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Why deposits of longitudinal dunes are rarely recognized in the geologic record

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ABSTRACT

Dunes that are morphologically of linear type, many of which are probably of longitudinal type in a morphodynamic sense, are common in modern deserts, but their deposits are rarely identified in aeolian sandstones. One reason for non-recognition of such dunes is that they can migrate laterally when they are not exactly parallel to the long-term sand-transport direction, thereby depositing cross-strata that have unimodal cross-bed dip directions and consequently resemble deposits of transverse dunes. Dune-parallel components of sand transport can be recognized in ancient aeolian sands by examining compound cross-bedding formed by small dunes that migrated across the lee slopes of large dunes and documenting that the small dunes migrated with a component in a preferred along-crest direction over the large dunes.

INTRODUCTION

Dunes that have been called linear or longitudinal are common in modern sand seas, but examples reported from the geologic record are surprisingly rare. The purposes of this paper are to document and explain this discrepancy and to present a new model of the internal structure of longitudinal dunes.

Terminology

Because the processes that control dune morphology and orientation are not well known, aeolian researchers have tended to adopt descriptive, rather than genetic or morphodynamic, classification schemes for dunes. Consequently the terms 'linear dune' and 'seif dune' have been used interchangeably with 'longitudinal dune' (McKee, 1979, 1982; Lancaster, 1982; Tsoar, 1983) despite the fact that the first two terms are morphologic, while the third term implies that the dune trend parallels some other trend such as the dominant wind direction or the resultant sand-transport direction. Similarly, the term 'transverse dune' is commonly used without regard to dune orientation, despite the orientation implied by the term 'transverse' (McKee, 1979, p. 257).

In this paper we have departed from current usage and have reserved the terms 'longitudinal dune' and 'transverse dune', respectively, for dunes that can be demonstrated to trend roughly parallel or roughly normal to the long-term resultant sand-transport direction. We believe that this approach is justified by the meaning of the words 'longitudinal' and 'transverse'. Limiting this classification scheme to two classes—longitudinal dunes and transverse dunes—might be taken to imply a tendency of dunes to prefer such alignments. To emphasize that such a tendency has not been demonstrated (and may not even exist), we use the term 'oblique dune' to identify dunes that are neither roughly parallel nor roughly transverse to the long-term resultant transport direction.

Before rigorously proposing limits on the boundaries between longitudinal, oblique, and transverse dunes, we are waiting to see if future work documents any natural tendencies in dune alignment. In the meantime, for the purposes of this paper, we follow Hunter, Richmond & Alpha (1983) in defining a longitudinal dune as a dune whose trend lies within 15° of the long-term resultant transport direction, and a transverse dune as one that trends within 15° of normal to the resultant transport direction. Oblique dunes are those with intermediate trends. Because these definitions are more restrictive than general usage, it is likely that all dunes that we would call longitudinal are, in a morphologic sense, linear dunes, but linear dunes are probably not all longitudinal; some may be oblique. Similarly, all dunes that we would call transverse probably have barchanoid or crescentic shapes, but dunes with these shapes are probably not all transverse; some of them may be oblique. Even with our relatively restrictive definition of longitudinal dunes, they need not be perfectly parallel to the resultant transport direction.

Linear dunes

Linear dunes have a variety of shapes, sizes, and exotic local names (Tsoar, 1978; Breed & Grow, 1979, table 26). Like other dunes that form in air and water, linear dunes commonly support smaller superimposed dunes, and some workers classify dunes by the absence or presence (and, if present, the type) of superimposed dunes (McKee, 1979).

Many hypotheses have been proposed to explain the origin of linear dunes, and the relative merits of the various hypotheses have been reviewed recently by Tsoar (1978, 1983), McKee (1979, 1982) and Lancaster (1982). Although some workers believe that linear dunes are generated by unidirectional winds (Hanna, 1969; Glennie, 1970), the existing evidence seems to suggest that (for a given transport rate) linear dunes form in response to wind patterns that are more multidirectional than those that form transverse dunes (Tsoar, 1978, 1983; Fryberger, 1979; McKee, 1979, 1982; Lancaster, 1982). As a result of reversing flows, linear dunes are relatively symmetrical in transverse profile and commonly have reversing crests and slipfaces (Bagnold, 1941; McKee, 1982). In contrast, barchanoid and crescentic dunes form in wind regimes that are relatively more unidirectional or narrowly unimodal (Fryberger, 1979) and are asymmetric.

RARITY OF DEPOSITS ATTRIBUTED TO LINEAR OR LONGITUDINAL DUNES

Dunes that are morphologically of linear type, many of which are probably of longitudinal type in a morphodynamic sense, are widespread, covering perhaps half or more of the area of large deserts of the world (Hanna, 1969; Tsoar, 1978; McKee, 1979; Lancaster, 1982). In contrast, in our literature survey of 28 interpretations of aeolian sandstones, only three interpretations attribute deposition, even partially, to longitudinal dunes or linear dunes (Shotton, 1937; Kiersch, 1950; Wright, 1956; Opdyke & Runcorn, 1960; Tanner, 1965; Laming, 1966; Thompson, 1969; Piper, 1970; Glennie, 1972; Gradzinski & Jerzykiewicz, 1974; Horne, 1975; Meinster & Tickell, 1975; Brookfield, 1979; Gradzinski, Gagol & Slaczka, 1979; McKee & Bigarella, 1979; Hubert & Mertz, 1980; Kocurek, 1981; Blakey & Middleton, 1982; Mader, 1982; Ross & Donaldson, 1982; Steele, 1982). Of the three interpretations of longitudinal or linear dunes (Tanner, 1965; Glennie, 1972; Steele, 1982) only Glennie's was based on the occurrence of the classical bimodal–bipolar cross-bed dip pattern theorized by Bagnold (1941) and believed by others to characterize deposition on opposite flanks of longitudinal dunes (Fig. 1A). The other two interpretations (Tanner, 1965; Steele, 1982) were based on sandbody surface relief (preserved dune forms) that trend parallel to the presumed transport direction. Burial and preservation of the dunes that deposited these two sand bodies allowed recognition of the longitudinal trend of the dunes. None of the three deposits is known to contain structures like Bagnold predicted. In fact, as far as we know, no sedimentologist has documented an aeolian deposit with more than a trace of oppositely dipping beds arranged in individual, vertically accreting duneform structures as theorized by Bagnold. Although we have found exposures that resemble Bagnold's model when seen in two dimensions, the dip angles are not diametrically opposed but are, rather, more nearly at right angles (Hunter & Rubin, 1983, figs 14 and 15).

Three explanations could account for the disproportionately few identified deposits of linear dunes: (1) linear dunes were rare in the past, (2) linear dunes rarely leave deposits, and (3) linear dunes deposit structures that are grossly different from those predicted by Bagnold's model. The hypothesis that linear dunes were rare in the past is unlikely, has never been suggested, and is untestable with existing data. The hypothesis that linear dunes rarely leave deposits is also untestable with existing data, but is compatible with previous hypotheses that linear dunes are erosional bedforms or non-depositional bedforms that are restricted to areas where sand is scarce. However, these hypotheses have been debated for several decades without general agreement (Melton, 1940; Bagnold, 1941; King, 1960; Tsoar, 1978, 1983; Breed, Grolier & McCauley, 1979; Kocurek & Dott, 1981; Twidale, 1981; McKee, 1982; Wasson & Hyde, 1983, 1984; Rubin, 1984). Although future research might demonstrate that some or all kinds of linear dunes are

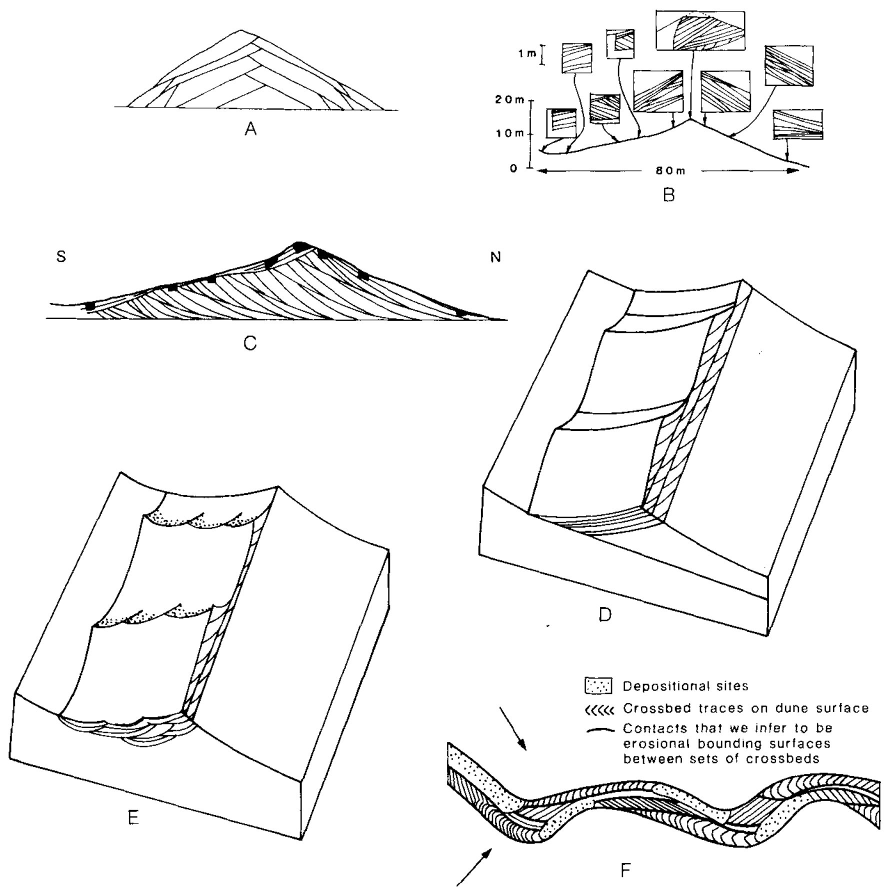

Fig. 1. Observed and inferred structure of linear dunes. (A) Bagnold model—dunes reverse direction of facing and accrete vertically without net lateral migration. (B) Structure observed by McKee & Tibbits (1964) in shallow pits on a linear dune in Libya. (C) Our proposed model of the deep internal structure of the dune studied by McKee & Tibbits. North-dipping crossbeds underlying the south flank suggested to McKee & Tibbits and suggest to us that the dune migrated northward. Structures like that shown, if found in aeolian sandstones, would traditionally have been attributed to deposition by transverse dunes. Pits dug by McKee & Tibbits are drawn to scale (in black) to emphasize that the deeper internal structures have not been observed. (D) Predicted structure of a laterally migrating linear dune with superimposed 2-D dunes migrating in an along-crest direction. Sediment transport is primarily in a longitudinal direction, but the dune migrates laterally. (E) Same as (D) but with 3-D superimposed dunes. (F) Internal structure of linear dune illustrated by Tsoar (1982). Arrows represent the two dominant wind directions. Bounding surfaces scoured by migrating dune sinuosities strike parallel to the dune trend. Crossbeds dip with a preferred along-crest component (to the right of the diagram).

non-depositional, we currently favour another explanation for the rarity of recognized deposits of linear dunes.

We hypothesize that the deposits of linear dunes have been misidentified because the dunes, despite their trending roughly parallel to the transport direction, can migrate laterally, accompanied by net deposition on one flank and net erosion on the other. As a result of net erosion on one flank, laterally migrating linear dunes will not have the bimodal-bipolar dip patterns expected of linear dunes except in unusual situations discussed below. Instead, the dip patterns will resemble those expected of transverse dunes—one dominant mode dipping in the direction of lateral migration. The second (opposing) mode is considerably reduced or absent entirely.

LATERAL MIGRATION OF LINEAR DUNES

The most direct technique for determining whether or not linear dunes have a tendency to migrate laterally is by direct observation. Unfortunately, observations have been made on only two linear dunes, to our knowledge, and the results are too inconsistent to indicate any general tendency. The first dune, studied by Besler (1975) in the Namib Desert, migrated approximately half as far in a lateral (dune-normal) direction as in the dune-parallel direction. In contrast, the Sinai Desert dune studied by Tsoar (1978, fig. 7.1) moved back and forth with little or no net lateral displacement over a 2 yr period. Although not indicating a general tendency for linear dunes to migrate laterally, these observations demonstrate that linear dunes have that capability. On Besler's (1975) Namib dune, where transverse transport was approximately half as large as the longitudinal transport, the resultant transport direction deviated from the dune trend by 30°. If Besler's observations are representative of the long-term behaviour of this dune, we would call it an oblique dune, not a longitudinal dune.

In addition to observations of dune displacement, other observations suggest that linear dunes commonly migrate laterally. For example, resultant sand transport directions calculated from wind data or inferred from regional wind patterns suggest that some linear dunes have dune-normal components of sand transport (Clos-Arceduc, 1967; Mabbut *et al.*, 1969; Brookfield, 1970; Glennie, 1970; Mainguet & Canon, 1976; Warren, 1976; Tsoar, 1978, 1983), suggesting that the dunes should migrate laterally.

Similarly, many linear dunes have profiles that, when any seasonal changes are averaged out, are asymmetric, with one side sloping more steeply than the other (Wopfner & Twidale, 1967; Mabbut *et al.*, 1969, Glennie, 1970; Warren, 1976; Tsoar, 1978, 1983). This asymmetry in form suggests an asymmetry in transport across the dune crest, which could be expected to cause lateral migration. For example, Tsoar (1978, p. 125) stated about the Sinai Desert linear dunes: 'The relatively steeper slopes of the southern flank of the dunes during the different seasons of the year (Appendix 27) are evidence of more work done by the northern winds . . .'

Although Tsoar (1978, 1983) noted this asymmetry in morphology and independently observed a corresponding asymmetry in the two directional modes of the wind regime, he still thought that the dunes did not migrate laterally. How did Tsoar reconcile the ideas of asymmetry in wind regime and lack of lateral migration? Tsoar (1978, 1983) made the valuable observation that non-transverse winds that intersect a dune crest are deflected and cause the direction of sand transport on the lee slope almost to parallel the dune crestline. Consequently, the component of transport parallel to a dune crest may be greater than would be predicted from external wind measurements. However, we cannot agree with Tsoar's apparent belief that the long-term dune-normal component of transport will be zero even when winds from the two sides of the dune transport unequal volumes of sediment across the dune crest. Lateral migration of linear dunes has been observed (Besler, 1975) and is even suggested by Tsoar's own tracer studies that document considerable dune-normal transport on stoss slopes and reduced but nevertheless observable dune-normal transport on lee slopes (Tsoar, 1978, fig. 5.12). We therefore consider long-term asymmetry in dune profile and divergence of the long-term transport direction from the dune trend to imply that dunes migrate laterally. As will be shown in the analysis section below, even a very small ratio of dune-normal to dune-parallel transport is sufficient to cause internal structures of a linear-dune deposit to be unlike what Bagnold predicted.

Lateral migration is also suggested by the internal structure of the linear dune that McKee & Tibbits (1964) studied in Libya. Details of the bedding within that dune, discussed below and reproduced in Fig. 1(B), led McKee & Tibbits (p. 11) to suggest that 'at an earlier stage in development, the dune crest was farther to the south than at present'. Thus, the observed movement, asymmetry, orientation relative to the resultant transport direction, and internal structure of many linear dunes suggest that they are not perfectly longitudinal and that they migrate laterally.

OBSERVED AND INFERRED STRUCTURE OF LINEAR DUNES

Because of the practical difficulties in cutting deep trenches through dunes, field studies of internal structures have generally only examined the upper metre or two of dunes that are as much as 60 m high (McKee & Tibbits, 1964; Breed & Breed, 1979; McKee, 1982). Consequently, models of internal structure are somewhat speculative, and the near-surface observations can be interpreted differently when inferring the structures deep within the dune.

For example, the study by McKee & Tibbits is commonly cited as verification of Bagnold's model of linear dune structure. However, the deepest cross-beds observed in two pits on the south flank of the dune dip steeply to the north (Fig. 1B), leading McKee & Tibbits to make the statement quoted above that the dune had migrated northward. Because of these north-dipping beds on the south flank of the dune, McKee & Tibbits' observations appear to be less compatible with Bagnold's model than with a model in which the cross-bedding within the dune dips in the direction of lateral migration (north) but is locally overlain by a thin transient veneer of oppositely dipping beds (Fig. 1C). In other words, the observations suggest that the internal structure of the dune resembles that commonly expected of a reversing transverse dune.

This alternative model of the internal structure of linear dunes (Fig. 1C) is attractive, because it predicts structures similar to those observed and theorized for many other migrating bedforms in reversing flows (for example, some—but not all—wave ripples (Newton, 1968; Clifton, 1982), subaqueous sand waves (Allen, 1980; Clifton, 1982), and reversing aeolian dunes (Sharp, 1966)). The comparison between linear dunes and wave ripples is particularly instructive because wave ripples commonly migrate laterally and deposit cross-laminae with unimodal dip patterns, despite the fact that the ripples are relatively symmetrical in profile and are generated by reversing flows that are relatively (though not perfectly) symmetrical. Similarly, lateral migration and unimodal cross-bed dip patterns can be expected of linear dunes where the sand transport back and forth across the dune crests is not exactly balanced. Two additional arguments in support of this alternative model follow: (1) specific aeolian beds that at first glance might appear to have been deposited by transverse dunes (because of unimodal dip patterns) can be shown to have been deposited by dunes with systematic dune-parallel components of transport, and (2) for theoretical reasons detailed in the analysis section below, winds are unlikely to supply a dune field with the sand necessary to cause vertical accretion without causing the dunes to migrate laterally, unless dunes are aligned almost exactly parallel to the transport direction.

If laterally migrating longitudinal dunes and oblique dunes produce deposits that resemble those of transverse dunes in having unimodal cross-bed dip patterns, how can deposits of these dune types be distinguished? The differences in their deposits become apparent if we consider bedding structures produced by spurs, ridges, scour pits, peaks, saddles, small dunes, or other topographic features superimposed on the large dunes.

On a transverse dune, individual superimposed features can be expected to migrate either to the right, to the left, or in the same direction as the main dune, depending on local dune orientation relative to the existing wind direction. Because the general trend of the main dune is transverse, however, the superimposed features would not be expected to migrate consistently in the same direction along the crest of the main dune. In contrast, topographic features that are superimposed on a longitudinal or oblique dune, or peaks and saddles that are part of the basic dune form, can be expected to migrate with a significant component in a preferred along-crest direction (Hunter, 1981; Tsoar, 1982; Rubin & Hunter, 1983).

Because aeolian sandstones rarely contain completely preserved dune forms (Rubin & Hunter, 1982), the crest trends and migration directions of ancient dunes must generally be inferred from cross-bedding. Cross-bedding that is ideal for this purpose is compound cross-bedding (Harms *et al.*, 1975; Rubin & Hunter, 1983) deposited by small dunes or other topographic features on the lee slope of a large dune. The small dunes scour into the large dune, thereby generating bounding surfaces that strike approximately parallel to the trend of the large dune (Fig. 1D, E); the small dunes also deposit cross-beds that can be used to determine the trend and migration direction of the small dunes (Rubin & Hunter, 1983). Thus, bounding surfaces and cross-stratified beds produced by small dunes on the lee slopes of large dunes can be used to determine the trends and migration directions of both scales of dunes and to identify components of transport along the crests of the large dunes. Where the large dunes are perfectly straight-crested and have no superimposed dunes migrating along their lee slopes, an along-crest component of sediment transport can be demonstrated by documenting that ripples on the lee slope of the dune migrate with a component in a preferred along-crest direction (Rubin & Hunter, 1983).

The structure Tsoar (1982) observed in a modern longitudinal dune supports this model. Tsoar found bounding surfaces striking approximately parallel to the dune trend and cross-beds dipping with a preferred along-crest component (Fig. 1F and Tsoar, 1978, fig. 6.10). However, in another aspect, Tsoar's model and the one presented in this paper conflict, because Tsoar's was developed for dunes that he presumed had equal rates of deposition on both flanks (thereby preserving equal amounts of north-dipping beds on

	Linear dunes without migrating sinuosities or superimposed dunes	Linear dunes with migrating sinuosities or superimposed dunes
Linear dunes that do not migrate laterally	Bagnold (1941) and Fig. 1A, this paper	Glennie (1970) Tsoar (1982) and Fig. 1F, this paper
Linear dunes that migrate laterally	Fig. 1C, this paper	Figs. 1D and 1E, this paper

Fig. 2. Assumptions (stated or unstated) used by various workers in their models of the internal structures of linear dunes.

the north-facing flank and south-dipping beds on the south flank).

The conflicts between the various models of internal structure of linear dunes can be explained by the different assumptions about dune behaviour that were used to develop the models (Fig. 2). The models developed by Bagnold (Fig. 1A), Tsoar (Fig. 1F), and Glennie (1970) (not shown here) are all restricted to linear dunes that do not migrate laterally. Bagnold's (1941) model is further restricted in that it does not try to account for structures produced by topographic features that migrate in a direction parallel to the dune crest, although Bagnold was well aware of peaks and saddles of the dune crest and speculated on their probable along-crest migration. All of the models of internal structure that have been developed for linear dunes with superimposed features have a characteristic feature in common. The cross-beds that are deposited by superimposed features do not dip normal to the crestline of the main dune. Instead, they have a component of dip parallel to the crestline of the main dune (in the direction of preferred along-crest migration of the superimposed features). Figure 1(D, E, F) illustrates three examples of such structures, but we have seen several other examples (Rubin & Hunter, 1983), and many other varieties undoubtedly occur. Because these structures can have drastically different appearances (depending on such factors as the shape and location of superimposed bedforms on the main dune, outcrop orientation, outcrop curvature, and how much of the main dune is ultimately preserved), identification of dune-parallel components of transport is not a simple matter of matching illustrations with outcrops. Detailed measurements of the attitudes of cross-beds and bounding surfaces are required.

Other characteristics have previously been proposed as diagnostic of dune type. McKee (1979, p. 194) states that the 'Amount of spread and distribution of cross-strata dip directions are perhaps the most satisfactory features for differentiating types of dunes in ancient rocks.' However, if we are correct that linear dunes can migrate laterally with net deposition on only one flank, then linear dunes may have cross-bed dip spreads that are considerably narrower than has been supposed. Furthermore, because the spread in cross-bed dip directions depends on dune sinuosity and on the shape and behaviour of superimposed dunes, cross-bed dip spread does not seem to be a simple indicator of wind variability. Consequently, the classical (but unverified) technique for identifying linear dune deposits by a wide spread in dip directions is likely to be unreliable.

POSSIBLE EXAMPLES OF DEPOSITS OF OBLIQUE OR LONGITUDINAL DUNES

Two aeolian sandstones that we examined on the Colorado Plateau of the western United States contain abundant compound cross-bedding formed by small dunes and other topographic features that migrated over the lee slopes of large dunes (Rubin & Hunter, 1983). In the Navajo Sandstone (Triassic? and Jurassic) in south-western Utah, superimposed dunes migrated with a mean direction 30° clockwise to the migration direction of the large dunes (Fig. 3A). Similarly, the Entrada Sandstone (Jurassic) in the vicinity of Page, Arizona, was deposited by superimposed dunes that migrated, on average, 45° clockwise to the migration direction of the large dunes. These observations indicate that these Navajo and Entrada dunes had systematic dune-parallel components of transport in addition to the dune-normal components that caused the dunes to migrate laterally. It is not yet known whether the Navajo and Entrada dunes were (1) transverse, but not perfectly so, (2) longitudinal, but not perfectly so, or (3) oblique. The hypothesis of a relatively longitudinal trend of Entrada dunes is suggested elsewhere by sand-body surface relief defining lineations that trend NE–SW (Vincellette & Chittum, 1981)—roughly parallel to the local transport direction inferred by Poole (1962) and Tanner (1965).

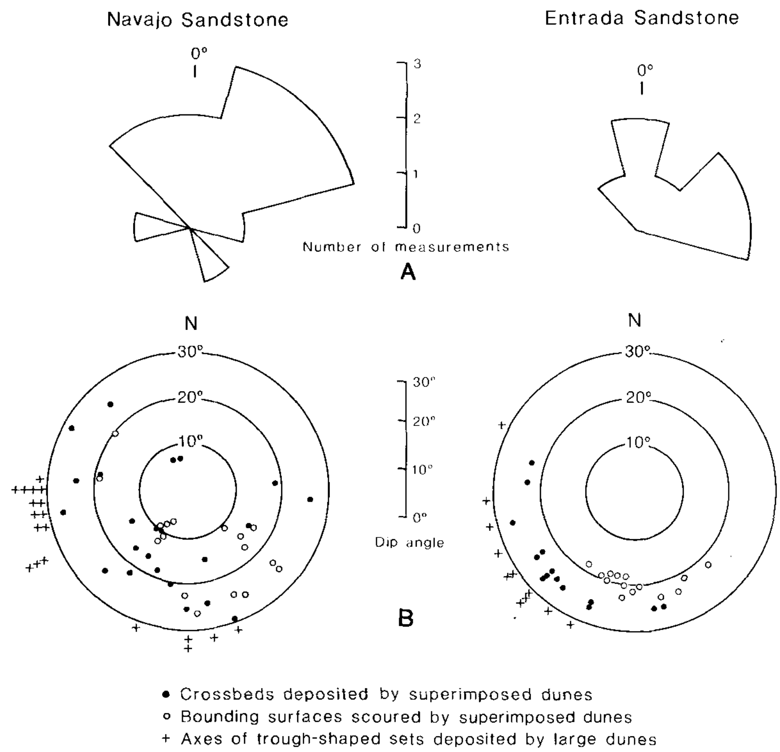

Fig. 3. Directional data for cross-beds in the Navajo and Entrada Sandstones deposited by dunes with components of sediment transport in a preferred along-crest direction. (A) Migration directions of small superimposed dunes relative to migration directions of the larger dunes that supported them. Migration in the same direction (that is, migration of the small dunes down the lee slopes of the larger dunes) is shown as 0°; upslope migration is 180°, and along-slope migration is 90° clockwise or counter-clockwise from 0°. Details of the interpretive techniques used in the field are given by Rubin & Hunter (1983). Small superimposed dunes that deposited these beds migrated an average of 30° clockwise of the main dunes in the Navajo Sandstone, and 45° clockwise of the main dunes in the Entrada Sandstone. (B) directional data for the same beds plotted in part (A). Planar data (cross-beds and bounding surfaces) plotted as points giving both dip directions (N = north) and dip angles. Linear data (axes of troughs) plotted as points giving direction only. Each measurement in part (A) is the angular difference between two points in part (B), specifically the difference between the dip direction of the cross-beds deposited by a train of superimposed dunes and the dip direction of the bounding surfaces scoured by the same superimposed dunes. Note that the directional data have relatively narrow spreads, and in this regard the beds resemble deposits of transverse dunes.

We cannot determine the exact ratio of dune-parallel to dune-normal transport of the dunes that deposited these beds, and the beds we examined may be too small a sample to allow generalizing about the entire Navajo and Entrada Sandstones. The important point is that these specific beds, with unimodal cross-bed dip patterns (Fig. 3B) like those commonly believed to characterize deposition by transverse dunes, were deposited by dunes with systematic dune-parallel components of transport. Details of the structure of these beds are given elsewhere (Rubin & Hunter, 1983).

ORIGIN OF OBLIQUE ORIENTATIONS OF DUNES

We have attempted to show that dune-parallel components of sand transport can readily be identified in deposits formed by migrating dunes and that such components indicate that the dunes were not perfectly transverse (and may have been more nearly longitudinal than transverse). Several mechanisms can be proposed to explain such oblique alignments. Either transverse or longitudinal dunes can become oblique if the wind regime changes over many years and causes the long-term (measured over a few years) resultant sand-transport direction to rotate more rapidly than the dunes can adjust in orientation. Similarly, transverse dunes can become oblique if the sand-transport direction changes downwind across distances too short for the dunes to adjust as they migrate. An originally transverse dune can become oblique if the dune itself rotates relatively to the sand-transport direction because of along-crest variations in migration speed caused by along-crest differences in dune height or in the rate of sediment transport. Some dunes may be oblique from their inception. For example, a dune may be constructed parallel to an elongate roughness element or sand source rather than parallel or transverse to flow. An oblique trend may even be the equilibrium state for dunes in some areas where boundary effects, topographic effects, or source effects are unimportant and where the wind regime is unchanging over the long term and uniform over a broad scale in both the downwind and the across-wind directions; in other words, an oblique trend may be solely the result of the wind regime measured at a single point. The oblique dunes of the Oregon coast are a probable example of dunes whose trend can be explained solely by the wind regime measured at a point (Hunter *et al.*, 1983).

ANALYSIS

Having presented evidence that linear dunes can migrate laterally and consequently may not deposit structures like Bagnold predicted, it is instructive to see what kind of exceptional flow conditions are required to produce structures like those commonly expected of linear dunes. Whether or not a linear dune can deposit a vertically accreting dune-form structure depends on the angle, ζ, that the dune climbs relative to the generalized depositional surface. In the classical Bagnold model (Fig. 1A), dunes build upward vertically without net lateral migration ($\zeta = 90°$), but this basic structure would probably be recognizable at angles of climb as low as approximately 30°. At lower angles, the oppositely dipping deposits of the windward and lee flanks would appear to migrate laterally rather than accrete at a high angle, and at angles lower than approximately 10–15° only the lee flank would be preserved.

The angle of climb (ζ) of a dune is defined by

$$\tan\zeta = \frac{V_z}{V_x} \qquad (1)$$

where V_z is the net rate of deposition and V_x is the dune migration speed, measured in a direction normal to the crest (Fig. 4A). Following an analysis like that applied to transverse dunes (Rubin & Hunter, 1982), $\tan\zeta$ can be evaluated by deriving expressions for V_z and V_x. For dunes that are perfect traps for sand blown over their crests (as has been reported by Wilson, 1972 and Tsoar, 1978), that are large in volume relative to the volume of sand in transport over the bed (as is true for almost any conceivable dune), and that in cross-section are triangles touching end-to-end,

$$V_x = \frac{2\bar{i}\sin\alpha}{H} \qquad (2)$$

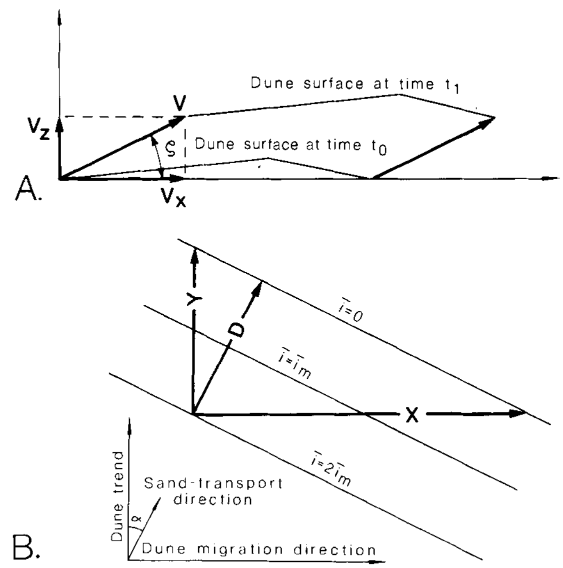

Fig. 4. Definition sketches for mathematical analysis of dune climbing in 3-D space. The x- and y-axes are both defined as lying parallel to the generalized depositional surface, the y-axis parallel to the dune trend and the x-axis normal thereto, and the z-axis is normal to the xy-plane. (A) Sketch of the xz-plane defining the angle of dune climb, ζ, and the vertical and horizontal components, V_z and V_x respectively, of the vector of dune climb, **V**. Because the dunes are defined as trending parallel to the y-axis, which is perpendicular to the xz-plane, the vector of dune climb has no y-component. (B) Sketch of the xy-plane showing contours of the dune-averaged resultant sand-transport rate, $\bar{i}$, which is assumed to be a linear function of x and y. The extent of the depositional area in the x-direction is X, in the y-direction is Y, and in the direction of resultant sand transport is D. The depositional area is assumed to be a band of unlimited extent in the direction normal to D; $\bar{i}$ ranges from $2\bar{i}_m$ at the upwind limit of the depositional area to zero at the downwind limit and is equal to $\bar{i}_m$ along a line mid-way between the two limits.

where $\bar{\imath}$ is the bulk-volume sediment transport rate across a unit length of depositional surface spatially averaged over an entire dune wavelength (dimensions of $l^3/lt = l^2/t$), H is the dune height, and α is the angle between the dune trend and the resultant transport direction (Fig. 4B). Note that α is 90° for a transverse dune and 0° for a longitudinal dune.

The rate of deposition is given by

$$V_z = -\left(\frac{\partial \bar{\imath}_x}{\partial x} + \frac{\partial \bar{\imath}_y}{\partial y}\right) \quad (3)$$

where $\bar{\imath}_x = \bar{\imath}\sin\alpha$ and $\bar{\imath}_y = \bar{\imath}\cos\alpha$. If, as is assumed here, α is constant throughout a dune field, equation (3) may be simplified to

$$V_z = -\left(\sin\alpha\frac{\partial \bar{\imath}}{\partial x} + \cos\alpha\frac{\partial \bar{\imath}}{\partial y}\right). \quad (4)$$

The terms x and y are horizontal distances in the dune-normal and dune-parallel directions, respectively; $-\sin\alpha(\partial\bar{\imath}/\partial x)$ and $-\cos\alpha(\partial\bar{\imath}/\partial y)$ are the two components of deposition arising from downwind decreases in transport in those directions.

The relation expressed in equation (4) can be put in a more useful form if the analysis is restricted to depositional areas in which the transport rate varies linearly, decreasing from $2\bar{\imath}_m$ (where $\bar{\imath}_m$ is the value of $\bar{\imath}$ in the middle of the depositional area) to zero over a distance D. For convenience in comparing the size of the depositional area to dune size, D can be converted into a non-dimensional form, D', where $D' = D/H$, H being the dune height. In the dune-normal direction, therefore, $\bar{\imath}$ decreases linearly by $2\bar{\imath}_m$ over a distance $D'H/\sin\alpha$ (Fig. 4B), and $\partial\bar{\imath}/\partial x$ in equation (4) can be replaced by $-2\bar{\imath}_m\sin\alpha/D'H$. Similarly, $\partial i/\partial y$ can be replaced by $-2\bar{\imath}_m\cos\alpha/D'H$. Making these substitutions in equation (4) and simplifying by using the trigonometric relation $\sin^2\alpha + \cos^2\alpha = 1$, it is found that

$$V_z = \frac{2\bar{\imath}_m}{D'H}. \quad (5)$$

In this analysis, 'depositional area' is defined in a more restrictive sense than common useage necessitates. Here the term describes the area across which the dune-normal and dune-parallel transport rates decrease to zero. This area can be smaller than a dune field (if deposition is localized within the field) or larger than a dune field (if sand is blown out of the downwind end of the field).

In the middle of the depositional area, $\bar{\imath}$ in equation (2) is equal to $\bar{\imath}_m$. The angle of climb at this point is found by substituting equations (2) and (5) in (1) and simplifying:

$$\tan\zeta = (D'\sin\alpha)^{-1}. \quad (6)$$

Equation (6) is graphed in Fig. 5. For the case where must exceed 30° (to produce the structure in question), $\tan\zeta > 0{\cdot}577$, and

$$D' < 1{\cdot}73(\sin\alpha)^{-1}. \quad (7)$$

Relation (7) is shown by the dotted area in Fig. 5.

The physical limitation described by relations (1–7) can be expressed in words: How can sand that is

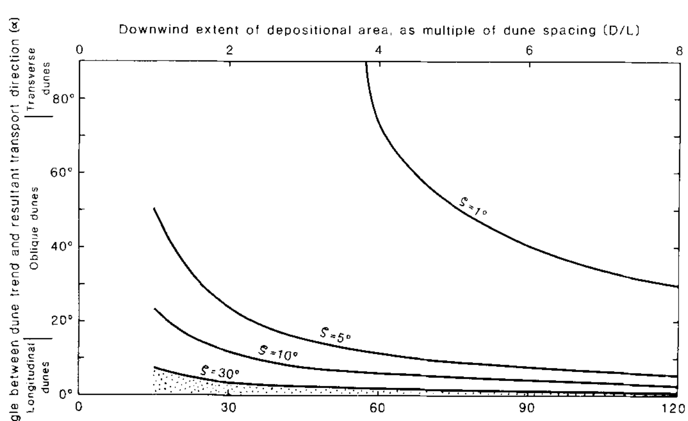

Fig. 5. Graph of the angle of dune climb, ζ, plotted as a function of the downwind extent of the depositional area, which is expressed as a multiple of dune height ($D' = D/H$) and as a multiple of dune spacing (D/L, assuming $L/H = 15$), and of the angle between the dune trend and the long-term resultant sand-transport direction, α. The figure is a graph of equation (6); the dotted area represents the inequality expressed by relation (7).

necessary for deposition be blown from a source area into a depositional area without causing dunes to migrate laterally at a rate that is fast relative to the rate of deposition? The analysis above indicates that these conditions are most likely to be met where sand is deposited in a small area (D' is small) or where the dune trend is almost perfectly parallel to transport. For example, if the depositional area extends downwind 60 times the dune height (approximately four wavelengths for typical aeolian dunes), then the dune crest must be aligned within 2° of the transport direction. A larger, more reasonably sized depositional area requires even more nearly perfect alignment. In other words, the structure predicted by Bagnold (1941) will be typical of a deposit only if the dunes trend almost perfectly parallel to the transport direction, if the depositional area is exceedingly small, or if one of the assumptions used to develop relations (1–7) is grossly incorrect.

CONCLUSIONS

(1) Modern linear dunes commonly have minor dune-normal components of transport and probably migrate laterally, thereby producing structures unlike Bagnold (1941) predicted.

(2) Dune-parallel components of transport can be documented in ancient deposits by demonstrating that small dunes systematically migrated with a preferred dune-parallel component over large dunes.

(3) Statistically, considering the abundance of linear dunes in modern deserts and the rarity of recognized ancient examples, it is likely that many of the aeolian sandstones that have been attributed to transverse dunes were deposited by dunes that would be called longitudinal or linear dunes in modern deserts.

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