The sedimentary structure of linear sand dunes

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Linear sand dunes—dunes that extend parallel to each other rather than in star-like or crescentic forms—are the most abundant type of desert sand dune[1]. But because their development and their internal structure are poorly understood, they are rarely recognized in the rock record[2]. Models of linear dune development[2–6] have not been able to take into account the sub-surface structure of existing dunes, but have relied instead either on the extrapolation of short-term measurements of winds and sediment transport or on observations of near-surface internal sedimentary structures. From such studies, it has not been clear if linear dunes can migrate laterally[2,7,8]. Here we present images produced by ground penetrating radar showing the three-dimensional sedimentary structure of a linear dune in the Namib sand sea, where some of the world's largest linear dunes are situated. These profiles show clear evidence for lateral migration in a linear dune. Moreover, the migration of a sinuous crest-line along the dune produces divergent sets of cross-stratification, which can become stacked as the dune height increases, and large linear dunes can support superimposed dunes that produce stacked sets of trough cross-stratification. These clear structural signatures of linear dunes should facilitate their recognition in geological records.

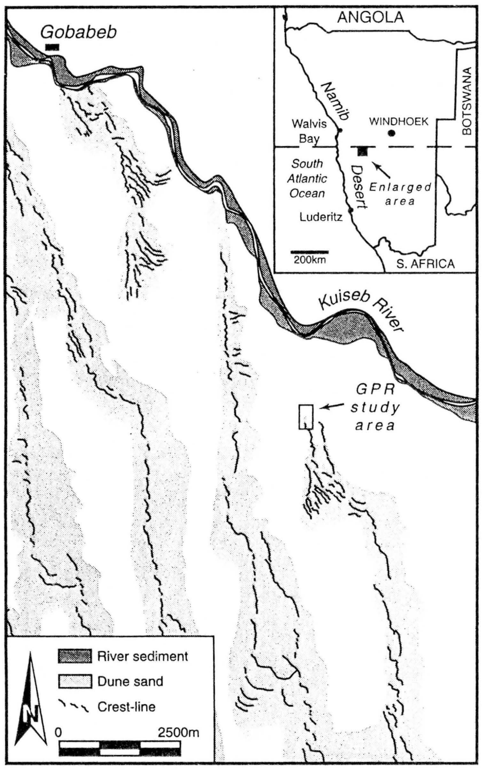

Figure 1 Locality map. The study site is at the northern end of a complex linear megadune in the Namib sand sea, Namibia.

A topographic survey and ground penetrating radar (GPR) profiles were collected across and along the crest of the northern, leading edge of a sinuous linear dune located 15 km southeast of Gobabeb (23° 37′ S, 15° 05′ E) on the northern edge of the Namib sand sea (Fig. 1). In this area there are marked seasonal variations in the wind regime. Winds from the southwest and the SSW are dominant during the summer months, while during the winter strong, but less frequent, winds blow from the east. The resultant sand drift direction is towards the NNE[9]. The northern end of the study dune is a low mound with no discernible slip face; to the south, the dune has a triangular cross-section with slopes (up to angle of repose on both sides) rising to a sharp crest. The crest-line is straight to slightly sinuous; sinuosity increases towards the south, with crest-line elevation rising to 20 m, and dune width increasing from 40 to 200 m. Superimposed crescentic dunes occur to the south where dune height exceeds 15 m. They are best developed where the sinuous dune flanks are convex in plan view.

We collected around 1.9 km of GPR profiles in a series of six profiles across the dune with one line along the dune crest. Data were collected with 100- and 200-MHz antennae. The 100-MHz antennae were spaced at 1 m with a step size of 0.5 m; 200-MHz antennae were spaced at 0.5 m with a step size of 0.2 m, except along the crest line where a step size of 0.5 m was used. A velocity of 0.17 m ns^{-1} has been calculated from a common midpoint survey, indicating theoretical values for resolution of 0.425 m for 100-MHz antennae and 0.21 m for 200-MHz antennae.

The GPR profiles show excellent resolution of sedimentary structures within the dune (Fig. 2). The sub-horizontal reflection at the base of each profile comes from the top of the underlying

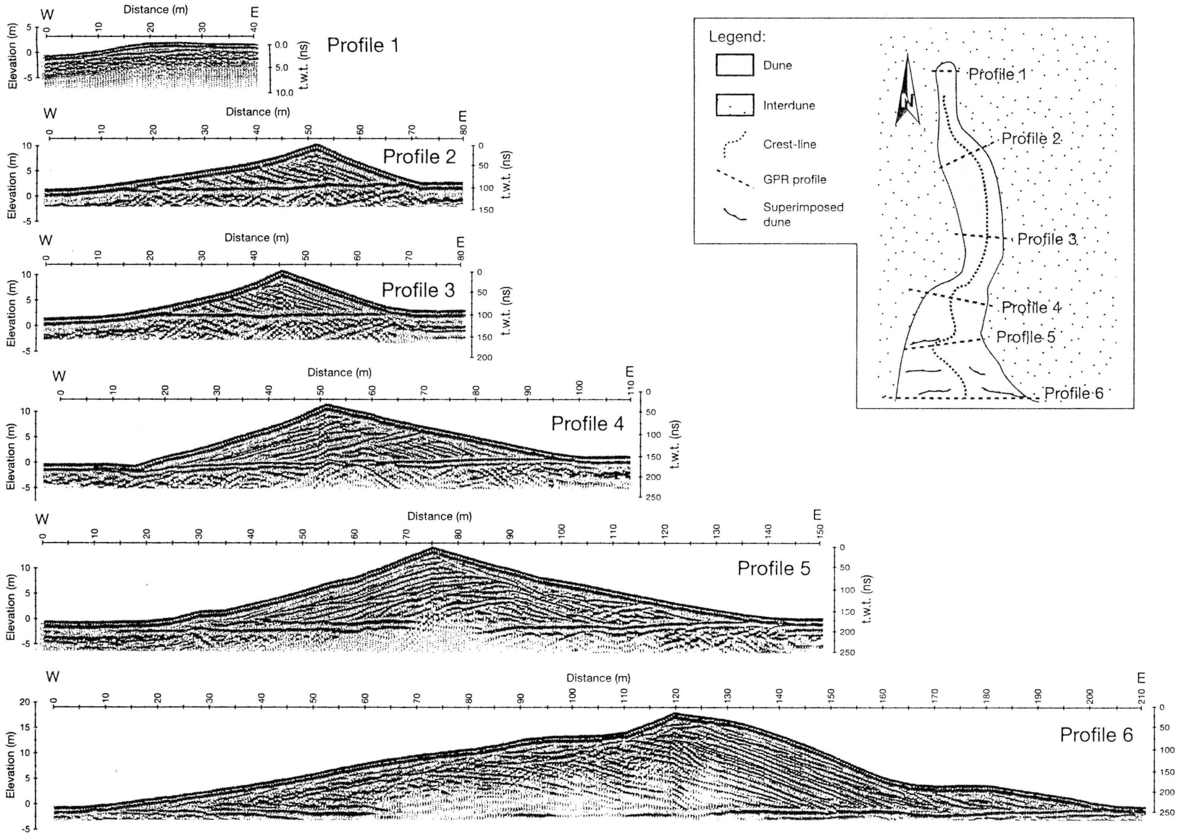

Figure 2 Dune structure from GPR profiles. GPR profiles across a sinuous linear dune show excellent resolution of sedimentary structures. On profile 1, structures are below the resolution of the GPR. Profiles 2 and 3 show planar sets of cross-stratification with dominant dips towards the east. Profiles 4 and 5 show bidirectional dips formed by northward migration of the sinuous crest-line. Profile 6 shows dominant dips to the east flanked by sets of trough cross-stratification from superimposed dunes. Profile 1 was collected using the higher-frequency 200-MHz antennae; the other lines were collected using 100-MHz antennae. t.w.t., two-way travel time. Topography was measured in the field at 5-m intervals and at breaks of slope along the profiles using a total station (an instrument that combines electronic distance measurement with a theodolite). Topographic correction has been applied to each profile based on an arbitrary local datum.

surface, because there is a strong contrast in dielectric properties between the modern dune sand and the underlying carbonate-cemented Tertiary fluvial gravel and aeolian sandstone. Reflections within the dune come from sets of cross-stratification[10]. The low northern end of the dune (profile 1 in Fig. 2) shows no discernible structure because it is composed of wind-ripple laminae which are below the resolution of the GPR; this sand has been blown north from the main dune. The easterly dipping sets of cross-stratification in profiles 2 and 3 (Fig. 2) were formed during northeastward movement of the dune towards the resultant drift direction. A profile along the dune crest (not illustrated) shows sub-horizontal planar reflectors dipping very gently towards the north, confirming the planar tabular nature of the cross-stratification.

The bimodal dips in profiles 4 and 5 (Fig. 2) are attributed to northward extension of the sinuous dune, which results in vertically stacked sets of cross-stratification dipping to east and west, separated by erosional bounding surfaces. The lower easterly dips are consistent with the planar cross-strata in the straighter, more northerly, parts of the dune (profiles 2 and 3). Truncation of the lower reflectors occurs within the concave section of the dune sinuosity. Younger sets that downlap onto the erosion surface are formed by westward deflection of the crest line as a convex sinuous element moves north. Repeated westward and eastward shifts in position of the crest-line due to the northward translation of crest-line sinuosity results in offset vertical stacking of sets of cross-stratification (profile 5). The easterly dips within profile 6 indicate dune migration towards the east, towards the resultant drift direction. Sets of trough cross-stratification on profiles 5 and 6 (Fig. 2) were formed by superimposed dunes migrating north along the dune flanks.

We recognize five stages in the evolution of a linear dune (Fig. 3): (1) an initial extension of wind-rippled sand ; (2) development of a relatively straight-crested transverse element that migrates in response to the dominant wind direction, producing planar sets of cross-stratification; (3) as the dune grows, sinuosity in the dune crest-line develops, probably as a result of some initial irregularity in morphology. The cross-sectional area also increases exponentially to the point where it cannot be remodelled in each wind season and form–flow interactions become significant. The dune develops a morphology that is controlled by more than one wind direction, and the dune's sedimentary structure changes, with the formation of two opposing sets of cross-stratification (Fig. 3). The bimodal dips are attributed to stacking of sinuous elements migrating along the dune. This contrasts with the reversing crest model[3], and at this stage the structure is similar to the model of Tsoar[6]; (4) superimposed dunes appear with increasing dune height, width and sinuosity, because sand transport rates are then sufficient to support migrating dunes on the dune slopes[11]. The dominant southerly and southwesterly winds produce small superimposed dunes with slip faces (1–2 m high) facing north; such slip faces are best developed on the outer, convex slopes of sinuous dune elements, where winds are deflected along both windward and lee-side dune flanks (Fig. 4). The development of superimposed bedforms results in another change in the style of deposition, with sets of trough cross-stratification overlying larger sets of cross-stratification with a dominant dip towards the resultant drift direction which resembles model C of Rubin and Hunter[2]. Profile 6 (Fig. 2) also shows some similarity to the supposed internal structure of the 'whalebacks' of the Egyptian sand sea, as given by Bagnold in ref. 3. However, Bagnold attributed lateral migration to a change in wind regime rather than a response to sediment transport within a bimodal wind regime. (5) Sets of cross-stratification from superimposed bedforms then start to dominate dune sedimentary structure (Fig. 3). GPR profiles across larger complex linear megadunes in the same area are dominated by sets of trough cross-stratification from superimposed dunes resembling model E of Rubin and Hunter[2]. The model of Bagnold[3] is not supported by our observations, despite the bidirectional winds and observations of reversing crest-lines in this area[7].

Dune topography has a strong effect on wind flow lines and sediment transport over the dune[12]. Idealized wind flow lines for southwesterly and easterly winds based on field observations are shown in Fig. 4. On windward slopes, concave surfaces act to focus flow lines, locally increasing sediment transport at low points in the

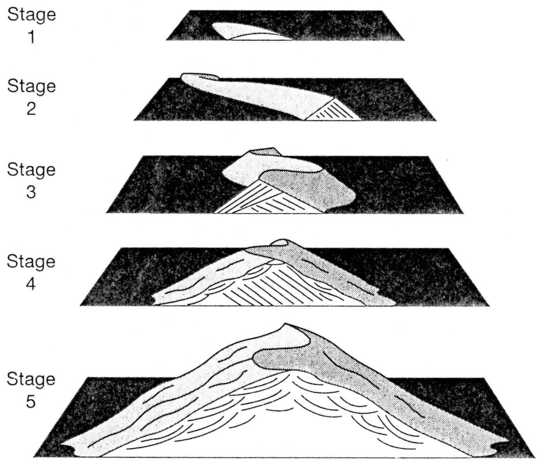

Figure 3 The five-stage model of linear dune evolution. Stage 1, initial plume of wind rippled sand. Stage 2, slip-face development and migration towards the resultant drift direction produces simple sets of cross-stratification resembling a transverse dune. Stage 3, lateral displacement of the sinuous crest-line creates bidirectional dips. Stage 4, flow deflection along dune flanks leads to the development of superimposed dunes. Stage 5, complex linear megadunes are dominated by sets of trough cross-stratification from superimposed dunes.

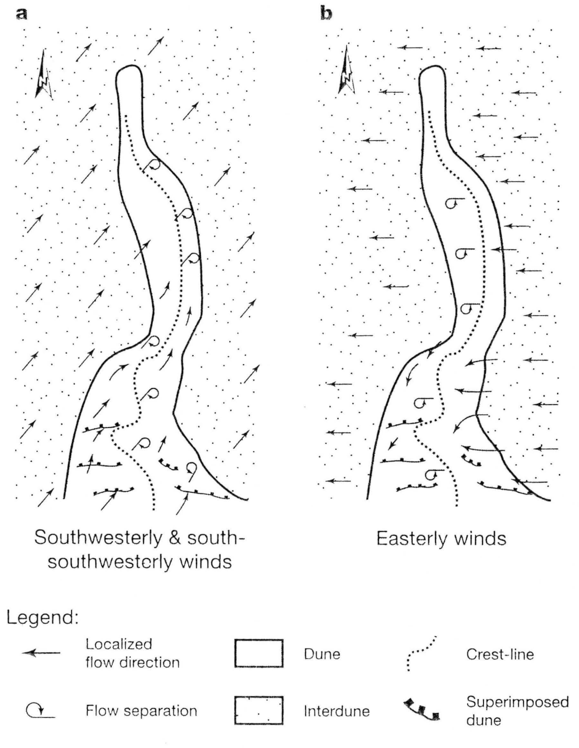

Figure 4 Wind flow lines. Idealized wind flow lines over a sinuous linear dune with a bidirectional wind regime, based on a field sketch of the study dune. Wind is locally focused where the windward dune flank is concave and deflected where the dune flank is convex. Flow separation occurs where the wind is almost perpendicular to the crest-line. Flow lines are locally deflected along both lee and windward slopes. Wind flow along the dune flanks promotes the development of superimposed dunes which are often best developed where the dune flanks are convex, especially on the eastern slope which is the lee side with respect to southwesterly winds.

crest-line. This results in increased deflection and sinuosity of the crest-line. Where the windward slope is convex in plan, wind flow lines tend to diverge and may be deflected along the face, locally increasing transport along the dune. On the lee side of the dune flow separation occurs where the wind is perpendicular to the crest-line; but separation does not always extend down or along the whole lee-side slope[12]. Lee-side flows may be deflected along the lee-side slope, especially on the convex dune slopes. Wind deflection over convex surfaces on both windward and lee slopes increases sediment transport along the dune and promotes the development of superimposed dunes. The oblique orientation of the dunes with respect to winds from the southwest and SSW leads to deflection along both dune flanks. Superimposed dunes are often best developed on the eastern side of complex linear dunes in the Namib sand sea, which is the lee side with respect to the more common SSW and southwesterly winds. The oblique orientation to the resultant transport vector may indicate alignment normal to the maximum gross transport[13].

By combining geomorphic and geophysical investigations into the morphology and structure of a linear dune, we have been able to determine its development and evolution. The high resistivity of aeolian sands gives good penetration (15–20 m), and the large sedimentary structures within dune sands are clearly imaged. The ability of GPR to image deep within the dune has been proven, and this technique provides a unique insight into the internal structure of dunes that cannot be achieved by any other non-destructive or geophysical method. Changes in dune morphology are reflected in the internal structures, and the results of this survey show that with increasing size and morphologic complexity, linear dunes become dominated by sets of cross-stratification from superimposed dunes. A simple, straight-crested linear dune which has migrated laterally could be mistaken for a transverse dune. The development of superimposed dunes results in the formation of stacked sets of trough cross-stratification that dominate the sedimentary structures of large, complex, linear megadunes, as well as many ancient aeolian sandstones, suggesting that deposits formed by large linear dunes may be much more common in the rock record than was previously thought. □

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