

## THE DEVELOPMENT OF LARGE AEOLIAN BEDFORMS

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### ABSTRACT

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Large aeolian bedforms (complex and compound varieties of dunes or draas) dominate over wide areas of many sand seas and are well represented in the rock record. Analyses of allometric relationships between dune height and spacing in several sand seas suggest that draas develop by vertical growth of existing dunes. In the Namib and other sand seas draa tend to occur in areas of low total and net sand transport rates. The distribution of such bedforms in a sand sea reflects long-term patterns of deposition which are related to regional-scale changes in wind regimes and sand transport rates.

Superimposed bedforms are almost ubiquitous on draa and develop only after a minimum size of draa has been reached. Formation of superimposed dunes reflects spatial and temporal variations in secondary flow patterns developed on the draa.

Measurements of winds and depositional patterns on complex linear dunes in the Namib Sand Sea suggest that an important mechanism for their growth is the migration of superimposed dunes from areas of high to low wind velocity on draa flanks, leading to the deposition of sediment by bedform climbing.

### INTRODUCTION

Large aeolian bedforms, termed compound or complex dunes in the terminology of McKee (1979) are a common feature of modern sand seas. Some 46.6% of the dunes in sand seas examined by Fryberger and Goudie (1981) are of compound or complex types. Such dunes are the largest elements in a hierarchical arrangement of bedforms and were called draas by Wilson (1972). They are characterised by the superimposition of smaller dunes of the same type (compound dunes) or different type (complex dunes) on larger structures (Fig. 1). In this paper, Kocurek (1981a) will be followed and the term draa will be used to refer collectively to complex and compound dunes.

In the rock record, the deposits of draas are a major component in a variety of aeolian sandstone units, including the Proterozoic Hornby Bay Group in Canada (Ross, 1983); Permian sandstones in Britain (Thompson, 1969; Brookfield, 1977; Steele, 1983); the Permian Coconino and Schnebly Hill sandstones of Arizona (Blakey and Middleton, 1983); and the Jurassic Entrada sandstone of Utah and



Fig. 1. (a) Compound crescentic dunes in coastal areas of the Namib Sand Sea. Note two orders of bedform spacing, the main dunes at 600–800 m and the superimposed dunes, with a spacing of 60–100 m. View to west. (b) N–S oriented complex linear dune in the Namib Sand Sea. View of east flank to show superimposed crescentic dunes which migrate obliquely to the main dune trend and decrease in size downwind (to NE) and away from the dune crest.

Colorado (Kocurek, 1981a, b). Migration of superimposed dunes over draas creates second-order bounding surfaces, whilst first-order bounding surfaces are the product of the migration of the draas themselves (Brookfield, 1977; Kocurek, 1981a).

Although draas are an important component of modern and ancient aeolian depositional systems, the factors which determine their size and spacing and the processes responsible for their formation and development are poorly understood. This paper explores some geomorphic evidence which indicates how such bedforms may develop.

#### PREVIOUS WORK

The morphology of aeolian bedforms is a product of interactions between the sand surface and the wind, but the exact nature of the factors which control dune size and spacing is poorly understood. Hanna (1969), Wilson (1972) and Folk (1976) have suggested that the spacing of dunes is determined by secondary transverse and longitudinal vortices in the atmospheric boundary layer. Wilson (1972) went on to develop a model of the grain size control of aeolian bedform spacing. He argued that the size of the coarse fraction sets the scale of turbulent atmospheric structures which determine dune spacing. For a given grain size, there is a minimum shear velocity that will move this sand and hence a minimum possible dune spacing. Wilson apparently sampled simple, compound and complex linear, star and crescentic dunes, as well as sand sheets (Wasson and Hyde, 1983a), and found a clear relationship between bedform spacing and the grain size of the coarse twentieth percentile ( $P_{20}$ ) of dune crest sands for each element of the bedform hierarchy in three northern Saharan sand seas. Wilson argued that changes in dune spacing were caused primarily by changes in the grain size of the source sediment. He concluded that dune and draa spacing varied approximately with the cube of wind shear velocity.

Wilson (1972) also developed models for the growth and development of aeolian bedforms. He suggested that dunes and draas grow to a dynamic equilibrium with the causal conditions, if these remain constant for a sufficiently long period. Once dynamic equilibrium is reached, transverse bedform elements then migrate downwind.

Since Wilson published his ideas on the development of aeolian bedforms, Landsat images have provided a large amount of new data on dune patterns in sand seas. These data, together with detailed studies of dune morphology, sediments and wind regimes in the Namib Sand Sea, suggest that a new approach to the development of large aeolian bedforms may be necessary.

#### THE NATURE OF AEOLIAN BEDFORM HIERARCHIES

In the Namib Sand Sea, as elsewhere in areas of compound and complex dunes (Matschinski, 1952; Wilson, 1972), there is a hierarchical system of aeolian bed-

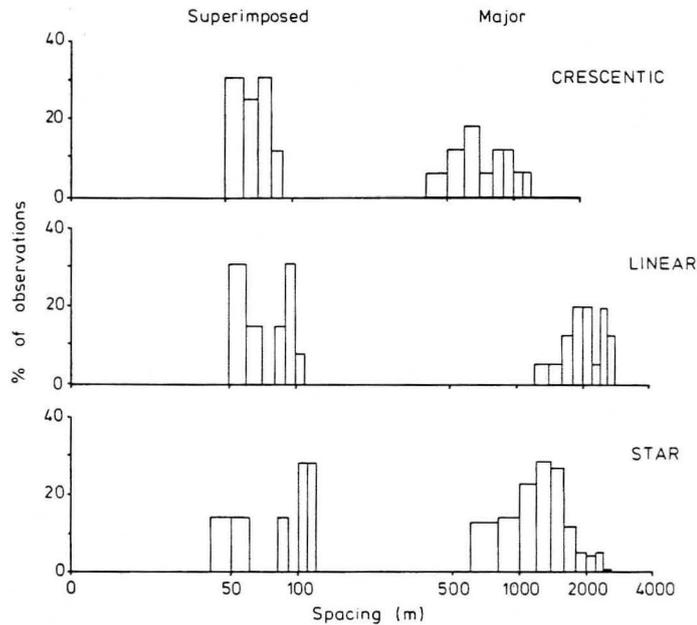


Fig. 2. Hierarchical arrangement of the spacing of major dunes (draas) and superimposed dunes in the Namib Sand Sea.

forms (Fig. 2). Following Jackson (1975), three orders of aeolian bedforms can be recognised: (1) microforms: wind ripples (spacing 0.1–1 m); (2) mesoforms: individual simple dunes or superimposed dunes on compound and complex dunes (spacing 50–500 m); and (3) macroforms: compound and complex dunes or draa (spacing > 500 m).

Each element of the hierarchy responds to the dynamics of a component of the wind regime in an area and possesses a characteristic time period, termed the relaxation or reconstitution time (Allen, 1974), over which it will adjust to changed conditions. In the case of aeolian bedforms, reconstitution time increases by up to several orders of magnitude from micro to meso and macro forms. Change in bedforms involves the movement of sediment, thus an increasing spatial scale is involved at each level of the hierarchy. Ripples, the smallest bedform in the hierarchy, have a morphology which is controlled by the nature of individual dynamic events (periods of sand moving winds) and a short life span (hours or days). The morphology of simple dunes and superimposed dunes on draas is governed principally by seasonal-scale patterns of wind direction and velocity and by spatial changes in wind over larger bedforms. The life span of these dunes is in the order of  $10-10^2$  years. Analogous subaqueous bedforms are megaripples and sand waves in tidal environments. The largest aeolian bedforms, draas or complex and compound dunes, respond only to changes in the overall geomorphological

regime (sensu Jackson, 1975). They are relatively insensitive to changes in local airflow conditions and may persist for  $10^3$ – $10^5$  years. Macroscale dune forms or draas are comparable in scale to point bars in river channels and sand banks in shallow seas.

This difference of scale between the elements of the aeolian bedform hierarchy suggests that the factors which control the size and spacing of simple dunes (mesoforms) should be considered separately to those which influence the size and spacing of draas (macroforms). Whereas the height and spacing of small, simple dunes in active sand seas probably tends towards a dynamic equilibrium with respect to contemporary sand supply conditions and wind regimes, the size and spacing of large complex and probably compound bedforms (draas) may be regarded as a function of the long-term pattern of accumulation of sand in certain areas of the sand sea determined by regional scale patterns of winds and sand transport. It is therefore not possible to explain draa size and spacing as an equilibrium response, as proposed by Wilson (1972).

#### NATURE OF THE RELATIONSHIPS BETWEEN DUNE HEIGHT AND SPACING

A range of sizes of aeolian bedforms occurs in all desert sand seas. Close relationships between their height, width and spacing have been documented by Wilson (1972), Breed and Grow (1979), Lancaster (1982a, 1983), Wasson and Hyde (1983a, b) and Lancaster et al. (1987). The available data are summarised in Fig. 3. In many sand seas, dune height and spacing vary from place to place in a systematic manner (Fig. 4).

The relationship between dune height and spacing reflects the amount of sand incorporated in the bedforms of an area. Analysis of this relationship using concepts of allometry (the analysis of the relative rates of change of two parts of a system) can provide information on the way aeolian bedforms may develop. Examination of dune height/spacing relationships in this way is an example of dynamic allometry in which changes in time are examined using spatial data (Bull, 1975).

The general form of the relationships between dune height and spacing can be expressed by a power function:

$$D_H = c D_S^n \quad (1)$$

where  $D_H$  is dune height,  $D_S$  is dune spacing,  $c$  is a constant and the exponent  $n$  is a measure of the rate of change of the dependent variable relative to the rate of change of the independent variable (the slope of the regression line).

There are three possible allometric models to explain dune height/spacing relationships:

(1) Isometry: dune height increases at the same rate relative to dune spacing such that the exponent of the power function equals unity. Thus a given amount of sand can be formed into a few widely spaced dunes or many small closely spaced dunes. Such a model was advocated for Simpson Desert linear dunes by Twidale (1972).

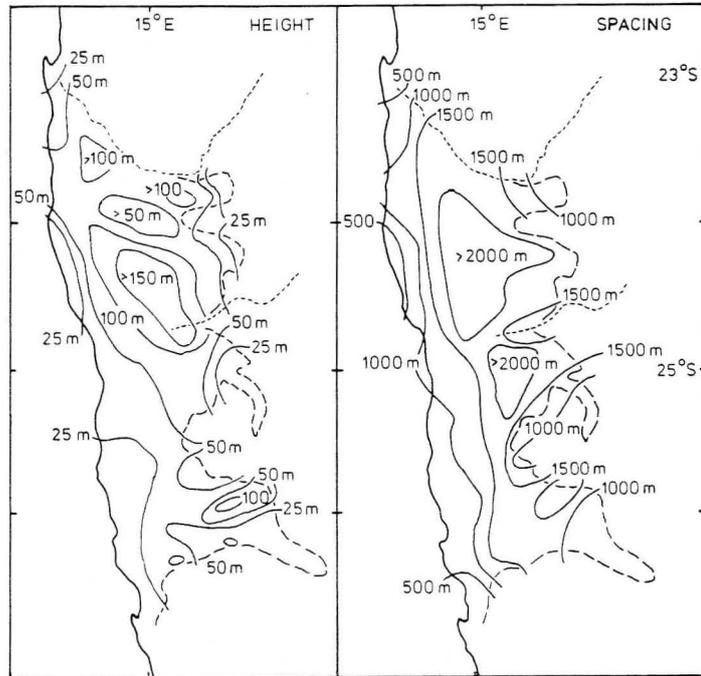


Fig. 3. Spatial variation in dune height and spacing in the Namib Sand Sea. Data for dune spacing obtained from air photographs. Dune heights determined from field survey and extrapolated to other areas from regressions of dune height and spacing.

(2) Positive allometry: dune height increases more rapidly than dune spacing, indicating a tendency for vertical growth of the dunes. The exponent of the power function is greater than unity.

(3) Negative allometry: dune height increases less rapidly than dune spacing. Dunes grow towards an "equilibrium" height and maintain that height thereafter. Further change takes place by dune extension or migration. The exponent of the power function is less than unity.

The value of the constant term in eq. 1 (Table 1) varies by up to 13 times between dune types and between the same dune type in different sand seas. For example, the crest to crest spacing of 5 m high simple crescentic dunes is 100 m in the Skeleton Coast dunefield in Namibia but 150 m in the Namib Sand Sea and 300 m in the Gran Desierto sand sea. Similarly, 10 m high simple linear dunes are 490 m apart in the Simpson-Strzelecki sand sea, but 1300 m apart in the Great Sandy Desert. In the Namib Sand Sea, compound linear dunes 2000 m apart will be 37 m high, yet complex linear dunes of the same spacing will have a height of 70 m and star dunes with the same spacing will be 180 m high. In this sand sea, the magnitude of the constant term increases from crescentic through compound linear to complex linear and star dunes.

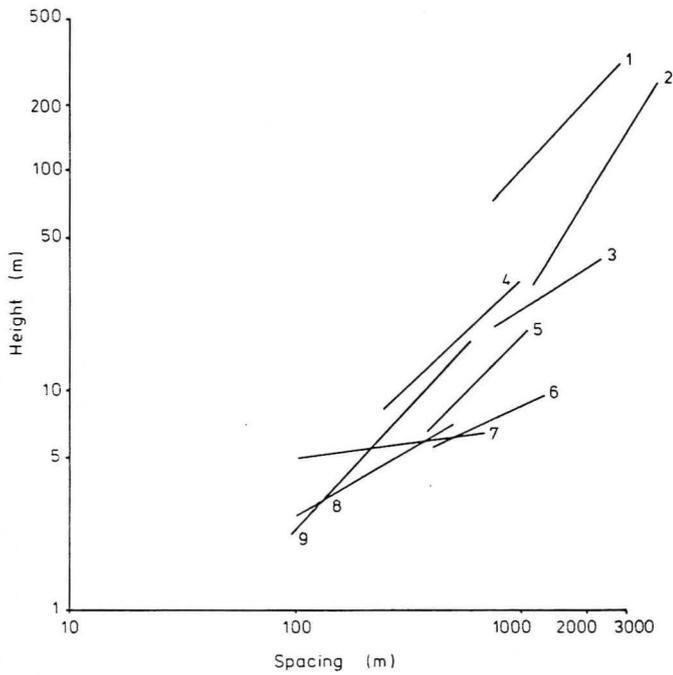


Fig. 4. Relationships between dune height and spacing. Data for Australian sand seas from Wasson and Hyde (1983). 1 = Namib Sand Sea star dunes; 2 = Namib Sand Sea complex linear dunes; 3 = Namib Sand Sea compound linear dunes; 4 = Namib Sand Sea simple and compound crescentic dunes; 5 = Simpson Desert simple linear dunes; 6 = Great Sandy Desert simple linear dunes; 7 = Skeleton Coast dunefield crescentic dunes; 8 = Gran Desierto simple crescentic dunes; 9 = Southwestern Kalahari simple linear dunes.

TABLE 1

Constants and exponents of power functions of dune height/spacing relationships in Fig. 4

	Constant	Exponent
Namib Sand Sea		
Crescentic dunes	0.040	0.97
Compound linear dunes	0.600	0.54
Complex linear dunes	0.002	1.72
Star dunes	0.001	1.20
Skeleton coast dunefield crescentic dunes	0.008	1.40
Gran Desierto crescentic dunes	0.192	0.58
Simpson-Strzelecki Sand Sea linear dunes	0.011	1.06
Great Sandy Desert linear dunes	0.230	0.52
Southwestern Kalahari linear dunes	0.014	1.10

Variations in the value of the constant term appear to be an index of differences in the amount of sand contained in the dunes of a sand sea. This is a product of sand supply, in the sense of the amount of sand available from source areas; dune type, which reflects wind regime characteristics; and time.

The exponents of the power function in eq. 1 vary from 0.52 to 1.72 (Table 1) between sand seas, as well as from one dune type to another in the Namib Sand Sea. Some areas or types of dunes follow positive allometric relationships, whilst others display negative allometry. Strong positive allometry is shown by complex linear dunes and star dunes in the Namib Sand Sea and crescentic dunes in the Skeleton Coast dunefield. Linear dunes in the Simpson-Strzelecki Desert and crescentic dunes in the Namib Sand Sea are close to isometry whilst compound linear dunes in the Namib Sand Sea, linear dunes in the Great Sandy Desert and crescentic dunes in the Gran Desierto display moderate negative allometry.

Concepts of allometry suggest that crescentic dunes and compound linear dunes in the Namib Sand Sea grow towards a maximum height at an asymptotic rate, whereas complex linear dunes and star dunes show a strong tendency for vertical growth without an equivalent change in dune spacing. Dune types exhibiting negative allometry occur in the southern and western parts of the Namib Sand Sea where annual total and resultant potential sand transport rates (Table 2) are higher

TABLE 2

Wind regime environments of different dune types in the Namib Sand Sea

Dune type and wind recorder	Annual potential sand flow ( $t m^{-1} yr^{-1}$ )		Wind regime character
	total	resultant	
Crescentic			
KMK	2312	2024	Very high to high-energy unimodal
MD	440	335	
Linear			
compound	671	386	High-energy obtuse bimodal
Complex			
D7	42	22	Low- to moderate-energy obtuse bimodal or wide unimodal
NRB	99	46	
FM	99	56	
NN	119	63	
RB	278	129	
GB	91	51	
CH	54	30	
Star			
D8	49	10	Low-energy, complex
MNZ	23	6	

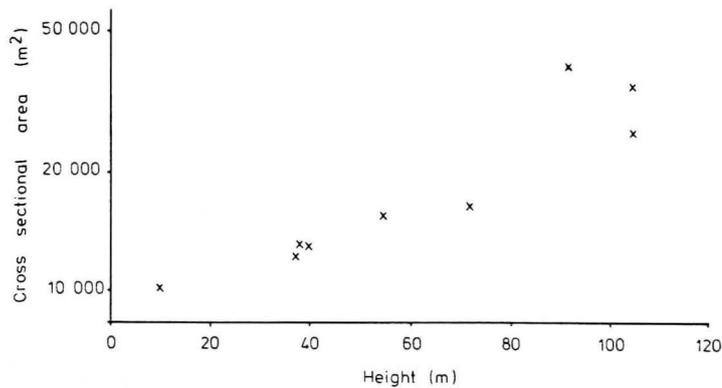


Fig. 5. Relationship between cross sectional area of dune and dune height for surveyed compound and complex linear dunes in the Namib Sand Sea.

compared with those in areas of complex linear and star dunes (Lancaster, 1983, 1985a). Thus negative allometric relationships between dune height and spacing may characterise dunes in zones of active throughgoing sand transport and rapid dune extension or migration and positive allometric relationships may indicate areas of net deposition and dune growth.

Data from surveyed cross-sections of linear and star dunes in the Namib Sand Sea shows that their cross-sectional area increases logarithmically with dune height (Fig. 5). Thus, large dunes contain proportionately more sand than do small examples of the same type. The amount of sand contained in the bedforms of an area may be represented by the equivalent or spread-out sand thickness (EST), obtained by dividing dune cross-sectional area by dune spacing. Figure 6 shows that

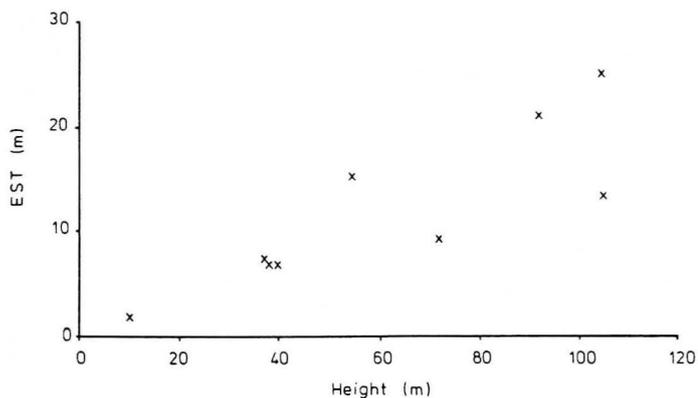


Fig. 6. Relationship between equivalent sand thickness and dune height for surveyed compound and complex linear dunes in the Namib Sand Sea.

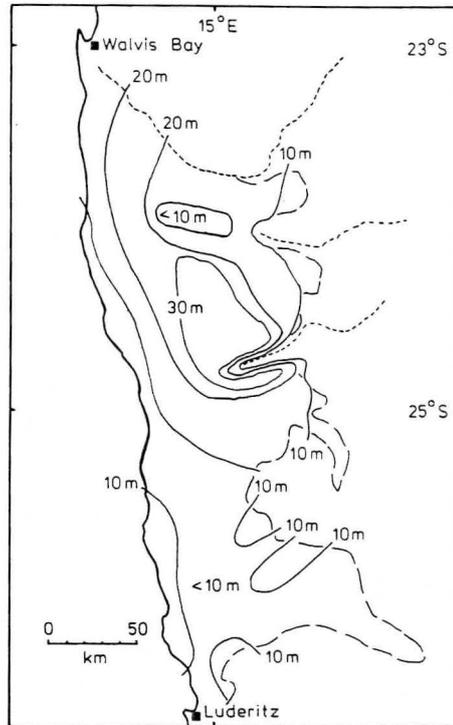


Fig. 7. Spatial variation of equivalent sand thickness in the Namib Sand Sea, representing amount of aeolian deposition contained in the bedforms of the sand sea. Map derived from relationship in Fig. 5.

there is a strong linear relationship between dune height and EST. Similar relationships were obtained for Saharan sand seas by Wasson and Hyde (1983a) and can be used to derive maps of EST for sand seas (Fig. 7). Comparison of Fig. 4 with Fig. 7 shows that, in the Namib Sand Sea, areas of large complex dunes, even though widely spaced, represent a greater accumulation of sand than do smaller, more closely spaced simple and compound dunes.

#### CONTROLS ON THE SIZE AND SPACING OF LARGE AEOLIAN BEDFORMS

Given that the distribution of large draa in a sand sea is an indicator of the pattern of aeolian deposition, it is important to examine the factors which control bedform size, in order to better understand how sand seas accumulate.

#### *Effects of grain size*

Grain size and dune spacing data for the Namib Sand Sea were used to test Wilson's hypothesis of a grain size control of dune spacing. It is clear that, in the

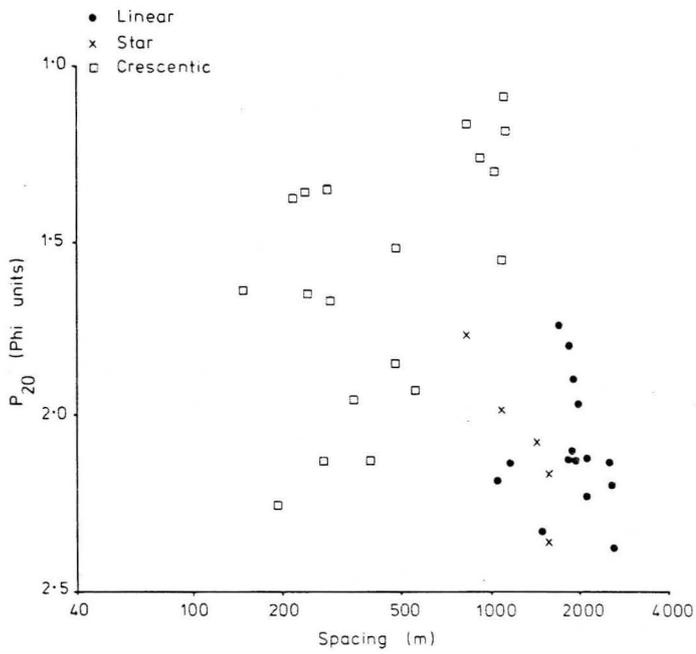


Fig. 8. Relationships between dune spacing and  $P_{20}$  for the Namib Sand Sea.

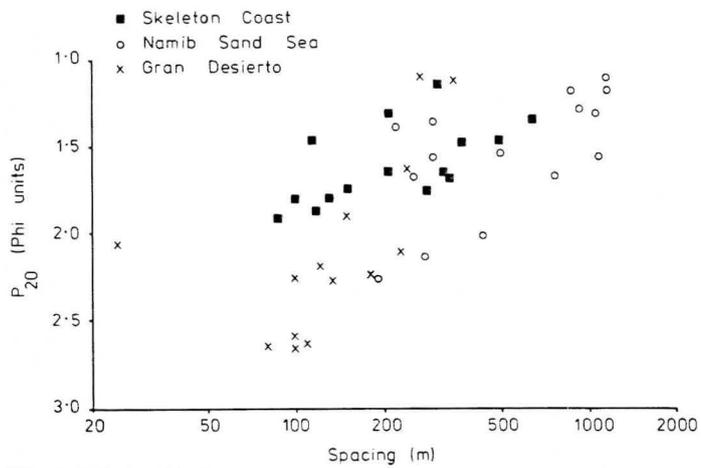


Fig. 9. Relationship between spacing of crescentic dunes and  $P_{20}$  in Namibian and Gran Desierto sand seas.

Namib Sand Sea, there is no relationship between  $P_{20}$  and the spacing of linear and star dunes (Fig. 8). Wasson and Hyde (1983a, b) also found that there was no relationship between dune spacing and  $P_{20}$  for linear dunes in Australian dune-fields.

Clearly, Wilson's hypothesis of a grain size control of dune spacing is not universally applicable. Large, widely spaced linear and star dunes are not associated with areas of coarse sand. In fact, they tend to be located in areas where sands are very fine and well sorted (Lancaster, 1982b, 1983). However, data from the Namib Sand Sea, the Skeleton Coast dunefield (Lancaster, 1982a) and Gran Desierto Sand Sea (Lancaster et al., 1987) indicate that there is probably some grain size control of the spacing of crescentic dunes (Fig. 9). Preliminary studies of the effects on dune morphology of observed variations in wind velocity and sand transport rates over dunes (Lancaster, 1985b) indicate that transverse dunes composed of fine sand will tend to develop shorter and steeper stoss slopes compared to those composed of coarse sand. For a given dune height, it appears therefore that stoss slope length may control the crest-to-crest spacing of transverse dunes. This link between grain size and dune shape may partly explain the observed relationships between  $P_{20}$  and dune spacing.

#### *Effect of sand transport rates*

In sub-aqueous environments, bedform spacing increases with flow depth and grain size (Allen, 1968). If flow depth and grain size are held constant, then bedforms increase in size as flow strength increases (Kennedy, 1969; Yalin, 1972). A downcurrent decrease in transport rate will consequently lead to a decrease in bedform size or number of bedforms (Rubin and Hunter, 1982).

It might be expected, therefore, that dune size is related to overall sand transport rates such that larger dunes are located in areas of high wind energy, as represented by high total potential sand transport rates, and small dunes in areas of low wind energy. However, for 100 km<sup>2</sup> areas of dunes in the Namib Sand Sea plots of mean dune height against both annual total and resultant potential sand transport calculated for adjacent wind recorders (Fig. 10) show that exactly the opposite situation occurs: large dunes are found in areas where annual potential sand transport rates are low and small dunes in areas of high sand transport rates. Similarly, equivalent sand thickness, which can be regarded as an index of the total amount of sand in the bedforms of a given area, varies inversely with total potential sand transport rates (Fig. 11). Information on dune size and EST contained in Wilson (1973), Breed and Grow (1979) and Breed et al. (1979) also suggests that large dunes, with a high EST, in Saharan sand seas also occur where annual total or net sand transport is low.

In the Namib Sand Sea, there is a progressive reduction in potential sand transport rates from south to north and west to east (Table 2 and Fig. 12) such that

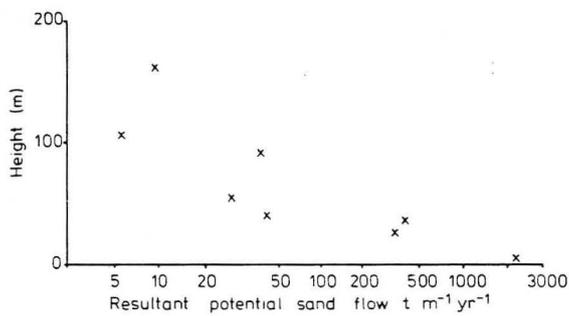
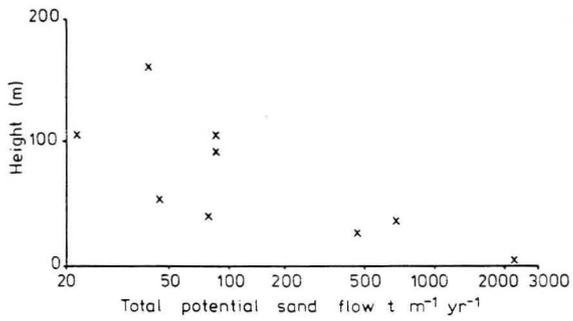


Fig. 10. Relationship between dune height and annual total and resultant potential sandflow in the Namib Sand Sea. Potential sand transport rates calculated using formula of Bagnold (1953).

central areas of the sand sea, with their large dunes are areas of low total and net potential sand transport (Lancaster, 1983, 1985a). Figure 3 shows that there is also a close correspondence between areas of low dunes in the southern part of the sand

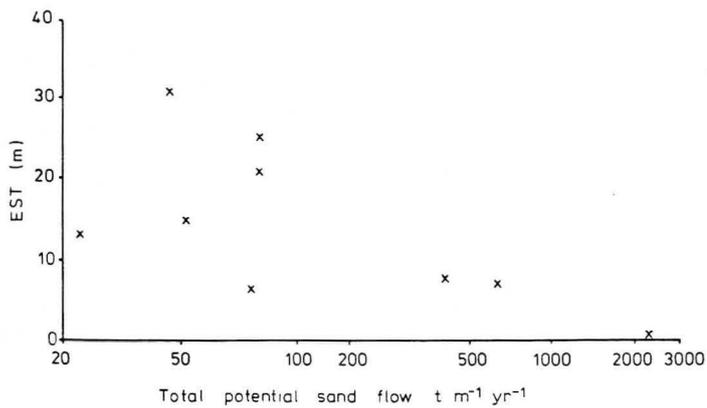


Fig. 11. Relationship between equivalent sand thickness and total potential sandflow in the Namib Sand Sea. Potential sand transport rates calculated using formula of Bagnold (1953).

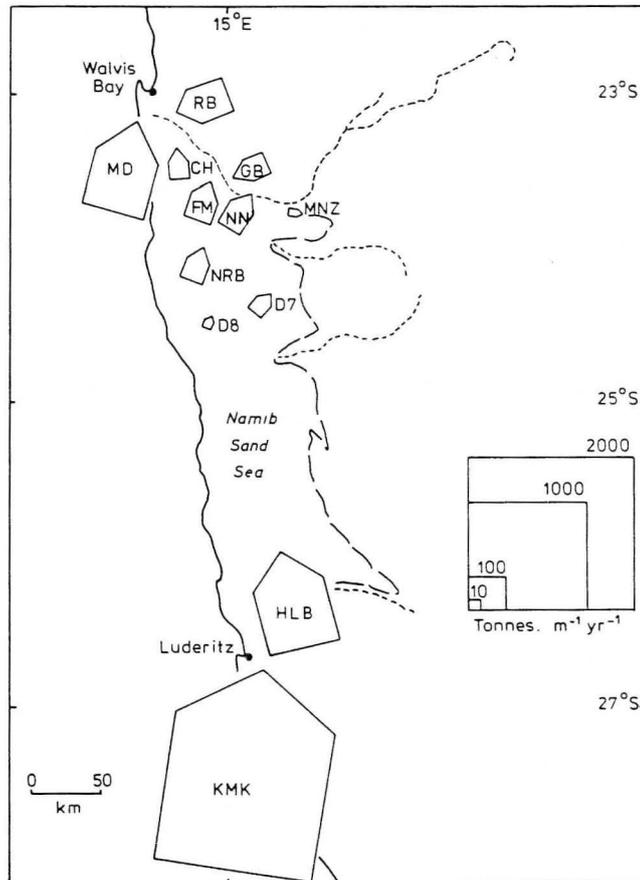


Fig. 12. Spatial variation in potential sand transport rates in the Namib Sand Sea. Area of arrows in proportion to amount of annual resultant potential sand flow. Data from stations in Table 2, with locations shown. Potential sand transport rates calculated using formula of Bagnold (1953).

sea and areas of high annual total and net potential sand transport rates. The distribution of large bedforms in a sand sea therefore reflects the spatial pattern of deposition. Their size is a result of long continued growth in conditions of abundant sand supply.

#### THE DEVELOPMENT OF COMPOUND AND COMPLEX DUNES

##### *Origins of superimposed dunes*

Large bedforms in sand seas are almost always compound and complex dunes which are characterised by the development of superimposed smaller dunes upon

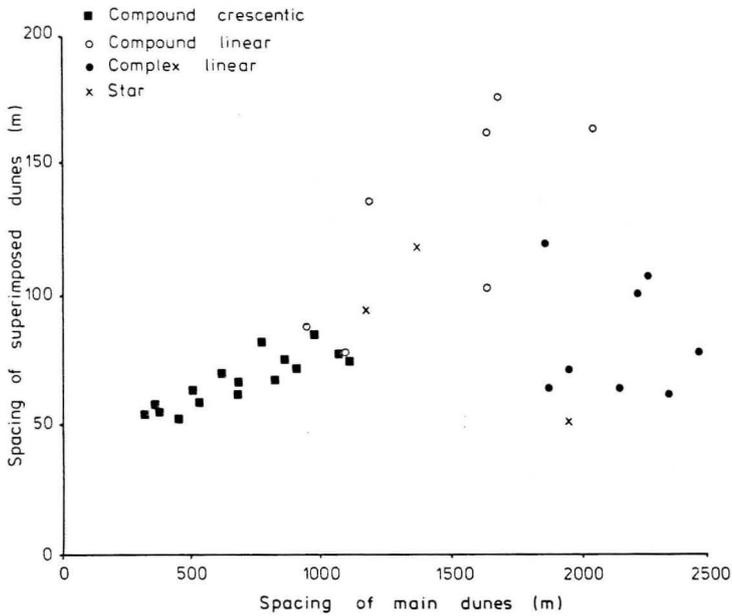


Fig. 13. Relationships between the spacing of main (draas) and superimposed dunes of each major type in the Namib Sand Sea.

them. To understand their origins and development, it is necessary to understand how superimposed dunes form. In subaqueous environments, there are two major models for the development of superimposed bedforms. Allen (1968, 1983) and others have suggested that they develop in response to temporal changes in flow conditions. Glennie (1970, 1983) and Besler (1980) have suggested that compound and complex dunes are a product of Quaternary climatic changes and were formed during periods of strong winds during Pleistocene glacial periods. Weaker modern winds can only form the small dunes which are superimposed on their flanks. Alternatively, Boothroyd and Hubbard (1975), Smith and McLean (1977) and Rubin and McCullough (1980) have shown that two or more scales of bedforms may coexist in equilibrium with steady flow conditions in rivers and estuaries. The widespread existence of compound dunes in clearly active modern sand seas, as well as in the rock record, suggests that superimposed bedforms are the product of contemporaneous aeolian environments.

In the Namib Sand Sea, there is a strong correlation ( $r = 0.84$  and  $0.75$ ) between the mean spacing of superimposed dunes and that of the draas on which they are situated in areas of compound crescentic and linear dunes, but no such correspondence in areas of complex linear and star dunes (Fig. 13). This suggests that the size of the superimposed dunes in areas of compound draas scales with that of the major dune and is the product of two components of the same airflow pattern. In areas of

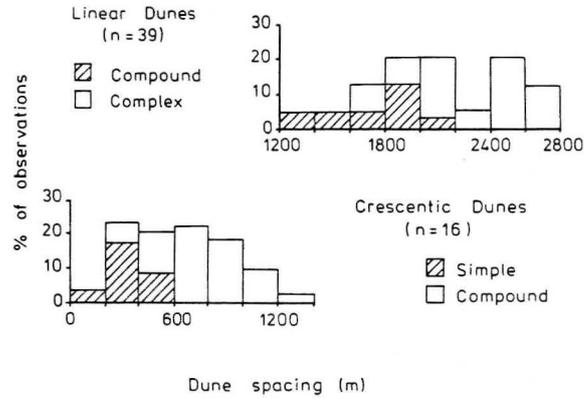


Fig. 14. The spacing of simple, compound and complex dunes of each type in the Namib Sand Sea. Major bedform spacings only considered.

complex linear and star dunes, there is no relationship between the spacing of the draas and the superimposed dunes, which are largely transverse to sand-transporting winds. Two different types of airflow pattern are apparently involved in this case.

Aeolian bedforms are a response to the dynamic instability of sand transport in conditions of fluctuating flow on planar sand surfaces. Given sufficient sand supply, ripples and dunes will be formed on flat desert surfaces. In the same way, the slopes of draas will present an effectively planar surface on which sand transport takes place. Therefore, variations in sand transport rates on draas in time or space (Lancaster, 1985b) will lead to the formation of superimposed dunes on draas if they are of sufficient size. This suggests that there is a minimum size for compound and complex dunes.

Although the sample size is small ( $n = 32$ ), data on the width and spacing of simple, compound and complex crescentic and linear dunes (Breed and Grow, 1979) indicate that the mean size of simple, compound and complex dunes is statistically significantly different (Mann-Whitney U test, significant at the 0.05 level). This indicates that a minimum dune size must be reached before superimposed dunes can develop. In the Namib Sand Sea, simple crescentic dunes have a spacing of less than 500 m, whereas compound dunes are all more than 500 m apart. There is, however, a continuum of the spacing of the major bedform from simple to compound and complex types (Fig. 14). This suggests that, given sufficient sand supply and time, dunes will grow into draas.

#### *Mechanisms for draa growth*

As suggested by Brookfield (1977), Kocurek (1981b), Ross (1983), Rubin and Hunter (1982, 1985), and Mader and Yardley (1985) complex and compound dunes

(draa) probably grow mostly by a combination of merging and modification as a result of the movement of superimposed dunes across draas. Modern complex and compound crescentic dunes can be observed to develop by merging, or shingling, as faster moving smaller dunes accrete onto larger, slowly moving examples as a result of downwind decreases in migration rates (Howard et al., 1978). This may be the product of topographic barriers, as in the case of the Great Sand Dunes, Colorado (Andrews, 1981) or regional climatic changes (McKee 1982). In the Namib Sand Sea, there appears to be a S-N decrease in wind strength and potential sandflow rates in coastal areas leading to the merging of crescentic dunes between Conception Bay and Sandwich Harbour. In the Gran Desierto, Mexico (Lancaster et al., 1987) crescentic dunes migrate towards and accrete onto clusters of large star and reversing dunes and compound crescentic dunes develop into complex forms with star dune peaks as they migrate into areas of seasonally reversing wind regimes.

Climbing of superimposed bedforms on the lee slopes of draa is a major mechanism in their growth. Its significance has been recognised by Brookfield (1977), Hunter and Rubin (1983) and Rubin and Hunter (1985). In the Namib Sand Sea superimposed barchanoid dunes on the eastern flanks of complex linear dunes (Fig. 1b) and star dunes migrate at rates of up to  $5 \text{ m yr}^{-1}$  from areas of higher to lower wind velocities and sand transport rates, as documented by Lancaster (1985b) and Livingstone (1986). Bedform dimensions decrease away from the dune crest as wind velocity and sand transport rates decline (Fig. 15). Excess sediment is deposited by bedform climbing.

Following Rubin and Hunter (1985), the angle of climb of a dune ( $\zeta$ ) is given by:

$$\tan \zeta = \frac{\text{net rate of deposition } (V_z)}{\text{dune migration rate } (V_x)} \quad (2)$$

The dune migration rate is given by:

$$V_x = \frac{2q \sin \alpha}{H} \quad (3)$$

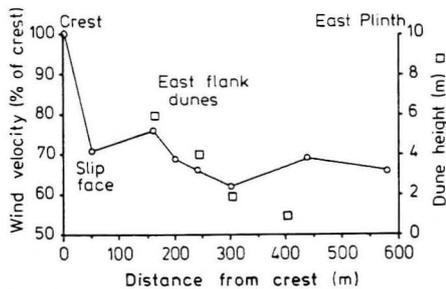


Fig. 15. Relationship between the size of superimposed bedforms on the lee flank of a complex linear dune in the Namib Sand Sea and measured velocities of dominant SSW-SW winds, expressed as a percentage of wind velocity at the adjacent dune crest.

where  $q$  is the mean bulk volume sediment transport rate,  $H$  is dune height and  $\alpha$  is the angle between the dune trend and the resultant direction of sand transport ( $90^\circ$  for a transverse dune).

The rate of deposition ( $V_z$ ) can be evaluated in terms of the sediment continuity equation (Middleton and Southard, 1978) such that:

$$V_z = -\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} \quad (4)$$

where  $q_x$  and  $q_y$  are the bulk volume sediment transport rates in the  $x$  and  $y$  directions, respectively. As sand transport may cross a dune obliquely:

$$V_z = -\sin \alpha \frac{\partial q_x}{\partial x} + \cos \alpha \frac{\partial q_y}{\partial y} \quad (5)$$

where  $x$  and  $y$  are distances in the across-dune and dune-parallel directions and  $\alpha$  is the angle between the dune and the direction of sand transport.  $x$  and  $y$  can be regarded as the dimensions of the depositional area ( $D$ ) over which transport rates decrease. This could be larger than the dune if sand leaves the dune or smaller than or equal to the dune if all sand remains on it. Assuming a linear decrease in  $q$  from  $2 q_m$  (where  $q_m$  is the value of  $q$  in the center of the depositional area) to zero over the distance  $D/\sin \alpha$ ,  $\partial q_x/\partial x$  in eq. 5 can be replaced by  $-2q_m D/\sin \alpha$  and  $\partial q_y/\partial y$  by  $-2q_m D/\cos \alpha$ . It then is possible to simplify eq. 5 by substituting these expressions and using the relation  $\sin^2 \alpha + \cos^2 \alpha = 1$ , such that:

$$V_z = \frac{2q_m}{D} \quad (6)$$

where  $D$  represents the distance over which sand transport rates decrease from their initial values on entering the depositional area to a final value. By substituting eqs. 5 and 2 in eq. 1:

$$\tan \zeta = H(D/H \sin \alpha)^{-1} \quad (7)$$

where  $H$  is the average height of the dunes in the area.

In the case of superimposed barchanoid dunes on the east flank of complex linear dunes in the Namib Sand Sea, measurements of wind velocities suggest that potential sand transport rates decrease to zero in all but the strongest winds over a distance of some 300 m. or the width of zone of east flank dunes. The average height of these dunes is 2.5 m and as they are transverse to S-SSW winds,  $\alpha$  is  $90^\circ$ . The average angle of climb ( $\zeta$ ) from eq. 6 is  $0.48^\circ$ , with a range between  $0.29$  and  $1.29^\circ$ . This compares with calculated angles of bedform climb for superimposed aeolian bedforms of  $0.3^\circ$  (Rubin and Hunter, 1982) and measured angles from the rock record of  $1.5^\circ$  (Kocurek, 1981b). The low angles of climb calculated suggest that accumulation of such large complex dunes is a slow process.

## CONCLUSIONS

(1) Variations in the relationship between dune height and spacing suggest that dunes of different types accumulate in different ways and that complex linear and star dunes appear to accrete vertically without a corresponding change in dune spacing.

(2) Areas of large compound and complex dunes, even though they may be widely spaced, represent areas of thick sand cover. Their distribution in a sand sea is therefore an index of the pattern of deposition. If relationships between dune height and equivalent sand thickness are known, then it is possible to map the spatial pattern of deposition in a sand sea.

(3) The size of large aeolian bedforms is not a direct function of grain size or sand transport rates, but the result of their long continued growth. Because such large bedforms have a history, it is not possible to use equilibrium concepts to explain their morphology.

(4) Each element of the aeolian bedform hierarchy is controlled by variations in winds and sand transport rates at different temporal and spatial scales. Large aeolian bedforms principally respond to regional changes in wind regimes over a time scale of millenia.

(5) Superimposed dunes can exist in equilibrium with larger forms in the same airflow conditions, because they respond to different scales of airflow variability. Dunes must reach a minimum size before superimposed dunes can develop on them.

(6) The growth of large linear and possibly star dunes is achieved largely through deposition of sediment by climbing of superimposed dunes on their lee flanks.

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