkhas.

Like the other aeolian sediments in Kuwait, quartz grains of the studied nabkhas are characterized by a wide spectrum of roundness values. Close similarity was found between the roundness values of the quartz grains of the various size classes in the studied nabkhas deposits and those in the other aeolian sediments of Kuwait as reported by Khalaf and Gharib (1985). It was also found that roundness values of the quartz grains in the very fine sand fraction of the studied nabkhas are also correlatable with those of the sabkha deposits. However, the quartz grains in the medium sand size fraction of the sabkha sediments are more rounded than those in the nabkha deposits. This finding may suggest that medium sand size quartz grains are mostly derived from the inland aeolian deposits while those in the very fine sand fraction could be derived from the sabkha deposits.

The mineralogical composition of the nabkha deposits studied suggests that they are derived from several sources. Physical properties, fabric and surface texture of coarse-grained quartz, feldspar and volcanic rock fragments suggest that they are mostly derived from aeolian sand deposits that cover most of the desert of Kuwait or from the sand fraction deflated from Al-Dibdibba clastic deposits exposed to the north and west of the studied area. The relative abundance of calcrete fragments, especially in the very coarse sand fraction of the nabkhas deposits in northern Kuwait bay area, is most probably derived from materials eroded from the exposed calcretic beds along the Jal Az Zor escarpment (Khalaf and El-Sayed, 1989). Shell fragments are derived from the beach sands that occur around the oyster banks along Khor Al-Subbiyah, in Ras Al-Subbiyah

and Ras Ushairig. Some of these beach sands are composed wholly of shell fragments. The source of oolites is the oolitic limestone (Quaternary aeolianites) exposed in the Ras Ushairig area. The fabric and texture of gypsum grains suggest that they are derived from the authigenic gypsum of the sabkha flat sediments.

The heavy mineral suite of the nabkha deposits studied can be closely correlated with that of the sabkha flat sediments, especially with regard to the relative abundance of dolomite. The texture of the dolomite grains of the sabkha sediments studied indicates that they are authigenically formed within the sabkha sediments. Authigenic dolomite was reported from the sabkha sediments in southern Kuwait by Gunatilaka *et al.* (1984).

However, the heavy mineral assemblage of the sabkha deposits is similar to that of the lower Mesopotamian flood plain deposits (Philip, 1968) and to that present in the dust fallout of Kuwait (Khalaf *et al.*, 1985). A similar heavy mineral assemblage was also found in the very fine sand and coarse silt fractions of the desert aeolian deposits of Kuwait (Khalaf, 1989). It was also found that the clay mineral composition of the nabkha deposits studied correlates easily with that of the tidal sediments in northern Kuwait (Khalaf & Ala, 1980) and that of the dust fallout on Kuwait (Khalaf *et al.*, 1985). This suggests that the majority of the fine-grained sediments of the studied nabkhas are mostly derived from the sabkha sediments. However, fallout of dust originated from Southern Iraq and Kuwait may also be considered as a secondary source.

Conclusions

The present multi-faceted investigations suggest the following:

(1) *Nitraria* nabkhas in the northern coastal plain of Kuwait occur as clustered fields on the landward side of sabkha flats in front of the alluvial fans; where the groundwater table is at a depth of between 50 and 110 cm. Their preferred occurrence in such areas is attributed to the recharge of sabkha ground water by alluvium water which reduces its salinity to the level suitable for the growth of *Nitraria retusa* shrubs.

(2) The morphology of nabkhas is controlled, to a great extent, by the growth pattern of the *Nitraria retusa* shrubs, wind conditions and availability of deflatable surface sediments.

(3) Erosion of nabkhas could be due to the deterioration of the holding plant or tidal flooding of sea water. The former may be due to fluctuation of the groundwater level or an increase in its salinity, or due to mechanical destruction by blasting sand during severe sandstorms.

(4) Nabkha deposits in the northern sabkha flat of Kuwait are mostly sandy silt and silty sand. They are the only fine-textured aeolian deposits in Kuwait. Textural and mineralogical investigations revealed that they are mostly developed by the deposition of deflated sabkha sediments within the wind shadows of *Nitraria retusa* shrubs.

(5) Local variations in the nature of surface sediments in the surrounding areas are responsible for the noticeable differences in the texture and composition of the associated nabkha deposits.

(6) *Nitraria retusa* shrubs are efficient horizontal traps for wind-laden sediments and can therefore be considered as a natural mobile sand control system capable of trapping and stabilizing considerable amounts of encroaching aeolian sediment. The shape and morphometric parameters of well-developed nabkhas are correlatable with the dimensions of accumulated aeolian sediments around short porous fences. Thorough understanding of the development and aerodynamic behaviour of nabkhas may provide useful information for the design of biological sand control measures in desert areas.

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