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GRAIN-SIZE VARIATIONS ON A LONGITUDINAL DUNE AND A BARCHAN DUNE

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ABSTRACT

Watson, A., 1986. Grain-size variations on a longitudinal dune and a barchan dune. Sediment. Geol., 46: 49–66.

The grain-size characteristics of the sand upon two dunes—a 40 m high longitudinal dune in the central Namib Desert and a 6.0 m high barchan in the Jafurah sand sea of Saudi Arabia—vary with position on the dunes. On the longitudinal dune, median grain size decreases, sorting improves and the grain-size distributions are less skewed and more normalized toward the crest. Though sand at the windward toe is distinct, elsewhere on the dune the changes in grain-size characteristics are gradual. An abrupt change in grain size and sorting near the crest—as described by Bagnold (1941, pp. 226–229)—is not well represented on this dune. Coarse grains remain as a lag on concave slope units and small particles are winnowed from the sand on the steepest windward slopes near the crest. Avalanching down slipfaces at the crest acts only as a supplementary grading mechanism. On the barchan dune median grain size also decreases near the crest, but sorting becomes poorer, though the grain-size distributions are more symmetric and more normalized. The dune profile is a Gaussian curve with a broad convex zone at the apex upon which topset beds had accreted prior to sampling. Grain size increases and sorting improves down the dune's slipface. However, this grading mechanism does not influence sand on the whole dune because variations in wind regime bring about different modes of dune accretion. On both dunes, height and morphology appear to influence significantly the grain-size characteristics.

INTRODUCTION

The variation in grain-size characteristics upon individual sand dunes has received little attention in the literature on aeolian bedforms compared with, for example, grain-size variations within (Sharp, 1966; Hastenrath, 1967; Warren, 1972; Lancaster, 1983) and between ergs (Wilson, 1972, 1973; Petrov, 1976; Ahlbrandt, 1979). Most studies of the grain-size variations upon longitudinal dunes (Alimen, 1953; Folk, 1971; Lancaster, 1981) have shown that there are significant differences in the size of the grain populations which make up the sand on the flanks and at the crests of the ridges. However, little detailed information is available on the systematic variation in grain-size characteristics across such dunes. Because samples

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have frequently been collected from predetermined morphological units of the dunes, observations that such dunes "are composed of two populations of sands" (Lancaster, 1981, p. 122) or three discrete populations (Bagnold, 1941, pp. 226–229) may be too simplistic.

In the case of transverse dunes, particularly barchanoid forms, several questions have been raised by the marked differences in grain-size variations on dunes in different areas. In general, the sand from the upwind toe of barchans is coarser than sand from the crest (Finkel, 1959; Hastenrath, 1967; Warren, 1976), though in parts of the Sahara the reverse has been noted (Alimen, 1953). On some dunes the arms (or horns) of barchans are composed of coarser sand than the crest (Hastenrath, 1967; Lindsay, 1973; Warren, 1976), in others the two sand populations are similar (Finkel, 1959). The nature of the source sediments and morphological considerations, particularly dune dimensions and variations in slope profile, may explain these inconsistencies. One of the few detailed studies of grain-size variations across a barchan, that by Barndorff-Nielsen et al. (1980, 1982), does not address the questions fully because the dune that was examined was less than 1.0 m high—not much larger than some granule ripples (Sharp, 1963; Weir, 1963).

The aims of the present study were, first, to characterize the variations in grain size across two dunes—a longitudinal dune and a barchan—and, second, to evaluate the relationship between these variations and changes in dune morphology.

The longitudinal dune is located southwest of Gobabeb in the central Namib Desert (Fig. 1). The site is at the northern edge of the Namib sand sea, about 50 km from the Atlantic coast. The longitudinal dunes in this area are seifs oriented north–south and are about 40–50 m high, nearly 1.0 km wide and up to 25 km in length; the sampled dune is 41 m high. Elsewhere longitudinal dune heights

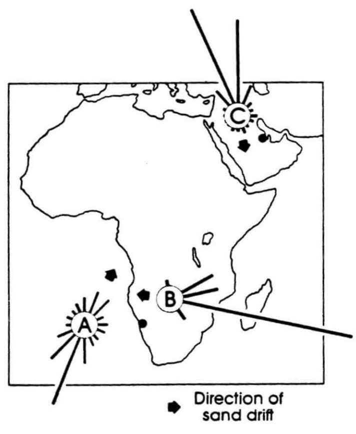

Fig. 1. Location of the two field areas and sand roses for nearby wind stations: A = Narabeb (after Breed et al., 1979, and Lancaster, 1980); B = Gobabeb (after Breed et al., 1979); C = Dhahran (after Fryberger and Ahlbrandt, 1979).

commonly range from 5.0 to 30 m (Mabbutt, 1977, p. 234), though in some areas they are much higher: 50 m in Egypt (Bagnold, 1941, p. 230); 100 m in Libya (Glennie, 1970, p. 95); 150 m in the Rub al Khali (Beydoun, 1966); and 200 m in southern Iran (Gabriel, 1938). The sand roses for Gobabeb (immediately north of the dunefield) and for Narabeb (within the sand sea, about 30 km south of the study dune) reflect the local variability in the wind regime (Fig. 1). The proximity of the dunes may mask the effective wind patterns (Breed et al., 1979) and the orientation of the ridges probably represents the resultant direction of sand drift under the influence of a dual-directional wind regime (Breed et al., 1979) with oblique air flow being deflected in the lee of the dune crests in a net direction parallel to the crest line (Tsoar, 1983). At Gobabeb, 24% of the potential annual sand flow is from the south to west-southwest and 46% from the east and northeast (Lancaster, 1981). During June and July, easterly and northeasterly winds (20–24 km h^{-1}) prevail for 8.0% of the period (Schulze, 1969; Seely and Stuart, 1976), producing marked asymmetry in the dune ridges' cross-profile. There is no evidence of significant lateral dune movement as has been suggested elsewhere (Rubin and Hunter, 1985). The position of the ridges is essentially static, being separated by gravelly interdune plains 1.0–2.5 km wide. It has been argued that the Namib dunes are relict features of Tertiary age (Besler, 1980), but the dune described here lies on a late(?) Pleistocene river terrace (Korn and Martin, 1957; Rust and Wieneke, 1974), so it is probably the product of northerly dune-building (Fryberger, 1979) under the present wind regime.

The barchan dune is located in the Jafurah sand sea of eastern Saudi Arabia (Fig. 1). The site is about 30 km southeast of the Al-Hasa oasis. Barchans in this area are up to 20 m high; the sampled dune is 6.0 m high. While this is significantly smaller than the longitudinal dune, barchan dunes in many deserts average 3.0–8.0 m in height (Finkel, 1959; Hastenrath, 1967; Lettau and Lettau, 1969, in Peru; Long and Sharp, 1964; Inman et al., 1966, in North America; Sarnthein and Walger, 1974, in Mauritania). The barchan described here is of average height for the area (Fryberger et al., 1984). In the Jafurah, the dunes travel roughly from north to south at rates averaging about 15 m yr^{-1} (Fryberger et al., 1984; Watson, 1985). Most movement occurs from April to June, during the *shamal* season, when strong northerly to north-northwesterly winds prevail (Fig. 1; the sand rose is for Dhahran, about 150 km north of the sampled dune). The dune is moving across a flat, level surface (serir) covered with material less well sorted than most of the dune sand (Table 3, sample 17). Within the vicinity, sparsely vegetated sand sheet, gravelly desert pavement and salt-encrusted sabkhas are also represented (Fryberger et al., 1983).

METHODS

The two dunes were sampled systematically. Samples weighing about 0.50 kg were collected from a depth of about 50 mm beneath the surface at points across the dunes. On the longitudinal dune, the traverse was from east to west, perpendicular to

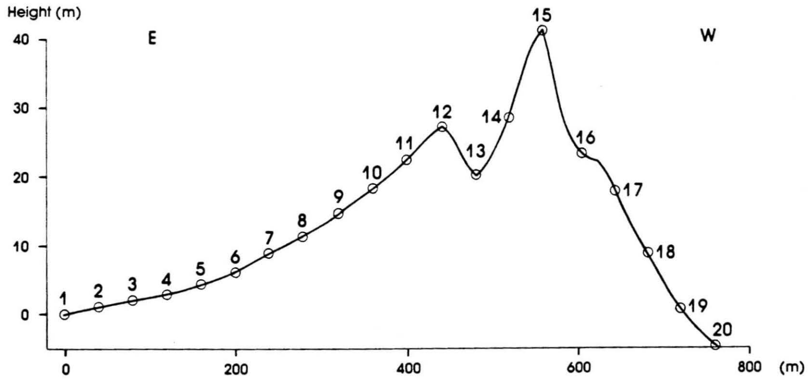

Fig. 2. Cross-sectional profile of the longitudinal dune from the central Namib Desert, showing location of sampling points. Vertical exaggeration is ×8.

the alignment of the ridge; samples were collected at 40 m intervals (Fig. 2). On the barchan dune, the traverse was from north-northeast to south-southwest, from the toe of the barchan along the axis of dune movement to the base of the slipface, and along the brink line of the western arm; samples were collected at 20 m intervals except on the slipface and serir (Fig. 3).

The Namib dune sands are reddish-yellow in colour (Munsell 7.5YR 6/6), the grains being coated with iron and aluminium oxides (Besler, 1972, 1976). Soluble salts derived from fog moisture (Boss, 1941; Nagel, 1962) are present in small quantities—less than 1.0% by weight. The sand samples from the Jafurah are pink in colour (Munsell 7.5YR 7/4) and typically contain a higher percentage of feldspar and heavy-mineral grains (totalling about 10%) than the Namib sands, which contain about 5.0% (Spreitzer, 1965).

The samples were not treated in any way prior to the grain-size analyses. Two

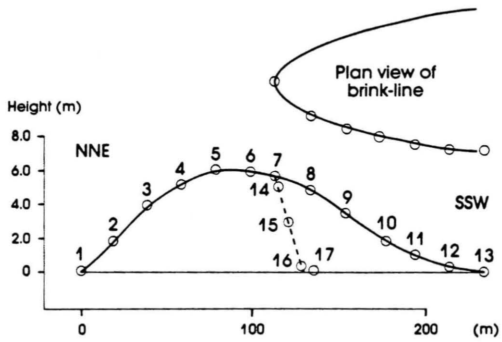

Fig. 3. Cross-sectional profile and plan view of the barchan dune from the Jafurah sand sea, Saudi Arabia, showing location of sampling points. Vertical exaggeration is ×10.

different techniques were employed. About 70 g of each sample from the Namib was divided into 11 size intervals of 0.50 ϕ from -1.0ϕ (2.0 mm) to 4.0ϕ (0.0625 mm) by sieving. The samples from the Jafurah were analysed using an optical particle-size analyser—an H.I.A.C. PA-720 system. Samples were split to less than 1.0 g. Using a vibratory feed system, a stream of grains was passed through a collimated light beam and the size of the individual particles determined by an optical sensor. A total of 500,000 grains from each sample were measured. The number of grains in each of 24 size classes from greater than 1.7334 to 0.0455 mm, approximating a 0.25ϕ interval, was determined by the particle-size analyser. Based upon these data, and assuming all the particles were spheres, the volume of grains in each size class was calculated and plotted graphically.

While it is not intended here to compare the grain-size data from the two areas, but only the variations in grain size across the two dunes, some comments on the comparability of the two analytical techniques are appropriate. The optical particle-size analyser determines the diameter of each grain by calculating the diameter of a circle with the same area as the randomly oriented grain's shadow. Only rarely will this diameter be less than the smallest mesh size the same grain can pass through during sieving. In this respect, therefore, the optical system will tend to overestimate grain diameter slightly. Moreover, in assuming that the particles are spherical when calculating the volumetric percentage in each size class, there is a potential for further relative overestimation of grain diameter. Though in terms of the size of individual particles such errors are small, their cumulative effect in those size classes containing large numbers of grains may be significant.

The main discrepancy in the data obtained employing the two techniques is a

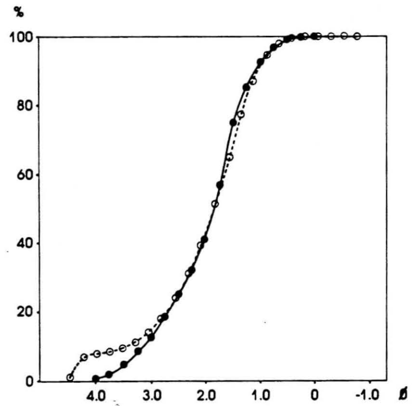

Fig. 4. Cumulative grain-size frequency curves for the same sand sample analysed gravimetrically, using 0.25ϕ interval sieves (solid line), and optically, using an H.I.A.C. PA-720 system (dashed line). The former is a cumulative curve of weight percentage and the latter a cumulative curve of estimated volumetric percentage, assuming all particles are spherical. Percentile grain sizes and distributional statistics for the two curves are presented in Table 1.

TABLE 1

Comparison of grain-size data obtained by gravimetric ($1/4\phi$ sieves) and optical (PA-720) particle-size analyses of the same sand sample

	Grain-size percentiles (ϕ)							Median	Graphic mean	Inclusive	Inclusive	Graphic
	5%	16%	25%	50%	75%	84%	95%	$Md(\phi)$	$Mz(\phi)$	graphic *SD* σ_I	graphic skewness Sk_I	kurtosis K_G
$1/4\phi$ sieves	3.46	2.89	2.51	1.82	1.50	1.28	0.88	1.82	2.00	0.79	0.30	1.05
PA-720	4.30	2.93	2.52	1.86	1.41	1.21	0.84	1.86	2.00	0.95	0.33	1.28

greater volumetric percentage of grains in the smallest size classes determined by the optical analyser in comparison to the weight percentage determined by sieving (Fig. 4). This probably results from overestimation by the optical analyser of the volume of the numerous angular, silt-sized particles—the pan fraction of the gravimetric technique. In practical terms the discrepancy results in a difference in those grain-size distribution statistics which utilize the diameter of the 5th percentile (plotting the frequency curve as shown in Fig. 4). In this example, standard deviation about the mean, and the skewness and kurtosis of the grain-size distribution curve all have lower values when they are calculated using data obtained gravimetrically (Table 1).

RESULTS

The results of the grain-size analyses are presented as distributional statistics (after Folk and Ward, 1957) in Tables 2 and 3.

TABLE 2

Grain-size characteristics across a longitudinal dune, central Namib Desert

Sample	Median $Md(\phi)$	Graphic mean $Mz(\phi)$	Inclusive graphic SD σ_I	Inclusive graphic skewness Sk_I	Graphic kurtosis K_G
1	2.64	2.47	1.13	0.27	1.06
2	1.75	1.90	1.10	0.04	1.14
3	1.80	2.02	0.88	0.29	0.87
4	1.50	1.76	0.78	0.49	1.06
5	1.50	1.88	0.88	0.55	0.91
6	1.45	1.66	0.76	0.40	1.22
7	1.72	1.96	0.81	0.41	0.89
8	1.67	1.92	0.89	0.50	1.37
9	1.95	2.12	0.80	0.30	0.80
10	1.90	2.10	0.72	0.40	0.86
11	2.06	1.95	0.67	0.26	0.88
12	2.68	2.71	0.64	0.09	0.89
13	1.40	1.58	0.65	0.46	0.92
14	2.25	2.26	0.38	0.07	1.02
15	2.56	2.56	0.30	0.01	0.98
16	2.22	2.26	0.54	0.11	0.75
17	2.30	2.30	0.46	0.26	1.03
18	1.95	2.05	0.58	0.28	0.90
19	1.77	1.91	0.56	0.39	1.04
20	1.65	1.82	0.85	0.25	0.77
Means [a]	1.94	2.07	0.73	0.26	0.97

[a] Means are calculated from percentile means.

Longitudinal dune

Across the longitudinal dune (Figs. 2, 5 and Table 2) median grain size decreases from the flanks toward the crest—the same pattern as noted in North Africa (Bagnold, 1941; Alimen, 1953; McKee and Tibbitts, 1964) but the reverse of that in the Simpson and Strzelecki Deserts of Australia (Crocker, 1946; Wopfner and Twidale, 1967; Folk, 1971), on some dunes in the Namib (Goudie, 1972) and Kalahari Deserts (Lewis, 1936), and in western Kansas (Simonett, 1960). On the Namib dune, a 50 m long trough parallels the 41 m high crest, separating it from a secondary ridge to its west which is 27 m high. Sand on the secondary crest has a smaller median grain size (2.68ϕ) than at the main crest (2.56ϕ), and the sand at the base of the trough is the coarsest on the dune (1.40ϕ). Because avalanching of sand down slipfaces carries larger, heavier grains furthest, relatively coarse sand accumulates towards the flanks of the crest (Figs. 2 and 5, and Table 2, samples 11, 13 and 16).

The average median grain size to the west of the dune crest is slightly smaller

TABLE 3

Grain-size characteristics across a barchan dune, Jafurah sand sea

Sample	Median $Md(\phi)$	Graphic mean $Mz(\phi)$	Inclusive graphic SD σ_I	Inclusive graphic skewness Sk_I	Graphic kurtosis K_G
1	1.75	1.85	0.75	0.25	1.14
2	2.12	2.21	0.83	0.29	1.24
3	1.88	2.01	0.99	0.30	1.02
4	1.68	1.89	0.88	0.50	1.30
5	2.28	2.58	1.26	0.26	0.86
6	2.26	2.31	0.85	0.21	1.21
7	1.70	1.89	1.02	0.38	1.05
8	2.45	2.63	1.20	0.15	0.99
9	1.87	2.12	1.05	0.40	0.99
10	1.52	1.67	1.00	0.38	1.20
11	1.68	1.86	0.86	0.45	1.37
12	1.81	2.04	0.97	0.43	1.16
13	1.73	1.91	0.90	0.44	1.14
14	1.75	2.07	1.10	0.31	0.98
15	1.90	2.05	0.95	0.33	1.19
16	1.20	1.24	0.65	0.30	1.63
(17	2.44	2.67	1.25	0.16	0.99) [a]
Means [b]	1.85	2.02	0.95	0.35	1.12

[a] Sample from surface over which the dune is moving.

[b] Means are calculated from percentile means, sample 17 excluded.

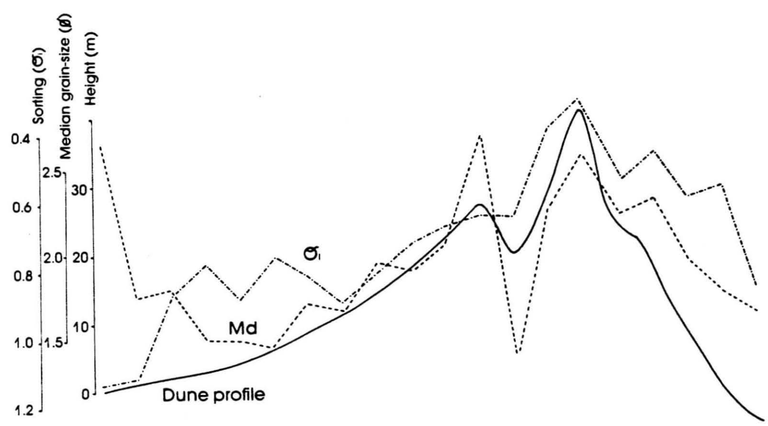

Fig. 5. Variation in median grain size and sorting of sand across the longitudinal dune (vertical exaggeration of the profile is ×8).

(1.98ϕ) than to the east (1.92ϕ). The average size of the 95th percentile (plotting from fine to coarse) is 0.87ϕ to the east of the crest, and 1.27ϕ to the west. This suggests that the smaller median grain size to the west results from the loss of the largest grains as easterly winds move sand up the dune and over the crest.

The sorting of the dune sand (inclusive graphic standard deviation, σ_I; Fig. 5 and Table 2) becomes better toward the main crest where the sand is very well sorted (0.30). Over the dune as a whole the sand is moderately to moderately well sorted, except on the eastern toe where sorting is poor. The average (calculated from percentile means) to the west of the crest (0.59) is better than to the east (0.80). Sand from the secondary crest and the trough are similarly sorted despite the marked difference in median grain size.

The grain-size distribution of the dune sand is generally strongly fine-skewed to fine-skewed, becoming less skewed toward the crest. Sand on the windward side of the dune—the eastern flank—is more strongly fine-skewed than on the leeward side. At the two crests, where the sands have a nearly symmetric size distribution, fine material has presumably been winnowed out of the populations. All of the grain-size distributions are mesokurtic, though they are more normalized on the windward side of the ridge. This probably reflects the more efficient removal of large grains than small as sand is transported across the ridge, fine material being reincorporated in the lee of the crest.

Barchan dune

Across the barchan dune, the relationship between grain size and position on the dune (Figs. 3, 6 and Table 3) is not as clear as it is across the longitudinal dune. The

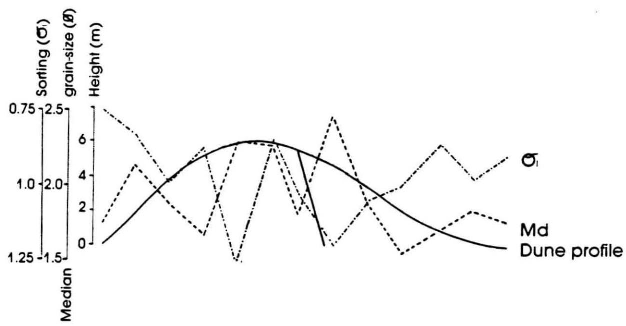

Fig. 6. Variation in median grain size and sorting of sand across the barchan dune—excluding samples from the slipface (vertical exaggeration of the profile is ×10).

upwind toe of the barchan and the arms are made up of sand of similar median grain size, and which is coarser than material from the crest. The larger median grain size of basal material has been attributed to the transport of coarser grains around the fringe of the dune rather than up the windward slope (Sidwell and Tanner, 1939; Simonett, 1960; Hastenrath, 1967; Warren, 1976). However, since large grains will avalanche down the slipface further than smaller grains, the coarseness of sand at the dune toe may result from the reappearance of basal foreset beds as a lag deposit as the dune advances (Bagnold, 1941, pp. 226–229; Finkel, 1959; Sharp, 1966; Lindsay, 1973). In this example, the sand at the base of the slipface is the coarsest on the dune ($Md = 1.20\phi$). The finest sands are found near the crest ($Md = 2.28\phi$) and in its lee ($Md = 2.45\phi$), though at the brink—the top of the slipface—the sand is markedly coarser ($Md = 1.70\phi$). This is attributed to the wind regime at the time of sampling. The dune was sampled in January when it was stationary, and when light southerly winds had modified the brink line slightly (Fryberger et al., 1984, Fig. 13). It is likely that the finer component of the sand at the brink was deflated, leaving a residue of coarser sand.

The sorting of the sand across the dune is moderate to poor; it is best at the base of the slipface (0.65) and at the toe (0.75), and worst at the crest (1.20)—a pattern also noted in the Nebraska Sand Hills (Ahlbrandt and Fryberger, 1980). This suggests that the dune's crest is a zone of accretion (Bagnold, 1941, pp. 226–229) and that the most effective sorting mechanisms are gravitational forces on the slipface and deflation of fine material at the toe.

The grain-size distribution is generally strongly fine-skewed to fine-skewed across the dune. Again no clear trend is apparent, but populations near the crest (Fig. 3 and Table 3, samples 5, 6 and 8) are more symmetric than elsewhere on the dune. The graphic kurtosis of the grain-size distribution becomes more normalized near the crest, becoming more positive on the flanks and down the slipface where there is a predominance of coarse grains.

DISCUSSION

Though the available information on the pattern of grain-size variations across dunes is in many respects ambiguous, some broad generalizations can be made. While on longitudinal dunes median grain size can either increase or decrease with height, sorting of the sand improves toward the crest (Bagnold, 1941, pp. 226–229; McKee and Tibbitts, 1964; Folk, 1971; Lancaster, 1981). Moreover, as with climbing/falling dune complexes (Evans, 1962), median grain size is smaller and sorting better on the leeward flanks. In the case of transverse dunes, the grain-size characteristics appear more variable. A lag of coarse grains, either only at the upwind toe or fringing the whole dune, is a common feature. Bagnold (1941, pp. 226–229) held that this lag was found to a height no greater than 5.0% of the height of the summit, the sand making up the rest of the dune being homogeneous. This has been confirmed on reversing barchans (Lindsay, 1973), but some transverse dunes have sand coarser at their crests than on their flanks (Alimen, 1953; Sharp, 1966). In contrast, Barndorff-Nielsen et al. (1982) found that there was a linear decrease in grain size with increasing height on a small barchanoid dune. Such a trend is to be expected because grain size increases down slipfaces and these foreset beds reappear on the windward slope as the barchan advances. It is striking, therefore, that such patterns are not evident on larger barchans.

In an attempt to evaluate the relationships between grain-size characteristics and dune morphology, median grain size, skewness, kurtosis and the grain sizes at the 5th and 95th percentiles of the cumulative frequency curves of individual samples have been correlated with their height on the dune, and with three simple slope parameters. The parameters are, first, the inclination of the dune surface between the sampling point and the next one upwind (40 m to the east on the longitudinal dune, 20 m to the north-northeast on the barchan). Second, a measure of slope concavity

TABLE 4

Coefficients of correlation (r) between grain-size characteristics and dune morphology; longitudinal dune, central Namib Desert (20 samples) [a]

	Height	Upwind slope [b]	Concavity/convexity	Change in slope
$Md\phi$	+0.53	+0.23	−0.49	+0.37
σ_I	−0.79	(−0.02)	+0.28	−0.39
Sk_I	−0.49	−0.19	+0.42	−0.49
K_G	−0.29	(+0.11)	(−0.06)	−0.18
95% dϕ	+0.76	(+0.13)	−0.40	+0.32
5% dϕ	−0.29	+0.25	(−0.14)	−0.25

[a] Correlation coefficients which are not significant at the 0.01 level are in parentheses.

[b] Upwind slope on this dune refers to the slope to the east of the sampling point.

TABLE 5

Coefficients of correlation (r) between grain-size characteristics and dune morphology; barchan dune, Jafurah sand sea (13 samples, except where stated) [a]

	Height [b]	Upwind slope	Concavity/convexity	Change in slope
$Md\phi$	+0.51	(+0.22)	(−0.24)	(−0.14)
σ_I	+0.62	(−0.20)	−0.52	(−0.20)
Sk_I	−0.21	(−0.10)	(−0.07)	(+0.13)
K_G	−0.51	(−0.04)	+0.38	(+0.13)
95% dϕ	(+0.17)	+0.40	(−0.05)	(+0.18)
5% dϕ	+0.55	(+0.01)	−0.77	(−0.04)

[a] Correlation coefficients which are not significant at the 0.01 level are in parentheses.

[b] 16 samples; includes samples from slipface.

or convexity at the sampling point, based upon the difference in gradient in the upwind and downwind directions (positive values reflect a steeper upward slope and therefore local slope concavity). And, third, a measure of the change in slope in the upwind direction, based upon the difference in gradient between the sampling point and the next point upwind, and the gradient between that point and the next upwind (positive values again indicate slope concavity and negative values convexity, but only upwind of the sampling point—over 80 m on the longitudinal dune and over 40 m on the barchan). The correlation coefficients (r) are presented in Tables 4 and 5.

Longitudinal dune

On the longitudinal dune there are significant variations in grain-size characteristics with height on the dune. Not only does grain size decrease toward the crest and sorting improve (Figs. 7 and 8), but the distributions are significantly more symmetric (less fine-skewed) and more normalized. The correlations between height and the grain size of the 5th and 95th percentiles reflect a significant decrease in the numbers of large and small grains toward the crest. With more positive slopes (greater windward inclines) median grain size decreases and the grain-size distribution is more symmetric. The sand from the gentler slopes on the eastern flank, and from the leeward side of the dune, is characterized by smaller 5th percentile grain diameters. In effect, there are significantly more small grains than near the crest. Median grain size is larger, sorting poorer and the grain-size distribution more finely skewed on these slope units which are more concave. There are also more large grains in the sand samples from more concave slopes—presumably because the grains become trapped there. The grain-size characteristics have broadly the same correlation with change in slope in the upwind direction as they do with height on the dune. This is because local slope generally increases toward the crest of the dune.

Bagnold (1941, pp. 226–229) identified three discrete sand population zones on

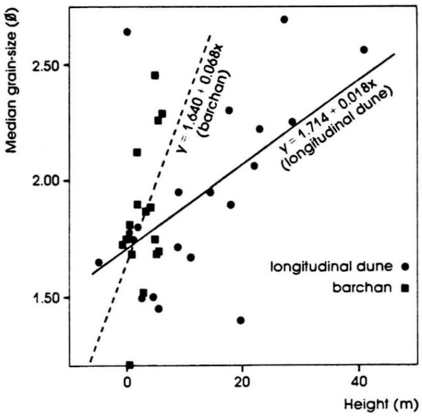

Fig. 7. Relationships between height on dune and median grain size of sand samples on the longitudinal and barchan dunes.

longitudinal dunes; a basal zone (not always represented) containing very poorly sorted sand; an accretion zone (the plinth) where median grain size is fairly constant but sorting improves with height; and the crest, where oversteepening and slipface formation carries larger grains toward the flanking plinths resulting in a decrease in grain size and better sorting toward the crest. Lancaster (1981) felt that on longitudinal dunes in the Namib, plinth and crest sand populations were distinct in their grain-size characteristics. On the dune discussed here, however, the decrease in grain size and improvement in sorting toward the crests is gradual. The relatively fine-grained, poorly sorted material on the eastern toe of the dune, represents Bagnold's basal zone.

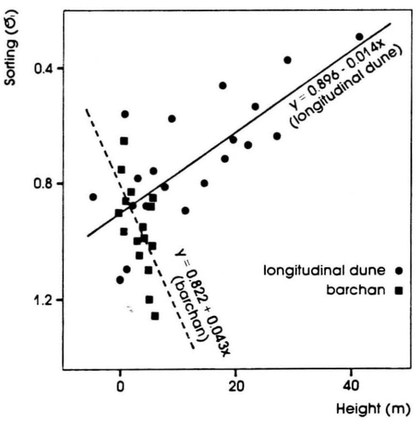

Fig. 8. Relationships between height on dune and sorting of sand samples on the longitudinal and barchan dunes.

On this dune the decrease in grain size and better sorting appears to result from the loss of both the largest and smallest grains as sand moves up the windward flank. Large grains accumulate on the more concave slopes at the base of the eastern plinth and also in the trough between the crests. Oversteepening and slipface formation at the main crest removes larger grains to its flanks. The steepest windward slopes near the crest are inclined at greater than 15°—the upper limit for successive aeolian saltation (Rumpel, 1985)—and sand transport is minimized. Small grains are deflated, probably being redeposited in the lee of the dune.

Barchan dune

There are fewer significant correlations between grain-size characteristics and morphological parameters on the barchan dune. As on the longitudinal dune, median grain size decreases toward the crest (Fig. 7), but on this dune sorting becomes markedly poorer (Fig. 8). The reason is probably the significantly larger population of small grains in the sand at the crest. One explanation for this is that the convexity of the crest results in accretion of poorly sorted sand containing an abundance of small grains. On the lower concave slopes, removal of the fine fraction improves the sorting of the sand.

On the barchan dune, variations in slope morphology play a major part in determining grain-size characteristics. While on the longitudinal dune, slope gradients increase with height and there are few convex slope units, the barchan profile is a Gaussian curve. On a dune of this shape, the relative decrease in surface shear stress where the profile becomes convex results in deposition of sand over a broad zone either side of the crest (Lai and Wu, 1978, p. 19). In contrast, on a dune with a dominantly concave profile, maximum deposition is at the crest (Lai and Wu, 1978, p. 19), though at high wind speeds separation in the air flow and slipface activation results in greater net accumulation in the lee of the crest.

The position of the slipface of a barchan in relation to the crest varies with wind velocity because this strongly influences rates of sand transport, erosion and deposition. Prior to the sampling of the barchan discussed here, the accretion of fine-grained, poorly sorted topset beds had occurred. During the period of strong northerly winds, more vigorous erosion on the steeper portions of the windward slope and higher sand transport rates up this slope, would result in increased deposition at and beyond the crest. In turn this causes oversteepening of the leeward side until the crest line is at the brink of the slipface. Under these conditions, profile convexity is reduced, topset beds largely disappear and most dune accretion is as foreset beds—on the slipface. However, seasonal fluctuation in wind regime and velocity will result in the accretion of distinct bedding units and diverse grain-size populations at different times of year. The reappearance of these deposits as the dune advances may explain the seemingly haphazard variations in grain-size characteristics on the windward slope.

SUMMARY AND CONCLUSIONS

On the longitudinal dune, though the three morphological units of Bagnold are represented, only the sand on the low-angle basal slopes has distinct grain-size characteristics. Elsewhere on the dune, there is a gradual decrease in median grain size and improvement in sorting from the lower plinths toward the crest. Large sand grains tend to lag on more concave windward slopes and small grains are winnowed from the sand on the steepest windward slopes. An abrupt change in the character of the sand, as a result of avalanching down slipfaces near the crest, is not well represented on this dune. However, the trough on the windward side of the main crest plays a significant role in trapping the larger grains. It appears that increasing height and gradient result in a progressive change in grain-size characteristics from the lower plinths to the crest, though at the crest avalanching probably acts as a supplementary grading mechanism.

On the barchan, the Gaussian curvature of the profile creates a broad zone of potential accretion on the convex slopes near the crest where potential surface shear stress is decreased. Coarse sand grains lag on the steeper, lower windward slopes but, unlike on the longitudinal dune, the sand's fine fraction is not winnowed out near the dune crest. So, while median grain size decreases with height, sorting becomes poorer. Though on the slipface median grain size increases and sorting improves toward the base, this grading mechanism can influence grain size on the whole dune only when high rates of sand transport are maintained. Under such conditions, the dune crest is at or near the brink of the slipface and accretion is as foreset beds—on the slipface—rather than as poorly sorted topset beds.

It is not the purpose of this study to discuss the specific distinctions in the grain-size characteristics on these two dunes. This would be inappropriate owing to the unknown influences the different wind regimes and sand sources have on the nature of the dune sands. However, upon each dune some variations in grain-size characteristics appear to be significantly related to dune morphology, and in comparing the two dunes some broad similarities and distinctions are evident. On both dunes, median grain size decreases with height (Fig. 7); sorting improves with height on the longitudinal dune, but becomes poorer with height on the barchan (Fig. 8). Variations in slope gradient or in the convexity/concavity of the profile appear to affect significantly both grain size and sorting. Such broad relationships are to be expected since height and morphology strongly influence wind velocity profiles and rates of sediment transport (Mercer and Haque, 1973). Though avalanching on slipfaces acts as a grading mechanism, the relative erodibility and mobility of coarse and fine sand grains on different slope units and under different wind regimes are probably the strongest influences on grain-size variations upon the two dunes.

Further investigations of grain-size variations on dunes of different types and dimensions, as well as in areas where the sand sources have different grain-size characteristics, are essential in order to evaluate the broader implications of these findings. The results of a limited number of analyses of dune sands from the western Rub al Khali indicate a pattern on a 50 m high longitudinal dune similar to that on the Namib dune; a 28 m high star dune shows a decrease in median grain size with increasing height, but uniform sorting. If such relationships between dune morphology and variations in grain-size characteristics are general, their elucidation should prove valuable in the anatomical investigation of ancient aeolian sedimentary environments (Mader and Yardley, 1985; Rubin and Hunter, 1985) and studies of present-day dune dynamics.

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