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Age and dynamics of linear dunes in the Namib Desert

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ABSTRACT

Ground-penetrating radar and luminescence dating studies of a large, complex, linear dune in the northern part of the Namib Sand Sea provide new information on the age and internal sedimentary structures of these dunes, with important implications for interpretations of paleoclimates and the rock record of eolian sandstones. The dune is a composite feature formed during several episodes of construction, including a hiatus of almost 2000 yr. The oldest sands within the dune are 5700 yr old, indicating complete turnover of sand during the Holocene. The dune has moved laterally by ~300 m during the past 2500 yr, proving lateral migration of a large linear dune. Dune construction has been affected by climate change, and we attribute the hiatus to increased rainfall and vegetation, which largely halted sand movement and dune building in the Namib Desert during the middle Holocene.

Keywords: linear dunes, Namib Desert, ground-penetrating radar, optically stimulated luminescence dating.

INTRODUCTION

Linear dunes are the most widespread type of desert sand dune (Lancaster, 1995), but they are rarely recognized in the geologic record (Rubin and Hunter, 1985). It has been argued that large linear dunes are relics of a cooler, drier, and windier climate during the Last Glacial Maximum, a hypothesis supported by luminescence dating of linear dunes in many areas (Lancaster, 2007) and by the considerable inertia of large dunes, which require thousands of years to respond to changes in wind regime (Warren and Allison, 1998). In addition, the large number of endemic species within the Namib Sand Sea has been given as evidence for a long and continuous period of hyperarid conditions within Namibia (Ward et al., 1983) and therefore potentially very old dunes. These ideas gave rise to the hypothesis that, although the linear dunes of the Namib Sand Sea are currently active, they should have some older, Pleistocene core. Livingstone (1989), however, questioned the "relic" dune hypothesis, suggesting that, given sufficient time, contemporary dune processes were capable of creating the present form of the dunes, although there were no techniques to determine the age or structure of large dunes at that time.

The two problems of determining dune age and sedimentary structure have now been solved using optically stimulated luminescence (OSL) dating and ground-penetrating radar (GPR) respectively. GPR exploits changes in permittivity within the dune sediments to image dune sedimentary structures (Van Dam et al., 2003) and has been shown to work very well in eolian sands (Bristow et al., 2000, 2005). We used GPR to image the sedimentary structures and stratigraphy of the dune. Based upon stratigraphic interpretation of the GPR profiles, sample locations for dating were selected and boreholes were drilled into the dune to obtain samples. We used OSL dating to determine when sand was last exposed to daylight and therefore how long it has been buried within a dune. When used together, these two techniques offer a powerful tool for investigation of sand accumulation and dune migration rates (Bristow et al., 2005).

THE STUDY AREA

The Namib Sand Sea is dominated by large, north-south–trending, complex, linear dunes (Lancaster, 1989), the orientation of which is controlled by a bimodal wind regime with a south-southwesterly wind blowing inland from the South Atlantic Ocean and an easterly "berg" wind that sweeps down the escarpment from the interior. The study dune is located close to the northern edge of the Namib Sand Sea, 7 km southeast of Gobabeb and the valley of the ephemeral Kuiseb River (Fig. 1). This dune has been surveyed repeatedly (Livingstone, 1993, 2003) to monitor annual to decadal changes in morphology. In the study area, the dune is ~70 m high and up to 600 m wide, decreasing in size toward the north. The dune has a sinuous crest and superimposed transverse dunes on both flanks. The dune crest shifts back and forth by ~15 m each year in response to the seasonally bimodal wind regime (Livingstone, 1989). The profile of the dune changes due to migration of superimposed dunes along the dune flanks, but the base of the dune shows no detectable lat-
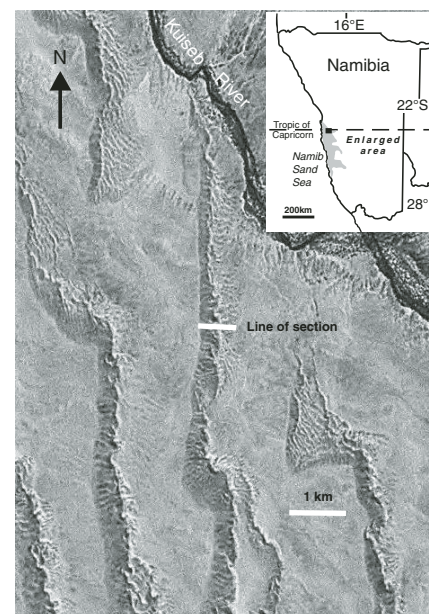

Figure 1. Location map showing the study site and the position of the linear dune in the northern part of the Namib Sand Sea.

eral migration over a 30 yr period (Livingstone, 2003). The section surveyed in this study is located between sites 1 and 2 of Livingstone.

METHODS

We carried out topographic surveys and collected over 4 km of GPR profiles across the dune. We obtained GPR data using a Pulse EKKO 100 with a 1000 V transmitter and 100 MHz antennae spaced 1 m apart. We collected data every 0.5 m

along the profile with 32 stacks at each point. Three-dimensional data were collected in blocks 25 m by 25 m with lines spaced 1 m apart at two locations on the west flank of the dune (100 and 200 m from the base) and one location on the east flank of the dune (200 m from the base). We calculated a velocity of 0.15 m ns^{-1} from common midpoint surveys on the dune, although the velocity probably increases slightly with depth as moisture content increases within the dune.

We used two drilling rigs to collect samples for OSL dating: a vehicle-mounted percussion auger for sampling depths less than 10 m and a Dormer sand auger with auger flights inside a counter-rotating core barrel for samples deeper than 10 m. Both drilling techniques were able to extract sand samples without exposure to daylight. Sampling from boreholes along a transect across the dune also allowed us to test models for lateral migration of linear dunes (Rubin and Hunter, 1985). We sampled sands from above and below the bounding surfaces identified on the GPR profile in order to constrain the timing of the unconformities identified and any age differences within the dune.

We carried out OSL dating on quartz grains extracted from the samples using standard laboratory procedures. These involved removal of carbonates and organics, dry sieving to isolate grains with diameters between 180 and 211 μm, density separation (2.62 < ρ < 2.70) using sodium polytungstate, and finally etching in 40% hydrofluoric acid for 45 min. The resulting quartz grains were measured in a Risø TL/OSL reader equipped with blue light-emitting diodes (470 ± 30 nm), and the resulting OSL signal was measured after being filtered through 6 mm of a Hoya U-340 filter. We employed the single-aliquot regeneration (SAR) procedure (Murray and Wintle, 2000) to determine the equivalent dose, and measured a minimum of 20 replicate aliquots for each sample (Table 1). For each sample, we undertook a dose recovery experiment to ensure that the analytical procedure was appropriate. We determined the natural radiation dose rate to the samples by a combination of thick-source alpha counting and beta counting.

RESULTS

The GPR profile illustrated in Figure 2 is one of three across the dune, all showing similar structures. It shows dipping reflections interpreted as sets of cross-stratification and bounding surfaces where reflections terminate. We have interpreted a relative chronology of dune construction from crosscutting relationships between the sets of cross-stratification. On the western dune flank, there is a marked unconformity between reflections within the dune that dip toward the east, which are truncated by reflections with an apparent dip toward the west. On the eastern flank, there is no such unconformity, and reflections from sets of cross-stratification and their bounding surfaces dip roughly parallel to the dune surface, indicating accretion toward the east. We interpret the unconformity on the western dune flank to have been formed by superimposed dunes migrating along the dune flank and eroding older east-dipping sets of cross-stratification. Northward migration of superimposed dunes along the dune flank is revealed in GPR cubes (Fig. 3). Reflections dipping toward the east and west at the dune crest formed during seasonal reversals at the dune crest and translation of crestline sinuosity.

OSL ages (Table 1; Fig. 2C) combined with the GPR surveys indicate that the construction of the dune was episodic, with three phases of dune building. The oldest part of the dune was deposited between 5.73 ± 0.36 ka and 5.24 ± 0.27 ka, indicated by sediments preserved at the base of the western flank of the dune. This was followed by a hiatus between 5.24 ± 0.27 and 2.41 ± 0.10 ka. The second phase of dune construction occurred between 2.41 ± 0.10 and 0.14 ± 0.01 ka, during which the dune built toward the east by as much as 300 m and increased in height from ~20 m to 45 m. The third and latest phase of dune construction comprises a reworking of the western flank of the dune by superimposed transverse dunes migrating north along the dune flank within the past 50 yr. In addition, there has been deposition on the eastern flank close to the dune crest due to the seasonal shifting of the crest and migration of the sinuous crestline. Superimposed dunes migrating along the eastern dune flank have also contributed to the eastward migration.

DISCUSSION

It is apparent that construction of this linear dune was episodic and included three phases with a hiatus separating the first two. The hiatus could be the result of northward migration of sinuosities in the dune crestline, but its lateral extent (1 km or more along the dune) as well as the absence of any similar discontinuities in the GPR profiles indicates that this mechanism is unlikely to have been responsible for such a hiatus. Alternatively, a change in wind regime resulting in increased frequency of easterly winds and therefore westward migration of the

TABLE 1. LUMINESCENCE DATING DATA AND RESULTS

Sample*	Depth (m)	Beta dose (mGy/yr)[†]	Gamma dose (mGy/yr)[†]	Cosmic dose (mGy/yr)	Total dose (mGy/yr)[†]	Number of aliquots[§]	Equivalent dose (Gy)[#]	Age (yr)
72-WD50-1	3.57 ± 0.20	1.24 ± 0.03	0.60 ± 0.02	0.14 ± 0.01	1.97 ± 0.04	21	11.26 ± 0.43	5710 ± 250
72-WD50-5	6.00 ± 0.20	1.25 ± 0.04	0.61 ± 0.03	0.10 ± 0.01	1.96 ± 0.04	24	11.21 ± 0.66	5730 ± 360
72-WD100-7	8.32 ± 0.20	1.28 ± 0.04	0.58 ± 0.02	0.08 ± 0.01	1.94 ± 0.04	18	10.74 ± 0.48	5520 ± 270
96-WD100-3	14.5 ± 0.20	1.35 ± 0.04	0.65 ± 0.02	0.05 ± 0.01	2.05 ± 0.04	22	10.7 ± 0.23	5240 ± 160
72-WD150-5	5.24 ± 0.20	1.35 ± 0.04	0.63 ± 0.03	0.11 ± 0.01	2.10 ± 0.05	22	0.11 ± 0.01	52 ± 4
72-WD200-1	7.22 ± 0.20	1.17 ± 0.03	0.60 ± 0.03	0.09 ± 0.01	1.86 ± 0.04	14	0.06 ± 0.01	34 ± 7
96-WD200-4	14.5 ± 0.20	1.20 ± 0.03	0.62 ± 0.03	0.05 ± 0.01	1.86 ± 0.04	22	3.82 ± 0.13	2050 ± 80
96-WD200-6	20.5 ± 0.20	1.03 ± 0.03	0.54 ± 0.02	0.03 ± 0.00	1.60 ± 0.04	22	3.85 ± 0.15	2410 ± 110
96-WD200-8	28.0 ± 0.20	1.21 ± 0.04	0.58 ± 0.02	0.02 ± 0.00	1.81 ± 0.04	23	4.17 ± 0.12	2310 ± 80
72-WD250-5	0.00 ± 0.10	1.15 ± 0.03	0.67 ± 0.04	0.30 ± 0.00	2.12 ± 0.05	12	0.02 ± 0.01	10 ± 3
72-WD250-1	4.88 ± 0.20	1.11 ± 0.03	0.62 ± 0.03	0.12 ± 0.01	1.85 ± 0.05	17	0.03 ± 0.01	13 ± 2
72-WD250-4	9.85 ± 0.20	1.02 ± 0.03	0.56 ± 0.03	0.07 ± 0.01	1.65 ± 0.04	18	0.04 ± 0.01	24 ± 3
96-WE200-1	2.00 ± 0.20	1.08 ± 0.03	0.54 ± 0.02	0.16 ± 0.02	1.78 ± 0.04	24	0.08 ± 0.01	50 ± 3
96-WE150-2	3.00 ± 0.20	1.13 ± 0.03	0.56 ± 0.02	0.15 ± 0.02	1.84 ± 0.04	21	0.25 ± 0.01	140 ± 10
96-WE150-3	8.00 ± 0.20	1.22 ± 0.04	0.57 ± 0.02	0.09 ± 0.01	1.88 ± 0.04	22	0.75 ± 0.02	400 ± 20
96-WE150-5	15.0 ± 0.20	1.19 ± 0.03	0.56 ± 0.02	0.05 ± 0.00	1.80 ± 0.04	21	1.63 ± 0.03	900 ± 30
96-WE150-8	21.5 ± 0.20	1.28 ± 0.03	0.64 ± 0.03	0.03 ± 0.00	1.95 ± 0.04	23	3.50 ± 0.10	1790 ± 70
72-WE100-1	3.85 ± 0.20	1.08 ± 0.03	0.55 ± 0.04	0.13 ± 0.01	1.76 ± 0.05	20	0.60 ± 0.02	340 ± 20
72-WE100-7	9.17 ± 0.20	1.23 ± 0.04	0.59 ± 0.04	0.08 ± 0.01	1.89 ± 0.05	22	0.85 ± 0.03	450 ± 20
72-WE50-1	3.60 ± 0.20	1.12 ± 0.03	0.64 ± 0.05	0.14 ± 0.01	1.89 ± 0.06	19	0.54 ± 0.02	290 ± 20
72-WE50-4	6.70 ± 0.20	1.17 ± 0.03	0.60 ± 0.04	0.10 ± 0.01	1.86 ± 0.04	22	0.67 ± 0.03	350 ± 20

* Samples are listed in order from west to east, and then with increasing depth. The complete laboratory code for each is Aber72-WD50-1, Aber72-WD50-5, etc.

[†] A water content of 3 ± 2% was used for dosimetry calculations. This value was based on estimates of current moisture content.

[§] The number of aliquots that were accepted for incorporation within the final estimate of equivalent dose. All SAR measurements were undertaken using a preheat of 200 °C for 10 s, and a cutheat of 160 °C.

[#] The equivalent dose for use in age calculation was obtained using the weighted mean of the individual equivalent doses obtained from each aliquot, and the uncertainty was calculated as the standard deviation divided by the square root of the number of aliquots.
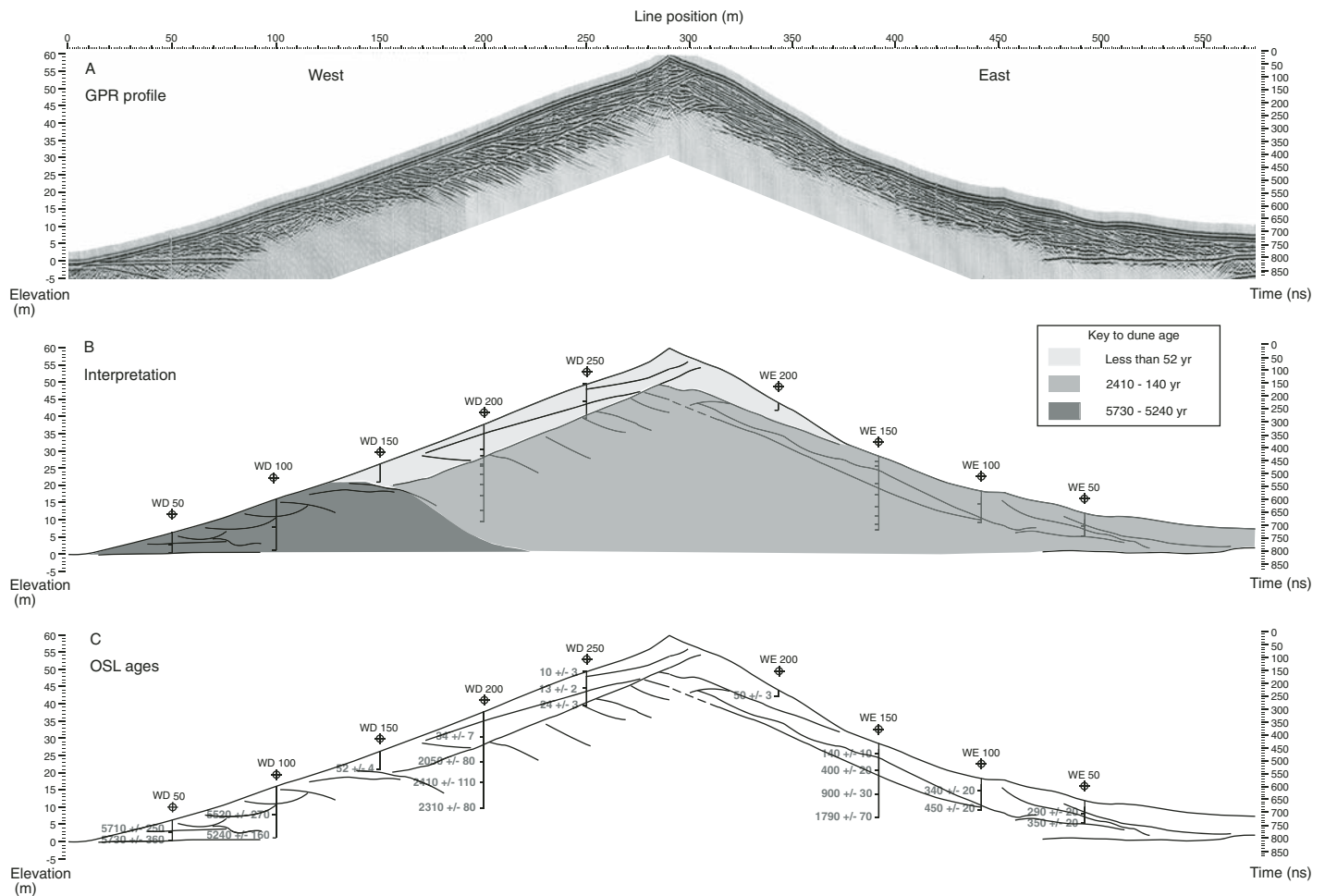
Figure 2. A: GPR profile across the dune showing dipping reflections interpreted as sets of cross-stratification and bounding surfaces within the dune. On the western flank of the dune, sets of cross-stratification formed by superimposed dunes truncate older east-dipping sets of cross-stratification. B: Interpretation of dune evolution based upon the ground-penetrating radar profile and optically stimulated luminescence (OSL) ages. C: OSL ages with locations of boreholes and OSL samples.

dune may have occurred, but there is no field evidence to support this suggestion.

Our favored hypothesis is that the hiatus results from an increase in rainfall and vegetation cover that temporarily stabilized the dune. Dune construction can be considered to be a function of sediment supply, availability, and mobility (Kocurek and Lancaster, 1999). In this part of the Namib Desert, sediment supply is not a limiting factor, as there is abundant sand available upwind of this dune. Sediment mobility is a function of wind energy. The northern Namib Sand Sea experiences a wind regime with a moderate sand-moving potential (Lancaster, 1989), and there is no evidence that wind strength in this area decreased significantly at any time during the Holocene. Availability of sediment for transport by the wind is strongly influenced by variations in vegetation cover, such that sand transport effectively ceases when vegetation cover exceeds 15%–20% (Lancaster and Baas, 1998; Wiggs et al., 1995). Therefore, the hiatus in dune construction may indicate vegetation

cover exceeding this amount for a period of hundreds of years. In the central Namib Desert, the vegetation cover on dunes increases from less than 1% in the west to as much as 10% in the east, along the sharp climatic gradient from the coast to inland. Recent studies indicate that rainfall was more frequent than today throughout much of the region in the middle Holocene (Gil-Romera et al., 2006). The effects of increased rainfall can be quite dramatic in the Namib Desert: The biomass of dune slope vegetation increased by over 50 times after 118 mm of rainfall in the period January–March 1976 (Seely and Louw, 1980).

The second phase of dune construction (2.41 ± 0.10 to 0.14 ± 0.01 ka) is marked by east-dipping reflections on the GPR profile. We interpret these reflections as sets of cross-stratification dipping toward the east, indicating that the dune was migrating from west to east at this time. The dune appears to have migrated east by ~300 m during this period, at an average rate of 0.13 m yr^{-1}, with the eastward migra-

tion of the dune best explained by a dominant southwesterly wind between 2.4 ka and the mid-twentieth century, indicating increased influence of winds from the South Atlantic high.

Recent changes in the dune morphology observed on repeated topographic profiles show movement of the crestline in response to seasonal variations in wind direction, and migration of superimposed dunes along the dune flanks (Livingstone, 1989, 2003). These observations are supported by the age and sedimentary structure of phase three, where the GPR profile shows sets of cross-stratification on the west flank truncating sets of cross-stratification within the dune. OSL dating demonstrates that these structures formed within the past 50 yr. The age of these most recent deposits is consistent with monitoring surveys that show no detectable change at the base of the dune but significant, seasonal changes at the dune crest. The northward migration of superimposed dunes is consistent with extension of linear dunes toward the north as recorded by Ward and von Brunn (1985).
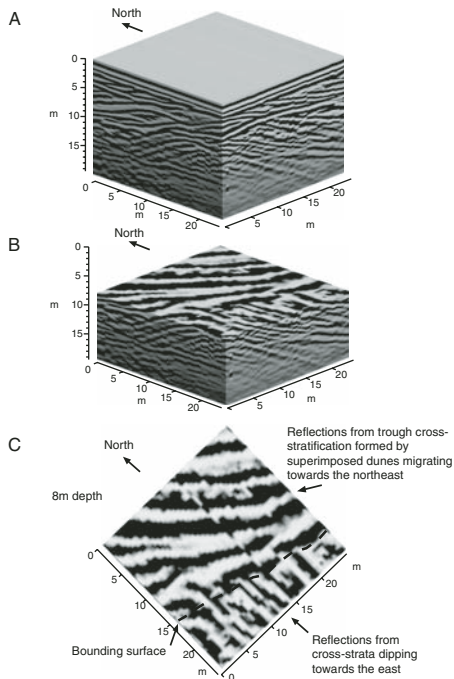
Figure 3. Three-dimensional ground-penetrating radar (GPR) showing reflections from sets of trough cross-stratification and bounding surfaces produced by superimposed transverse dunes migrating along the western flank of the linear dune. A: Sets of cross-stratification produced by superimposed transverse dunes migrating north along the dune flank. The orientation of the superimposed dunes can be confirmed using a time slice at a depth equivalent to 8 m (B) into the dune, which shows the strike of foresets produced by the north-northeastward migration of the superimposed dunes, which truncate earlier east-dipping sets of cross-stratification (C). GPR data were collected 200 m up the west flank of the dune.

CONCLUSIONS

Our studies show that large, complex, linear dunes in the northern Namib Sand Sea are younger than expected and are Holocene in age. The relative youth of the dune indicates complete turnover of sand during the Holocene, leaving no relic of older Pleistocene dunes, if indeed they existed in this area. It is possible that there are older dune deposits preserved within the Namib Sand Sea farther to the south, but we have no evidence for this.

The lack of a preserved late Pleistocene core to the dune shows that large linear dunes can be entirely reworked during the Holocene in hyper-arid environments such as the Namib Desert. Dune construction was episodic. The first phase of dune construction (prior to 5.24 ± 0.27 ka) was followed by a hiatus during which the climate was probably wetter. The second phase (2.41 ± 0.10 to 0.14 ± 0.01 ka) is characterized by an eastward migration of 300 m at a rate of ~0.13 m yr^{-1}, indicating a dominant sand-moving wind from the southwest. The record of deposition in the past 50 yr is dominated by migration of superimposed transverse dunes along the dune flanks, seasonal reversals at the dune crest, and adjustments of the sinuous crestline.

Our investigations support models of linear dune formation (Rubin and Hunter, 1985) in which dune construction is accompanied by lateral migration. The sedimentary structures revealed by GPR surveys show that a large part of the dune is made up of sets of east-dipping cross-stratification. When combined with the OSL ages, they indicate that, as the dune was constructed during the Holocene, it also migrated to the east, thereby producing sedimentary structures almost identical to those hypothesized by Rubin and Hunter (1985), including structures produced by superimposed dunes migrating parallel to the axis of the dune. Our studies therefore provide firm evidence for lateral migration of linear dunes and indicate that the deposits of many dunes preserved in the rock record previously interpreted to be transverse to the mean transport direction may in fact be those of dunes of linear form that combine the deposits of flow-parallel and flow-transverse elements. This has important implications for interpretation of ancient eolian sandstones, past wind regimes, and resulting paleoclimatic and paleogeographic reconstructions.

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