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# Grain-size variation on a 'complex' linear dune in the Namib Desert

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SUMMARY: Against a background of increasing knowledge of regional grain-size variations, particularly in the Namib Desert, this paper reports an investigation of small-scale grain-size variations using 25 sample points on the cross-profile of a single linear dune. The results suggest that a discernible pattern of grain size across the dune does exist, and that changes are gradual rather than discrete. From an examination of the near neighbours of the main study dune there is also some evidence of measurable differences between dunes in the same area. The fact that grain sizes are not randomly distributed across the width of the dune indicates a response to spatial variations of process, but grain size does not seem to control dune form in the way that some earlier workers have envisaged. Furthermore, monthly sampling provides preliminary evidence that grain-size values on this dune respond to a seasonal wind regime, and that time of sampling may therefore be a crucial determinant of the results obtained.

For almost a century, grain-size analysis has been carried out on a large number of ancient and contemporary sediments in the belief that it is possible to define diagnostic properties of individual sedimentary regimes from the size frequency distribution of their deposits. As a result, there is now a considerable literature on beach/dune/river systems, but the number of detailed studies of the sands of linear dunes remains remarkably small.

In recent years, however, several workers have investigated regional patterns of grain size at sand-sea scale, notably Besler (1980) and Lancaster (1982*c*) for the Namib Desert, Lancaster (1986) for the SW Kalahari, and Warren *et al.* (1985) for the Wahiba Sands. Indeed, largely as a result of the endeavours of Besler and Lancaster there is now a fairly comprehensive picture of the regional variation of grain size throughout the Namib Desert. Little is known, though, about the changes that take place at a smaller scale, *eg* on a single linear dune. Data comparing interdune, plinth and crest sediments from several sand seas have been presented by various authors (Table 1), but until Watson's (1986) recent paper reporting data from 20 sample points on a linear dune in the Namib Desert, no study had exceeded seven samples from a single dune cross-profile. The object of the present paper is to intensify the investigation of small-scale grain-size changes by detailed sampling of an individual linear dune. The examination of grain-size variation is part of a wider study of the geomorphological dynamics of the dune (Livingstone 1985).

## Study site

The main study dune lies at the northern edge of the Namib Sand Sea in Namibia, southern Africa, approximately 8 km SE of the Namib Desert Research Station at Gobabeb (23°34'S, 15°03'E) (Figs 1 and 2). The dune here is aligned roughly N–S, is approximately 350 m wide and 50 m high. It stretches some 30 km to the S of the study site and 3 km N to the Kuiseb River. Interdune corridors in the area are between 1.5 and 3.0 km wide. The study dune displays the morphometric asymmetry typical of dunes in this part of the Namib Sand Sea, with a relatively uniformly sloping west flank, but a series of secondary ridges and barchanoid features on the E flank. As a consequence of its size and its support of secondary dunes, this dune is termed 'complex' after McKee (1979) and Lancaster (1982*b*), although in Wilson's (1972*b*) classification it would be a 'draa'.

The central Namib Desert is subjected to a seasonal wind regime so that, broadly speaking, the dunes are affected by low- to moderate-force winds from the SW and NW in summer, and by high force but low frequency winds from the E in winter (Lancaster *et al.* 1984). Under the influence of this regime, the crest of the dune moves back and forth laterally by some 14 m each year (Livingstone 1985). Besides movement of the crest, there is a northward extension of the dune into the Kuiseb River valley of between 0 and 1.85 m $a^{-1}$ (Ward 1984). Contrary to the belief of Rubin & Hunter (1985), there is no evidence that the imbalanced wind regime is leading to any lateral shift of the dune base.

The source of sand for the Namib dunes has been a matter of some debate. Beneath the present sand sea lie deposits of a former erg which have undoubtedly been partially reworked into the present dune system, but this is not the major source of sand. Besler (1980) regards the dunes as a Pleistocene reworking of fluvial deposits from a former alluvial plain system,

*From* FROSTICK, L. & REID, I. (eds), 1987, *Desert Sediments: Ancient and Modern,* Geological Society Special Publication No. 35, pp. 281–291.

TABLE 1. *Grain-size parameters of linear dunes (phi units)*

| Dune Location and Sampling Site | Mean | Standard Deviation | Skewness | Kurtosis | Reference |
|---|---|---|---|---|---|
| Namib Desert, Namibia | | | | | |
| Crest | 2.15 | 0.54 | — | 0.98 | Besler (1980) |
| Base | 1.98 | 0.85 | — | 1.03 | |
| Crest | 2.11 | 1.71 | 0.04 | 1.30 | Goudie (1970) |
| *Compound linear dunes* | | | | | |
| Crest | 2.25 | 0.39 | 0.19 | 0.50 | Lancaster (1983*b*)* |
| Slip faces | 2.33 | 0.41 | 0.04 | 0.47 | |
| Plinths | 2.01 | 0.86 | 0.22 | 0.46 | |
| Interdunes | 1.96 | 1.04 | 0.29 | 0.46 | |
| *Complex linear dunes* | | | | | |
| Crest | 2.49 | 0.36 | 0.13 | 0.51 | Lancaster (1983*b*)* |
| Slip faces | 2.51 | 0.37 | 0.03 | 0.50 | |
| Upper W | 2.40 | 0.51 | 0.09 | 0.49 | |
| Plinths | 2.07 | 0.76 | 0.32 | 0.48 | |
| Interdunes | 1.98 | 0.90 | 0.34 | 0.47 | |
| E flank dune | 2.30 | 0.44 | 0.17 | 0.52 | |
| Crossing dunes | 2.19 | 0.48 | 0.26 | 0.55 | |
| 1 (E base) | 2.47 | 1.13 | 0.27 | 1.06 | Watson (1986) |
| 2 | 1.90 | 1.10 | 0.04 | 1.14 | |
| 3 | 2.02 | 0.88 | 0.29 | 0.87 | |
| 4 | 1.76 | 0.78 | 0.49 | 1.06 | |
| 5 | 1.88 | 0.88 | 0.55 | 0.91 | |
| 6 | 1.66 | 0.76 | 0.40 | 1.22 | |
| 7 | 1.96 | 0.81 | 0.41 | 0.89 | |
| 8 | 1.92 | 0.89 | 0.50 | 1.37 | |
| 9 | 2.12 | 0.80 | 0.30 | 0.80 | |
| 10 | 2.10 | 0.72 | 0.40 | 0.86 | |
| 11 | 1.95 | 0.67 | 0.26 | 0.88 | |
| 12 | 2.71 | 0.64 | 0.09 | 0.89 | |
| 13 | 1.58 | 0.65 | 0.46 | 0.92 | |
| 14 | 2.26 | 0.38 | 0.07 | 1.02 | |
| 15 (Crest) | 2.56 | 0.30 | 0.01 | 0.98 | |
| 16 | 2.26 | 0.54 | 0.11 | 0.75 | |
| 17 | 2.30 | 0.46 | 0.26 | 1.03 | |
| 18 | 2.05 | 0.58 | 0.28 | 0.90 | |
| 19 | 1.91 | 0.56 | 0.39 | 1.04 | |
| 20 (W base) | 1.82 | 0.85 | 0.25 | 0.77 | |
| Kalahari Desert, southern Africa | | | | | |
| Crest | 2.21 | 1.76 | 0.03 | 1.35 | Goudie (1970) |
| Slope | 2.51 | 0.88 | −0.14 | 0.92 | Lewis (1936) |
| Crest | 2.37 | 0.57 | 0.07 | 0.86 | |
| Street | 2.49 | 0.89 | −0.26 | 0.91 | |
| Crest | 2.16 | 0.49 | 0.14 | 0.52 | Lancaster (1986)* |
| NE flank | 2.21 | 0.62 | 0.05 | 0.52 | |
| SW flank | 2.26 | 0.59 | 0.07 | 0.53 | |
| Interdune | 2.12 | 0.90 | 0.02 | 0.52 | |
| Negev Desert, Israel | | | | | |
| Base wind | 1.41 | 0.70 | 0.88 | 3.79 | Tsoar (1978) |
| Mid wind | 1.70 | 0.47 | 0.31 | 7.32 | |
| Crest | 1.87 | 0.42 | 0.80 | 5.28 | |
| Slip face | 2.05 | 0.47 | 0.32 | 3.24 | |
| Base lee | 1.18 | 0.75 | 0.52 | 4.00 | |
| Great Indian Sand Desert | | | | | |
| Crest | 2.72 | 2.15 | — | 1.02 | Goudie *et al.* (1973) |
| Simpson Desert, Australia | | | | | |
| Crest | 2.53 | 0.43 | 0.11 | 0.52 | Folk (1971)* |
| Flanks | 2.75 | 0.57 | — | — | |
| Reg | 2.85 | 0.95 | 0.04 | 0.48 | |

* Lancaster (1983*b*, 1986) and Folk (1971) use transformed values of graphic kurtosis ($KgI$), such that $KgI = Kg/(Kg+1)$.

FIG. 1. A 'complex' linear dune in the northern Namib sand sea. Sample transects 1 and 2 lie across this dune.

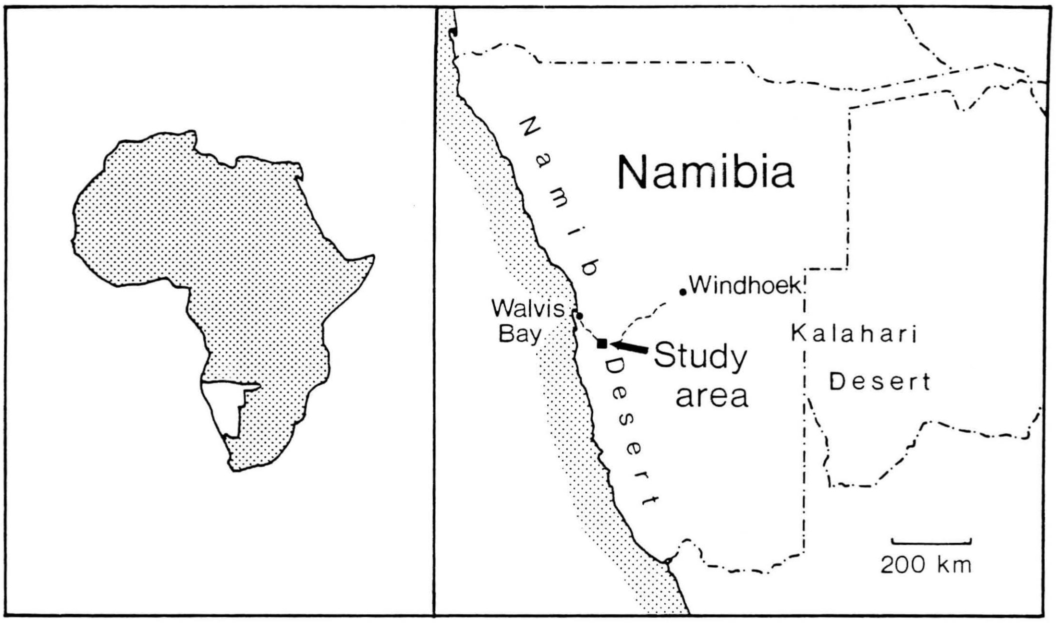
while Lancaster & Ollier (1983), following Rogers (1977), provide substantial sedimentological evidence to support their belief that the majority of the Namib sand has been brought inland from the continental shelf under the influence of a predominantly southwesterly wind regime.

## Techniques

Samples of surface sand were collected from 25 points across the width of the study dune at monthly intervals throughout the period April 1981 to April 1982, giving a total of 325 samples. Sample points were marked by steel posts. These were also used for measuring surface height changes (Livingstone 1985). The sampling sites were designated by the letters A to Y, from W to E across the dune, and were generally 20 m apart. However, near the crest and on the secondary dunes, samples were taken every 10 m. A sample was also taken from the dune crest.

In addition, and in order to examine the extent to which the main study dune could be considered representative of linear dunes in this part of the sand sea, samples were taken from eight cross-profiles on four other complex linear dunes: *ie* two dunes immediately to both the E and W of the study dune (Figs 2 and 3). All samples were collected in a two-day period to avoid the effect of changing wind regime. Samples were usually collected every 20 m across each dune profile, but where exceptionally long dune plinths were encountered this distance was extended to 40 m. A total of 180 samples was collected from these eight profiles. It should be noted that transects 1 and 2 of the present study are on the study dune of Watson (1986).

A portion of each sample was sieved at half-phi size intervals in the range +0.5 to +4.0 phi (0.707 to 0.063 mm); particles finer than +4.0 phi (0.063 mm) were collected in a receiver. The amount of sand retained in each sieve was weighed, and this information plotted as a cumulative frequency curve on arithmetic probability paper. From these graphical representations of the data, percentile values were extracted, and grain-size parameters (mean, standard deviation, skewness and kurtosis) were then calculated according to the formulae of Folk & Ward (1957).



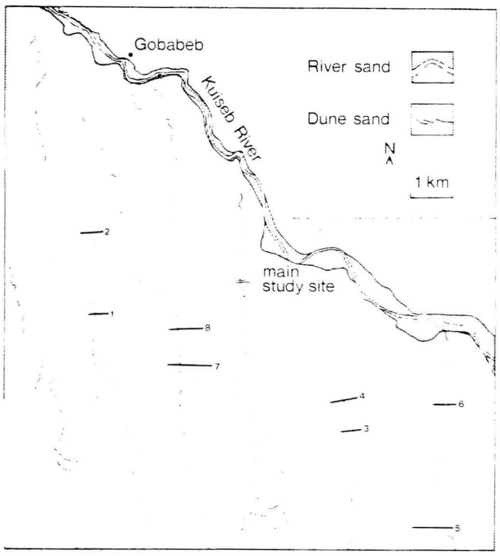




FIG. 2. Location maps of the main study dune and the eight supplementary dune transects.

A summary of the values from the main study dune is given in Table 2; the results are reported in full elsewhere (Livingstone 1985).

## Discussion

### The pattern of variation in grain size and sorting on a complex linear dune

The samples collected from the main study dune and from the other eight transects provide a very clear picture of the change in grain size and sorting across a linear dune profile. Figure 4 is a plot of the mean values of the four grain-size parameters against position across the main study dune, while Fig. 5 shows the changing pattern of mean grain size across the other eight transects. In Fig. 5 position in the cross-section is plotted as distance from the dune crest in an attempt to make the transects sit in comparable positions on the diagram; the values of mean grain size are five-point moving averages—aggregating the data overcomes the problems posed by occasional idiosyncratic values.

A feature of the data from all the dunes sampled is that the range in values of the size distribution parameters is not great. Thus, on the

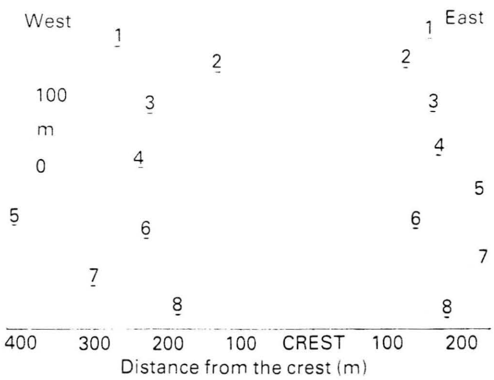



FIG. 3. Cross-sections of the linear dunes at the eight sample transects located in Fig. 2.

TABLE 2. *Average values and range of mean grain size and other size distribution parameters for the main study dune, northern Namib—derived from the 13 monthly samples*

| Sample point* | Size distribution parameters | | | | | |
|---|---|---|---|---|---|---|
| | Mean | | Standard deviation | | Skewness average | Kurtosis average |
| | average $\phi$ | range $\phi$ | average $\phi$ | range $\phi$ | $\phi$ | $\phi$ |
| A | 1.86 | 1.72–1.98 | 0.50 | 0.36–0.61 | 0.36 | 1.31 |
| B | 1.89 | 1.76–2.22 | 0.44 | 0.28–0.57 | 0.32 | 1.41 |
| C | 1.98 | 1.78–2.08 | 0.48 | 0.35–0.55 | 0.33 | 1.10 |
| D | 2.11 | 1.93–2.56 | 0.47 | 0.37–0.52 | 0.32 | 1.00 |
| E | 2.19 | 2.04–2.59 | 0.43 | 0.37–0.50 | 0.31 | 1.02 |
| F | 2.21 | 1.95–2.62 | 0.37 | 0.29–0.45 | 0.25 | 1.07 |
| G | 2.30 | 2.08–2.64 | 0.38 | 0.32–0.46 | 0.18 | 1.00 |
| H | 2.34 | 2.03–2.63 | 0.36 | 0.32–0.41 | 0.13 | 1.02 |
| I | 2.40 | 2.15–2.66 | 0.37 | 0.27–0.43 | 0.12 | 0.99 |
| J | 2.47 | 2.27–2.73 | 0.32 | 0.25–0.36 | 0.03 | 1.02 |
| K–L | 2.52 | 2.32–2.67 | 0.33 | 0.28–0.40 | 0.05 | 1.01 |
| M | 2.50 | 2.16–2.63 | 0.32 | 0.27–0.38 | 0.03 | 1.03 |
| N | 2.44 | 2.25–2.56 | 0.30 | 0.25–0.36 | 0.01 | 0.98 |
| O | 2.08 | 1.88–2.44 | 0.38 | 0.25–0.49 | 0.16 | 0.98 |
| P | 2.40 | 2.10–2.58 | 0.33 | 0.24–0.40 | −0.02 | 0.97 |
| Q | 2.49 | 2.41–2.63 | 0.32 | 0.23–0.42 | −0.04 | 1.04 |
| R | 2.53 | 2.24–2.67 | 0.26 | 0.20–0.34 | 0.01 | 1.03 |
| S | 2.47 | 2.31–2.73 | 0.27 | 0.21–0.34 | 0.04 | 1.03 |
| T | 2.57 | 2.47–2.66 | 0.25 | 0.22–0.29 | 0.04 | 1.01 |
| U | 2.66 | 2.53–2.84 | 0.21 | 0.16–0.29 | 0.06 | 1.06 |
| V | 2.64 | 2.48–2.95 | 0.20 | 0.16–0.25 | 0.10 | 1.05 |
| W | 2.34 | 2.13–2.52 | 0.24 | 0.18–0.34 | 0.07 | 1.07 |
| X | 2.46 | 2.32–2.69 | 0.23 | 0.15–0.34 | 0.15 | 1.15 |
| Y | 2.15 | 1.96–2.29 | 0.38 | 0.27–0.49 | 0.02 | 1.08 |
| Crest | 2.37 | 2.16–2.71 | 0.30 | 0.23–0.35 | 0.07 | 0.99 |

* See Fig. 4 for location.

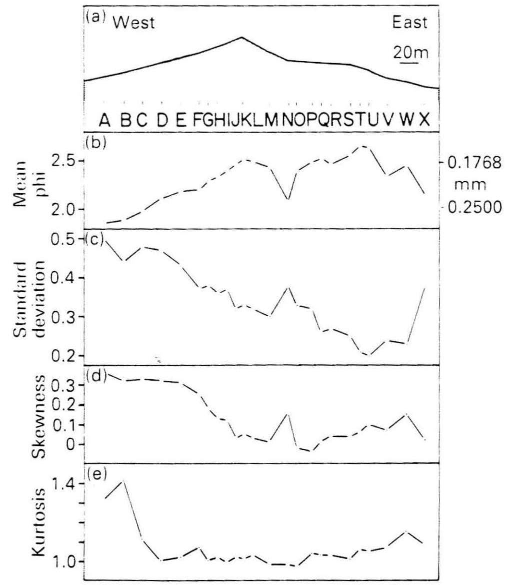



FIG. 4. Variation of the four grain-size distribution parameters across the main study dune.

main study dune, the range of values for mean grain size is from 1.72 to 2.84 phi (0.30 to 0.14 mm). This is directly comparable with the results from the other eight transects. It compares, too, with Lancaster's (1981) reported range of 1.80 to 2.55 phi (0.29 to 0.17 mm), and with Watson's (1986) values of between 1.58 and 2.71 phi (0.33 and 0.15 mm). The measures of grain-size sorting show equally small variations.

Despite the limited range of values, there exist very distinct patterns of variation in grain size and sorting over the dune cross-profiles. Results for mean grain size show that there is a progressive fining of sand from dune base to dune crest. This trend in mean grain size is matched by decreasing values of both standard deviation (*ie* sorting) and skewness from plinth to crest, indicating that the finer crestal sands are also better sorted and the size-distribution less skewed than the coarser plinth sands.

Kurtosis of the size frequency distribution does, however, not seem to be significant in discriminating geomorphic position on the main study dune, returning values close to 1.0 in all the

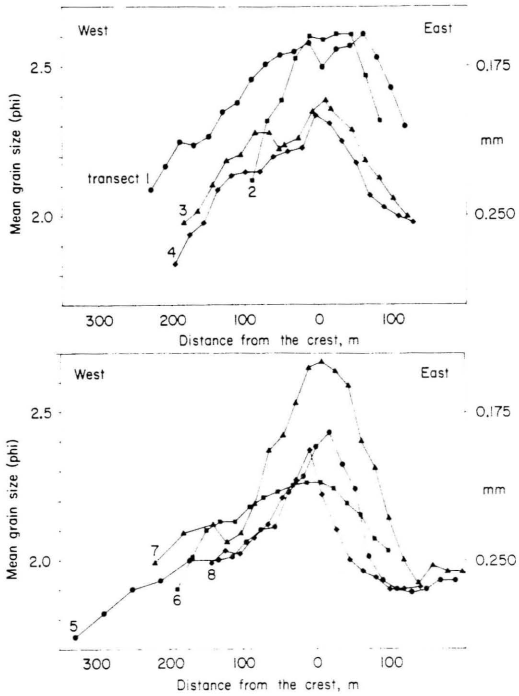



FIG. 5. Five-point moving averages of mean grain size across the eight dune transects located in Fig. 2.

samples except those close to the base of the W slope. Kurtosis is an indication of peakedness in the size distribution, and is therefore a valuable test of a normal distribution. The fact that all the values reported here are close to 1.0 suggests that grain-size populations in most of the samples tend towards a normal distribution. Whereas kurtosis has been used as a good discriminatory parameter in studies that compare widely different sedimentary environments, there is such a small range of values in the samples from the linear dunes in this investigation that it appears to be of little value as a discriminant in a single environment such as here.

In the past, several writers have attempted to show the existence of two or three distinct grain-size populations on linear dunes, and their sampling has often been based on identifiable morphological zones. Bagnold (1941), for instance, divides the dune cross-profile into three main components. First, there is an active crest moving back and forth in response to the seasonal wind regime. Here, finer grains move towards the crest. The crest surmounts a zone that has never been incorporated into a slip face; its sands are of virtually constant grain size. Below this are the coarser grains of the interdune corridor sands. In the Namib Desert, Besler (1983) has divided the dunes into zones of 'aeolian mobility' and 'aeolian stability', while Lancaster (1981) has distinguished between 'crest' and 'plinth' sands.

The present method of systematic sampling at 25 points on a dune cross-profile suggests that there are differences in grain-size distribution at a smaller scale than has been indicated by these previous studies. Indeed, as Watson (1986) has already noted, rather than demonstrating discrete populations, small-scale sampling indicates that there is a progressive change in the grain-size distribution parameters across the dune (Figs 4 and 5).

It is possible, however, to move beyond Watson's general observation of gradual change. Assuming that the values derived here for monthly samples at each point on the study dune are representative of the sand at that point, the 13 samples from one point can be compared with the 13 samples from another using a statistic such as the Mann–Whitney U. It is apparent, using this statistic for values of mean grain size, that there is a statistically significant change every 20 or 30 m along the dune surface, although the pattern becomes less clear in the upper part of the dune. This contrasts strongly with Warren's (1971) data that show uniform mean grain sizes over most of a seif dune E of Adrar Madet.

Given the progressive change in grain size across the dune, the implication is that it would be difficult to find a justifiably representative sampling point on morphological criteria alone. For example, samples from point C (Fig. 4) are no more or less representative of sand from the W plinth of the study dune than samples from point E, but they are statistically significantly different. When Folk (1971) observed that it was important to know how size parameters varied with the micro-morphology of the sampling site he was warning against one sample from a dune being taken as typical of the whole dune, but this warning can now be seen to be too conservative. In a system the size of a Namib linear dune, there are significant and progressive changes in grain-size distribution right across the dune profile.

Within the general pattern of grading from coarser, poorly sorted, and more skewed samples at the dune base to finer, better sorted and less skewed samples at the crest, some deviations do occur. On the main study dune, the progressive fining that is evident in traversing up the W slope continues beyond the crest to the zone of secondary dunes around points U and V. This pattern is broken only by the coarser sand found towards the base of the summer slip face around point O. This pattern is repeated on the only other transect with a secondary dune system (transect 1), and is also found in the results reported by Watson (1986). So, while Lancaster

(1983*b*) believes that the sands of E flank dunes tend to be slightly coarser than adjacent crest sands, the evidence from the present study suggests that this is not always the case. It would be difficult to generalize from the results of three dunes, but clearly Lancaster's assertion is not universally true.

Thus far, the discussion has centred on *intra*-dune variation of grain size and sorting parameters. The data from the main study dune along with the results from the other eight transects also provide an opportunity to investigate *inter*-dune grain-size and sorting variations on five neighbouring complex linear dunes. Once again, the Mann–Whitney U Test has been employed to examine the significance of any variation of mean grain size between dunes. It is apparent from the results that there is little basis for assuming homogeneity of the dunes in this part of the sand sea. While there appear to be no significant differences between any pair of transects from the same dune (*eg* transect 1 *cf* transect 2, *etc.*), there are statistically significant differences between dunes.

This has some implications for studies which seek to provide regional grain-size values. Studies such as those of Besler (1980) and Lancaster (1982*c*) for the Namib Desert, Folk (1971) for the Simpson Desert, and Warren *et al.* (1985) for the Wahiba Sands have based work on the premise that it is possible to calculate characteristic, regional values for grain-size values. Lancaster (1982*c*), for instance, has described a progressive fining to the N and W in the Namib Desert, reporting crestal sands with mean sizes coarser than 2.30 phi (0.2 mm) in the S and finer than 2.50 phi (0.18 mm) in the NW. The lack of any wide-ranging variation in the results of this study lends some support for this belief in a regional context. However, any assertions about transport processes and so on must be qualified by the fact that there may be considerable between-dune variance even though the range of values is relatively small.

A number of conclusions can be drawn from the spatial variation of grain sizes on the main study dune and its near neighbours. First, there are definite, discernible patterns of change in three of the grain-size distribution parameters—the mean, the standard deviation and the skew—but not in kurtosis. However, in general, the range of values for each parameter is small. The cross-profile trends demonstrated by the first three moments of the distribution are not dissimilar to those published by other workers, but greater detail highlights some important deviations from the general trends. Furthermore, the discovery of significant between-dune differences, when coupled with the fact that there are small-scale differences within a single dune, suggests that the exact location of the sampling point on the dune should be declared if comparisons are to be facilitated with other work and other places.

## The relationship of grain size and sorting measures to process

In grain-size studies it is axiomatic that different processes provide different combinations of grain sizes, that certain modes of transport move grains of particular size preferentially, and, therefore, that cross-dune patterns describe dune dynamics in some way. Within a linear dune environment there are four discernible modes of aeolian transport: creep, saltation, suspension and the avalanching of sands on an active slip face. It would be of value to link these dynamic processes with grain-size measures, yet any attempt to discern process from grain size is fraught with difficulty, for it requires a high degree of inference, and there is always a danger that an argument will become circular. It is, none the less, possibie to make some preliminary observations about the relationship between geomorphic process and sedimentary characteristics.

For the majority of samples, the cumulative grain size–frequency plots give more or less straight lines, indicating that the sand at each point comes from one population rather than from the mixture of two or more populations; this is confirmed by skewness values close to 0.0 and kurtosis values close to 1.0. The supposition might therefore be that these distributions, composed largely of sand within the size range from +2.0 phi to +2.5 phi (0.25 to 0.18 mm), indicate material which is predominantly moved by one process, presumably saltation. The apparent mixing of two populations at the base of the dune slopes, illustrated by Fig. 6, could then be the result of a combination of saltation and traction loads. The coarser fraction would represent material moved by creep along the inter-dune corridors and largely unable to ascend the dune slopes. This confinement would also explain the increased fining of sands towards the crest; a progressively smaller proportion of these coarse grains would be transported to the crest (Lancaster 1981).

Within this pattern of gradual fining towards the crest, some variation exists. There is some statistical similarly between dune base sand and sand at the base of the slip face, represented by samples from point O. As Bagnold (1941) noted, in an avalanching slip face, coarser grains tend

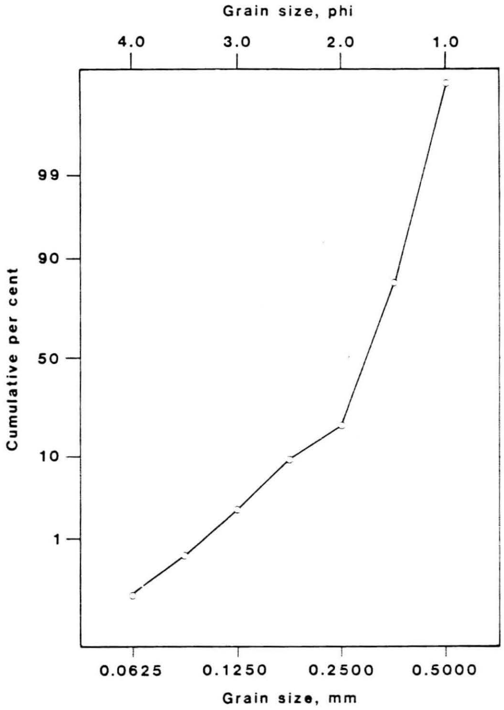



FIG. 6. Cumulative frequency grain size curves for a dune base sample. A probability scale is used for the ordinate.

to be pushed preferentially to the surface and thence to the base of the slope. Conversely, residual slip-face sand tends to be finer and skewed, the skewness representing a truncation of the coarse fraction.

It is not universally the case that dune crests are finer than plinths. In Australia, for instance, an explanation based on the nature of the source sand has been forwarded by Folk (1971) to explain the much finer reg deposits of the Simpson Desert linear dunes (Table 1). His suggestion is that the source of material for the dunes is fine-grained alluvial deposits, and that the fraction most mobile in air (around +2.5 phi, 0.18 mm) has been removed to build the dunes. This is reflected in average values for mean grain size on the crests of 2.53 phi (0.17 mm), and finer residual reg deposits with a mean grain size of 2.85 phi (0.14 mm). This reference to source material might also explain the results of Lewis (1936) and Lancaster (1986) for the Kalahari, although these sands show only small differences between crest and corridor samples (Table 1).

According to Buller & McManus (1972), the sand fraction which can be moved by the wind lies in the range 2 to 3 phi (0.25 to 0.13 mm). This would seem, however, to be only the fraction moved by saltation for coarser grains can be moved by creep, and Friedman (1961) suggests an absolute upper limit for sands to be moved by wind of +1.49 phi (0.36 mm). In fact, Tsoar's (1978) figures do not confirm that it is exclusively the 2 to 3 phi (0.25 to 0.13 mm) fraction from which dunes can be built. He reports sand at the crest of a linear dune in the Negev Desert, Israel, with a mean grain size of 1.87 phi (0.27 mm), compared with 1.41 phi (0.38 mm) and 1.18 phi (0.44 mm) at the base. Cooke & Warren (1973) report that most sand-sea deposits lie in the range −1.0 phi to +4.0 phi (2.00 to 0.06 mm), and this tallies with Ahlbrandt's (1979) reported range from −0.68 phi to 3.40 phi (1.60 to 0.09 mm) for 506 dune-sand samples. The evidence would suggest that, as long as sand (or indeed clay peds in lunettes) of a size which can be transported by the wind is available, factors other than grain size control dune form. Wherever possible, the processes of sand transport will move sand of around 2.5 phi (0.18 mm) to build dunes; but, as the results of Tsoar's (1978) study show, dunes can be built even when the source sand is outside this range.

In his discussion of bedform hierarchies, Wilson (1972*a*) proposed a causal link between grain size, represented by the size of the 20th percentile, and dune geometry (dune height and wavelength). Lancaster (1982*a*) has supported this argument, presenting a strong relationship between the size of the 5th percentile in a grain-size distribution and the spacing of transverse and barchanoid dunes of the Skeleton Coast in northern Namibia, though he has not been able to find such a clear relationship for Namib linear dunes (Lancaster 1983*a*). Watson (1986) finds a strong linear relationship between height above the interdune corridor and median grain size on his study dune. But while this same general trend towards finer sand at the crest has been found in this current study, there is no *general* relationship between dune height and sand size (Figs 4 and 5): taller dunes do not have finer crests.

The range of values for grain size from linear dunes in different sand seas suggests that grain size does not control dune form. This is supported by the work of Wasson & Hyde (1983*a*, *b*) in Australia, who also fail to find good relationships between grain size and dune geometry. They suggest that dune form is better understood by referring to the volume of sand supplied and to the wind regime.

Even though grain size may not control dune form, grain-size distributions are a response to process, though the nature of the relationship remains to be explained. Besler (1983) has used

Friedman's diagram (Friedman 1961) and plotted mean grain size against standard deviation for 393 samples from the Namib, the Kalahari, the Sahara and the Rub al Khali deserts. Besler re-labels Friedman's zone of overlap between aeolian and fluvial deposits as a zone of 'aeolian stability', by which she mean deposits which are stable in an aeolian environment. Yet both Vincent (1985) and Livingstone (1987) have shown that active aeolian sediments may lie in Friedman's zone of 'overlap', and both argue that there is no justification for Besler's division of aeolian deposits. Livingstone demonstrates that there is a progressive rather than discrete change of surface activity across the dune profile, and that there is no more validity in dividing the sand samples on the basis of activity than there is on the basis of morphology.

It is apparent that the grain size of the source sand does not control aeolian dune form except in that material within the range moveable by the wind must be available. Grain-size distributions certainly do respond to process as shown by the fact that patterns across the Namib linear dunes are not random. Indeed, it is possible to make inferences about the relationships between grain size and process. However, it is not possible to divide the Namib dunes into discrete zones that carry connotations for grain size and process or grain size and morphology as Bagnold, Besler and Lancaster have done.

### Variation of grain-size parameters with time

Given that grain-size parameters reflect process, even if not in the manner envisaged by some workers, it might be expected that there would be a temporal pattern in sympathy with changes in process. The seasonal, multi-directional wind regime found in the northern part of the Namib Sand Sea controls dune dynamics. Broadly speaking, in summer, there is erosion on the W flank of the dunes and deposition on the E flank, and in winter, the converse occurs (Livingstone 1985). Thus the slip face which develops in the lee of the crest is on the E side in summer and on the W side in winter. Consequently, we would expect to be able to recognize seasonal variations in surface grain size in response to these changing patterns of wind.

In order to test this, samples were taken from the main study dune every month for a year. The results for any one sampling point show no obvious pattern of change related to time. However, inability to find patterns at individual sampling points may reflect the fact that sand is so mobile that it is adjusted to highly localized factors. It is possible to smooth out the effects of some of these micro-scale, localized factors by aggregating data. Figure 7 shows the month-by-month variation of the average of two parameters (mean grain size and skewness) for the 25 sample points on the study dune. Difficult though it is to invoke a cyclic trend from the study of only one cycle, Fig. 7 shows that the dune sand becomes finer and its size distribution less skewed in the winter months of easterly winds. This pattern can be explained by the seasonal movement of finer sand from the E flank onto the crest and upper W slopes. In other words, the crest zone has a finer grained source area at this time of year. There is no seasonal trend in values of the standard deviation. However, a seasonal pattern of skewness values emerges. Negative (finer-grained) skewness in aeolian sediments is often associated with slip faces, and apart from a single value of −0.08 recorded at sample point H in January, the other 10 negative (fine) skews recorded on the W slope of the study dune all occurred in the winter months, five of these in September 1981 after particularly strong easterly winds.

It has been possible to demonstrate for the first time that, on one particular linear dune in the northern Namib Sand Sea, cyclical changes in the wind regime produce cyclical changes in

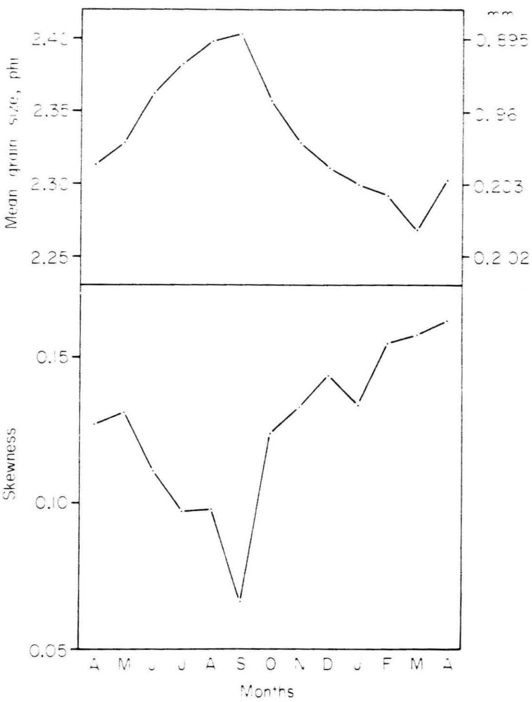



FIG. 7. Month-by-month change of mean values of: *Top*—mean grain size; *Bottom*—skewness.

sedimentary characteristics. This supports the belief that grain size at the surface of a dune responds dynamically to process. The implication of this finding is that it may not be possible to compare samples taken at different stages in the annual sedimentary cycle. It further implies that samples taken over long periods of time as part of studies of grain size over extensive geographical provinces might not be strictly comparable.

## Conclusion

A number of points should be made factors that may affect grain-size parameters before moving to the specific conclusions of this study. Firstly, the sampling of more than a single lamina at the sand surface may well involve inclusion of a number of sedimentary events, although Bagnold believes that 'differences between such layers are usually of a very minor nature' (Bagnold 1941, p. 119). Secondly, in a zone of the dune where the surface is subject to erosion rather than deposition, the sampling of the surface may involve mixing the currently mobile load and the deposits of past events: a surface sand sample is not always the product of contemporary processes. Thirdly, micro-topographical features may induce very small changes in a sediment as mobile as dune sand.

This intensive study of grain-size variation on a single complex linear dune and its near neighbours in the Namib Desert has shown that a discernible pattern across the dune does exist, and that changes in the size distribution are gradual, not discrete. In general, crest samples are finer, better sorted and less skewed than samples from the dune plinths. There is also evidence that measurable differences occur between dunes in the same area, and that while they may not diverge far from regional averages, they may be significant. It is therefore important that studies reporting grain-size parameters should be more specific about the location of sample points, both within the sand sea and on each individual dune.

The fact that grain size is not random across the width of the dune indicates a sympathetic response to variations in process across the dune. However, grain size does not seem to control dune form in the way that some workers have envisaged.

Finally, there is some indication that grain size has a seasonal regime. As a whole, the dune sand becomes finer under the E winds of winter while the size distribution becomes negatively (fine) skewed. There is sufficient evidence to suggest a cyclical change in grain size.

ACKNOWLEDGMENTS: The funding for the project came from a NERC Research Studentship held at the School of Geography, University of Oxford. Permission to work in the Namib Naukluft National Park was granted by the Department of Nature Conservation, Namibia, and facilities at the Namib Desert Research Station were made available through the Desert Ecological Research Unit. I am indebted to Jane Sinclair and Rose Whittington who helped with the laborious tasks of sample collection and analysis.

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