New Models for the Formation of Linear Sand Dunes

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ABSTRACT. Bagnold's explanation of linear dune form which invokes thermally driven roll vortices has enjoyed considerable popularity for over thirty years. However, recent small-scale single dune studies suggest that the key to linear dune origin and maintenance may be the modification of the pattern of air flow by the dune's intrusion into the atmospheric boundary layer. This paper reviews the evidence for the Bagnold theory and then outlines two more recently proposed models.

Introduction

When Brigadier R. A. Bagnold speculated in 1953 that linear sand dunes might be caused by roll vortices, he provided the basis of a very elegant teaching model. Indeed, it is such an attractive theory, explaining all the main features of linear dune form, that it has been widely reproduced in both textbooks and academic papers. Yet little field evidence has been presented to support the theory. Instead, sufficient progress has been made in linear dune studies to suggest that Bagnold's model should at least be set aside for the time being. A range of recent research suggests that other mechanisms may be responsible for the dunes' formation and maintenance. This paper reviews the major shifts of thinking on the dynamics of linear dunes which have occurred in the past decade.

Linear dunes

Satellite photographs have shown that linear dunes are by far the most common dune type, they are found in all the world's major low latitude deserts (Lancaster, 1982). Figure 1 is a photograph of the northern Namib sand sea in southern Africa which demonstrates many of the characteristic features of linear dunes. The dunes exhibit an outstanding regularity of cross-sectional form, continuity of pattern and parallelism, often extending with relatively constant interdune spacing for many kilometres. Dunes sometimes join at 'tuning fork' junctions which open upwind and in some sand seas, such as the Kalahari Desert of southern Africa and the Simpson Desert of Australia, this is a common feature. It has been the obscurity of the relationship of these dunes to the formative wind, combined with their striking geometry, which has made them one of the most contentious of desert landforms.

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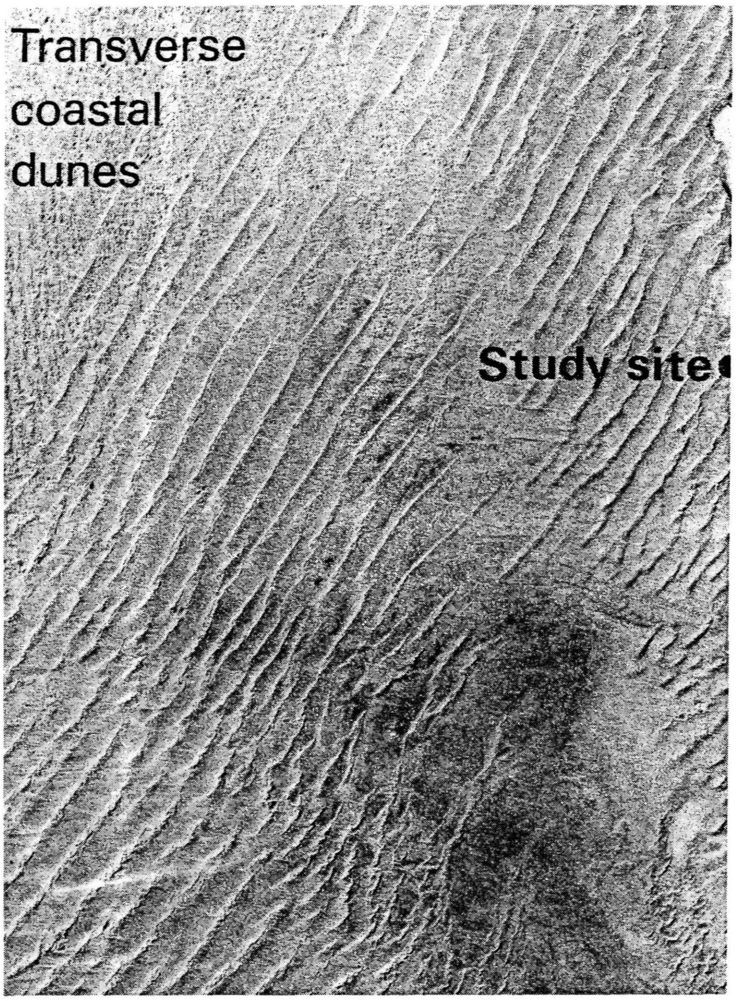

Fig. 1. — Photograph taken from the NASA space shuttle of the northern Namib sand sea in Namibia, southern Africa showing the characteristic geometry and continuity of pattern linear dunes. The dunes here are up to 150 metres high with a spacing of 2 or 3 kilometres.

Linear dunes vary considerably in dimension and can be hundreds of metres wide, tens of metres high and between 100 metres and hundreds of kilometres long (Table 1). The largest appear to be over 200 metres high, while the smallest may only be a few metres high. This diversity has been recognised in Lancaster's (1982) classification, which is based on the terminology of McKee (1979). Lancaster divides linear dunes into 'simple', 'compound' and 'complex' types, the cross-profiles of which are illustrated in Fig. 2. According to Lancaster (1982, pp. 476-479),

> Simple linear dunes consist of a single narrow dune ridge with a single straight or sinuous crestline which may be rounded or sharp in profile. Two subtypes appear to exist . . . the classical seif dune of Bagnold (1941); and the long, straight dunes of the Kalahari and Simpson deserts.
>
> Compound linear dunes consist of two or more closely spaced parallel or converging narrow dune ridges on the crest of a much wider and larger plinth.
>
> Complex linear dunes are larger still . . . Both Namib and Rub al Khali examples . . . consist of a single main ridge, with regularly spaced, sometimes star form peaks *en echelon* with a sharp sinuous crestline joining them and a major slip face to one side. Secondary dunes . . . are frequently developed on the lower slopes.

Table 1
Dimensions of linear dunes

	Spacing (km)	Width (km)	Height (m)
Simple			
Simpson Desert, Australia	0.90	0.22	10-25
Kalahari Desert, southern Africa	0.70	0.29	5-20
Rub al Khali, Saudi Arabia	1.41	0.38	—
Navajo, Arizona, USA	0.15	0.04	2-10
Complex			
Rub al Khali, Saudi Arabia	3.17	1.48	100-200
Namib Desert, Namibia	2.20	0.88	50-160
Northern Sahara, Algeria	3.24	—	—
Compound			
South-western Sahara, Mauritania	1.93	0.94	—
Southern Sahara, Niger	3.28	—	—
Southern Namib, Namibia	1.90	0.65	25-45

SOURCE: Data from Breed and Grow (1979); Hack (1941) and Lancaster (1982).

This great range in the size and morphology of features termed 'linear dune' is well demonstrated by the dunes illustrated in Figs 3 and 4, and may well indicate that it would be a mistake to expect to describe a single, all-embracing process to explain them.

The dunes usually comprise two main facets; an active crest and a relatively less mobile base or plinth. The proportion of the dune included in these two zones varies. For instance, in the Australian and Kalahari deserts the plinth forms the greater part of the dune, has been stabilised by vegetation,

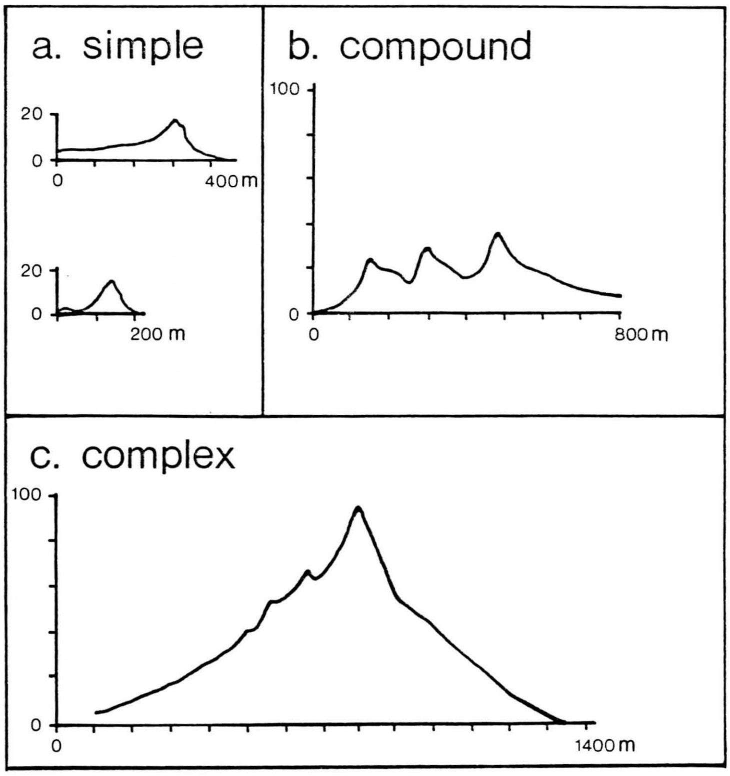

Fig. 2. — Examples of cross-sections from the three major types of linear dune (after Lancaster, 1982).

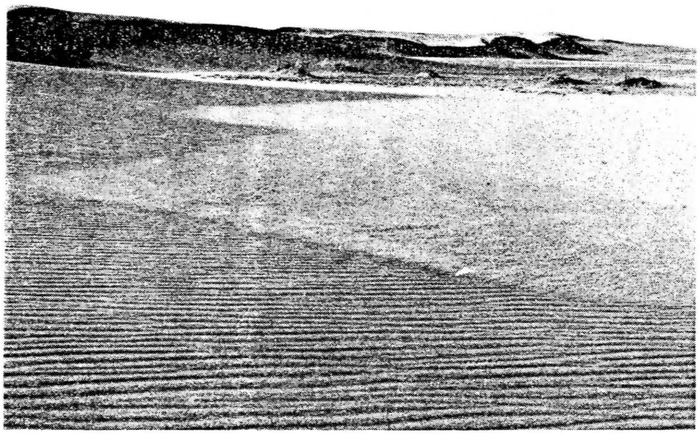

Fig. 3. — A 'simple' linear dune in the Namib Desert. This dune is only a few metres high, and displays the classic meandering form of the 'seif'.

and is therefore largely fixed in position. Plinth slopes are characteristically concave displaying angles as low as 2-5° near the interdune corridor, steepening to 10° or 20° further upslope. Crestal slopes are steeper still, frequently incorporating slip faces at the sand's 'angle of response' of around 34°. Dunes are often asymmetrical, one flank being steeper than the other, and secondary, barchanoid dunes on one or both flanks have been described from linear dune fields in, for instance, Libya (Kadar, 1934), northern Sinai (Sneh and Weissbrod, 1983) and the northern Namib (Livingstone, 1985). In the Australian and Kalahari deserts linear dunes form a pattern circulating around the centre of the country, with steeper slopes facing towards the outer margin. This has been related, by some workers, to anticyclonic air flows (Clarke and Priestley, 1970; Goudie, 1970; Lancaster, 1980a; 1981).

Linear dunes are also commonly known as longitudinal dunes or seifs. The generic term 'linear dune' should be preferred to avoid the genetic connotation of winds blowing parallel to the long axis of the dune which the term 'longitudinal dune' has; as will be shown later, this implication

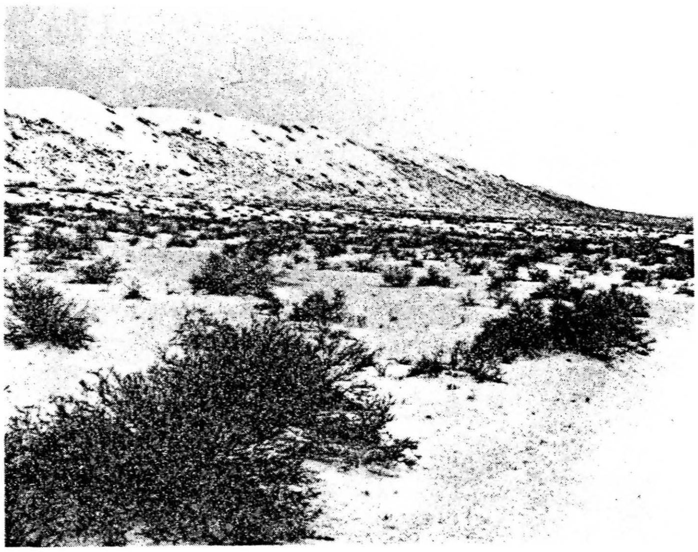

Fig. 4. — A 'complex' linear dune in the Wahiba Sands, Oman. These dunes are around 80 metres high (cf. the ' complex' dunes in the Namib Desert in Fig. 1).

may not be fully justified. 'Seif' and its variants such as 'sayf' and 'saif' are arabic words for sword, and refer to a particular sort of linear dune which characteristically has a sharp crest, is symmetrical and has two slip faces.

Bagnold's model

A range of hypotheses has been offered to explain the origin of linear dunes. These have included the asymmetric extension of one arm of a crescentic barchan dune (Bagnold, 1941; Lancaster, 1980b; Tsoar, 1984) and the 'blow out' of the central part of a parabolic dune to leave two parallel linear dunes (Twidale, 1972; Verstappen, 1968). In 1953, however, Bagnold speculated that linear dune form might be related to helical roll vortices, created by shearing in the boundary layer of the atmosphere (the 1000 metres nearest the ground) and sometimes known as Langmuir circulation. If the mechanism was found to be operating in linear dune fields, the model would explain dune formation, spacing and maintenance. Bagnold cited laboratory experiments by Brunt (1937) in which polygonal convection cells were created by heating a metal plate. When a glass plate was then moved above the heated metal plate a shear of the boundary layer was caused and the polygonal cells were moved producing spiral vortices. Bagnold proposed, therefore, that the two essentials for the creation of roll vortices were thermal convection and a strong geostrophic wind. He suggested that paired, horizontal roll vortices in the lower atmosphere, whose axes are parallel to the dominant wind direction, might sweep sand out of the troughs and onto the ridges where currents would meet and ascend. In this model the wind pattern would create the dune and the dune spacing would represent the width of a pair of vortices (Fig. 5).

Bagnold's model was initially proposed extremely cautiously, and he concluded the paper by stating that "Much of what I have said is speculative. But in a field in which we know so little, some speculation often indicates new lines for research and observation. My main object has been to stimulate the collection of more upper air data over hot arid regions, and much more data on the ground wind in relation to thermal instability and surface drag." (Bagnold, 1953, p. 93).

Despite Bagnold's reservations, the roll vortex model has since become widely supported by meteorologists and geomorphologists (Brown, 1983, Cooke and Warren, 1973; Folk, 1971; 1976; Hanna,. 1969; Hastings, 1971; Wilson, 1972a; 1972b; Wippermann, 1969), often being presented in school and college textbooks as the only theory of linear dune formation. But while the theory is attractively simple, and there is no doubt that roll vortices do exist in the atmospheric boundary layer, there are a number of objections which must be answered.

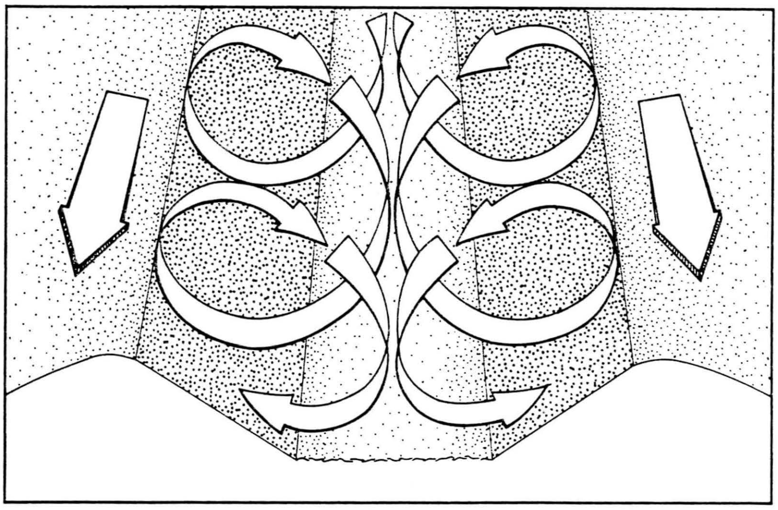

Fig. 5. — Bagnold's (1953) roll vortex model. A pair of rolls sweep sand from the inter-dune towards the crest.

First, there is little coincidence in the wavelengths (lateral spacing) of linear dunes and the measured sizes of roll vortices. In his recent review, Kelly (1984) reports roll wavelengths of between 1.5 and 13.7 kilometres. Because the theory requires that a pair of roll vortices occur in each interdune corridor, linear dunes with wavelengths between 3.0 and 27.4 kilometres can be inferred from these figures. In fact, measurements of dune spacing lie in the range 0.15 to 3.50 kilometres (Table 1), so that in reality helical roll vortices are much larger than dune spacings with little overlap between the two size distributions.

The second basis for criticism has been that roll vortices display measured transverse velocities well below that required to move sand. In addition, the theory appears to require that sand moves on the entire dune surface and from the interdune corridors onto the dune. Observations in a number of linear dune fields suggest that sand is actually often moving only in the crestal zone of the dunes. Furthermore, there seems to be some doubt about whether the roll vortices would be sufficiently stable to create dunes in fixed positions.

Finally, the model also requires that winds blow parallel to the dune trend, an event which occurs rarely in many linear dune fields. Hanna (1969), for instance, mistakenly believes that the dominant wind in the Namib Desert is the southerly trade wind blowing parallel to the dunes, while in fact the Namib is subject to a complex wind regime and winds rarely blow parallel to the dunes. Besler (1980) overcomes this difficulty of non-parallel, present-day winds by proposing that the dunes were created during a much windier episode at the time of the last of the last glacial maximum and she suggests that the present dune alignment is a palaeomorph, a 'fossilised' remnant of a past wind regime. Yet in such a hyper-arid environment as the Namib, where average rainfall is only 27 mm per annum, it must surely be the case that the dunes are currently sufficiently active for them to respond to the contemporary wind regime.

Only Glennie (1970, Fig. 74) has provided any field evidence in support of the roll vortex mechanism. This comes in the form of a photograph showing a linear dune in the Wahiba Sands of Oman where slip faces on either side of the main dune crest face towards the crest. This seems to indicate movement of sand on both flanks of the dune from the interdune towards the crest, and this is what would be expected were the roll vortex mechanism operating.

There is, though, no direct, observational evidence to support Bagnold's theory and, if they exist in desert regions at all, roll vortices are certainly not the great corkscrew spirals sweeping sand from the interdunes which have been envisaged by some geomorphologists. It remains the case that "it would be interesting to track neutral lift balloons over . . . any . . . large desert to see if counter-rotating roll vortices could be detected" (Hanna, 1969, p. 880). But at best the verdict must be that the possibility of other mechanisms should be entertained.

Tsoar's model

A more recent, pioneering study of the processes on a single, 'simple' linear dune in the Negev Desert, Israel, has been undertaken by Tsoar (1978; 1983). Using anemometers, wind vanes and smoke flares, Tsoar has found that in the immediate lee of the crest the wind flow separates from the dune surface to create a lee side eddy and that when crossing the crest at any angle whatsoever the wind is deflected on the lee flank in the direction parallel to the crest line (Fig. 6). Consequently, Tsoar hypothesises that net sand flow on the lee side of the dune is always along the dune, parallel to the crest.

Tsoar's work is innovative because it suggests that linear dunes form in bi-directional wind regimes rather than the uni-directional, parallel regimes of Bagnold, and because Tsoar proposes that every wind is deflected on the lee side of the dune. In order for Tsoar's mechanism of linear dune evolution to operate two conditions must be fulfilled. First, the dune must have a sharp profile so that flow separation occurs at the crest and a lee side eddy is formed. The second condition is that there must be a bi-directional wind regime. In a uni-directional wind regime the dune crest is normal to the wind flow and a transverse dune is formed. Progress is then in the direction of wind flow. In a bi-directional wind regime, however, the dune advances by elongation along the resultant vector of the wind regime as a consequence of the lee side deflection of flow.

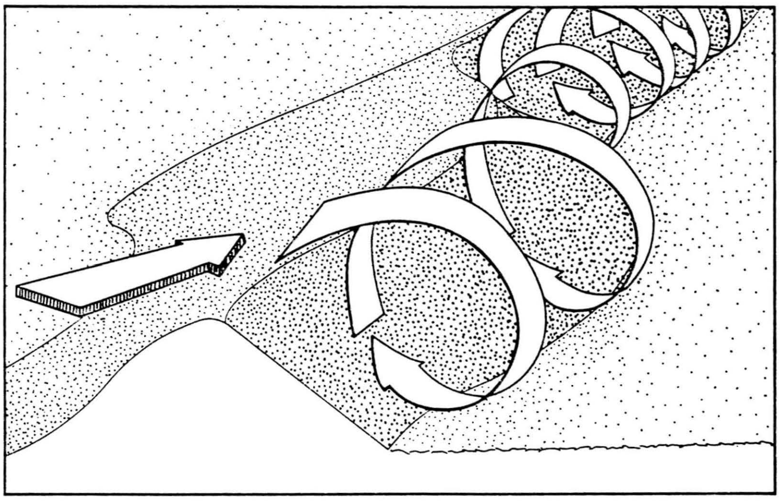

Fig. 6. — Wind flow patterns on a 'simple' linear dune according to Tsoar (1978; 1983). An incident wind oblique to the dune alignment separates from the surface at the crest and creates an eddy covering the entire lee slope. Sand is thus prevented from leaving the downwind slope.

Tsoar's model is almost the equal to Bagnold's in its simplicity. Both models invoke secondary air flows as the control of linear dune form. In the case of Bagnold's model, however, the secondary air flow is a consequence of meteorological conditions, while in Tsoar's model it is the intrusion of the dune itself into the atmospheric boundary layer which creates vortices conducive to its own self-perpetuation. While Bagnold's theory requires that winds flow parallel to the dune, Tsoar believes that linear dunes form in bi-directional wind regimes.

Tsoar also attempts to explain the apparently regular spacing of linear dunes. He draws on the literature on wind breaks which suggests that the wind recovers its speed in the lee of an obstacle at a distance downwind of around fifteen times the obstacle's height. Tsoar's proposal is therefore that linear dune spacing is determined by the dune's height.

Work on a larger, 'complex' linear dune in the Namib Desert indicates, however, that Tsoar's model does not fully explain linear dune dynamics (Livingstone, 1985; 1986). Measurements of wind flow over the dune document separation of flow and a lee side eddy very similar to that described by Tsoar, but while Tsoar's study dune never exceeds a height of 12 to 14 metres, the Namib study dune is over 50 metres high. As a result, a lee side eddy of similar dimensions does not cover the entire lee slope of these larger dunes (Fig. 7). Tsoar's statement that, "the longitudinal dune . . . does not furnish sand to the interdune area because of the deflection in the direction of the wind of the lee flank" (Tsoar, 1978, p. 133), is not, therefore, directly applicable to the majority of linear dunes, and Livingstone has reported that sand does indeed cross the interdune corridors. In addition, Livingstone has found that the dune does not act like a wind break in the manner described by Tsoar, but that the wind speed across the interdune corridor is virtually constant. Some further explanation is thus required.

A third model

In a recent paper, Livingstone (1986) has suggested that it might be possible to explain linear dune dynamics by reference to the pattern of wind speed change over the dune cross-profile. Measurements of wind speed by Lancaster (1985), Livingstone (1986) and Tsoar (1985) suggest that wind speed increases towards the crest on the windward slope of a dune (or indeed any similarly sized intrusion in the boundary layer) as a result of the compression of streamlines above the dune

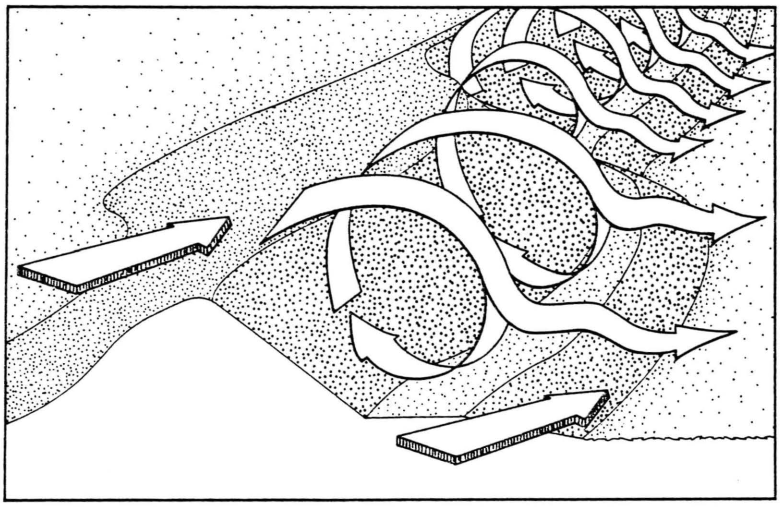

Fig. 7. — Wind flow on a 'complex' linear dune according to Livingstone (1985). On a dune of this size the lee side eddy does not cover the entire lee slope. Sand does leave the dune's downwind slope and crosses the interdune corridors.

surface. Conversely, wind speeds on the lee slope of the dune decrease away from dune crest.

Bagnold (1941) established that, once the threshold velocity for sand movement is exceeded, the amount of sand carried by the wind is directly proportional to the wind speed. But landform change (erosion and deposition) is achieved as a result of variations in the capacity of the wind to carry sand. So a simple intuitive model can be proposed whereby increasing wind speed produces erosion and decreasing wind speeds leads to deposition (Livingstone, 1986).

Consider an idealised linear dune cross-profile in a simplified bi-directional wind regime (Fig. 8). In summer the dunes of the Namib sand sea, which are aligned roughly north-south, are subjected to winds from the west side: north-westerly in the mornings and south-westerly in the afternoons. As the wind speed increases up the windward, west flank of the dune it causes erosion of the dune surface. Sand is then deposited on the lee side and the net movement of the dune is eastward (Fig. 8a). In the winter this dune is attacked by ferocious but relatively rare easterly winds, and the pattern of erosion and deposition is reversed: the east flank is eroded and sand deposited on the west flank (Fig. 8b). Constant wind speeds across the interdune corridors indicate that sand may be transported from one dune to another, but is not eroded or deposited. The dune crest therefore moves back and forth according to the annual cycle of winds, but there is no net lateral movement of the dune base. The fundamental aspects of dune dynamics inferred from this model are confirmed from measurements of surface change covering a period of two years (Livingstone, 1985).

The model describes the effect of the winds as if they were blowing normal to the dune crest. In fact, of course, most winds blow obliquely to the crest and because of the lee side deflection of flow parallel to the crest described by Tsoar there is a net longitudinal extension of the dune along some line of resolution of the winds (Fig. 9). In the case of the Namib dunes sand is moved predominantly from south to north until their progress is checked by the ephemeral Kuiseb River (see Fig. 1).

For this model to operate, the only requirement is a non-uni-directional wind regime. Clearly, however, this is a highly idealised representation of what happens in reality, and the model does have its limitations. The first is that it does not tackle the problem of dune initiation which is common to all dune studies. While Bagnold's roll vortex theory does explain dune initiation, Tsoar sees linear dunes as a development from some pre-existing dune form, either by the extension of one arm of a barchan or as a longitudinal extension of a zibar (a low sand mound). This merely pushes the problem of dune initiation further upwind and much work remains to be done before the general mode of dune initiation is elucidated fully.

The second major problem, particular to linear dunes, is that of spacing. Again this is explained

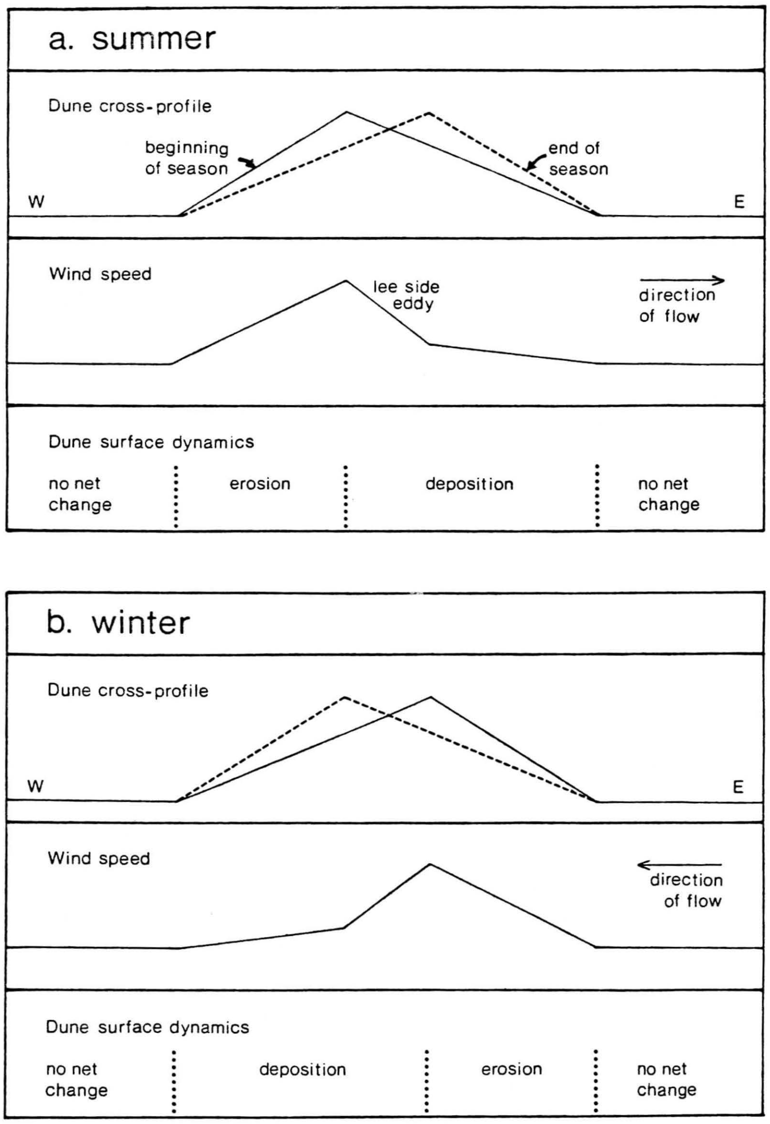

Fig. 8. — Idealised representation of the reversing pattern of erosion and deposition related to wind speed change on a linear dune in a seasonally bi-directional wind regime.

by the roll vortex theory. While spacing in some dune fields displays a wide range of values and may therefore be some response to wind regime and sand supply, it is equally true that there are areas of linear dunes where spacing is outstandingly regular. It is difficult, therefore, to avoid the inference that this is a response to some secondary flow or wave pattern in the wind. If this secondary flow control of dune spacing does exist, it remains to be discovered.

Finally, the model uses the pattern of wind speed change as an indication of sand movement. In fact, sand mobility is a response to the wind shear created at the dune's surface; that is the pressure exerted by the wind on individual sand grains to mobilise them. Generally, wind speed can be used as a surrogate for wind shear by employing an empirical formula derived by Bagnold (1941). This is advantageous as wind speed is easier to measure in the field than wind shear, but using wind speed is a gross simplification of the situation in reality and future fieldwork and modelling will concentrate on measurements of wind shear on dune surfaces.

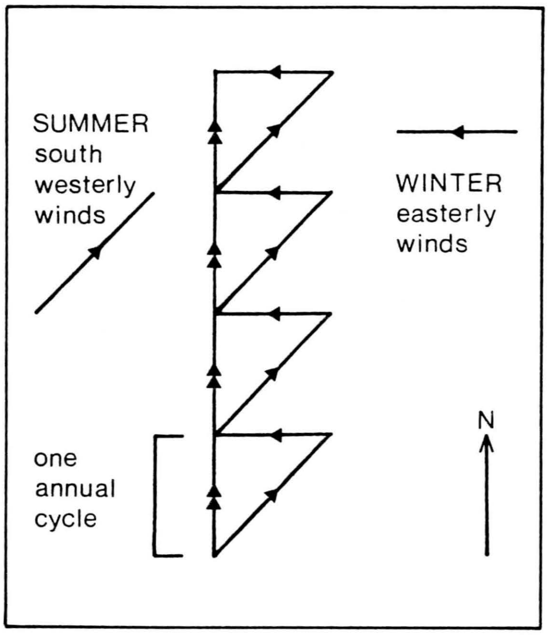

Fig. 9. — Advance of a linear dune in a bi-directional wind regime: simplified representation of the situation in the northern Namib sand sea. The resultant advance is shown by the double arrows.

Palaeoenvironmental implications

Although Bagnold has related some linear dunes to bi-directional wind regimes (Bagnold, 1941), his roll vortex theory postulates a wind blowing parallel to the long axis of the dunes. If this were the formative mechanism, the dunes would be truly longitudinal. However, the dunes studied by both Tsoar and Livingstone are developing in complex wind regimes and the models described by them invoke necessarily bi-directional or, more accurately, non-uni-directional regimes. Because until recently the working hypothesis has been that linear dunes form parallel to the formative wind, a number of studies have used the alignment of currently fixed or 'fossil' linear dunes as an indication of the direction of wind flow in the past. Recent examples of work of this sort include a study of Tasmanian linear dunes by Bowden (1983), of southern African dunes by Lancaster (1980a; 1981) and Thomas (1984) and of American dunes by Marrs and Kolm (1982). If, however, linear dunes are formed in bi-directional wind regimes, the use of relict dunes as indicators of palaeowind direction is rendered highly suspect if alignment alone is used; additional supporting information on internal structure would also be required.

Conclusion

The past decade has seen a change of method in tackling the apparently intractable problem of linear dune origin and maintenance. There has been a move away from the monolithic, highly deductive roll vortex theory of Bagnold towards more empirically-based, inductive, single dune studies. Rather than invoking thermally-driven vortices, these new explanations are based on the pattern of wind flow created by the intrusion of the dune itself into the atmospheric boundary layer.

Despite these recent advances much remains to be done before the geomorphology of linear dunes is fully understood, but it is to be hoped that these single dune studies will lead to more careful field investigations of linear dunes. It is, of course, possible that the wide range of dunes termed 'linear' which has been revealed through satellite imagery and field study indicates that the linear dune is an equifinal form, and that no single model will explain the origin of all these dunes.

Acknowledgements. The author's research in the Namib Desert was funded through a Research Studentship from the Natural Environmental Research Council held at the School of Geography, Oxford. Permission to work in the Namib/Naukluft National Parry was granted by the Department of Nature Conservation, Namibia and facilities at the Namib Desert Research Station were made available by the Desert Ecological Researtch Unit.

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