EARTH SURFACE PROCESSES AND LANDFORMS, VOL. 14, 317–332 (1989)

MONITORING SURFACE CHANGE ON A NAMIB LINEAR DUNE

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Received 9 May 1988
Revised 17 October 1988

ABSTRACT

In tackling the apparently intractable problem of linear dune initiation and maintenance there has been a move away from large-scale deductive models to smaller-scale field studies of individual dunes. This paper reports a study of surface change on a large, complex linear dune in the Namib Desert, southern Africa.

The dune surface responds to a markedly seasonal wind regime. In summer westerly winds erode sand from the west flank of the dune and deposit it on the easterly lee side of the dune crest. In winter this pattern is reversed. Easterly winds erode sand from the east slope and deposit it on the west slope. The crest therefore moves back and forth some 15 m each year returning at the end of a year's cycle to its position at the beginning. The position of the base of the dune appears to remain fixed, even though sand is moving throughout the dune system. The dune does extend northward along some resultant of the westerly and easterly winds.

Despite relatively high levels of activity, especially at the dune crest, there is no evidence of the breakdown of the linear dune form. The conclusion must therefore be that linear dunes can be maintained in bimodal wind regimes and are not necessarily related to unidirectional parallel regimes as others have suggested.

KEY WORDS Sand dunes Linear dunes Namib Desert

INTRODUCTION

The past decade has seen a shift in approach to the problem of linear dune initiation and maintenance. Deductive theories have given way to smaller-scale field studies, often of individual dunes. The thinking has been that until there are careful empirical studies of sand budgets and wind flow patterns on these dunes, little can be said about their dynamics. In the final sentence of his review Lancaster stated that

> 'The character and formation of linear dunes has remained difficult to explain for so long only because detailed studies of process and form have been so few.'
> (Lancaster, 1982, p. 501),

and, in similar vein, Warren and Knott observed that

> 'the scale of study that will yield and is now yielding the greatest advance is the 'graded' scale of the single dune.' (Warren and Knott, 1983, p. 343).

The most notable recent advances in the understanding of linear dune dynamics have therefore resulted from single dune studies. These studies have been concerned either with sand budget, surface change and surface sand movement (Lancaster, 1987b; Tsoar, 1983; Tsoar and Yaalon, 1983), or with wind flow patterns over these dunes (Lancaster, 1985; Livingstone, 1986; Tsoar, 1985). In particular, researchers have started to explore patterns of shear stress acting on the dune surface, and the effect of changes in surface shear stress on the equilibrium form of dunes (Lancaster, 1987b; Watson, 1987).

It is apparent that if an understanding of the dynamics of linear dunes is to be approached, information

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about the way in which the dune is changing with time must be collected. This involves an investigation of the sequencing of events—the history or evolution of the landform—and some measurement of the rates at which the morphology of the dunes is changing. In order to gather this information, a study was undertaken of the dynamics of a complex linear dune in the northern Namib sand sea (Livingstone, 1985). This paper reports that part of the project concerned with dune surface change.

LINEAR DUNES

A wide range of terms—including longitudinal dune, seif dune, and sand ridge—has been used to describe dunes which can all be covered by the single term 'linear dune'. A 'linear dune' is defined here as a dune in which net sand transport is parallel to the crestline and in which the long-axis dimension greatly exceeds the cross-dune width. This definition involves no implication of formative wind direction.

Lancaster (1982), following McKee (1979), subdivided linear dunes into 'simple', 'compound', and 'complex' types. Simple dunes consist of a single narrow dune ridge without secondary features; compound dunes consist of two or more closely spaced parallel or converging narrow dune ridges on the crest of a much wider or larger plinth (equivalent to Bagnold's (1941) 'whalebacks'); complex dunes are generally the largest type with a variety of secondary forms (often star and barchanoid dunes) developed on their flanks or summits.

There exists a considerable literature, reviewed by Lancaster (1982), covering the origin of linear dunes. While Mainguet (e.g. 1984) argued that the dunes are residuals of erosion of interdune corridors, most believe them to be predominantly depositional. The central debate has been between those who regard them as formed by strong, unidirectional winds, often associated with paired roll-vortices (e.g. Bagnold, 1953; Besler, 1980; Glennie, 1970, 1987; Hanna, 1969), and those who believe linear dune extension to be along a vector resultant of a bi- or multidirectional wind regime (e.g. Livingstone, 1986, 1988a; Tsoar, 1978, 1983; Wasson and Hyde, 1983).

Some recent work has attempted to establish a distinction between longitudinal dunes or sand ridges and seifs (sayfs) (Mainguet, 1984; Tsoar and Møller, 1986). This distinction is made on both morphological and genetic criteria. Morphologically, sand ridges have concave slopes and relatively straight crests, while seifs have very sharply defined crests and a more meandering plan-form. Genetically, it is argued that longitudinal dunes or sand ridges are formed by uni-directional winds blowing parallel to the long axis. Mainguet (1984) invokes a single roll vortex as the dune-forming mechanism, while Tsoar and Møller (1986) argue for a process related to vegetation cover for dunes which, confusingly, they term 'linear'. It is argued that seifs, on the other hand, are formed in non uni-directional winds. The term 'linear dune' avoids these genetic connotations.

TECHNIQUE

In order to monitor dune surface variation, a grid of 58 steel posts was established in October 1980 at one site on a complex linear dune in the northern Namib sand sea in southern Africa. The site is approximately 8 km southeast of the Namib Research Institute at Gobabeb (23°34′S, 15°03′E) (Figure 1). Here the dune is aligned roughly north–south, is 350 m wide and 50 m high. The study dune displays the cross-sectional asymmetry typical of dunes in this part of the sand sea, with a relatively uniform west flank and a series of secondary ridges and barchanoid features on the east flank (Figures 2 and 3).

At the start of the project an optical theodolite was used to establish the relative positions of the posts and thereby of the dune surface. The steel posts were then measured every week using a steel tape for four years until October 1984.

There is no published report of this technique of post measuring being used to monitor movement on linear dunes, although barchans (Howard *et al.*, 1978), blow-outs (Harris, 1974; Jungerius *et al.*, 1981), networks (Warren and Kay, 1987; Warren, 1988) and draas (Havholm and Kocurek, 1988) have been examined in this way. Fryberger *et al.* (1984) reported a simpler variation of the technique which is better suited to smaller dunes. They monitored the progress of a small barchan in Saudi Arabia by establishing a single post in front of the dune and making measurements of the advancing dune front from the post using a tape and compass. Tsoar (1978) monitored the development of a simple linear dune by using level and staff measurements made

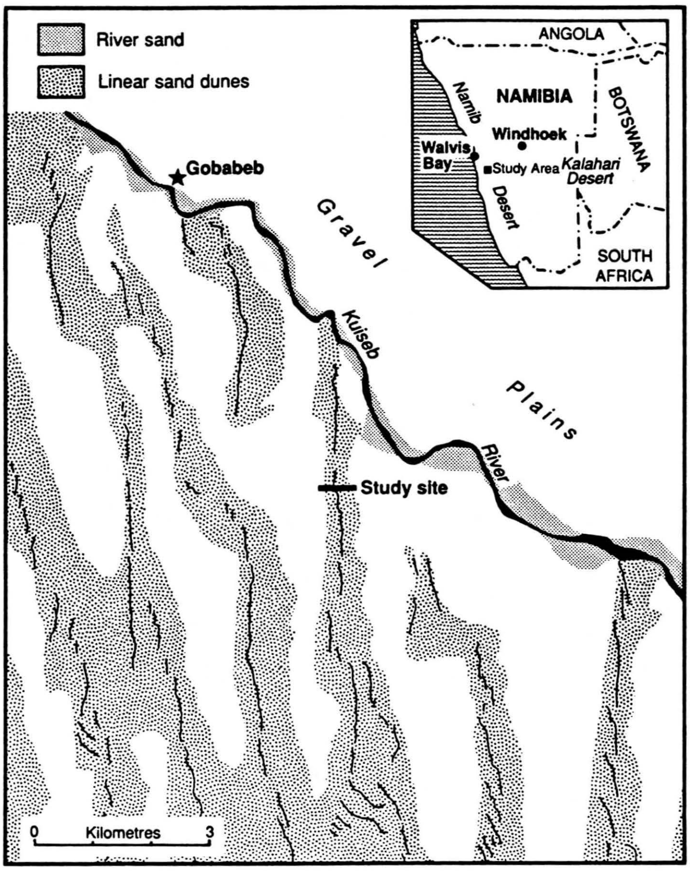

Figure 1. Location of the study site in the Namib Sand Sea, southern Africa

at the end of the summer and winter seasons. Warren and Kay (1987) and Warren (1988) have employed a variety of techniques including photogrammetry and successive theodolite surveys every six months at three sites in the Wahiba sand sea in Oman to construct computer-based Digital Terrain Models (DTMs). Theirs is the first study to examine the behaviour of a group of dunes in a network rather than single dunes.

In the Namib Desert, Besler (1975, 1980) has been monitoring the advance of the tips of small, simple linear dunes throughout the northern part of the sand sea since 1969. Her study sites are not typical, however, of the massive linear dunes which cover much of the Namib sand sea. Concurrently with the present study, as part of the Kuiseb River Project, Ward (1984) measured the northward advance of the tips of the linear dunes into the bed of the ephemeral Kuiseb River using steel posts arranged in a series of grids. He reports rates of advance between 0 and $1{\cdot}85\ \mathrm{m\,a^{-1}}$. Lancaster also undertook a one-year post-measuring project at three sites on complex linear dunes, taking measurements once a month. The results of neither of these studies have been published in full, although a summary of Ward's results is presented in Ward (1984) and Lancaster has reported some of his results (Lancaster, 1985, 1987b).

WINDS IN THE NORTHERN NAMIB SAND SEA

The wind regime of the northern Namib sand sea is well documented as a result of the efforts of the Desert Ecological Research Unit at the Namib Research Institute (Lancaster *et al.*, 1984). The dunes are subjected to a seasonal regime in which winds of low to moderate speed blow from the southwest and northwest during

Figure 2. West flank of the study dune

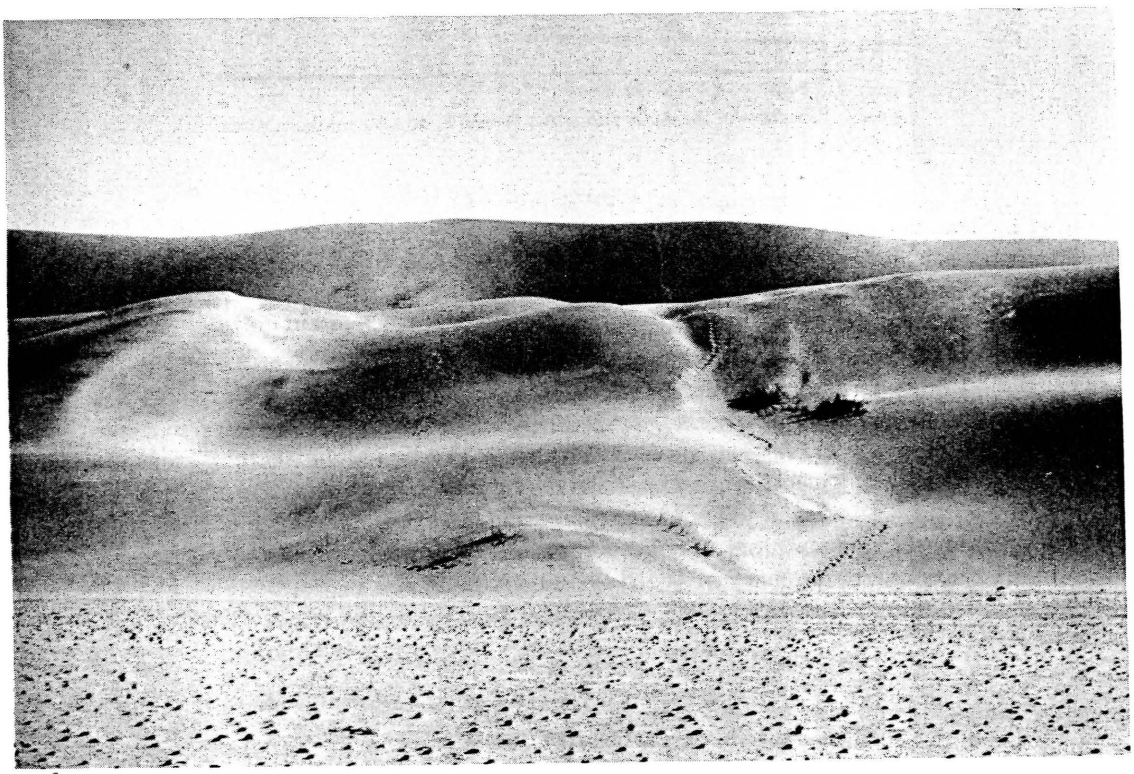

Figure 3. East flank of the study dune

summer (October to April) while high magnitude, low frequency, easterly winds occur in winter (May to September).

The seasonality and asymmetry of the wind regime is illustrated in the sand roses drawn from the wind data provided by a wind recorder (anemometer and vane) established in the middle of the interdune corridor immediately to the west of the study site. When calculating bulk transport of sand, most authorities follow Bagnold (1941) and others in employing some variation of the third power of velocity, usually excluding winds below the threshold for sand movement. Sarre (1987) has provided a review of these equations. For this study calculations of sand drift potential for each compass direction were made using the simplified formula

$$Q \propto V(V - V_t)^2$$

where Q is the sand drift potential, V is the measured wind velocity, and V_t is the threshold velocity for sand movement (Fryberger, 1979). As each record was of one hour's wind no term allowing for duration is required.

From the sand transport roses (Figure 4) the seasonality of the wind regime in the northern Namib sand sea is plain. There is also an asymmetry of the frequency distributions of wind speeds from either side of the dune (Figure 5). It is clear that the linear dunes of the northern Namib sand sea exist in bidirectional wind regime, not in a subparallel regime.

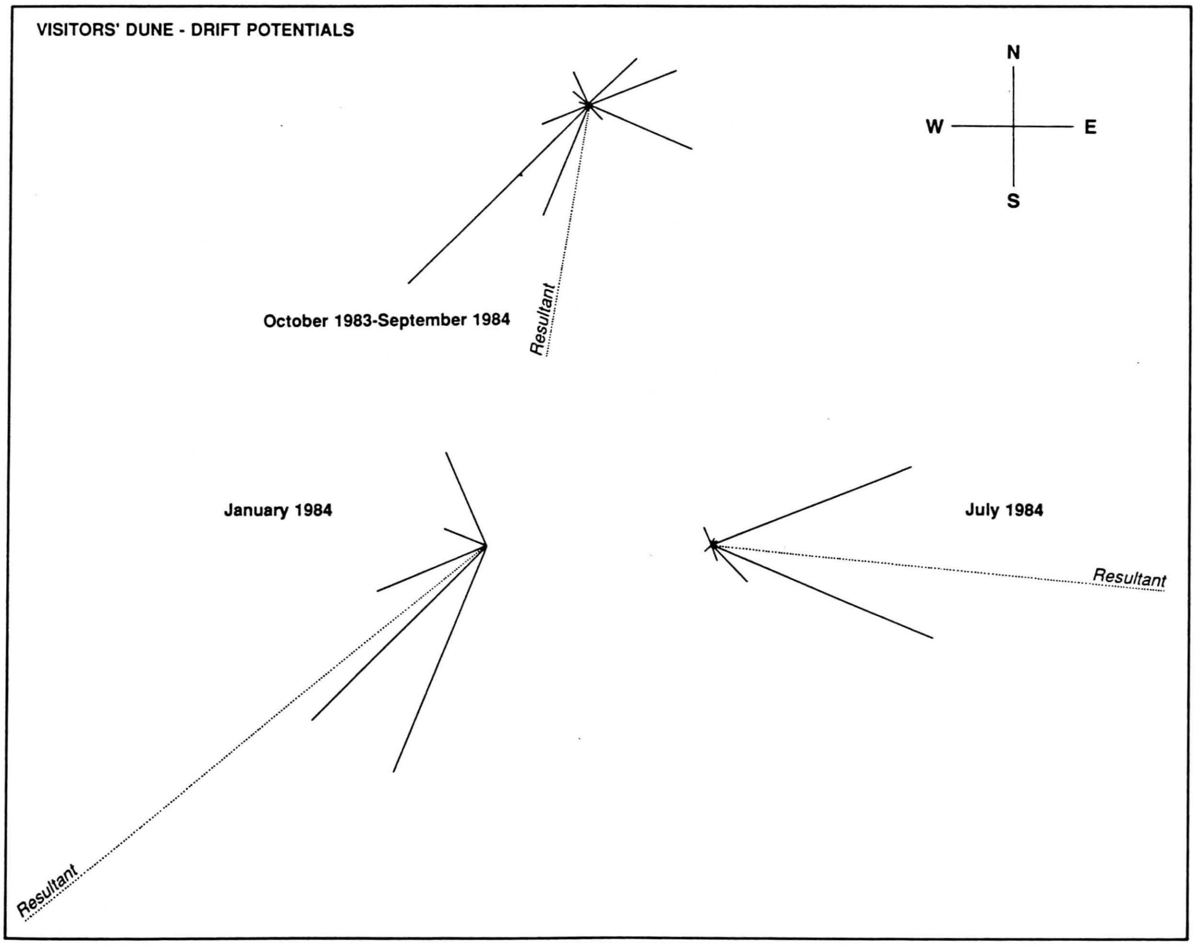

Figure 4. Sand drift 'roses' for: (a) the year October 1983–September 1984, (b) a summer month (January 1984), (c) a winter month (July 1984). Values are calculated using the expression $V(V - V_t)^2$. Arm lengths are therefore proportional to sand drift potential but do not represent calculated values for bulk transport

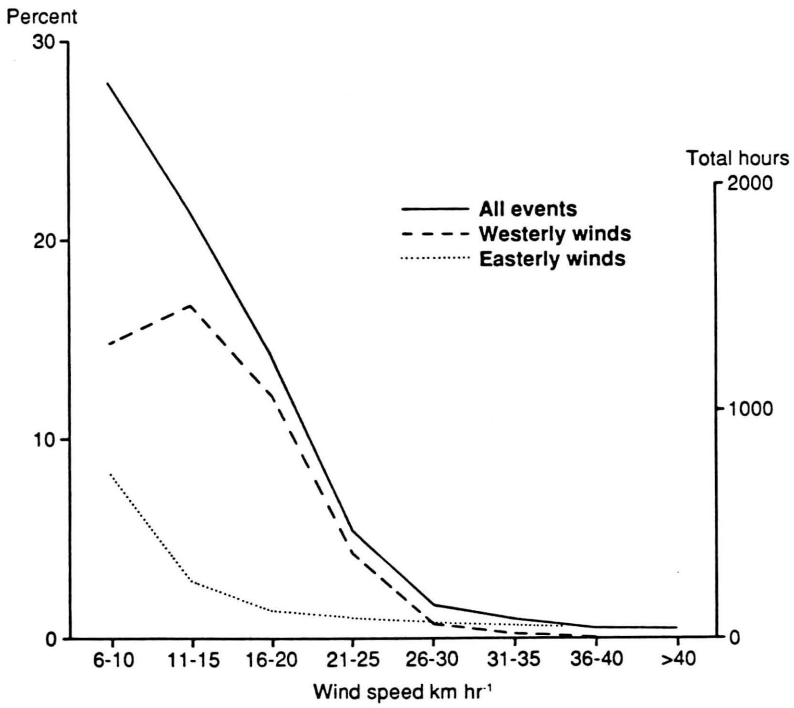

Figure 5. Frequency distribution of wind speeds from the east and west

There is, however, some discrepancy between the calculated resultant for potential sand transport which is from roughly 10 degrees west of south and the dune alignment which is roughly 10 degrees east of south. Discounting errors in the data, the most likely explanation is that a single wind recorder on an interdune corridor provides only a crude indication of wind regime on a dune, particularly dunes of the size of those in the Namib. Drawing heavily on the work of micrometeorologists and applied mathematicians, geomorphologists have shown recently that a dune's intrusion into the atmospheric boundary-layer has an effect on both the speed and direction of that wind (Lancaster, 1985; Livingstone, 1986, 1988a; Tsoar, 1985). The 'speed up' of winds as they flow over the dune means that the highest speeds are recorded at dune crests and therefore that sand moves at the crest more often than at the base. The 'actual' threshold for sand movement at the wind recorder on the interdune corridor is higher than the 'apparent' threshold at which sand moves at the crest. The speeds and directions documented by the wind recorder are therefore only surrogates for the recorders which could be placed throughout the dune system. The discrepancy between calculated and actual resultant sand transport direction may therefore be more an indication of the inadequacy of recording than a true variation. If this is the case, it may be that 20 degree discrepancies documented elsewhere are not so much indicative of relic features as of the complexity of wind flow patterns over the dunes.

DUNE SURFACE CHANGE

Patterns of activity on a dune cross-profile

Monitoring dune surface change by measuring posts provides data concerning the sand budget. Figure 6 gives some indication of levels of activity in different zones of the dune's cross-profile. It is clear that these dunes are far from dynamically homogeneous. The dune cross-profile can be divided in to six morphological and dynamic units (Figure 7), and these zones of geomorphological activity correspond very closely to the morphological units recognized by others (Besler, 1980; Lancaster, 1982). The study site has a relatively restricted east plinth when compared with others in the region and an east plinth with similar levels of activity

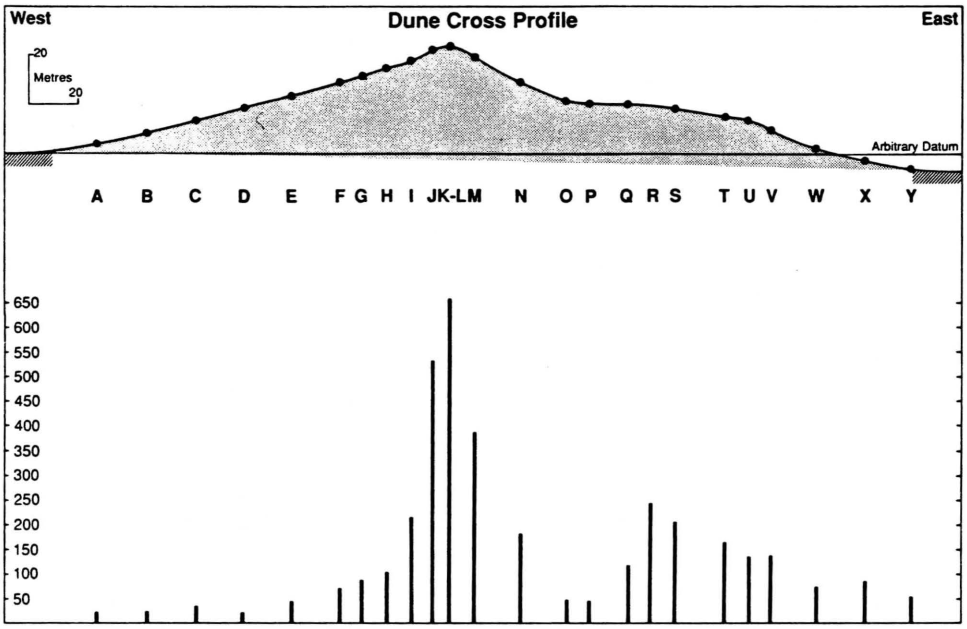

Figure 6. Levels of surface activity across the dune. Ordinate scale is average surface change (erosion and deposition) in a four week period in mm. Averages are calculated from four years' data

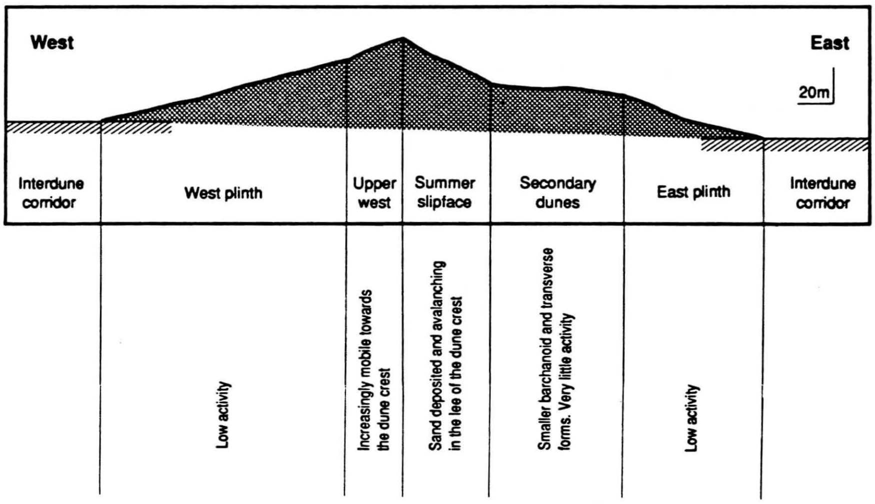

Figure 7. Zones of geomorphological activity at the study site

to the west plinth could be predicted on other dunes. These results are confirmed by data from another site on the same dune and by results from Lancaster's three sites.

The pattern of surface change is directly related to the pattern of wind speeds. On the windward slope wind speeds increase towards the crest as a result of the compression of streamlines effected by the dune's intrusion into the boundary-layer (Lancaster, 1985; Livingstone, 1986, 1988a; Tsoar, 1985). Elsewhere, Livingstone (1985) has shown that values of wind speed calculated from the Jackson (1977) equation, formulated from work on isolated low hills, correspond closely with values measured in the field (see also Tsoar, 1985). Figure 8 shows that dune surface activity is directly related to a measure of relative surface wind speed derived from the Jackson equation.

Seasonal (cyclic) patterns of erosion and deposition

The dune responds to seasonal variations of the wind regime. The combination of across-dune patterns of activity with seasonal cycles of erosion and deposition is illustrated in Figure 9. At post J, for instance, peaks of surface altitude are clear around weeks 52, 104, 156, and 208 in October at the end of winter season of easterly winds. On the other side of the crest at post N peaks are in summer. Towards the dune base levels of activity are far lower, although even at post A with the 'eye of faith' it is possible to discern peaks at the end of winter.

In summer, when winds blow predominantly from the west, wind speeds increase up the west slope of the dune (Livingstone, 1986; 1988a). Increasing wind speed increases sand transport capacity (see equation above), and the surface is eroded. A sudden drop of speed in the lee of the crest leads to considerable, rapid deposition, and the build up of a slipface at the sand's angle of repose of around 34 degrees. In winter, when sand-moving winds are largely from the east, the pattern is reversed and erosion is on the east flank, deposition on the west. This reversing pattern of zones of erosion and deposition is shown in Figure 10 which represents summer and winter months (see also Lancaster, 1987b, Figure 1, p. 517).

The net transfers of sand from west to east in summer and east to west in winter which cause the vertical shifts of the surface seen in Figures 9 and 10 also cause a lateral movement of the dune crest. Figures 11 and 12 show the cross-section and plan views respectively of the dune crest at different moments in time. These diagrams show a repeated pattern of change in which the crest returns to more or less the same position each year. This cyclicity is seen to a lesser degree right across the dune surface. The northward movement of sinuosities in the dune crest adds some 'noise' to the pattern, and it would be foolish to make unequivocal statements about cyclic change in a system moving this slowly on the basis of only four cycles. Nonetheless, there is every indication of a balance of westward against eastward movement of the dune crest. There is also evidence of this seasonality in some secondary features on the east flank of the dune (Livingstone, 1988b).

In the southwesterly winds of summer the lee side slipface is to the east of the crest, while in the easterly winds of winter the slipface is on the west side of the crest. The dunes are forming normal, not parallel, to the formative winds. It is only the coincidence of a seasonally reversed wind pattern which produces these linear dunes.

It is nevertheless somewhat misleading to think of linear dunes as supporting two transverse dune systems in the same pile of sand at different times of the year (Tsoar, 1985). In order to maintain its cross-sectional form as it progresses downwind, a transverse dune must undergo erosion at each point on its stoss slope

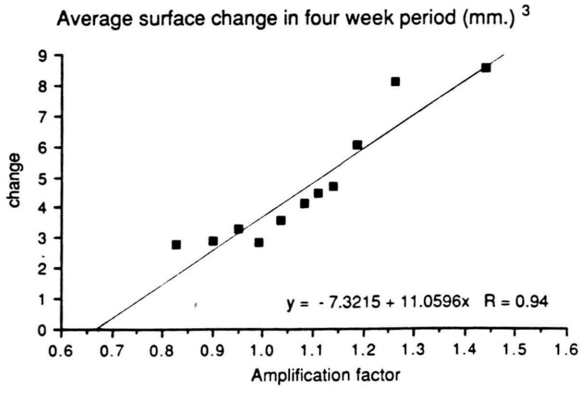

Figure 8. Relationship between the relative wind speed (amplification factor (Jackson, 1977)) and dune surface change

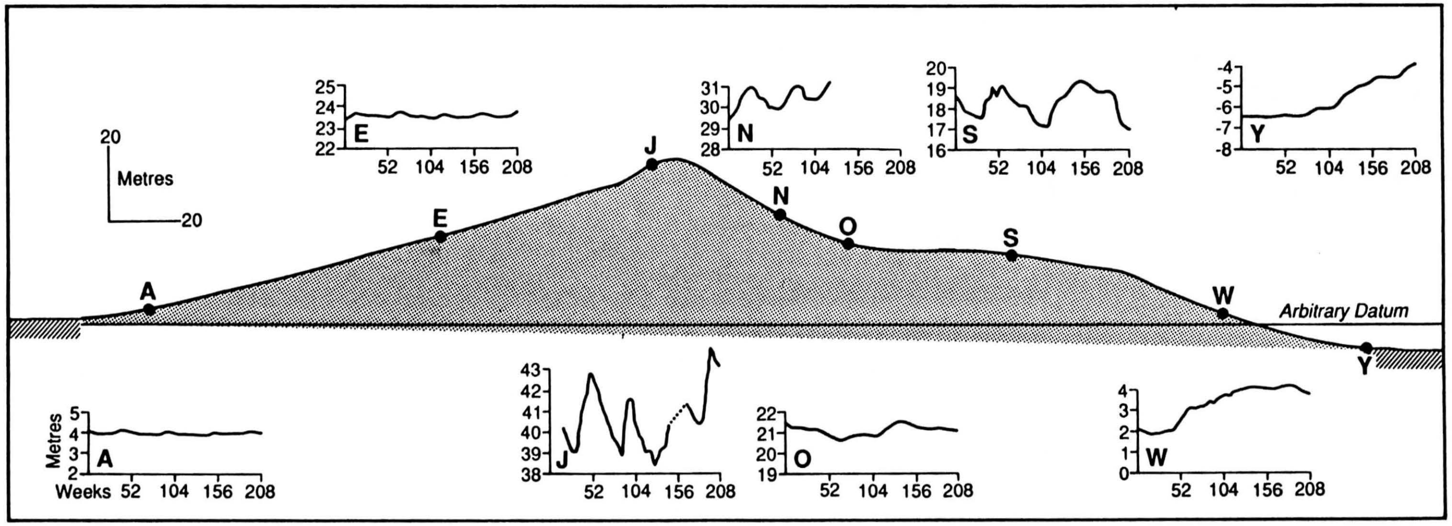

Figure 9. Variation with time of surface altitude at selected points on the dune cross-profile. Ordinate scale is metres above the arbitrary survey datum. Week 0 = 15.10.80; 52 = 14.10.81; 104 = 13.10.82; 156 = 12.10.83; 208 = 10.10.84

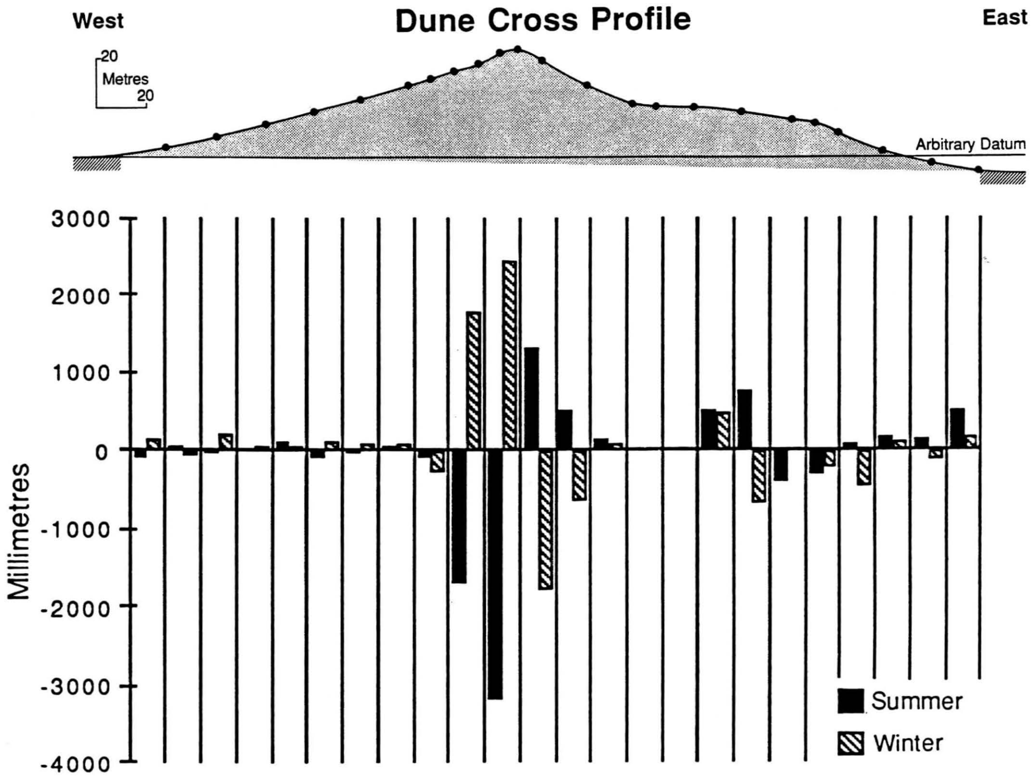

Figure 10. Patterns of surface change in (a) summer and (b) winter. Bars represent total surface change in one six-month period

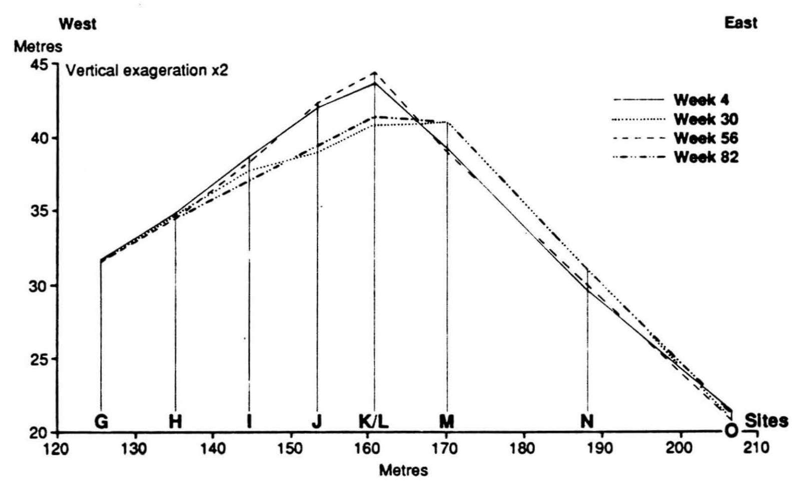

Figure 11. Cross-section of the end-of-season position of the sand surface at the dune crest. Weeks 4 and 56 illustrate the end-of-winter position, and weeks 30 and 82 illustrate the end-of-summer position

(Figure 13a) although the amount of erosion may decrease near the crest because of the convex profile (Bagnold, 1941). Downwind progress may not be a prerequisite for definition of a transverse dune but it is an inevitable consequence of the erosion which occurs on the stoss slope. On a linear dune, however, there is no continuity of cross-sectional form because one season's slipface must be eroded to form the next season's stoss

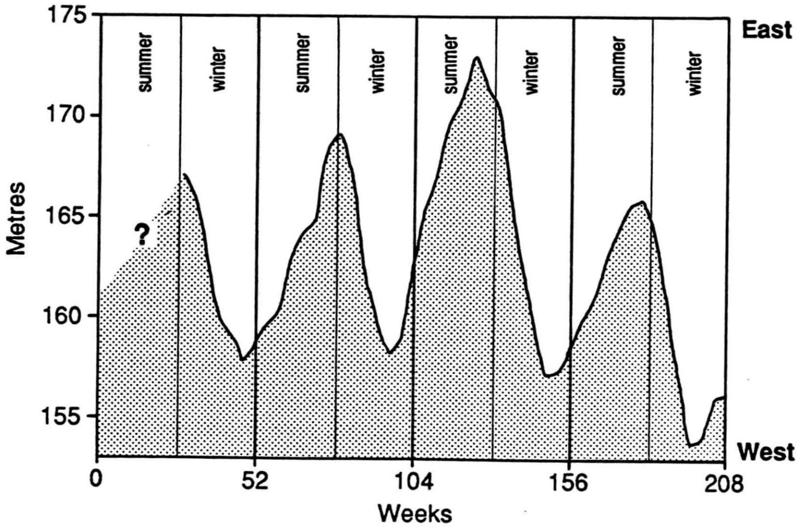

Figure 12. Plot of the lateral position of the dune crest against time. The crest is at its most westerly position at the end of summer (around weeks 0, 52, 104, 156, and 208) and at its most easterly position at the end of winter

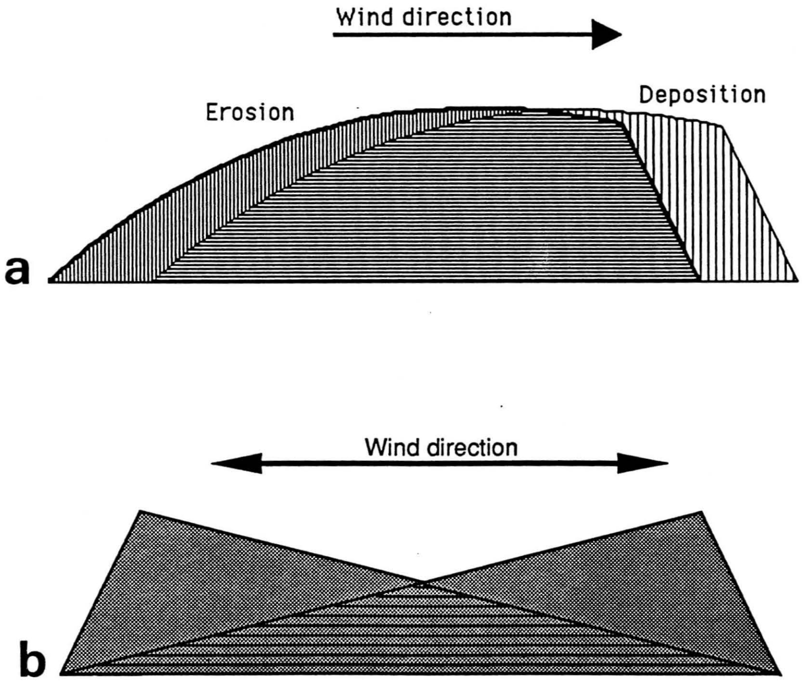

Figure 13. Cross-sections of fundamental dune forms. (a) transverse dune; (b) linear dune

slope. More sand must be eroded from the top of the slope than from the foot to lessen the slope angle (Figure 13b). This variation in erosion may be effected by the wind speed change causing a feedback mechanism which leads to greater erosion of steeper slopes. It is probable, though, that the adjustment of the windward slope which occurs on the linear dune is towards the same equilibrium stoss slope form as is displayed by transverse dunes. This is a key area of dune dynamics which requires further research.

From Figure 11 it is clear that the form of the crest at the end of summer is not a direct mirror image of the crest at the end of winter. The winter form has a steeper stoss slope, a shorter slipface, and a higher crest line. However, the volume of sand in the crestal zone is roughly the same in each season. Warren (1988) notes a similar pattern in a dune network in Oman which is subjected to a seasonal wind regime. The progress northeastward of a dune network, dominated by transverse elements under the influence of southwesterly winds, is checked by more moderate easterly winds in the winter. These easterly winds produce an overall increase in summit heights in the network and an overall steepening of slopes. Warren attributes this to smaller transverse dunes being built by lighter easterly winds on top of the main transverse elements related to the southwesterly winds.

On the Namib dunes the seasonal difference in crestal form may be due to seasonal differences in the duration and strength of sand-moving winds (Figure 5). Beginning-of-season cross-sectional form is also important, and it would be useful to have some measure of how far this varied from an equilibrium form. It may well be that the Namib dunes never reach an equilibrium (or form continuity) position at the end of a season. While Warren's dune network responds very quickly to a change of direction, and new equilibrium forms are created within a matter of days, the Namib dunes which are larger seem to respond much more slowly.

Progressive change

In addition to a cyclic regime of sand budget and dune dynamics there is also evidence of progressive change in some secondary features. On the east flank of the main dune there is a series of ridges running roughly normal to the main crest and moving northward roughly parallel to it (Figure 3). There is here a reversal of the ergodic transformation (see e.g. Thornes and Brunsden, 1977) for here a landform's progress over time is plotted at one point in space, thereby giving an indication of its form. Its progress through two points on the dune is clear from Figure 14, and no cyclicity apparent in these plots except that the ridge's northward progress is slowed during the easterly winds of winter.

There is no evidence in the results of this study to suggest that there is any lateral shift of the dune base. The progress of the dune is northward along some vector resultant of sand movement. Net sand movement is longitudinal. Ward's (1984) figures for rates of dune advance into the bed of the ephemeral Kuiseb River in the range 0 to 1·85 m a^{-1} indicate that these dunes advance very slowly.

IMPLICATIONS FOR MODELS OF LINEAR DUNE DYNAMICS

It is clear that on this linear dune higher wind speeds effect higher levels of dune surface change at the dune crest than at the base. In addition, the patterns of surface erosion and deposition are seasonally reversed in response to a bidirectional wind regime. Results such as these from small-scale field studies can never hope to explain fully the dynamics of a geomorphic system. Nevertheless, the findings can be used to provide either direct empirical results or more circumstantial evidence to support or cast doubt upon certain theories of linear dune origin and maintenance.

Contemporary or relic?

In some quarters the argument has been that many linear dunes, particularly the larger ones, were formed at some time in the past, probably the last glacial maximum, by strong, unidirectional winds creating paired roll vortices. These dunes are not being formed at present, it has been argued, because winds today are too moderate. Big winds, it is said, form big dunes (e.g. Besler, 1980; Glennie, 1970), and strong winds occurred at glacial maxima.

The border line between active and relic dunes is blurred. Some consolidation of the sand, probably through pedogenesis, is taken as an indication that the dune is no longer moving. Vegetation on a dune may be an indicator of lack of movement or a cause of it (Ash and Wasson, 1983), but dunes may continue to move even if they are quite considerably vegetated. Indeed, Tsoar and Møller (1986) have recently suggested that linear dunes tend to become vegetated because even in active examples there is no lateral movement of the

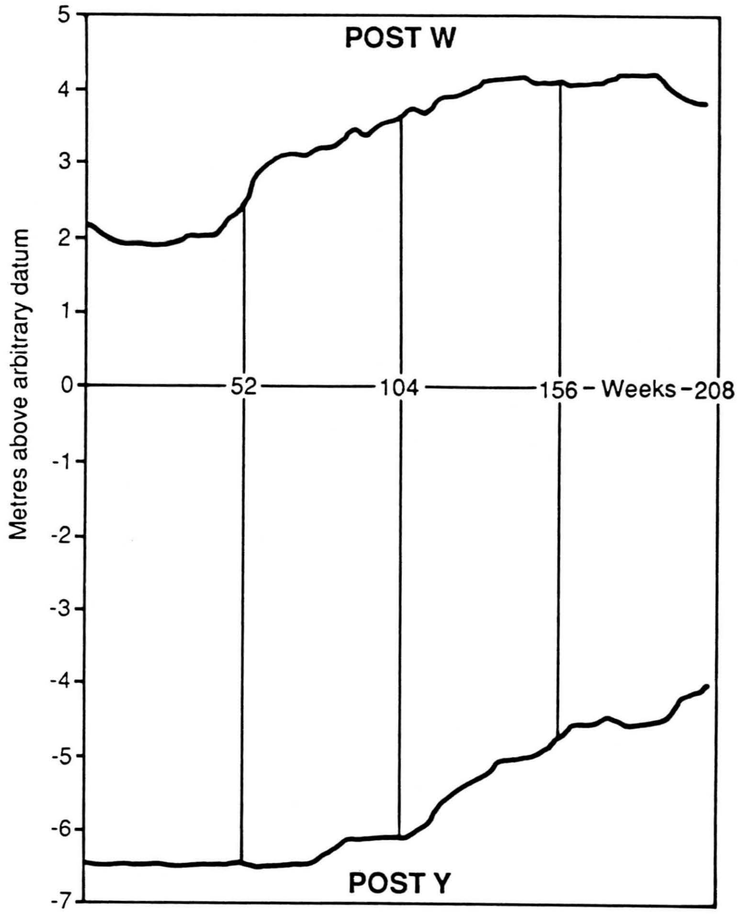

Figure 14. Indication of the progress of a secondary ridge along the east flank of the parent dune from plots of dune surface position at two posts (X and Y) against time

dune base. Unlike the transverse dune which progresses downwind, the linear dune's dynamic regime lends itself to becoming fixed and vegetated.

The problem is therefore one of assuring that the dunes studied are a genuine response to the present wind regime rather than a relic of past regimes. Dune form does not respond instantaneously to changes in wind regime: there is a lag time. They therefore display quasi- rather than dynamic equilibrium. Warren (1988) has recently employed the term 'memory' to indicate the lag time between a change in regime and attaining equilibrium form. This is similar to Allen's (1974) concepts of reaction, relaxation, and lag times. Big dunes move more slowly and take longer to respond to changes in regime than smaller dunes. They therefore have 'longer memories'.

There can be little doubt that the Namib dunes are currently active and are therefore responding to the present wind regime. The results presented in this paper outline a crestal movement of up to 15 m per year back and forth, a very respectable figure when compared with advance rates of active dunes elsewhere. Despite these very considerable levels of activity especially at the crest, however, there is no sign of the dune form disintegrating. The most likely conclusion is that the present dune form is in equilibrium with the contemporary wind regime.

There is no reason, of course, why 'most likely' answers are necessarily true. It is possible that, although sand is currently moving on the dunes, they were far more active in the past. It is also possible that the wind regime which maintains these linear dunes today is not that which formed them. The argument would be that the intrusion of dunes of this size into the boundary-layer creates a wind pattern condusive to their perpetuation and that the present relatively moderate winds cannot reform the dunes.

It is impossible to flaw this line of argument on theoretical grounds and it is impossible to prove or disprove an equilibrium linear dune form in the field: the argument would be circular. Of course, relic linear dunes do exist. But when it is possible to show high levels of activity on the dunes, and a direct process–response relationship of dune form to the present wind regime, it is a tenuous argument to suggest that the dunes are relics. Big dunes may not necessarily require big winds. Widely divided modes in a wind regime tend to pile up sand into star dunes (Lancaster, 1987a, 1988; Wasson and Hyde, 1983), so linear dunes in bimodal regimes with a large angle between the modes would progress slowly and build to considerable heights. Long periods of undisturbed aridity might also produce big dunes (Lancaster, 1982, 1983; McKee, 1982). It is somewhat disingenuous therefore to remove the dunes to some period in the past when they do not fit deductive models.

As the Namib linear dunes are being maintained by a complex wind regime, it is impossible to argue that they are currently a response to a parallel, unidirectional wind regime or that they are being maintained by helical roll vortices. The evidence here is that they can be maintained in these bidirectional regimes and this theory is supported by the only other empirical study on a linear dune (Tsoar, 1978, 1983).

Asymmetry

The Namib linear dunes display a considerable asymmetry of cross-sectional form, as do many linear dunes elsewhere. Rubin and Hunter (1985) averred that

> 'asymmetry in form suggests an asymmetry in transport across the dune crest, which could be expected to cause lateral migration' (Rubin and Hunter, 1985, p. 150)

They hypothesize a dune trend different from 'long-term resultant transport direction' which leads them to a classification of dunes into transverse, longitudinal, and oblique types. It is their belief that the asymmetry of linear dunes has resulted in the misidentification of their deposits in the geological record.

The dune in this study is asymmetrical but there is no evidence that this is leading to the lateral shift of the dune base. If the dunes are moving sideways, it is at a rate imperceptible in a study of four years' duration. The results presented here show that it is possible for the two extremes of the cycle not to be mirror images. The model of asymmetrical linear dune deposits proposed by Rubin and Hunter would be close to the internal structure of the dune in this study, but this does not necessitate lateral movement, and it is difficult to conceive of a system in which dune trend was different from net sand movement direction.

The asymmetry of the dune form must be due to a difference in the magnitude and incident direction of winds from the two sides of the dune (see Figure 5). Tsoar (1978) showed that the size of the eddy formed on the lee slope of the dune as a result of the separation of flow at the crest was related to the wind speed and its angle of incidence at the crest. When the wind speed was high or the incident angle of the wind with the crest line was at a right angle, the lee side eddy was large. Gentler winds or more oblique winds give smaller eddies. In the northern Namib sand sea the summer winds are of moderate velocity and from the southwest or northwest, while winter winds are of higher magnitude and often more or less normal to the dune crest. The lee side eddy in winter winds therefore tends to be much larger than its summer counterpart. Indeed, while the largest summer lee side eddy reaches only to the secondary dunes on the east flank, in winter the lee side eddy can reach almost to the interdune corridor. The secondary, barchanoid dunes develop on the east slope outside the limit of the lee side eddy in winds originating in summer from the west side (Livingstone, 1988b), but secondary dunes do not form on the west slope where the lee eddy of winter, easterly winds covers most or all of west flank.

CONCLUSION

Controversy still surrounds the mechanisms of genesis and maintenance of linear dunes and there remains much which can be learnt from their observation in the field. The technique employed here, of elucidating patterns of erosion and deposition by measuring posts once a week, while admittedly highly labour intensive, has proved remarkably successful in providing quantitative, base-level data concerning both spatial and temporal change in a linear dune system of this scale.

It is clear from this study that active linear dunes can be maintained in bimodal wind regimes. The crest moves laterally back and forth in response to seasonal switching of wind direction, but returns at the end of a year's cycle to its position at the beginning. This suggests that the dune is an equilibrium response to the wind regime. There is no evidence of lateral shifting of the dune. Neither is there any evidence that the Namib dunes are relics of the past, although they are certainly very long-lived.

The key issue in dune dynamics which now has to be tackled is the recognition of equilibrium forms in the field. It is essential that criteria are developed by which we can be sure that the dune form we are studying is a genuine response to contemporary wind regimes. With transverse dunes progressing downwind where the whole dune form is translated, it is reasonably likely that this is an equilibrium form rather than a relic of the past. But the nature of linear dunes (and star dunes) is that their base remains relatively 'fixed' while activity is manifested as crestal oscillation and downwind long-profile extension. This crestal activity could be the equilibrium form or the minor reworking of some antecedent landform. The most fruitful line of investigation would be to develop models of equilibrium linear dunes both mathematically and in wind tunnels, and that is the area in which most progress will be made in the coming years.

ACKNOWLEDGEMENTS

Funding for the project was provided by a Natural Environment Research Council research studentship held at the School of Geography, Oxford and from a grant from the Dudley Stamp Memorial Fund. Permission to work in the Namib/Naukluft National Park was granted by the Department of Nature Conservation, Namibia and facilities at the Namib Research Institute were made available through the Desert Ecological Research Unit. Much of the post measuring after I had left the research station was undertaken by Rose Whittington to whom I am extremely grateful.

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