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Barchan Dunes in Northern Kuwait

Abstract: Sand dunes represent the most significant aeolian land features in Kuwait. In this study, field and laboratory work were undertaken to describe Kuwait dunes, presented as crescent-shaped dunes, in terms of morphology, sedimentology and mineralogy. The annual rate of movement of most dunes of Kuwait exceeds 20 m/yr.

المستخلص: تمثل الكثبان الرملية أهم الملامح الرئيسية للرواسب السطحية في دولة الكويت، في هذه الدراسة، أجريت قياسات حقلية ومختبريه لوصف الكثبان الكويتية و التي تأخذ الشكل الهلالي، و ذلك لدراسة الظواهر الجيومورفولوجية و الرسوبية و المكونات المعدنية للكثبان. و دلت الدراسة على أن معظم الكثبان الرملية في الكويت تتحرك بسرعة اكبر من ٢٠ متر لكل سنة.

Introduction

The desert surface of Kuwait is mostly covered by erosional and depositional aeolian sediments (Khalaf *et al.*, 1984; Khalaf, 1989a; Khalaf and Al-Ajmi, 1993). Aeolian features in Kuwait have different forms, mainly sand sheets and sand dunes, depending on the wind regime and the geomorphology of the area. Barchan sand dunes are one of the most significant aeolian land features in the northern part of Kuwait. New sand dune fields are being created in the southern part of the country (Fig. 1). The Al-Huwaimliyah sand dunes, for example, are clustered into six successive belts; each extends in a NE-SW direction for about 10-15 km. The 2886 sand dunes in these belts, counted using aerial photographs, represent about 62.8% of the total dunes in the northeastern Kuwait. In the Al-Atraf, northern Kuwait, 1466 dunes are sporadically distributed over 424 km^2 in irregular groups, each comprising 3 to 80 dunes (Al-Dousari, 1997). Landsat images of southern Iraq and northern Kuwait indicate that mobile sand sheets and their associated barchan dunes, which form the dominant shape, extend from Al-Najaf through Al-Samawa and Al-Nasiriyah in southern Iraq to northern and northwest Kuwait (Kwarteng and Al-Ajmi, 1997). Most barchan sand dunes in Kuwait are associated with the mobile sand sheets (Omar *et al.*, 1989).

Several studies have been conducted to examine different aspects of mobile barchan dunes in Kuwait (e.g., Khalaf and Al-Hashash, 1983; Khalaf *et al.*, 1984; Al-Awadhi, 1988; Khalaf, 1989b; Nayfeh, 1990; Khalaf and Al-Ajmi, 1993; Al-Enezi, 1996; Al-Dabi *et al.*, 1997; Al-Dousari, 1997). These aspects included textural characteristics, genesis, morphology, dune formation and dune stabilization. None of these studies, however, gives a comprehensive picture of related aspects of the mobile barchan dunes. Thus, in this paper, emphasis is given to barchan dunes that exist in the northern part of Kuwait. It describes their aerodynamic, morphometric, sedimentologic and minerologic characteristics.

Study Areas

Kuwait covers an area of about 17818 km^2 in the northwestern corner of the Arabian Gulf between latitudes 28° 30`N and 30° 05`N, and between longitudes 46° 33`E and 48° 35`E. The surface of Kuwait is generally flat and slopes gradually northeastwards towards the Arabian Gulf, with an average gradient of about 2 m/km. In Kuwait, the average daily maximum temperature is 45° C for July and 18° C for January. The average daily minimum temperature fluctuates between 29° C for July and 8° C for January. Precipitation is scanty and

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seasonal; the mean total is about 112 mm/yr. The prevailing winds in Kuwait are from the northwesterly quadrant throughout all four seasons, but are stronger and more frequent in summer, about 60%. The wind also blows from the southeast, but to a lesser extent. Winds from other directions are less frequent and of short duration. Statistical analysis of wind data collected during 1957-1997 indicates that the average annual wind speed in Kuwait is about 4.3 m/s, and 16% of the year has calm weather. The average monthly wind speed reaches its highest in June (5.1 m/s), and its lowest in October (2.8 m/s).

Five dune areas in the northern part of Kuwait were selected for detailed consideration in this study. These are Al-Huwaimliyah, Al-Atraf, Al-Subiyah, Umm Al-Eish and Umm Al-Negga (Fig. 1). The area of the Al-Huwaimliyah includes one of the most extensive mobile sand sheet and sand dune belts in Kuwait. Smooth sand sheets occupy considerable areas at Al-Huwaimliyah. They have an almost featureless surface with a thin veneer of pebbles on the top.

The Al-Atraf area is characterized by an undulating surface that gradually slopes towards the northeast. The area has almost no vegetation cover, and it is blanketed with some residual gravels completely covered with active sand sheets.

The Al-Subiyah, Umm Al-Eish and Umm Al-Negga areas are characterized by the presence of sand sheets covering the entire areas in patch-like form and with sand tongues extending in the NW-SE direction. The areas are also blanketed with residual gravels partially covered by smooth and active sand sheets.

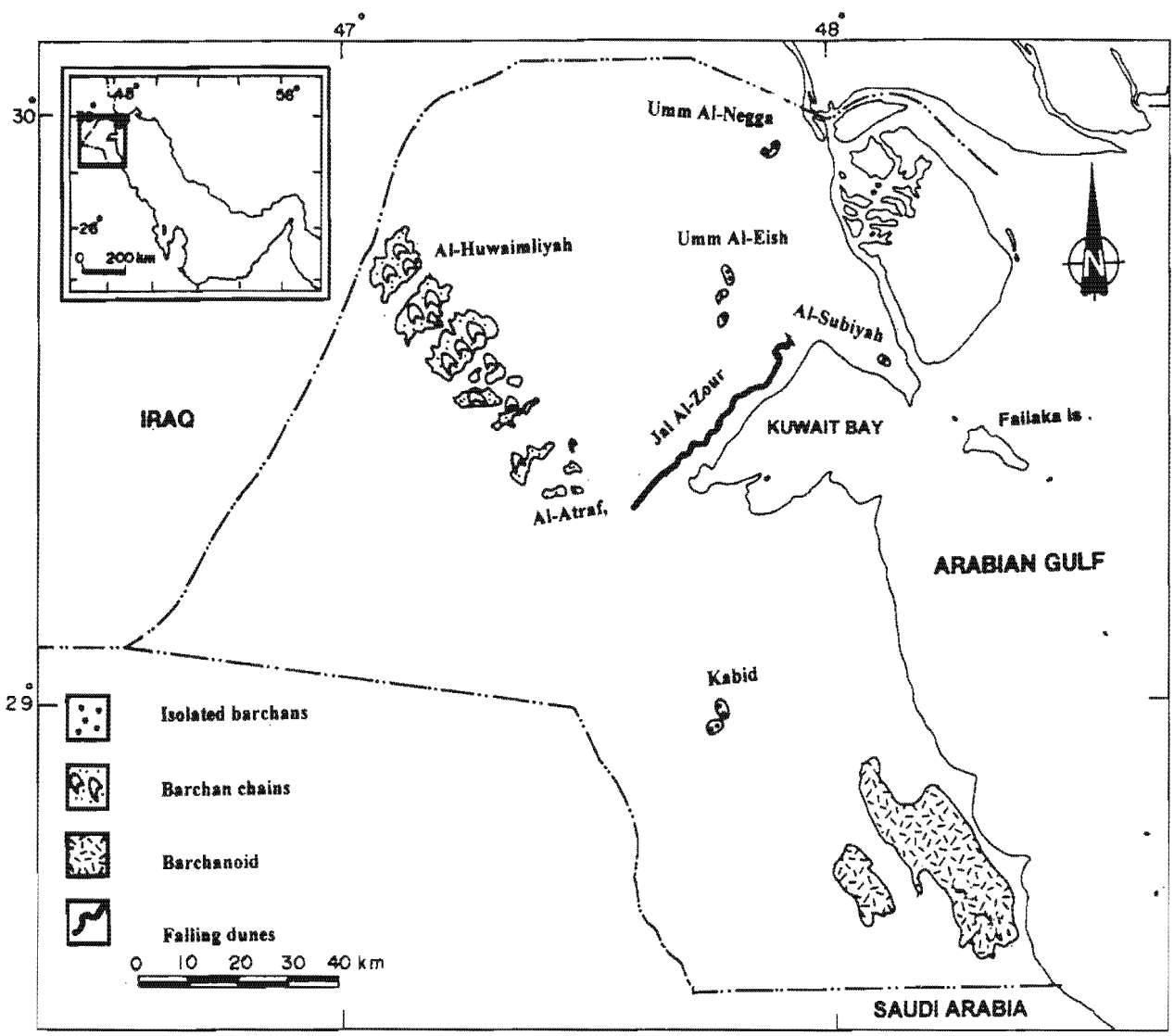


Fig. 1. Sand dune fields of Kuwait

Methodology

Twelve iron posts were installed around each selected dune to study its movement (Fig. 2). The selected dunes were monitored once in winter or spring, when their movement was expected to be limited because of the low wind speeds and more frequent rains during these two seasons, More frequent monitoring was carried out during the summer months (June, July and August). The dimensions of the dunes were also measured.

Sediment samples were collected from each selected dune for grain size analysis using standard dry sieving techniques (Folk, 1968). Cumulative curves were prepared, and the main graphical statistical size parameters, mean size, sorting , skewness and kurtosis, were determined.

Mineralogy of the sand was determined by separation of heavy minerals using heavy liquids. The coarse (> 0.5 mm) and very fine (0.125-0.063 mm) sand fractions were chosen for this study. The mineral composition of both light and heavy mineral fractions was determined using the standard counting technique, i.e., two hundred grains of either heavy or light minerals were randomly selected and counted.

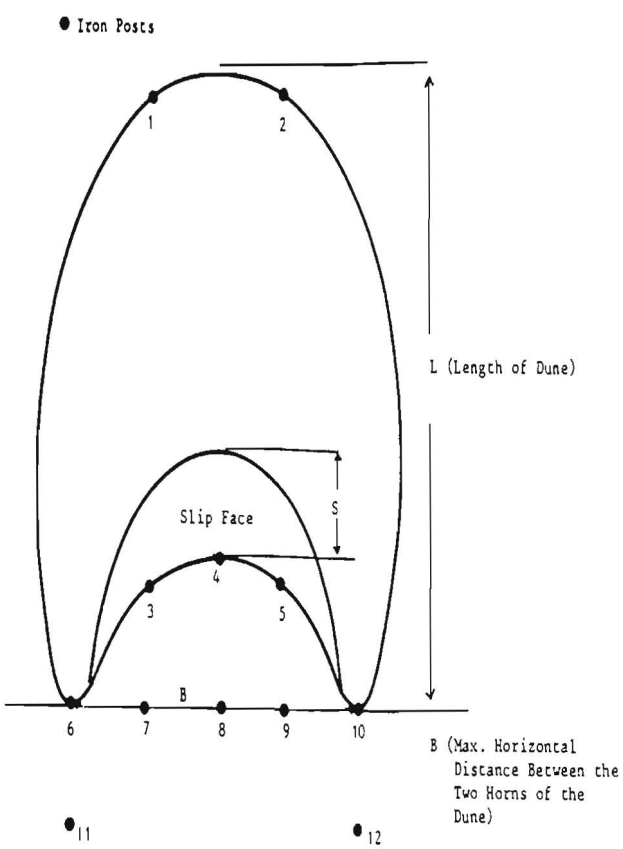


Fig. 2. Initial positions of the iron posts used to measure the rate of barchan sand dune movement

Morphology Of Dunes

Sand dunes in the studied areas are mostly present as crescent-shaped dunes (barchans) having slip faces bounded by two horns oriented downwind. The fields of the barchan dunes are associated with mobile sand sheets. These barchans mostly occur as isolated dunes and sometimes as compound or complex barchans, developed as a result of two or more dunes coalescing due to differential rate of movement. The orientation of barchan dunes is NW-SE, where the gently sloping, windward side of the dunes faces northwest and the steep, leeward side faces southeast. The height of the dunes ranges between 1 and 7 m above their base level. Parallel to the dominant wind, the length varies from 24 to 135 m and the width between the horns is 12 to 78 m.

For a better understanding of the pattern of barchan dunes, the various morphometric parameters of 44 dunes were measured. The relationships between different morphometric parameters of the studied dunes are plotted in Figs. 3a, 3b, and 3c. The diagrams reveal the following relationships between the height (h), width (W) and length (L) of the dunes:

$L = 15.2 + 14.9h$ with an R^2 value of 0.72 (1)
$W = 15.5 + 6.7h$ with an R^2 value of 0.64 (2)
$W = 14.96 + 0.36L$ with an R^2 value of 0.615 (3)

Hesp and Hastings (1998) indicated that a strong statistical relationship occurs between the height of crescentic dunes and the width of the horns ($W = 8.82h + 7.6$ with an $R^2 = 0.808$). The difference between their finding and the Equation 2 of this study could be related to two main reasons: (1) in their study, a larger number of dunes from different countries (i.e., dunes from different wind regimes) were studied, while the dunes of this study occur in almost a unique wind regime, and (2) difficulty in defining the morophometric parameters of the dune precisely, especially, the width and the length.

Dune Migration

The dunes in Umm Al-Nega area are considered less active compared with the very active dunes in the other four study areas. Foda *et al.* (1984) determined the annual migration rate of the large dunes in Umm Al-Nega area (8m height) to be 8 m/yr. In this study, the rates of movement of 17 active dunes were determined in all areas of the study except Umm Al-Nega area. The rate of movement of sand dunes was defined as the lateral

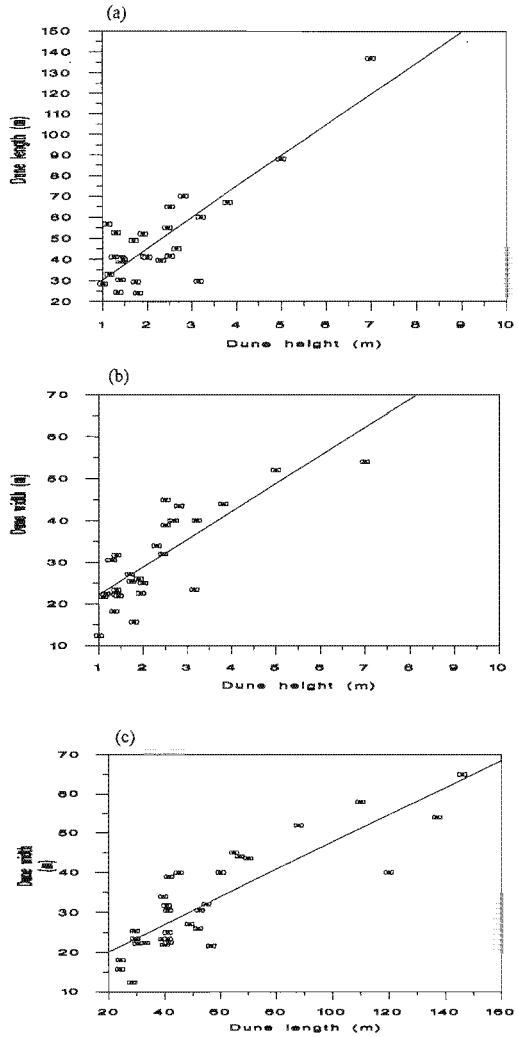


Fig. 3. Relationships between morphometric parameters of barchan sand dunes:
(a) length and height,
(b) width and height,
(c) length and width

movement of the slip face in the front of the dune. Previous field monitoring studies found that higher dunes move more slowly relative to the lower dunes under similar conditions (Norris and Norris, 1961; Howard *et al.*, 1978). This relationship was also observed in this study. For example, in the Al-Huwaimliyah area a dune that was 7 m high had a rate of movement of 7.2 m/yr, and a dune that was 1.8 m high had a rate of movement of 44 m/yr. The location of the dune among other features surrounding it is also an important factor in dune migration. Some dunes seem to have been slower than expected: this is because they are located on the lee side of a gravel ridge where the wind speed is slower than over the ridge.

The factors that control dune movement are little understood. However, the dune shape, its volume, the interrelation among dune parameters and composition and size of grains forming the dune are known to have some effect on dune movement (e.g., Bowler, 1973; Fryberger, 1979; Wasson and Hyde, 1983; Thomas, 1992). Fig. 4 shows a reasonably good exponential relationship between barchan dune height ($1< h \leq 7$m) and annual rate of displacement (D), which is expressed as:

$$D = 85.3 * 10^{-0.159h} \text{ with an } R^2 \text{ value of } 0.76 \quad (4)$$

It was noticed from field observations that individual dune movement is some-what complicated since the different parts of the dune move at variable speeds. For example, a dune in the Al-Atraf area had completely changed its shape after a period of time due to either variable wind speed over the whole dune or an increase in material supply.

Creation Of Sand Dunes

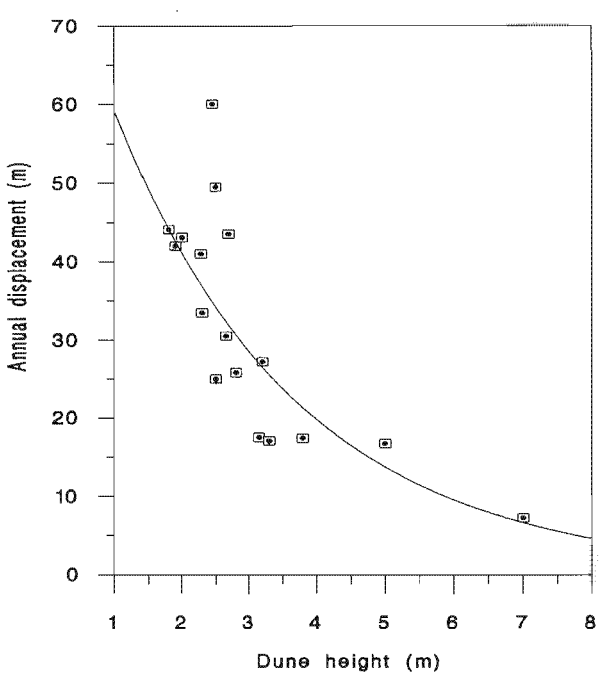
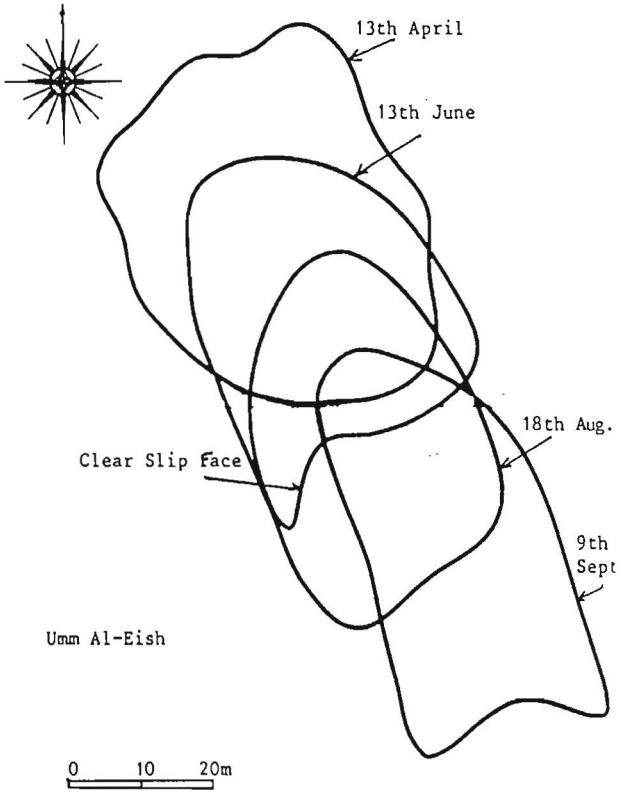


Fig. 4. Relationships between annual displacement and height of barchan sand dunes

Both natural and man-made factors play important roles in creating dune fields. The most important human factors are overgrazing of range lands and excessive cutting of trees and grasses (e.g., Mainguet, 1991). It was recognized by Hagedorn *et al.* (1977) that the process of dune formation starts when there is a topographical change on the surface of the desert. This recognition was also observed in this study. The sand dunes in

Al-Subiyah area, for example, were formed immediately after the Gulf War (1990-1991). The topography of this area had been severely disrupted by the Iraqi military operations and some 42,686,181 m^3 of surface sand was excavated from the northeastern area of Kuwait (including Al-Subiyah area) to build defensive systems like bunkers, trenches, weapon pits, berms, etc. (Al-Ajmi *et al.*, 1994).

In this study, a sand patch of about 90-100 m^2 and about 30 cm high in Umm Al-Eish area was monitored in the summer period to study the possible stages of its transformation into a sand dune (Fig. 5). The monitoring showed that this patch grew systematically and reshaped itself into a barchan dune of about 2.0 m height. Fig. 6 shows a lengthening of the dune by the development of horns downwind from and on either side of the center of the dune. The figure also shows that the horns and the slip face started to develop after five months, during which the blowing of the wind was strong (sometimes reaching 30 m/s) and unidirectional (the northwest wind known as 'Shamal').



Grain Size Parameter

Fig. 5. Stages of transformation of sand accumulation into barchan sand dunes

A total of 88 active dune sand samples were collected from four areas containing active sand dunes as follows: Al-Huwaimliyah (40 samples), Al-Atraf (12 samples), Umm Al-Eish (8 samples) and Al-Subiyah (28 samples). The grain size histograms from various parts of the crescentic dunes indicate that they are all unimodal, with the grain size mostly varying between medium and fine sand (Fig. 6). The mean grain size of the dunes ranges between 1.82ϕ and 2.35 ϕ, with an average of 2.09 ϕ (fine sand). The leeward and crest samples were dominated by medium sand with mean sizes 1.97ϕ and 2.03 ϕ, respectively, whereas the windward and horn samples were dominated by fine sand with mean sizes 2.24ϕ, and 2.12ϕ, respectively. Very fine sand size is less dominant with an average grain size distribution of 9.7%. Very coarse and coarse sand fractions account for less than 5.3 % of the total average grain size distribution. These fractions were found mostly in the leeward and crest samples where higher wind velocities are dominant.

In general, cresentic dune deposits are moderately-well sorted to moderately sorted with a range of sorting value between 0.56 ϕ and 0.85 ϕ, with an average of 0.67 ϕ (moderately-well sorted). The sands are better sorted at the crest (0.62 ϕ), at the leeward slope (0.63 ϕ), and at the horn (0.7 ϕ), than at the windward slope (0.74ϕ). The skewness of various parts of the barchan dune deposits varies from coarsely skewed to strongly fine-skewed, with an average skewness value of 0.09 ϕ (nearly symmetrical). For the same part of a dune, the measured skewness differed from one study area to another. Kurtosis values ranged widely from 0.78 ϕ to 3.19ϕ, with an average kurtosis value of 2.29ϕ (platykurtic).

Dune Mineralogy

Coarse Size Fraction (≥ 0.5 mm)

The coarse size fraction of the studied dune deposits is composed mainly of quartz, feldspars, rock fragments, and carbonate. Two types of quartz grains are recognized. The first type is well-rounded grains, with most having frost surfaces and some having smooth surfaces. The second type is subrounded to subangular and smooth. Feldspar grains are mostly equant subhedrals ranging in color from milky white to rose and pink. Orthoclase and perthite, which is an intergrowth of albite and anorthite, are the most abundant varieties of feldspar.

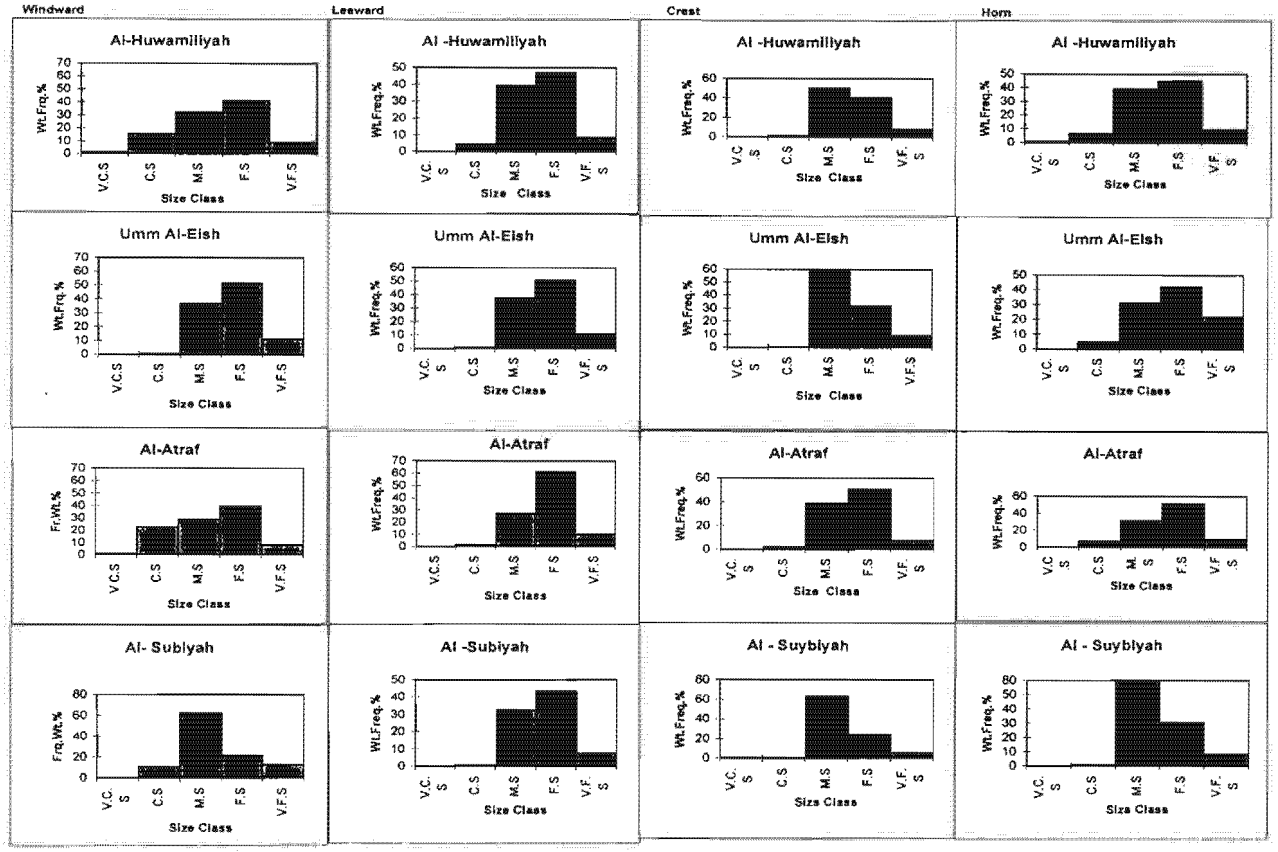


Fig. 6. Average grain size distribution histograms for various positions on barchan sand dune

Three main types of rock fragments are presented in the dunes studied: volcanic, gypcrete and calcrete. The calcrete fragments occur as rounded white grains and aggregates of fine-grained quartz cemented by micritic calcite. Volcanic rock fragments occur as well-rounded to subrounded dark grains, whereas gypcrete fragments are generally irregular in shape and bright white or yellow. The latter are composed of aggregates of fine quartz grains cemented by fibrous gypsum.

Gypsum is also present as anhedral to subhedral elongated crystals, which are usually colorless or light yellowish. Carbonate grains are generally present as irregular, angular or rectangular, colorless rhombohedrals. In general , the average relative frequencies of the percentage compositions of coarse sand fraction of the dunes varies insignificantly from place to place. Table 1 shows the mineral percentage in coarse sand fraction in four dune areas: Al-Huwaimliyah, Al-Atraf, Umm Al-Negga and Al-Subiyah.

Table 1. Mineralogy of coarse sand fraction of the dune (≥0.5mm)

Mineral Type	Umm Al-Negga Dunes	Al Subiyah Dunes	Al-Huwaimliyah Dunes	Al-Atraf Dunes
Quartz	79.64	81.51	79.73	77.30
Orthoclase	8.84	5.88	6.53	3.10
Plagioclase	2.65	0.84	2.52	0.19
Carbonates	2.65	7.56	6.43	8.69
Gypsum	3.54	4.20	1.70	8.5
V. R. F.	2.65	0	2.50	1.60
N	2	2	8	3

V R F: Volcanic rock fragments

Table 2. Percentages of light minerals in the studied sand dunes

Mineral Type	Umm Al-Negga Dunes	Al Subiyah Dunes	Al-Huwaimliyah Dunes	Al-Atraf Dunes
Quartz	46.15	55.12	44.85	43.89
Feldspars	12.31	16.66	15.90	15.92
Carbonates	29.23	19.23	10.77	17.30
Gypsum	7.69	3.84	6.16	7.06
Chet	1.53	1.28	2.81	2.37
Mica	3.07	3.84	2.58	2.23
N	2	2	8	3

N: Number of samples

Very Fine Size Fraction (0.125-0.063 mm)

Light Minerals

The light minerals fraction of the studied dunes is mainly composed of quartz, feldspars and carbonate rock fragments. They constitute about 70-90 % of the very fine sand of the dune deposits. Next in abundance are gypsum grains, which, on average, represent about 6% of the total samples. Chert and mica are present in smaller amounts (about 5%; Table 2).

Heavy Minerals

Heavy minerals in the fine size fraction are composed mainly of iron oxide minerals. The dunes in Umm Al-Nigga and Al-Subiyah areas, which face the coastal zone along the Arabian Gulf, showed larger average percentages of opaque minerals (45.1 and 41.9%, respectively) than the dunes in Al-Atraf and Al-Huwaimliyah areas (30 and 28.8%, respectively). Dolomite is the most common non-opaque mineral present in the heavy fraction. It constitutes about 31% of the total of non-opaque minerals. Next in abundance are amphibole and pyroxene grains. Their average percentage values range from about 10 to 16% and 5 to 12%, respectively. Epidote, garnet, zircon tourmaline mica, apatite topaz, sillimanite and kyanite are present in subordinate amounts (Table 3).

Pyroxenes are represented by augite, hypersthene, diopside and enstatite. Amphiboles are represented mainly by green hornblende, basaltic hornblende, and actinolite with green hornblende. Garnet is present as colorless, pinkish and violetish grains of angular to subangular shape. Epidotes occur as pistachite and zoisite. Zircon is present as well-rounded euhedral grains. Dolomite occurs as rounded to sub-rounded grains.

Surface Texture

Quartz grain surface textures of 68 samples collected from 11 sand dunes in Al-Huwaimliyah

Table 3. Percentages of heavy minerals in the studied sand dunes

Mineral type	Umm Al-Nigga Dunes	Al Subiyah Dunes	Al-Huwaimliyah Dunes	Al-Atraf Dunes
Opaque	45.13	41.91	28.82	30.02
Carbonate	17.69	21.32	16.77	25.69
Amphiloboles	15.92	13.23	9.83	10.32
Pyroxene	5.31	6.61	11.9	11.22
Epidote	2.65	2.21	3.99	4.45
Garnet	1.77	0.73	2.29	2.22
Zircon	0.88	1.47	1.46	1.52
Tourmaline	0.88	0.73	0.95	2.24
Mica	1.77	1.47	1.52	5.35
Apatite	0.88	0.73	1.22	1.60
Topas	0	0	0.85	0.71
Sillimanite	0.88	0.73	0.20	0.37
Kyanite	0.88	0.73	0.32	0.4
N	2	2	8	4

N: Number of samples

and Al-Atraf areas were analyzed using the scanning electron microscope (Al-Dousari, 1997). The analysis revealed that the most common mechanical surface features within each dune are dish-shaped depression V-shaped pits, rounded and cresentic pits and upturned plates. Some characteristic surface features reflect chemical activity, in the form of deep grooves, silica precipitation and triangular oriented pits.

Some quartz grains show extensive fracturing and abrasion as well as weathering. Others show a very distinctive smooth surface texture. The weathering processes such as insulation and thermal expansion and frosting are believed to be the main shapers of sand grain texture.

Discussion

The distribution and morphometric characteristics of the barchan dunes in the northern part of Kuwait suggest that their development is controlled by the general sedimentological, local geomorphic, and climatic conditions of the areas. Loose sand covers most of the northern area. It consists mainly of quartz, which makes up 94% of the sand particles (Khalaf *et al.*, 1984). The grain size distribution pattern of the dunes is generally similar to that of the aeolian deposits of active sand sheets and wadi fill as stated by Omar *et al.* (1989). They found that the average mean sizes of active sand sheets and wadi fill deposits in Kuwait were 0.26 and 0.23 mm, respectively. The average mean size of active sand dunes investigated here is found to be 0.23 mm.

Playas and depressions within the study areas provide ideal conditions for local aeolian activity, especially during dry periods. There are 12 playas and depressions in the northern part of Kuwait. The average length and width of these elongated hollows is 450 m and 150 m (Al-Dabi *et al.*, 1997). Most of the playas are covered by dunes. For example, there are 465 sand dunes within the playas and their margins in Al-Huwaimliyah and Al-Atraf areas (Al-Dousari, 1997). Some of the wadis in the northern part of Kuwait cut through ridges oriented parallel to the prevailing wind direction, thus acting as wind funnels for the flow of mobile sand. As a result, dunes are observed to be formed downwind of these wadis.

According to the classification of celerity (forward propagation; Zhenda *et al.*, 1986), the studied dunes are considered very fast dunes because most of them are moving over at 20 m/yr. The speed of movement of the studied dunes is greater for the smaller dunes than for the larger dunes under similar conditions (Fig. 4). Size dependency under the same conditions is not surprising, since the larger the dune, the greater the volume of sediment that has to be moved up to the dune crest before it falls on the slip face (Howard *et al.*, 1978; Thomas, 1992). It was observed that the heights of the studied barchan dunes changed slightly over the fields study period. In the summer season, for example, when stable winds of constant direction (NW) occur the dunes advance, and tend to change direction slightly (less from than 5^{O}) from the NW-SE. In winter, when the wind is mostly southeasterly, sand particles move from the desert surface and accumulate in front of the slip face and between the horns of the dune. The sand dune itself moves from the crest. As a result, the slip face changes direction to face the tail of the dune. The result is complete deformation of the original dune. When the prevailing wind blows again, the dune's original shape is gradually restored. Therefore, dune movement is a process that affects the entire barchan, causing it to undergo some appreciable change in size.

Table 4 shows a comparison between the grain characteristics for sand dunes in different areas in the Arabian Peninsula. Except for the grain sorting, the Qatar sand dunes, which are nearest to the Kuwait sand dunes, show clearer similarities to the Kuwait dunes than do some distant dunes in the region. Such similarities may be related to the fact that the natural system of aeolian sand deflation from Iraq and deposition in the Gulf countries is considered a main regional source of sediment supply for the formation dunes beside local sources like paleo lakes and wadi fill deposits.

Table 4. Grain size parameters of dune sand from different areas of Arabian Gulf countries

Country	Author	Mz ϕ	S D ϕ	Skewness ϕ	Kurtosis ϕ
Qatar	Ashour, 1985*	1.93	0.48	0.09	0.72
Oman	Goudie *et al.*, 1987*	2.6	NA	0.03	1.04
Saudi Arabia, Jeddah	Gheith & Abou Ouf, 1996*	2.6	0.46	0.04	0.99
Kuwait	This study	2.09	0.67	0.09	2.29

* After Embabi and Ashour, 1993

Conclusions

The barchans, in Kuwait, mostly occur as isolated dunes with height ranging between 1 and 7 m above their base level. Local topography and wind regimes greatly affect the morphology and distribution of the Kuwaiti sand dunes. The dunes are characterised by a unimodal sand size distribution, with an average grain size of 0.23 mm. Good statistical relationships between length, width, and height of dunes are obtained (Equations 1 to 3). The annual rate of displacement of small barchans exceeds 44 m/yr, depending on the dune's height.

Coarse size fraction of the dune deposits is composed mainly of quartz, feldspars, rock fragments, and carbonate. The non-opaque heavy minerals are more common than opaque ones. The Light mineral fraction is dominated by quartz, carbonate minerals, and feldspars. The quartz grain micro-textures of the sand dunes reveal the occurrence of mechanical and chemical surface features in different percentages from one dune to another.

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