Reprinted from: Progress in Physical Geography 6 (1982).

Linear dunes

by N. Lancaster

I Introduction

Dunes of linear form, frequently known as seif or longitudinal dunes, are the most widespread of all dune types in desert sand seas. Despite their consequent sedimentary and environmental importance, the conditions under which linear dunes form and develop are still poorly known. Although Price (1950) discussed some aspects of the then existing views on linear dune formation and Folk (1971) has penetratingly reviewed the literature on the formation of linear dunes, no attempt has been made to compare the character and environments of linear dunes in different sand seas and to relate these to models of linear dune formation. This paper aims to do this, with the hope of providing a general model of linear dune formation.

Linear dunes are characterized by their considerable length, often more than 20 km, straightness, parallelism, regular spacing and low ratio of dune to interdune areas. Frequently linear dunes consist of a lower plinth area (Figure 1), often lightly vegetated, and an upper crestal area where sand movement is more active. Slip faces may develop on the lee side of the crest, their orientation depending on the direction of the sand moving winds of the time. The whole dune, or the crestal areas only, may be asymmetric. Following the morphological classification of McKee (1979) three varieties of linear dunes can be identified, in order of increasing size and intricacy of form: simple, compound and complex. In terms of Wilson's (1972) hierarchy of aeolian landforms: simple types are of dune size, whereas compound and complex linear dunes are of draa or megadune size.

1 *Occurrence of linear dunes*

Until recently, the lack of accurate maps and complete aerial photographic cover for many desert areas has precluded assessment of the areas covered by different dune types, although Jordan (1964) did estimate that 72 per cent of Saharan sand seas were covered by linear dunes. The advent of LANDSAT imagery, on which the morphology of different dune types is clearly visible, has considerably facilitated mapping of dune types as McKee and Breed (1976) and Breed *et al.*

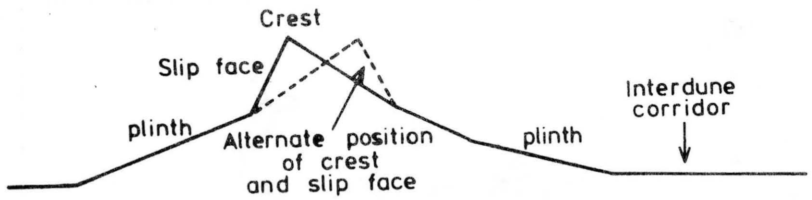

Figure 1 Facets of linear dunes.

(1979) have demonstrated. Using the maps in Breed *et al.* (1979), Fryberger and Goudie (1981) have estimated that 30 per cent of all aeolian depositional surfaces are composed of linear dunes. If areas of dunes only are considered, then approximately 50 per cent of them are composed of linear types. The area covered by linear dunes varies widely from one sand sea to another, from 85 per cent of the area of the southwestern Kalahari to 1.5 per cent of the Ala Shan. From an overview of LANDSAT images of desert areas it is evident that linear dunes are the dominant form in sand seas in the southern hemisphere and cover most of the sand seas in the southwestern Kalahari, Namib and Australia, in the southern Sahara (ergs Tomboctou and Azouad) and in the southwestern Sahara (Amoukraz). They are also common in the Great Sand Sea of Libya, the Erg Chech, the northern Mauritanian sand seas, the ergs Bilma and Ténéré and in the southern and western Rub al Khali. Linear dunes appear to be rare in sand seas in Asia, apart from the Thar desert, and in the New World, but the only major sand seas where linear dunes are absent appear to be the Erg Oriental in the Sahara and the Nafud and Jafura in Arabia.

On a world scale, probably half to two thirds of all sand seas are covered by linear dunes, with simple and compound forms being the most widespread. Complex linear dunes are a subsidiary form in most sand seas, except the Erg Chech, the Namib and parts of the Rub al Khali.

II Characteristics of linear dunes

1 *Morphology and morphometry*

The morphometric character of linear dunes of different varieties is summarized in Table 1 and indicates the range of sizes found; from the narrow, low, simple linear dunes of the Simpson and Kalahari deserts to the large complex ridges of the Namib sand sea and Rub al Khali.

Simple linear dunes (Figure 3a,b) consist of a single narrow dune ridge with a single straight or sinuous crest line which may be rounded or sharp in profile. There are no secondary dunes developed on their flanks. Two subtypes appear to exist

Figure 2 Principal areas of linear dunes, arrows indicate general trend of dune. (Data from Breed *et al.*, 1979). 1 Mauritania; Makteïr, Amoukrouz sand seas; 2 Erg Chech; 3 Mourzuq sand sea; 4 Great Sand Sea; 5 Ergs Ténéré and Bilma; 6 Sahel: Ergs Tomboctou and Azouad; 7 Namib sand sea; 8 Southwestern Kalahari; 9 Rub al Khali; 10 Trucial Coast; 11 Wahiba Sands; 12 Thar Desert; 13 Great Sandy Desert; 14 Simpson Desert; 15 Great Victoria Desert.

Table 1 Morphometric characteristics of linear dunes in different sand seas.

	Simple		Compound		Complex	
	Simpson	Kalahari	Southern Namib	SW Sahara	Namib	SW Rub al Khali
spacing (km)	0.90	0.70	1.90	1.93	2.20	3.17
width (km)	0.29	0.22	0.65	0.94	0.88	1.48
height (m)	10–25[1]	5–20[2]	25–45[3]	no data	50–160[4]	100–200[5]

Data from Breed *et al.* (1979) with additions from:
[1] Twidale (1972)
[2] Goudie (1970)
[3] Lancaster (unpublished data)
[4] Lancaster (1981c)
[5] Holm (1960)

and are distinguished by Breed and Grow (1979): the relatively short, sinuous, sharp crested type with a pointed downwind end, the classical seif dune of Bagnold (1941), which is very similar to those in Sinai studied by Tsoar (1974, 1978) and the silk of Mainguet (1976); and the long, straight dunes of the Kalahari and Simpson deserts.

Compound linear dunes (Figure 3c) consist of two or more closely spaced parallel or converging narrow dune ridges on the crest of a much wider and larger

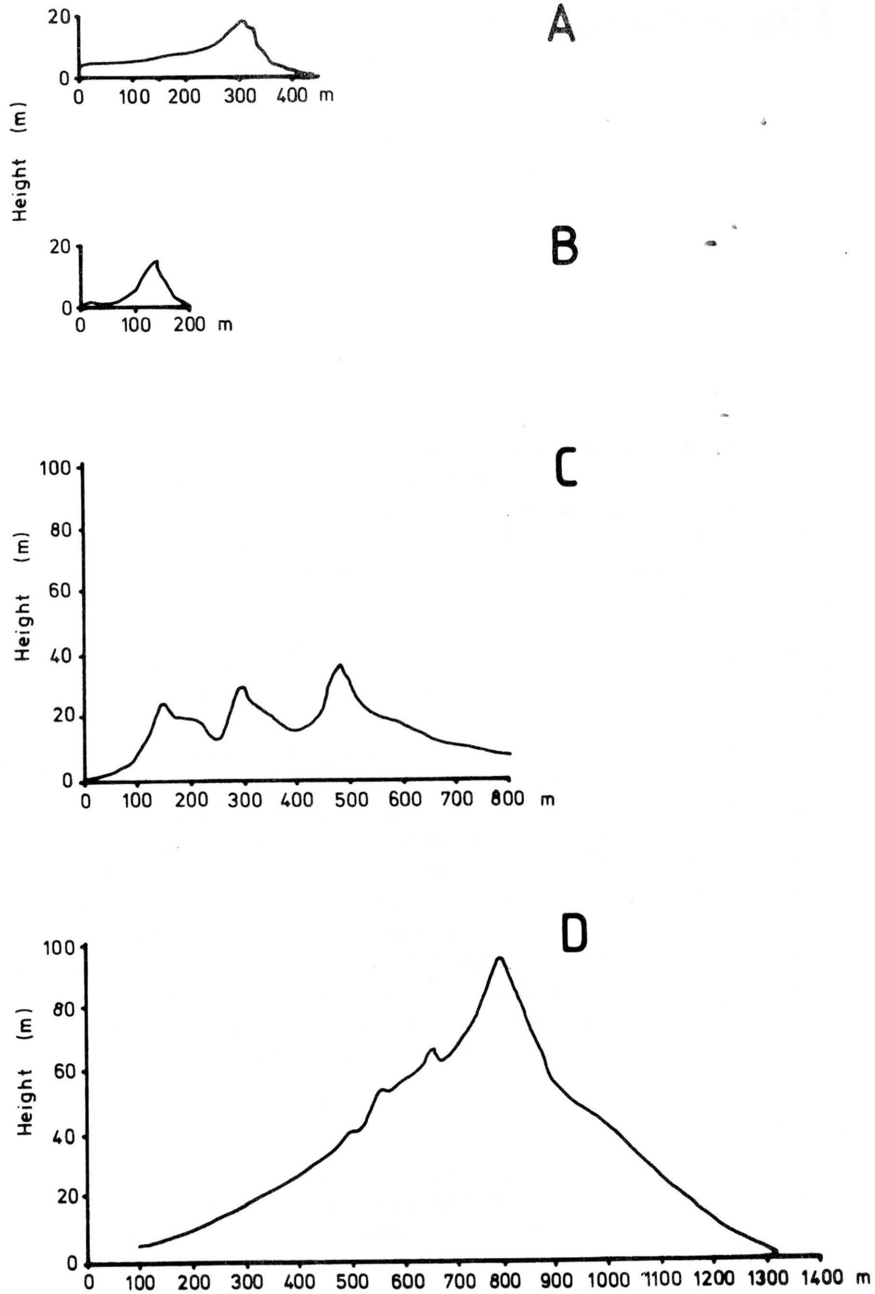

Figure 3 Profiles of simple, compound and complex linear dunes. A: Simple, Simpson Desert (after Mabbutt and Sullivan, 1968). B: Simple, Sinai (after Tsoar, 1978). C: Compound, southern Namib sand sea. D: Complex, northern Namib sand sea (Lancaster, unpublished data).

plinth (cf. the 'whaleback' of Bagnold (1941)). Comparable forms are the 'bouquets de silks' of Mainguet (1976), the anastomosing linear complexes of Holm (1960), the clustered dendritic ridges of Goudie (1970) and the slouk described by Monod (1958). Related types are the dunes described as feather barb from the Rub al Khali by Breed *et al.* (1979).

Complex linear dunes (Figure 3d) are larger still and reach heights of 100–150 m in the Namib (Lancaster, 1981c) and 150–200 m in Arabia (Holm, 1960) where they are known as 'uruq'. Both Namib and Rub al Khali examples appear to be similar and 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, often oblique or transverse to the main trend are frequently developed on the lower slopes or plinths of these dunes. Complex linear dunes are apparently equivalent to the *chaines ghourdiques* of Mainguet (1976) and some draa ridges such as those described by Monod (1958) and Wilson (1972).

2 *Linear dunes in the Simpson desert, Australia*

Dunes in the Simpson desert cover an area of approximately 300 000 km and form the southeastern part of the great anticlockwise wheel round of dunes in the arid interior of Australia. The character of these dunes was first described by Madigan (1936; 1946). Much detail has been added by subsequent workers in the region, notably Mabbutt (1968), Mabbutt and Sullivan (1968), Folk (1971) and Twidale (1972). They can be considered the type example of many simple linear dunes.

Simple linear dunes in the Simpson desert consist of 10–35 m high, straight parallel ridges 150–300 m apart on a SSE–NNW trend. In places the ridges converge to form Y junctions, open towards the south. Most dunes are 20–25 km long, although individual examples have been traced for over 200 km (Madigan, 1936).

The Middle and lower flanks of the dunes are partly vegetated with spinifex and are markedly asymmetric in profile with a gentle western slope (12°) and a steeper eastern slope (20°). Crestal areas are lightly vegetated with cane grass and consist of a series of sharp crests arranged *en echelon* obliquely to the trend of the dunes as a whole. Slip faces are developed on these elements, facing mainly to the east in western areas and west towards the eastern part of the desert, reflecting regional wind regime changes (Mabbutt, 1968). However, Wopfner and Twidale (1967) point out that slip face orientation may change daily from west to east according to the direction of the current sand moving winds. Interdune areas are often relatively well vegetated and may be sand covered or reflect the substrate over which the dunes pass; locally alluvial deposits or gibber (desert pavement).

Both Mabbutt (1968) and Twidale (1972) have noted that dune height and spacing are related. In the west, dunes are 10 m high and spaced 150–200 m apart; whilst to the northeast they are 25 m high, but 250–300 m apart. In any area dune height and spacing are consistent, suggesting equilibrium relationships to Mabbutt (1968) and implying a constant sand volume per unit area to Twidale (1972).

As Table 1 and the descriptions of Lewis (1936) and Goudie (1970) indicate, dunes in the southwestern Kalahari are essentially similar in form to those in the Simpson desert in their size, straightness, parallelism, existence of Y junctions and asymmetry (in the Kalahari to the southwest). However, except where overgrazing has occurred most Kalahari dunes are well vegetated with grasses and even small shrubs and trees on their crests and are effectively palaeoforms (Lancaster 1981b).

3 *Complex and compound linear dunes in the Namib sand sea*

The character of larger complex and compound linear dunes is not well known except in the Namib sand sea. Here, dunes of these varieties dominate the 34 000 km^2 Namib sand sea except for a belt, 20–40 km wide, of compound crescentic dunes along the coast. These dunes have been briefly described on the northern margin of the sand sea by Goudie (1970) and Barnard (1973) provides a general account of dunes based mostly on air photo interpretation. More detailed investigations were made by Besler (1977; 1980) and are continued by the writer (1980; 1981a; 1981c; 1981d; and in press). Compound linear dunes dominate in southern areas of the sand sea and in a fixed state occur along its eastern margins. In central and northern areas the linear dunes are of complex form.

Typically the compound linear dunes (Figure 3c) consist of three and locally five slightly sinuous narrow sharp crested ridges 5–10 m high and spaced 120–150 m apart running parallel on a SE–NW or SSE–NNW alignment along a 500–700 m wide plinth with the same alignment. Total height of the dunes is 25–40 m and each compound linear dune is spaced ± 1.5–2 km apart. Locally the small ridges converge in Y junctions, open to the south (upwind) and elsewhere 'feather barb' or dendritic patterns of ridges occur. The small ridges may be continuous, especially the outermost one on the southwestern side of the dune; or discontinuous, particularly those in the centre and on eastern sides. Each ridge is asymmetric, but the orientation of the slip faces at 32–33° varies seasonally from southwest or west in May to August to northeast or east in September to April according to the seasonal direction of the sand moving winds. Windward slopes are at 15–20°. The sand covered interdunes are formed into low rolling dunes without slip faces 2–3 m high and spaced 100–200 m apart, comparable with the 'zibar' of Holm (1960). These undulations continue onto the plinths of adjacent linear dunes.

Complex linear dunes in the Namib sand sea consist of a single main ridge 50–150 m high and 600–1000 m wide on a N–S to NNW–SSE trend. The crest line is generally sharp and sinuous and connects a series of regularly repeated peaks, often with almost a star form, particularly in eastern areas where the linear dunes are effectively chains of star dunes. In profile this gives the dunes a saw toothed appearance. The major slip face (5–30 m high) has an angle of 32–33° and faces east or northeast. Seasonally (May to September) it reverses to face west but is rarely more than 5 m high except to the east of the sand sea where the easterly winds are more persistent. Slopes on the western side of the dunes are 5–10° on the plinth, steepening to 16–20° near the crest. Below the slip face on the eastern side of the main ridge is a wide plinth, on the upper parts of which are frequently developed secondary dunes 2–10 m high and up to 100–150 m apart. Generally these are of barchanoid or transverse form on an alignment of NW–SE or transverse to winds from SSW–SW. In many cases the secondary dunes join to the crest at the start of the westerly turn of the sinuosity, giving an *en echelon* pattern to the crest. It appears that east flank barchanoid dunes are associated with a sinuous main crest line and concave slip faces. Where the crest line and main slip face are straight, east flank dunes are poorly developed. In some areas, especially to the west of the area of linear dunes, the eastern ends of one of the barchanoid elements is recurved at intervals and links with the low simple linear dunes which cross the corridor between the main linear dunes on a WSW–ENE alignment. Apart from some areas of the northern parts of the sand sea interdunes are sand covered and develop low undulations normal to the trend of the main linear dunes. In places these undulations extend up the western flanks of the main dunes and may develop slip faces towards their crests.

Lancaster (1981d) has shown that the size and spacing of compound and complex linear dunes varies systematically over the Namib sand sea. Larger and more widely spaced linear dunes occur in central and northwestern areas of the sand sea, with progressively lower and more closely spaced dunes towards the margins. Over much of the southern parts of the sand sea dunes are less than 50 m high. Comparing the spatial variability of wind regimes with the pattern of dune size and spacing suggests that large dunes are associated with areas of net sand accumulation. A similar idea has been suggested by Mainguet and Callot (1974) for Saharan sand seas. The height and spacing of linear dunes at 16 sites throughout the sand sea are directly correlated ($r = 0.59$ significant at 0.05 level), as are dune width and spacing ($r = 0.68$) and dune width and height ($r = 0.59$) (Lancaster, 1981c).

III Sediments of linear dunes

1 *Grain size characteristics*

Many investigators of linear dunes have noted changes in grain size and sorting over the dunes. Bagnold (1941) observed that, in the Libyan desert, crest sands of linear dunes were finer than those from the base or plinth. Broadly similar conclusions were arrived at by McKee and Tibbitts (1964) and Glennie (1970) for simple linear dunes in southwestern Libya and Oman; and by Alimen (1953) and Lancaster (1981a) for complex linear dunes in Algeria and the Namib.

However, in the Simpson desert, crests of simple linear dunes are coarser than flanks (Crocker, 1946; Folk, 1971). Further, some workers, e.g. Warren (1972) have reported that there are no differences in grain size and sorting over linear dunes they investigated. To resolve these apparent contradictions it is necessary to refer to detailed studies of linear dune composition, such as those of simple

Table 2 Grain size characteristics of linear dunes (phi units except where indicated)

Simpson desert	Crests	Flanks	Interdunes
Mean grain size	2.53 (0.175 mm)	2.75 (0.15 mm)	2.85 (0.14 mm)
Standard deviation	0.43	0.57	0.95
Skewness	0.11	0.08	0.04
Kurtosis (kg')	0.52	0.495	0.475

Namib sand sea		Slip faces		Upper west slope	Plinths		
	Crests	Mid	Base		East	West	Interdunes
Mean grain size	2.44	2.49	2.32	2.41	2.08	2.07	1.99
Standard deviation	0.37	0.34	0.40	0.50	0.63	0.75	0.82
Skewness	0.17	0.03	0.05	0.11	0.20	0.35	0.22
Kurtosis	0.54	0.52	0.52	0.50	0.49	0.46	0.51

Data from Folk (1971) and Lancaster (1981a)

linear dunes in the Simpson desert (Folk, 1971) and complex linear dunes in the Namib (Lancaster, 1981a). The grain size characteristics of these dunes are compared in Table 2.

a Grain size and sorting character of Simpson desert linear dunes: Crocker (1946) established the basic grain size character of Simpson desert dunes: that their crests are coarser, but better sorted, than dune flanks and the fine poorly sorted interdune areas of bimodal sands (Figure 4b). Folk (1971), in a detailed study of dunes in the northwestern part of the desert, confirmed Crocker's findings and added much to the understanding of grain size and sorting processes in dunefields. He found crests to be coarser but better sorted (average mean grain size 2.53 phi, average standard deviation $\bar{\sigma}_1$ 0.43) than dune flanks ($\bar{x}$ 2.75 phi, $\bar{\sigma}$ 0.57) and interdune areas ($\bar{x}$ 2.85 phi, $\bar{\sigma}1$ 0.95). Interdunes were polymodal or bimodal, as a result of relative abundance of coarse sand and a significant admixture of silt sized particles (5–20 per cent). By comparison with other sand seas, Simpson desert dunes are relatively poorly sorted, due apparently to their proximity to the source area, and Breed and Breed (1979) demonstrated the close similarities between dune and alluvial materials. Folk explained his results by reference to the nature of the source material for dune sands and the way in which wind acted upon it. He suggested that the wind selected material in the 2.5 phi range from the source sediment and concentrated it into dunes. If, as in the Simpson desert, the source was a fine grained alluvium, then it would tend to become finer, more poorly sorted and bimodal over time as the sand was removed, leaving dune crests coarser, but better sorted. In the case of a coarse source material the converse would be the result. Dune flanks are intermediate in composition as they trap weakly saltating coarse sand and receive some fine sand by avalanching from slip faces.

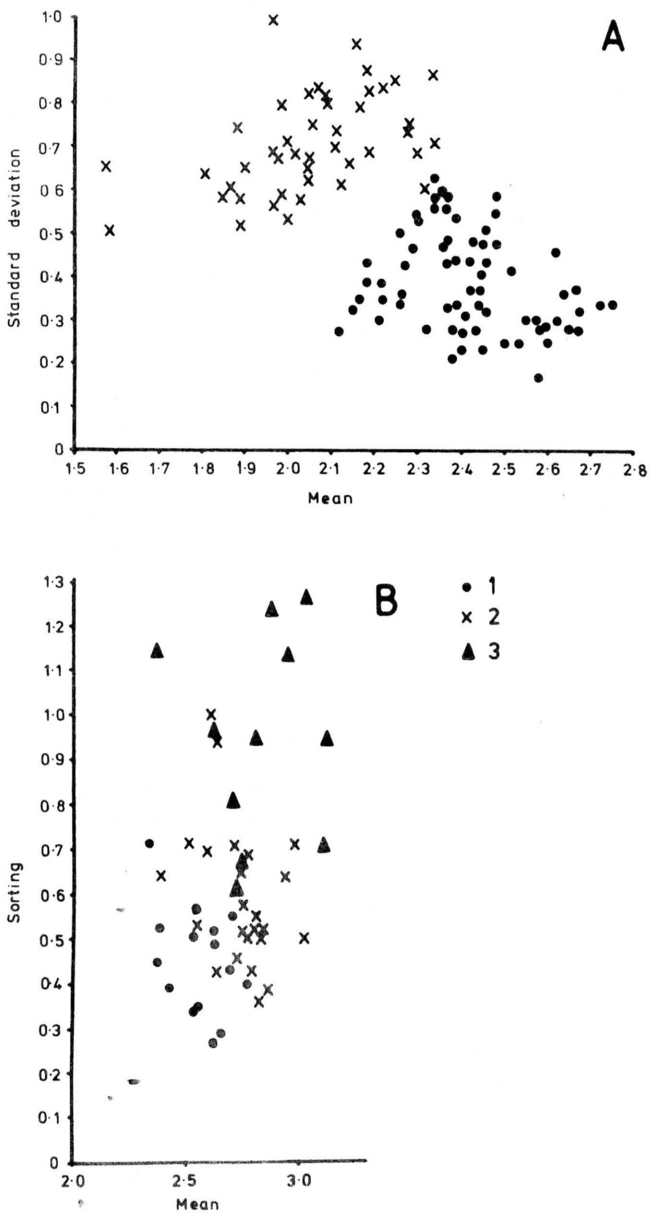

Figure 4 Differences between the grain size and sorting character of crest, plinth and interdune sands. A: from Lancaster (1981a). B: from Folk (1971). 1: Crests, slip faces; 2: Flanks and plinths; 3: Interdunes.

b Grain size characteristics of Namib desert linear dunes: Although it might be expected, following Alimen (1953), that complex dunes would be characterized by a complex pattern of grain size and sorting variability, this does not appear to be the case in the complex linear dunes of the Namib sand sea. These dunes are composed of two distinct groups of sands (Figure 4a) (Lancaster, 1981a). Although this study covered dunes in the northern part of the sand sea the subsequent extension of a systematic sampling of linear dunes to all areas has confirmed that essentially the same pattern occurs in all linear dunes.

Sands from the crests, slip faces and upper west slopes of the linear dunes are characteristically fine (average mean grain size 2.41–2.47), well to very well sorted (phi standard deviation 0.35–0.36) and near symmetrical (phi skewness 0.05–0.13). By comparison, those from the plinth area are coarser (average mean grain size 2.08 phi); moderately sorted (0.70–0.80) and frequently strongly positively or fine skewed (0.24–0.32). Interdune areas are coarser still (average mean grain size 1.98) and moderately to poorly sorted (average standard deviation 0.90).

Although Besler (1976; 1980) has attributed the grain size and sorting pattern of Namib desert linear dunes to the existence of fluvial sands in basal areas and aeolian sands on the crests, the differences can be better explained in terms of the pattern of sand movement on the dunes (Lancaster, 1981a). As sand comes on to the windward slope of the dunes, the coarser, traction load slows down as the slope increases and saltation efficiency decreases. Towards the crest, the slowly moving traction load is steadily left behind, resulting in a progressive fining of sands towards the crest. On the slip face, avalanching leads to the preferential downslope movement of coarser grains which accumulate at its base. With seasonal changes of slip face orientation these processes are reversed, leading to the accumulation of coarser grains on the plinths.

2 *Internal sedimentary structure*

Regretably few studies have been made of the internal structure of desert dunes, for they are potentially valuable sources of information on the way in which the dunes accumulate. Bagnold (1941) was the first to recognize and describe the internal structure of desert dunes and published a hypothetical section of a linear dune, in which laminae were divided into steeply dipping avalanche deposits on the crest and central areas of the dunes, and low angle accretion laminae on the dune plinths. McKee and Tibbitts (1964) confirmed this basic pattern for a 15 m high simple linear dune in the Libyan desert (Figure 5a). They found that upper parts of the dunes were composed of high angle cross strata with dips of 26–34°, with low angle cross strata (4–14°) in lower areas. The high angle strata were interpreted as avalanche or slip face deposits formed in a diurnally bidrectional wind regime, with winds blowing at around 45° to the dune.

Tsoar (1978) recognized two groups of laminae on a small simple linear dune in the Sinai. The first group were deposited parallel to the crest in a 1–2 m wide area and dipped at 33° perpendicular to the crest line, whilst the second, with

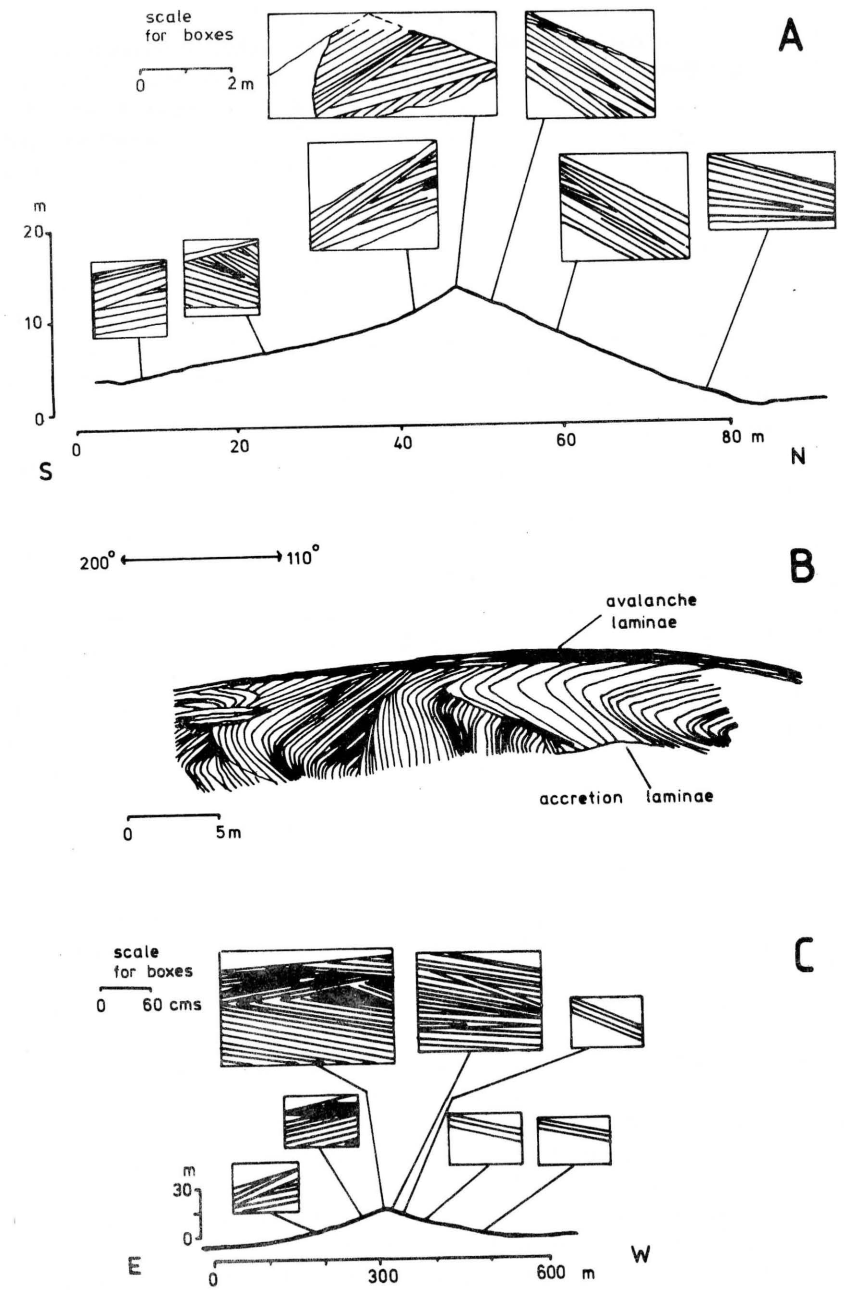

Figure 5 Internal structures of linear dunes. A: after McKee and Tibbitts (1964). B: after Tsoar (1978). C: after Breed and Breed (1979).

dips of 20–25° oblique to the crest line, formed the bulk of the dune. Tsoar called the first group 'avalanche laminae' and suggested that they were formed in the separation zone next to the crest, where sand falls out of the wind. The bulk of the dune was composed of lee acretion laminae formed by depostion of sand as it moves along the lee flank.

Breed and Breed (1979) studied internal structures of simple linear dunes in Australia and Arizona. They describe them as consisting mostly of medium scale, thin crossbeds with dips commonly less than 20°, occurring in tabular and wedge shaped sets bounded by near horizontal plaina erosion surfaces. Comparing these structures to those described by McKee and Tibbitts (1964) Breed and Breed argued that winds blowing for long periods from one direction would deposit sand in much larger lateral sets than those blowing for a few hours only, and that differences in internal structures could be explained in terms of wind regimes.

These thin cross beds with a moderate dip can be compared to acretion bedding of Tsoar (1978) and are probably the result of deposition by winds blowing at a small angle to the dune. Steeply dipping, avalanche deposits probably only occur when winds blow at a high angle to the dune. Thus the type of internal structure is dependent on the wind regime obtaining, and the apparent contradictions between the studies described above can be explained by differences in the wind regimes between the areas investigated.

IV Environments of linear dunes

1 *Position of linear dunes in sand seas*

Although dunes other than linear are rare in sand seas in Australia and the Kalahari, in most sand seas linear dunes occupy a part of sand accumulation only. In sand seas adjacent to coasts with onshore winds, such as the Namib, Wahiba and Sinai, barchanoid and transverse dunes occur along the coast and linear dunes inland (Besler, 1980; Breed *et al.*, 1979; Tsoar, 1974). This is probably largely the result of the decreasing effects of the sea breeze from the coast to inland, where other directions occur. However, Tsoar (1978) suggests that the age of the dunes may also be a factor and that the coastal dunes have not had time to evolve into linear dunes which he considers to be a climax form.

Elsewhere, regional changes in wind regimes may be a major factor in the spatial distribution of dune types. In the Sahara, northern areas are often characterized by complex and star dunes and eastern, southern and western areas by linear dunes. This pattern can be related to circulation patterns with linear dunes being best developed in areas dominated by anticyclonic circulations of persistent winds and complex dunes in areas affected by the passage of cyclones in winter months. Even here, there is some evidence to suggest Tsoar's contention that linear dunes are a more evolved form than transverse dunes, as in both the Ergs Chech and Grand Oriental satellite images (Breed *et al.*, 1979) show linear dunes developing downwind from complex and compound barchanoid dunes. A similar situation may also apply in the Rub al Khali.

2 *Winds in areas of linear dunes*

Fryberger and Dean (1979) have noted that linear dunes are found in a range of wind regimes both of total energy and directional variability. They are commonly found in wide unimodal (winds from one broad directional sector) or bidirectional wind regimes (winds from two distinct directions) and occasionally occur in complex wind regimes (more than two modes). Fryberger and Dean (1979) also noted that dunes tended to extend parallel to the resultant direction of sand movement, even in complex wind regimes. However, especially in low energy situations, dunes become less regular and shorter as the complexity of the wind regime increases; a point also noted by Mabbutt (1968) in central Australia.

Systems of linear dunes are frequently found in large arcs corresponding approximately to the pattern of outblowing winds around anticyclonic cells, but influenced also by winds associated with temperate cyclones on their poleward sides, especially in Australia (Brookfield, 1970) and the ITCZ on their equatorward margins (Fryberger and Dean, 1979). Such systems, often in part palaeoform, have been described from the Sahara (Mainguet and Canon, 1976) where they form part of a major sand transport system; Australia (Jennings, 1968, Brookfield, 1970) and southern Africa (Lancaster, 1981b). It would appear that development of linear dunes is favoured by the wind regimes associated with this type of circulation with relatively persistent winds from one major direction, together with seasonally important cross winds. When combined with the effects of rugged topography, the absence of such strong anticyclonic circulations in the deserts of central Asia and North America may largely explain the virtual absence of linear dunes in these areas.

a Wind regimes in areas of simple linear dunes: The wide unimodal wind regime of the southern part of the Simpson desert is typified by that of Oodnadatta (Fryberger and Dean, 1979) (Figure 6a). Here southerly winds and sand movements are important in most months and over the year form the dominant direction of sand movement which is parallel to dunes in adjacent areas. Seasonally, winds from southeasterly or southwesterly directions are important. During the winter and autumn (May to November) sand movements from WSW to SW directions dominate and it may be these which cause the asymmetry of the dunes in this area. During the period January to April sand movements from SSE to E are important. Essentially similar wind regimes with a single major direction parallel to the linear dunes and seasonally important adjacent direction of sand movement are illustrated by Fryberger and Dean (1979) for the southwestern Kalahari, Mauritania and the Erg Bilma.

Some linear dunes occur in areas where there is a clearly bidirectional wind regime. Tsoar (1978) describes winds adjacent to his study site in the northwestern

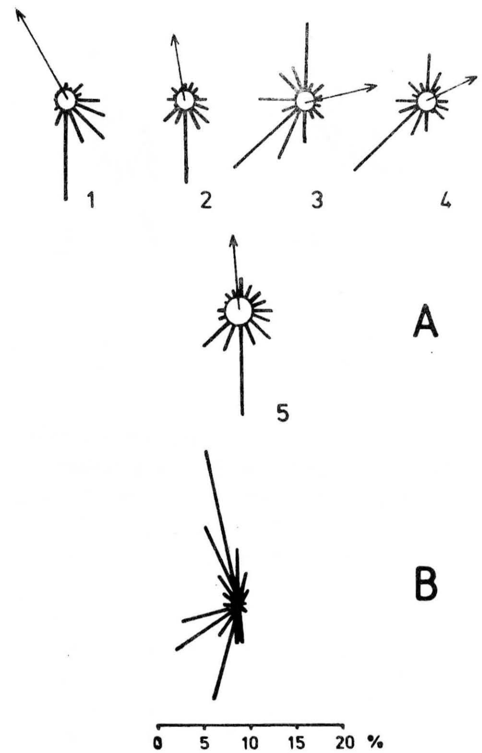

Figure 6 Sand movement roses for areas of simple linear dunes. A: Oodnadatta, Australia. 1 January, 2 April, 3 July, 4 October, 5 Whole year. B: Sinai, annual percentage of effective (6 m sec^{-1}) winds (after Tsoar, 1978).

Sinai desert (Figure 6b). He identified two sectors of effective (i.e. sand moving) winds, southerly winds associated with cyclonic circulation dominated in winter of 190–200° (SSW). In summer, northwesterly sea breezes blow and 85 per cent of effective winds are from between 320–360° with a mode at 340–350°. These winds are generally not strong and rarely exceed 10 m sec^{-1} but are more constant and are regarded by Tsoar as having a greater influence on the dunes in this area.

It is possible that the differences in form between the long straight Simpson desert and Kalahari simple linear dunes and the shorter seif type linear dunes of the Sinai and the Rub al Khali may result from differences in wind regime as was suggested originally by Price (1950), with a wide unimodal wind regime with a high proportion of wind parallel to the dunes in the former case and a clearly bidirectional wind regime in the latter, with few winds parallel to the dunes. Such a view also appears to be supported by the data from the internal structure of dunes in these areas.

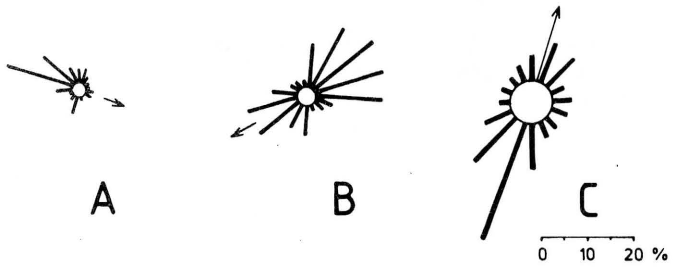

Figure 7 Sand movement roses for areas of complex linear dunes. A: As Shariqah (Trucial Coast). B: Timmimoun (Algeria) after Breed *et al.*, 1979). C: Narabeb (Namib sand sea) (after Lancaster, 1980).

b Winds in areas of complex linear dunes: It might be expected that wind regimes in areas of complex linear dunes might generally be of a complex type. This does not appear to be the case, although the available information is rather scanty. Information contained in Breed *et al.* (1979) suggests that, although directional variability is greater in areas of complex linear dunes, compared with simple and compound varieties, one or more adjacent directions are persistent, and these appear to determine the overall alignment of the dunes (Figure 7a). In some cases, winds from directions at 90° to the dunes form an important subsidiary component of the wind regime. Detailed information on wind regimes in areas of complex linear dunes in the Namib sand sea is in preparation, but available data and the sand movement rose in Lancaster (1980) (Figure 7c) indicate that three main directional sectors are important: N–NW, SW–SSW and NE–E. The southwesterly winds are the product of the sea breeze and are most persistent and strongest during summer months (September to April). Some 40 per cent of annual sand movement is from this sector. North to northwest winds occur during December to February and account for only 9 per cent of annual sand flow, but 15–16 per cent of sand flow during the summer. Strong easterly winds occur during the winter months and are responsible for 25–30 per cent of sand flow. Thus there are two major sand moving winds from sectors 130° apart, but the southwesterly sector dominates, giving a net sand movement at an angle of 20–30° to the trend of the dunes.

3 *Wind patterns over linear dunes*

Tsoar's (1978) detailed measurements of winds and sand movements on a 6–13 m high simple sinuous linear dune in the Sinai represent an important advance in our knowledge of the behaviour and development of linear dunes. For the first time, we have detailed and quantitative data on the pattern of wind speed and direction on a linear dune.

Tsoar monitored changes in wind velocity and direction across the dune using closely spaced anemometers and smoke candles. He observed that a separation zone exists in the lee of the crest even when winds blow obliquely to the dune. Here wind velocities are 20–70 per cent of those at the crest and deposition occurs by avalanching. Surface winds in this zone are erratic, but often are directed towards the crest, suggesting that there is a small lee roller eddy in the separation zone. At the point of attachment of the separated flow, 5–7 m from the crest, wind velocities increase again, and may reach values 5–20 per cent greater than those measured at the crest. Wind directions observed in this zone were parallel to the dune. Beyond this area, wind velocities tended to decrease again and to resume their original direction (Figure 8).

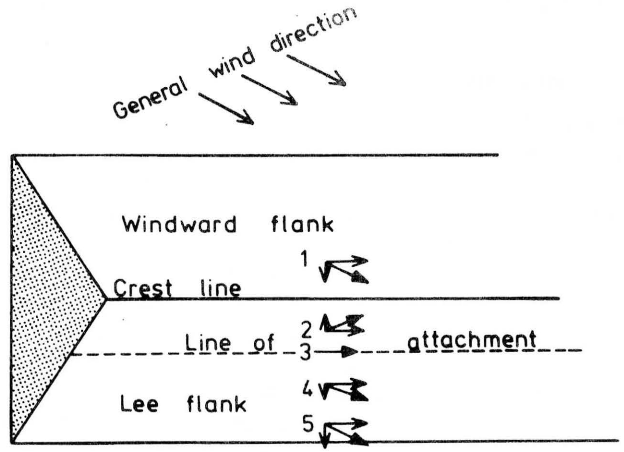

Figure 8 Changes in wind direction over a simple linear dune (after Tsoar, 1978). Solid arrow heads indicate wind direction, others wind velocity components normal and parallel to dune: 1 before separation; 2 in separation zone; 3 at line of attachment of separated flow; 4, 5 on lower lee flank.

Tsoar explained the observed changes in the following way. The wind has two velocity components, one parallel to the dune and one perpendicular to it. Thus the separated flow does not form a closed eddy, but one with helical form. In the attachment zone, the component of velocity perpendicular to the dune is very small but the dune parallel component is large. Therefore the wind will tend to blow parallel to the dune at this point. Tsoar argued that every wind that encountered the dune at an angle of 90° or less to the crestline would be diverted to produce movement parallel to the dune. The magnitude of the change depends largely on the angle between the wind and the crestline, the smaller the angle, the greater the dune parallel component of the wind and the greater the longitudinal movement. The increased velocities, and hence sand movements, in the attachment

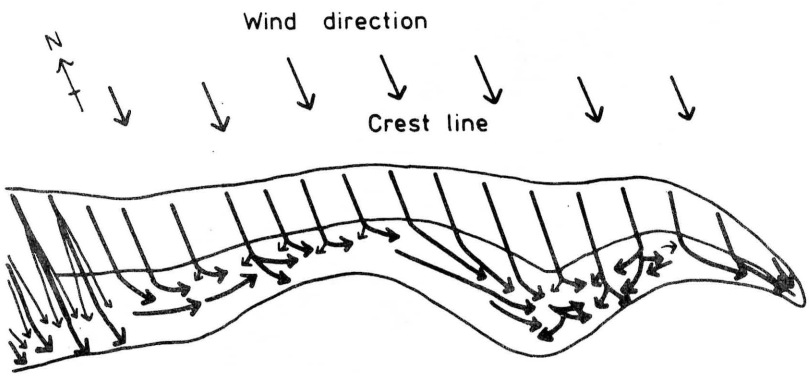

Figure 9 Idealized sand movement pattern on a simple linear dune (after Tsoar, 1978). Arrow indicates path followed by sand grains.

zone are the result of the concentration of streamlines as a result of the return of the separated flow to ground level. Thus the velocity of the wind parallel to the crest line at height $z(Cp_z)$ can be expressed as

$$Cp_{(z)} = V_{w(z+\Delta z)} \cos a$$

where $V_{w(z)}$ is the velocity of the wind at the crest at height z, Δz is the addition of height to the wind flow as a result of separation and cos a is the angle between the wind and the crest line. From experimental evidence, Tsoar concluded that the greatest increase in movement along the dune occurred when the wind crossed the crest at an angle of 30° ± 10° to the dune. He was able to confirm his studies of winds by observing sand movements traced with fluorescent dyed sand. With a wind blowing obliquely to the dune, sand moves along the lee flank parallel or subparallel to the crestline (Figure 9). The zone of attachment of the lee roller eddy is one of active erosion and transport of sand. Deposition occurs when the dune crest curves so that the magnitude of the deflection of winds and sand flows decreases; and also where the lee flank winds encounter streamline divergence.

Tsoar could find no evidence for any large scale helical flow. The only helical vortices present were small (5–7 m in diameter) and the result of separation flow over the crest of the dunes. From his studies, Tsoar (1978) concluded that the effect of winds which blow at angles less than 90° to the crest of linear dunes will be to move sand along the dune and thus extend it. This process is most effective when the angle between the wind and the dune is 20–40°, and persistent

winds from this direction relative to the dune play a major role in determining dune alignments.

V Hypotheses regarding the origins of linear dunes

From a consideration of the morphological and sedimentary characteristics of linear dunes and the wind regimes at macro and micro scale with which they are associated we turn now to a consideration of the various hypotheses which have been put forward to explain the origins of linear dunes and to an assessment of how adequately they explain the observed character of the dunes.

Most workers have to date concentrated upon the relationships between dune trends and wind regimes and from their conclusions on these have put forward suggestions as to the origins of the dunes. From this process, there have emerged two main hypotheses for the formation of linear dunes: that they form parallel to the direction of dominant or prevailing winds (variously defined) or that they form parallel to the resultant or vector sum direction of winds from two or more directions.

1 *The prevailing wind hypothesis*

Many workers, e.g. Blandford (1876), Aufrere (1928), Madigan (1936), Folk (1971) have noted the similarities between the alignment of linear dunes and the direction of the prevailing winds and have concluded that linear dunes form parallel to these winds. However, difficulty has arisen in trying to explain the growth of dunes separated by wide, often sand free, corridors. Some investigators have considered that the dune landscape is in part erosional. The 'windrift hypothesis' (King, 1960) argues that dunes are formed partly as or wholly by the lowering of adjacent interdune areas by deflation. Such a model was first proposed by Blandford (1876) who stated that dunes in the Thar desert were formed by the erosion of a deep, preexisting sand cover. In the Sahara, Aufrere (1928) and in Arizona, Melton (1940) suggested that linear dunes originated as U shaped dunes, becoming parallel ridges after the loss of the head of the U and further erosion of interdune areas. A similar hypothesis was advocated, at least for the initiation of linear dunes, by Verstappen (1968) on the basis of his observations in the Thar desert. King (1960) made borings through linear dunes near Lake Eyre, Australia and found that they had cores up to 6 m thick of older alluvial sediments. He concluded that the dunes rested on ridges of the underlying substrate and were formed by wind chanelling of the desert floor, with the eroded sand being moved towards the dunes. However, in a different part of the Simpson desert, Mabbutt and Sullivan (1968) found that the subdune floor continued uninterupted beneath the dunes in both areas of unconsolidated alluvial sediments and indurated gravels. King also cited the evidence of the Y junction in support of his hypothesis, equating them with the deflation rims of parabolic dunes. But many workers including

Madigan (1936) and Mabbutt and Sullivan (1968), point out that they are often asymmetric with a subsidiary ridge joining a main one and regard them as simply the convergence of adjacent ridges caused by deflection of the downwind ends of growing dunes. Despite this, Folk (1971) favoured the view that linear dunes are erosional and formed on preexisting areas of unconsolidated sandy sediments.

A number of other workers, whilst noting the parallelism between dune alignments and prevailing winds have put forward alternative explanations for the origins of linear dunes and have regarded them as essentially depositional forms. Madigan (1936) rejected the notion of deep, preexisting sand deposits in the Simpson desert. He suggested that linear dunes were formed in areas of strong dominant winds, and were initiated by the deposition of sand in strips following periods of sand movement. In support of this hypothesis he drew analogies with snow movement on ice surfaces in Antarctica and in a later paper (Madigan, 1946) was able to use the observations of Bagnold (1941) to confirm his views. Bagnold noted the transverse instability of a wind moving over a gravel surface which produced parallel longitudinal wavy ribbons of sand transport. When the wind speed dropped he suggested that these could be deposited as longitudinal sand strips, and under favourable circumstances they might ultimately develop into linear dunes, as surface roughness differences would encourage deposition on the sandy area. Glennie (1970) further developed this model and argued that once the dunes were formed pressure gradients would be created between their crestal areas and the interdune, as a result of the resistance to the wind of the dune itself. 'Wind cells' in the dune/interdune unit are thus formed which give the air an overall spiral motion in which surface eddies are directed outwards towards the dunes. However, there is no such field evidence for the movement of sand from interdune to dune, nor for winds directed towards the dunes.

Bagnold felt that the regular repetition of the sand streams implied a larger scale roller movement of the air, a view he developed in his 1953 paper. In this, Bagnold pointed to the thermal instability of air over desert surfaces, which would lead to the development of vertical convection cells in still air, but which, following Brunt (1937), in moving air would become organized into pairs of longitudinal roller vortices spaced at a distance three times that of the height of the convectional layer. This helical motion of the air would impart an alternate left and right hand oblique component to the surface wind which would then sweep sand into long parallel ridges spaced the width of a vortex pair apart (Figure 10). In support of this view, Bagnold stated that linear dunes in Egypt were parallel to the resultant of winds during the hottest months but not to those of the whole year.

This model was further developed by Hanna (1969) who hypothesized that linear dunes were depositional forms created at the convergence between the surface winds of two counter rotating helical roll vortices formed in strong trade winds crossing hot desert surfaces. Hanna reviewed the laboratory and field evidence for helical roll vortices and demonstrated their widespread occurrence. He then compared data on the spacing of linear dunes with the expected dimension of helical roll vortices in subtropical desert areas, concluding that their probable

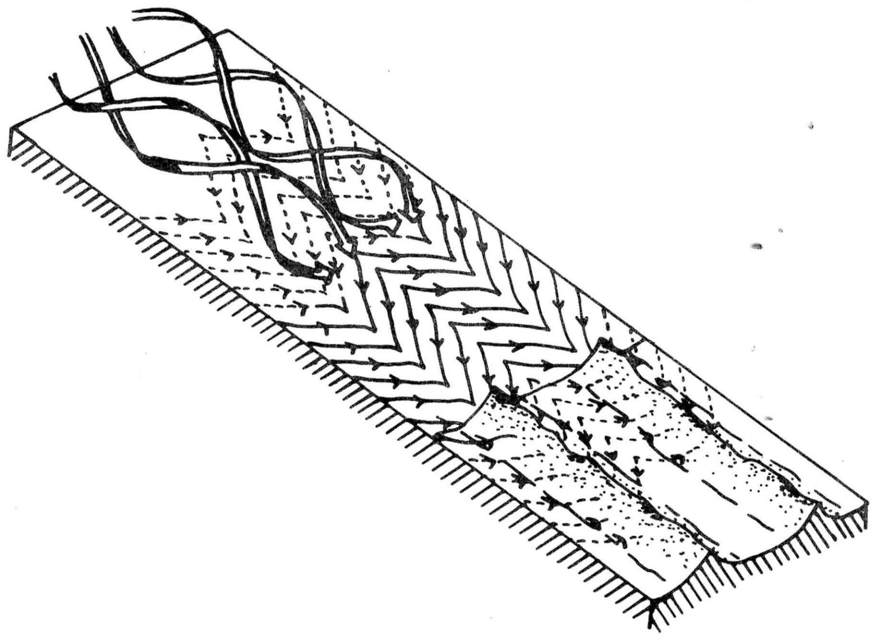

Figure 10 The formation of linear dunes by horizontal roll vortices (after Cooke and Warren, 1973).

wavelength was 2–6 km (two to three times the convective layer thickness of 1–2 km), a figure which was 'in general agreement' (*sic*) with observed dune spacings. A major flaw in this argument is that if linear dunes are created by helical roll vortices of approximately circular form, as is widely assumed, then they should be spaced at two times the diameter of the vortices or 4–12 km apart. The available evidence (Breed and Grow, 1979) is that the maximum spacing of linear dunes in regular patterns is 3–3.5 km and that there are large areas, such as the Simpson and Kalahari deserts, where dune spacings are commonly less than 1 km, much smaller than any reported dimensions of helical roll vortices (Le Mone, 1973).

It would seem, therefore, that the observed scale of helical roll vortices is much larger than average dune spacings, which would imply that linear dunes are not the product of such atmospheric motions. Further, if helical roll vortices are responsible for the formation of linear dunes then we would expect to find evidence for the movement of sand from interdune to dune, but no published observations can be found for this, nor for the existence of helical roll vortices in linear dune landscapes. Tsoar (1978) found that the only vortex flows that exist are restricted to the separation zone immediately adjacent to the crest of the dune. In any event, the horizontal velocities deduced from the tetroon flights of Angell *et al.* (1968) are between 2 and 6 km/hr^{-1} and unlikely, therefore, to move much sand. Angell *et al.* also noted that helical roll vortices tended to drift laterally to the mean wind. If this is indeed the case, then stable linear dune patterns can hardly be developed by the action of helical roll vortices. Despite these objections, the helical roll vortex model of linear dune formation has been widely adopted (Wilson, 1972; Cooke and Warren, 1973; Warren, 1979).

Folk (1971) combined the windrift and helical roll vortices models of linear dune formation in a composite scheme in which winds move sand from deep pre-existing sand deposits into uniformly spaced dunes. Thus, although major air movement is parallel to the dunes, local winds move sand diagonally up their flanks. With this model, Folk explained Y junctions as places where the axes of the vortices rise slightly, possibly as the air is heated. If such a hypothesis is correct, then we should expect to find extensive desert sand plains without dunes, as possible future sites for linear dune formation. This is not the case. Further, there are many areas where linear dunes are developed over indurated substrates or bedrock, in situations where a former sand cover is unlikely to have existed.

Although it is an elegant hypothesis and satisfactorily explains the parallelism, length and regular spacing of linear dunes, the helical roll vortex model of linear dune formation must be rejected on account of the great differences between the observed scale of the vortices and the spacing of desert dunes.

2 *Two wind, or resultant, models of linear dune formation*

Bagnold (1941) suggested that many linear dunes extend in a direction parallel to the resultant direction of sand movement. He illustrated this by reference to a hypothetical situation in which a barchan dune moved into a bidirectional wind regime. Over time, it would be transformed into a linear dune by the elongation of one horn. Strong winds from an oblique direction would add sand to one horn which would then be extended by gentler winds from the original direction. Repetition of this cycle would lead to the creation of a linear dune with regularly repeated summits and a sharp sinuous crest line. Spacing of the dunes would, Bagnold thought, be related to regularities in the winds parallel to the dunes. There is some field evidence for such a process. Barchans with extended arms are common in some parts of the Sahara (Clos-Arceduc, 1967) and may relate to the elongation of one arm by an asymmetry in the wind regime. Warren (1976) argued that small linear elements in the Nebreska sand hills dune field were created by weaker southwesterly winds in a wind regime dominated by strong winter northwesterly winds. In the Namib, Lancaster (1980) reports linear dunes 1–1.5 km long and 3–8 m high with a WSW–ENE alignment developing from barchans. Stronger southwesterly and south-southwesterly winds supply sand to the linear dunes which is then redistributed along the dunes by weaker west-southwesterly to west-northwesterly winds.

Although, as Bagnold mentioned, such a model is not perhaps a universal mechansim for the formation of linear dunes, it has given rise to the view that linear dunes are the product of bidirectional wind regimes and extend in the resultant direction of sand movement. To a large extent most of the arguments advanced are based upon correlations between dune alignments and wind directions (e.g.

Striem, 1954) and on the differences between wind regimes in adjacent areas of transverse and linear dunes, Tsoar (1974), Fryberger and Dean (1979). They are supported by studies of internal structures and processes.

In Libya, McKee and Tibbitts (1964) explained the existence of large scale cross strata with a steep dip (24–34°) each side of the crest of an E–W aligned dune as the product of a bidirectional wind regime with southeasterly winds in the morning and northeasterly in the afternoon. Wopfner and Twidale (1967), Clarke and Preistley (1970) and Twidale (1972) argue that linear dunes in the Simpson desert are constructional forms created by strong bidrectional winds from one main directional sector. In support of their argument they note the day to day reversal of slip faces near the crest and the cross bedded internal structures.

Perhaps the most closely reasoned two wind model of linear dune formation is that of Tsoar (1978). He made use of his observations on winds and sand movements on a dune to provide a dynamic process-response scheme for linear dune formation. The basis of this is that winds which blow at an angle of less than 90° to the crest line of the dune are diverted to run parallel to the dune crest. The effects of this process will be to elongate the dune downwind. Thus any wind from a sector of 180° centred on the dune will be deflected in this way and linear dunes will form in a wind regime where winds blow from one wide sector. The relatively high velocities of the diverted winds cause sand not to be deposited directly on the lee flank, except in a small slip face zone, but to be moved along the dune, and in the attachment zone even to be eroded from the lee flank. Large scale deposition on the lee flank will only occur where the angle between the crest line and the wind angle is close to 90°. Most deposition on the dune is not, therefore, of the avalanche type, but by lee side accretion.

Seasonal or daily changes in the wind direction will cause changes in the erosion/deposition pattern on the dune, creating a sinuous pattern of narrower, lower saddles and higher, wider peaks (Figure 11). This then maintains itself by interaction between the dune and the wind. For winds from either side of the dune, the crest line will consist of flow parallel and flow transverse segments, with erosion on the former and deposition on the latter. The dune will narrow when erosion exceeds deposition, other areas will be sites of net deposition and widen and grow in height. However, as deposition will be spread over a greater area, the growth rate will progressively decrease and eventually a dynamic equilibrium state will exist, with peaks and saddles at a uniform equilibrium height.

Tsoar suggested that the overall tendency will be for the dune to extend downwind, with the sinuosities gradually moving along the dune. The height of each peak and saddle and the regularity of the sinuosities of the crestline, are dependent upon the consistency of winds from the formative direction. In the Sinai, the overall trend of the dune is determined by the summer wind (northeasterly), which crosses the dune at the optimal angle for lee flank erosion and movement along the dune. Winter winds (southwesterly) in the Sinai also move sand along the dune and reverse the position of erosion and deposition areas, but do not cross the dune at optimal angles and so contribute less to its elongation. According

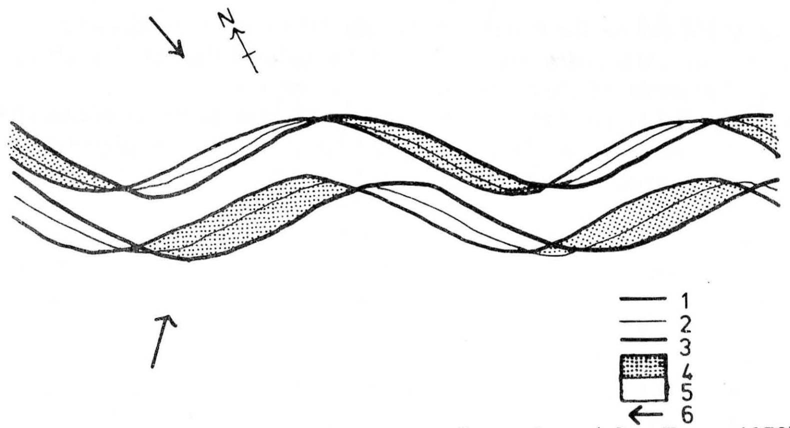

Figure 11 Erosion deposition pattern on a linear dune (after Tsoar, 1978): 1 original form of dune; 2 dune form after first phase of erosion and deposition; 3 dune form after second phase of erosion and deposition; 4 depositional areas; 5 erosional areas; 6 wind directions.

to Tsoar, if the winds from each side of the dune are equal in strength then no peaks and saddles will form. Tsoar's model represents an important advance in an understanding of how linear dunes maintain their form and extend longitudinally by relating form and sedimentary characteristics to processes and wind movements. As will be seen later, it can be used to develop a general model to explain linear dune formation and characterization.

Less convincingly, Tsoar presents a model for the initiation of linear dunes from parallel longitudinal ridges of coarse sand or 'zibar'. Linear dunes start to grow when the wind has winnowed out sufficient fine sand from these areas to form sharp crests with a lee separation zone. Once this has taken place, the flow separation and diversion phenomena discussed above can occur and the dune begins to develop and grow downwind. This process appears to take place in Sinai, as Tsoar shows, but its general applicability may be limited. 'Zibar' also occur widely as forms transverse to the wind (Warren, 1972), and it is difficult to see how the process described would operate in this case. However, Tsoar shows examples of linear dunes forming downwind of longitudinal 'zibar' in the Ténéré desert and in the southern Namib the writer has observed similar processes operating. However, Tsoar also allows the possibility of the formation of linear dunes from transverse dunes and barchans, when, for example, they move into areas of bidirectional winds. In this case one directional sector of the wind regime may select preferentially one barchan horn and elongate it. Further wind action will then inevitably turn this into a linear dune.

There is much to support the view that linear dunes form as a result of the action of winds from two major convergent directions, or from a wide convergent sector. Such wind regimes with a seasonal variation of directions over 120–180° are common and it can be shown that if linear dunes are subjected to winds from

one major direction only they will eventually erode and break up. Tsoar's observations show, however, that persistent winds from one direction will have a major effect upon the dune alignment, and it is perhaps this which has been identified previously with the 'prevailing wind'. There is little evidence to suggest that linear dunes form parallel to this wind direction, but as Tsoar states, they will tend to form at oblique angles of 20–30° to it. This helps to explain the observations of Cooper (1958), Clos-Arceduc (1967) and Cooke and Warren (1973) that linear dunes frequently seem to be oblique to persistent wind directions.

However, this type of model does not satisfactorily explain why linear dunes are regularly spaced. Tsoar (1978) suggests that they are spaced 12–15 times the height of the dunes, which theoretically (Oke, 1978) should be the distance at which the disturbance of the wind by the dune should have ceased. But the winds blow obliquely to the dune and thus the separation between the dunes along the wind direction is much greater, as also observed by Twidale (1972) in the Simpson desert. The height/spacing correlations observed in areas of linear dunes (Twidale, 1972; Lancaster, 1981c) do however suggest that there is some aerodynamic control of dune spacing, but until winds in interdune areas have been measured this will remain a matter of speculation.

VI Towards a general model of linear dune formation

A general model of linear dune formation should ideally be able to account for the straightness, parallelism and regular spacing of linear dunes; as well as their sinuous crest lines and characteristic internal structures. Such a model should also be able to explain why linear dune morphology varies from place to place.

The observations of erosion-deposition patterns and wind strength and direction of linear dunes made by Tsoar (1978) provide the basis for such a model. For all wind directions erosion will take place on windward flanks. In addition winds blowing obliquely to the dune are deflected to blow parallel to the dune on its lee side and erode and transport sand along this flank. This process extends the dune and provides the essential mechanism for linear dune formation. It further explains why such dunes are generally narrow, but very long. Movement parallel to the dune is greatest when the wind crosses the dune at a small angle (less than 30°). As the angle between the wind and the dune increases the amount of deflection decreases and consequently there is less lee flank erosion and transport of sand parallel to the dune. Ultimately, when the wind crosses the crestline at ± 90°, deposition, by avalanching on a slip face, dominates. The other limiting case is when the wind blows parallel to the dune and erosion and longitudinal movement will take place on all parts of the dune, so lowering and extending it.

Thus the effects of winds from different directions are related to the angle at which they cross the crest line of the dune. If this is small, then that element of the dune will tend to be extended. Consequently, certain elements of a dune pattern will be emphasized by some winds but not others. Depending on the character of the wind regime this pattern element may become a major or subsidiary part of the dune alignment in an area. Two or more dune alignments can coexist, with the major alignment at a small angle to the most persistent wind. Lack of a persistent wind direction will probably result in irregular dune patterns. The alignment of dunes may in some cases change rapidly, the 'phase change' of Wilson (1972), when a gradual change in the regional wind regime may cause one direction to cross a 'threshold' angle relative to the dune and thus become effective at extending it. At the same time, the former effective direction may cease to have a marked effect on the dune. Some wind directions may have little effect on the overall morphology, despite their high potential for sand movement. For example, in the northern parts of the Namib sand sea, infrequent, but often high velocity, easterly winds encounter the crest lines of the dunes at close to 90° and appear to do little more than reverse the crestlines and deposit sand on the western side of the dune. Further, there is no reason to suppose that linear dunes extend parallel to the resultant wind. More probably, they are aligned at a small angle (20–30°) to the most persistent sand moving winds, and are parallel to the resultant direction of the sand moving winds only when winds from each side are equally persistent.

From Tsoar's observations, winds from two directions are necessary for the origins and maintainance of a linear dune form. The effect of the persistence of a wind from one direction is to concentrate erosion and deposition at the same locations on the dunes. If this wind blows obliquely or parallel to the dune, then the dune will eventually break up by the continued erosion of the saddles and by the growth of the peaks by deposition. Thus a linear dune may ultimately be reformed into a series of individual or linked barchans. Such a process is close to happening in the northern parts of the Namib sand sea, where the persistence of southwesterly winds is producing short linear dune chains separated by areas of barchanoid and transverse dunes. A similar process, noted by Hanna (1969) for the Kharga Oasis and Lancaster (1980) for the Tsondab Flats, may happen when the tip of the linear dune is too low for separation flow to occur and the end of the linear dune becomes transformed to a series of barchans, which stream off at an oblique angle.

Because of the varying effects of winds from different directions relative to the dune it is possible to suggest that if a high percentage of the winds blow at an optimal angle for lee side movement, then the dune will tend to extend strongly, especially if winds also blow parallel to the dunes. Often one flank will be steepened preferentially, giving rise to the consistent asymmetry noted by Clarke and Preistley (1970). Deposition on dunes in such a wind regime is mostly by accretion and may be at quite a low rate. Internal structures will be dominated by low angle accretion bedding (Breed and Breed, 1979). They are thus analagous to the 'sand passing' dunes of Wilson (1972). Perhaps because the rate of deposition is low such dunes tend to be relatively low. The very long, low, Kalahari and Simpson desert type linear dunes are of this type and have developed in a wind regime of this character as reference to Figure 6a will show.

If winds blow at higher angles to the dunes then longitudinal movements of

sand will decline and avalanche deposition will increase. Such dunes will tend to be shorter, perhaps more sinuous, at least in their crestal areas and may be relatively higher. Because lee side avalanche deposition is common, then steeply dipping cross bedding will be a feature of their internal structures, as in the example of McKee and Tibbitts (1964).

A limiting case will occur when winds are opposed at 90° to the dunes, producing a reversing type, which may have a linear form especially if there are occasional oblique winds. Sand movements will consist of alternate erosion and deposition on each flank, with the probability that once on the dune, sand will stay there, leading to dunes which tend to grow in height but not extend much. Dunes of this type, developed under a wind regime with opposed southwesterly to west-northwesterly and north-easterly to easterly winds, are common in the eastern parts of the Namib sand sea. Further, in a complex wind regime, winds will move sand up and down the dune and from side to side. There will be little extension of the dune, but great vertical growth. Thus star dunes tend to be the highest of all dune types.

Dunes will tend to be larger and have a complex form in conditions of abundant sand supply and a wind regime which favours deposition. One effect of large size may be to create secondary winds on the dune which produces two scales of erosion and deposition patterns. One maintains the dune, the other creates and maintains the secondary dunes, such as the east flank barchanoid dunes of the Namib complex linear dunes.

The parallelism of linear dunes is a striking feature of their morphology, but one which is relatively easily explained. The processes operating on linear dunes lead to dune extension. Thus, as the dunes in one area are affected by the same wind regime they will then extend parallel to each other. Their regular spacing is more difficult to account for, but may be an aerodynamic effect related in some way to the distrubance of the wind as it passes over a dune. More research is needed to clarify this point.

VII Conclusions

Such a model as proposed above is only a first approximation, and does not attempt to explain every feature of linear dune morphology. It is intended to provide a broad conceptual framework to stimulate further study of linear dunes and into which field observations may be fitted. Neither does it satisfactorily account for all varieties of linear dunes. For example, compound linear dunes are not easily explained by the model. Nor does it provide an explanation for the regular spacing of linear dunes.

However, it is clear that a single detailed field study (Tsoar, 1978) has contributed more to our understanding of linear dunes than years of hypothesizing. The need now is to test the model proposed by more studies of erosion and deposition patterns on dunes and the relation of these patterns to the winds of the time on linear dunes of different sizes and characters. Studies of winds are also needed, not only on linear dunes but on dune/interdune units.

The character and formation of linear dunes has remained difficult to explain for so long only because detailed studies of form and process have been so few.

Desert Ecological Research Unit, PO Box 953, Walvis Bay, SWA/Namibia

Acknowledgements

I thank the CSIR and Transvaal Museum for assistance and the Division of Nature Conservation, SWA Adminsitration, for facilities and permission to work in the Namib Desert Park.

VIII References

Alimen, M.H. 1953: Variations granulométriques et morphoscopiques du sable le long de profils dunaires au Sahara Occidental. *Actions Eoliennes, Centre Nationale de Recherches Scientifiques, Colloques Internationaux* 35, 219–35.

Angell, J.K., Pack, D.H. and **Dickson, C.R.** 1968: A langrangian study of helical circulations in the planetary boundary layer. *Journal of Atmospheric Science* 25, 707–17.

Aufrere, L. 1928: L'orientation des dunes et la direction des vents. *Comptes Rendus, Académie des Sciences* 187, 833–35.

Bagnold, R.A. 1941: *The physics of blown sand and desert dunes.* London: Chapman and Hall.

1953: The surface movement of blown sand in relation to meteorology. In *Desert research: Proceedings of International Symposium, Jerusalem, May 1952,* Research Council of Israel Special Publication 2, 83–93.

Barnard, W.S. 1973: Duinformasies in die Sentrale Namib. *Tegnikon, Des 1973,* 5, 2–13.

Besler, H. 1976: Wasseruberformte dunen als glied in der landschaftgenese der Namib. *Baseler Afrika Bibliographen* 15, 83–106.

1977: Untersuchungen in der dunen Namib (Sudwestafrika). *Journal of the South West Africa Scientific Society* 31, 33–64.

1980: Die dunen-Namib: entstehung und dynamik eines ergs. *Stuttgarter Geographische Studien* 96 (241 pp.)

Blandford, W.T. 1876: On the physical geography of the Great Indian Desert, with special reference to the existence of the sea in the Indus valley and on the origin and mode of formation of the sand hills. *Journal of the Asiatic Society of Bengal (Calcutta)* 45, 86–103.

Breed, C.S. and **Breed, W.J.** 1979: Dunes and other windforms of central Australia (and a comparison with linear dunes on the Moenkopi Plateau, Arizona). In El-Baz, F. and Warner, D.M., editors, *Apollo-Soyuz test project, volume 2: earth observations and photography,* Washington DC: National Technical Information, 319–58.

Breed, C.S., Fryberger, S.C., Andrew, S.E., McCauley, C., Lennartz, F., Gebel, D. and **Horstman, K.** 1979: Regional studies of sand seas using Landsat (ERTS) imagery. In McKee, E.D., 1979, 305–98.

Breed, C.S. and **Grow, T.** 1979: Morphology and distribution of dunes in sand seas observed by remote sensing. In McKee, E.D., 1979, 253–304.

Brookfield, M. 1970: Dune trend and wind regime in central Australia. *Zeitschrift fur Geomorphologie, Supplement Band* 10, 121–58.

Brunt, D. 1937: Natural and artificial clouds. *Quarterly Journal of the Royal Meteorological Society* 63, 277–88.

Clarke, R.H. and **Preistley, C.H.B.** 1970: The asymmetry of Australian desert sand ridges. *Search* 1, 77–78.

Clos-Arceduc, A. 1967: La direction des dunes et ses rapports avec celle du vent. *Comptes Rendus, Académie des Sciences* 264, 1393–96.

Cooke, R.U. and **Warren, A.** 1973: *Geomorphology in deserts.* London: Batsford.

Cooper, W.S. 1958: Coastal sand dunes of Oregon and Washington. *Memoir of the Geological Society of America* 72 (169 pp.)

Crocker, R.L., 1946: The Simpson Desert Expedition 1939. Scientific Reports, 8, The soils and vegetation of the Simpson desert and its borders. *Transactions of the Royal Society of South Australia* 70, 235–58.

Folk, R.L. 1971: Longitudinal dunes of the northwestern edge of the Simpson desert, Northern Territory, Australia. 1 Geomorphology and grain size relationships. *Sedimentology* 16, 5–54.

Fryberger, S.G. and **Dean, G.** 1979: Dune forms and wind regime. In McKee, E.D. 1979, 137–70.

Fryberger, S. and **Goudie, A.S.** 1981: Progress report: arid geomorphology. *Progress in Physical Geography* 5, 409–28.

Glennie, K.W. 1970: *Desert sedimentary environments. Developments in sedimentology* 14. Amsterdam: Elsevier.

Goudie, A.S. 1970: Notes on some major dune types in southern Africa. *South African Geographical Journal* 52, 93–101.

Hanna, S.R. 1969: The formation of longitudinal sand dunes by large helical eddies in the atmosphere. *Journal of Applied Meteorology* 8, 874–83.

Holm, D.A. 1960: Desert geomorphology in the Arabian Peninsula. *Science* 132, 1369–79.

Jennings, J. 1968: A revised map of the desert dunes of Australia. *Australian Geographer* 10, 408–9.

Jordan, W.M. 1964: Prevalence of sand dune types in the Sahara desert. *Geological Society of America, Special Paper* 82, 104–105.

King, D. 1960: The sand ridge deserts of south Australia and related aeolian landforms of Quaternary arid cycles. *Transactions of the Royal Society of South Australia* 79, 93–103.

Lancaster, N. 1980: The formation of seif dunes from barchans – supporting evidence for Bagnold's model from the Namib desert. *Zeitschrift fur Geomorphologie* NF 24, 160–67.

1981a: Grain size characteristics of Namib desert linear dunes. *Sedimentology* 28, 115–22.

1981b: Palaeoenvironmental implications of fixed dune systems in southern Africa. *Palaeogeography, Palaeoclimatology, Palaeoecology* 33, 327–46.

1981c: Aspects of the morphometry of linear dunes of the Namib desert. *South African Journal of Science* 77, 366–68.

1981d: Spatial variations in linear dune morphology and sediments in the Namib sand sea. In *Paleoecology of Africa,* Proceedings 6th SASQUA Conference, Pretoria, May 1981 (in press).

Le Mone, M.A. 1973: The structure and dynamics of horizontal roll vortices in the planetary boundary layer. *Journal of Atmospheric Science* 30, 1077–91.

Lewis, A.D. 1936: Sand dunes of the Kalahari within the Union. *South African Geographical Journal* 19, 23–32.
McKee, E.D. editor, 1979: *A study of global sand seas.* United States Geological Survey Professional Paper 1052. (429 pp.)
1979: Introduction to a study of global sand seas. In McKee, E.D., 1979, 3–19.
McKee, E.D. and **Breed, C.S.** 1976: Sand seas of the world. *United States Geological Survey Professional Paper* 929, 81–88.
McKee, E.D. and **Tibbitts, C.** 1964: Primary structures of a seif dune and associated deposits in Libya. *Journal of Sedimentary Petrology* 34, 5–17.
Mabbutt, J.A. 1968: Aeolian landforms in central Australia. *Australian Geographical Studies* 6, 139–50.
Mabbutt, J.A. and **Sullivan, M.E.** 1968: Formation of longitudinal dunes, evidence from the Simpson desert. *Australian Geographer* 10, 483–87.
Madigan, C.T. 1936: The Australian sand ridge deserts. *Geographical Review* 26, 205–27.
1946: The Simpson Desert Expedition 1939. Scientific Reports, 6, The sand formations. *Transactions of the Royal Society of South Australia* 70, 45–63.
Mainguet, M. 1976: Propositions pour une nouvelle classification des édifices sableux éoliens, d'après les images des satellites Landsat 1, Gemini. *Zeitschrift fur Geomorphologie* NF20, 275–96.
Mainguet, M. and **Callot, Y.** 1974: Air photo study of typology and interrelations between the texture and structure of dune patterns in the Fachi-Bilma erg, Sahara. *Zeitschrift fur Geomorphologie, Supplement Band* 20, 62–68.
Mainguet, M. and **Canon, L.** 1976: Vents et paléovents du Sahara, tentative d'approche paléoclimatique. *Revue de Géographie Physique et de Géologie Dynamique* 18, 241–50.
Melton, F.A. 1940: A tentative classification of sand dunes. *Journal of Geology* 48, 113–73.
Monod, Th. 1958: Majabat Al-Koubra. *Mémoires de l'Institut Français D'Afrique-Noire* 52. (406 pp.)
Oke, T.R. 1978: *Boundary layer climates.* London: Methuen.
Price, W.A. 1950: Saharan sand dunes and the origin of the longitudinal dune: a review. *Geographical Review* 40, 462–65.
Striem, H.L. 1954: The seifs on the Israel-Sinai border and the correlation of their alignment. *Bulletin of the Research Council of Israel* 4, 195–98.
Tsoar, H. 1974: Desert dunes, morphology and dynamics, El Arish (northern Sinai). *Zeitschrift fur Geomorphologie, Supplement Band* 20, 41–61.
1978: *The dynamics of longitudinal dunes.* Final Technical Report, European Research Office United States Army. (171 pp.)
Twidale, C.R. 1972: Evolution of sand dunes in the Simpson desert, central Australia. *Transactions of the Institute of British Geographers* 56, 77–110.
Verstappen, H.Th. 1968: On the origin of longitudinal (seif) dunes. *Zeitschrift fur Geomorphologie* NF12, 200–20.
Warren, A. 1972: Observations on dunes and bimodal sands in the Ténéré Desert. *Sedimentology* 19, 37–44.
1976: Morphology and sediments of the Nebraska sand hills in relation to Pleistocene winds and the development of aeolian bedforms. *Journal of Geology* 84, 685–700.
1979: Aeolian processes. In Embleton, C. and Thornes, J., editors, *Process in geomorphology,* London: Edward Arnold, 325–51.
Wilson, I.G. 1972: Aeolian bedforms – their development and origin. *Sedimentology* 19, 173–210.

Wopfner, H. and **Twidale, C.R.** 1967: Geomorphological history of the Lake Eyre basin. In Jennings, J.N. and Mabbutt, J.A., editors, *Landform studies from Australia and New Guinea,* Cambridge: Cambridge University Press.