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Combining ground penetrating radar surveys and optical dating to determine dune migration in Namibia

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Abstract: Ground penetrating radar (GPR) profiles across a complex linear dune in the Namib Sand Sea have been used to image sets of cross-stratification and their bounding surfaces. A combination of radar facies analysis and radar stratigraphy has been used to interpret the radar profiles and define a relative chronology. Thick sets of cross-stratification indicate when the dune was most active, whereas thin sets of cross-stratification are interpreted to indicate the increased prevalence of wind reversals and lower rates of dune migration, with bounding surfaces formed during periods of stabilization, non-deposition or erosion. A drilling and dating campaign was designed on the basis of the dune stratigraphy as defined by the GPR survey. Sampling was targeted at large sets of cross-stratification formed when the dunes were most active, and avoiding bounding surfaces formed when the dune was stable or even eroded. The results from optical dating give ages between 0.34 ± 0.02 ka and 1.57 ± 0.07 ka, indicating a time-averaged dune migration rate of 0.12 m a^{-1} over the past 1600 years.

Keywords: Holocene, Namib desert, GPR, OSL, stratigraphy, aeolian dune migration.

The Namib Sand Sea is reputed to be one of the oldest deserts in the world (Ward *et al*. 1983) but until now the dunes themselves have not been dated. The results of this study, which uses a novel combination of ground penetrating radar (GPR) and optically stimulated luminescence (OSL) dating, provide evidence for relatively recent dune migration at the northern edge of the Namib Sand Sea. Aeolian sediments are usually good targets for GPR surveys because they have a high resistivity, which allows good penetration, and contain large-scale sedimentary structures that can be resolved by GPR. GPR has been successfully used previously to interpret the 2D and 3D structure and shallow stratigraphy of aeolian sands from a variety of aeolian dune settings (Schenk *et al*. 1993; Bristow *et al*. 1996, 2000*a*, *b*; Clemmensen *et al*. 1996, 2001; Harari 1996; Bristow & Bailey 2000; Neal & Roberts 2000, 2001; Van Dam 2002).

Optical dating can be used to determine the period of time that has elapsed since the mineral grains were last exposed to daylight. Aeolian sands are ideal materials for the application of this dating technique because quartz grains are usually well exposed to light during aeolian transport in the desert, ensuring that their signal is zeroed prior to deposition and burial (Wintle 1993). Minerals that are common in most sediments, such as quartz and feldspar, may be used to measure the ionizing radiation dose that they have been exposed to during burial, as a proportion of this energy is stored by electrons becoming trapped between the valence and the conduction bands. Within the laboratory, the stored energy can be released by stimulating the crystal using light of a restricted wavelength, normally in the blue or green part of the spectrum. A proportion of this energy appears in the form of light emitted by the crystal; this is optically stimulated luminescence (OSL). A full description of the OSL measurements necessary to calculate the radiation dose that a sample has been exposed to since burial (known as the equivalent dose) has been given by Duller (2004). To calculate the period of time since deposition, this equivalent dose is divided by the annual rate at which the sample is exposed to ionizing radiation. This is measured either by directly counting the alpha, beta and gamma radiations from the sample, or by making chemical measurements of the concentration of uranium, thorium and potassium and calculating the dose rate.

The sands have been dated using a single aliquot regenerative dose (SAR) protocol that corrects for sensitivity changes (Murray & Wintle 2000), and the dose rates measured using a combination of alpha and beta counting, and measurement of the potassium content using atomic absorption spectrometry, following the method described by Bailey *et al*. (2001). In this paper, we present an approach that combines GPR and optical dating to identify and date dune migration.

Survey location

This study presents results from the southern end of a linear dune at the northern edge of the Namib Sand Sea, around 5 km south of the Kuiseb River (Fig. 1). The dune is known locally as 'Station Dune' because of its proximity to the Desert Research Foundation of Namibia research station at Gobabeb. The dune is a complex linear bedform that is oriented broadly north–south and supports many smaller superimposed dune forms. In plan-form the dune has an irregular outline but the eastern margin is more complex and irregular than the western edge. The dune has an asymmetric cross-section with a well-developed linear crest along the western side of the dune. The western slope is relatively smooth with few superimposed dunes but the wider eastern slope is undulating as a result of the presence of low, north–south-oriented superimposed dune crest lines. Four GPR profiles have been collected across the dune in a loose grid (Fig. 2). GPR profiles SD1 and SD2 trend SE–NW perpendicular to the dune crest, whereas profile SD3 runs along the dune crest and SD4 is perpendicular to profiles SD1 and SD2. Station Dune was selected for the study because the GPR profiles are of a high quality and show a complete section through the dune. In addition, there is relatively

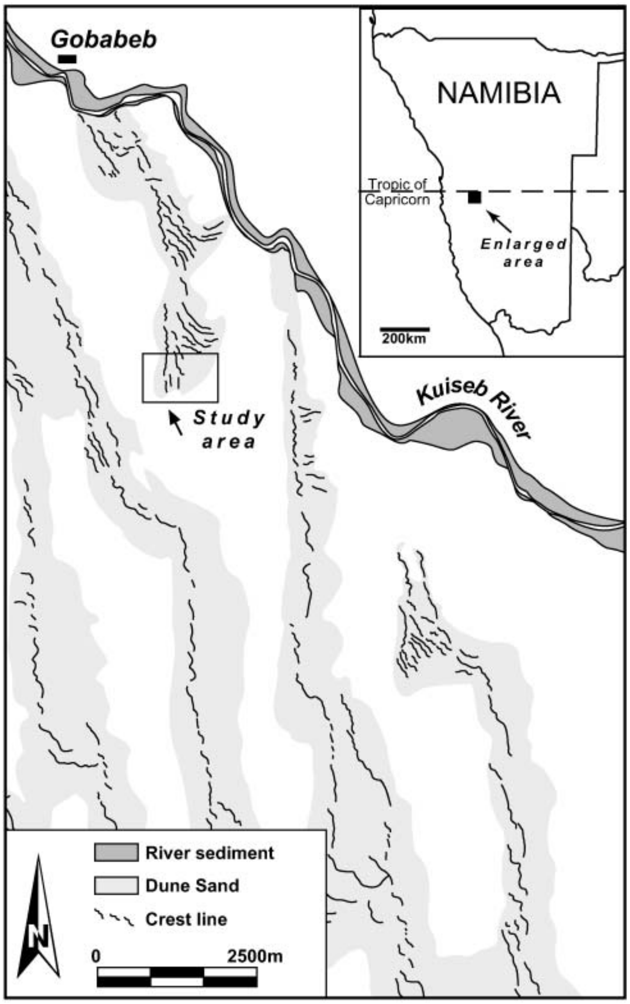

Fig. 1. Location of the study area at the southern end of Station Dune, a complex linear dune at the northern edge of the Namib Sand Sea near Gobabeb in Namibia.

good access to this site, which was an important practical consideration for deployment of the drilling rig.

Data collection

The GPR profiles presented in this paper have been collected using a Pulse EKKO PE 100 radar system using a 1000 V transmitting antenna with a central frequency of 100 MHz. In the field, the antennae were placed on the ground, 1 m apart, parallel to each other and perpendicular to the direction of the survey line. Measurements were taken at 0.5 m intervals along the survey line with 32 stacks at each point. The 100 MHz antennae have been found to give optimal results in several studies of dune sands around the world (Bristow & Bailey 2000; Bristow *et al*. 2000*a*, *b*; Neal & Roberts 2001; Botha *et al*. 2003). The survey lines were laid out in the field using 50 m tape measures, and the topography was measured at 5 m intervals, also noting the positions of breaks of slope, using a Sokkia SET5 total station. The velocity used to calculate depth on the GPR profiles is 0.15 m ns^{-1}, a value that has been determined from common mid-point (CMP) surveys, and is a typical velocity for dry sand (Jol & Bristow 2003). The GPR processing sequence includes Dewow, AGC (automatic gain control) and topographic correction.

GPR interpretation

Radar stratigraphy

The principles used in the stratigraphic interpretation of GPR profiles follow seismic interpretation techniques. The concepts of radar stratigraphy were introduced by Beres & Haeni (1991) and Jol & Smith (1991). The terms radar sequence and radar sequence boundary are based on the terminology developed for seismic interpretation by Mitchum *et al*. (1977) and were first introduced by Gawthorpe *et al*. (1993). Radar stratigraphy is similar to seismic stratigraphy but at a much higher resolution (tens of centimetres instead of tens of metres). Following seismic stratigraphic interpretation principles, it is necessary to identify reflection terminations to identify radar sequence boundaries. The identification of reflection terminations is the basis for constructing a relative chronology for sedimentary environments because reflections are regarded as isochronous surfaces (Vail *et al*. 1977); terminations or truncations therefore mark breaks in

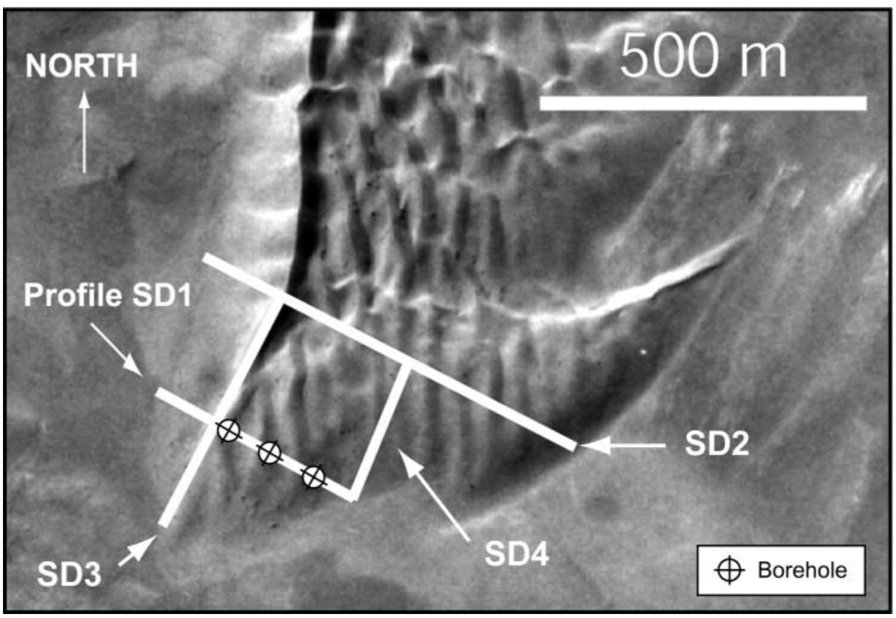

Fig. 2. Aerial photograph showing the southern end of Station Dune with the location of the GPR profiles and boreholes.

time (chronostratigraphic gaps). Successive radar sequences can be used to construct a relative chronology following the laws of superposition and cross-cutting relations. This interpretation method has been applied to radar profiles at Station Dune (Fig. 3).

Figure 3 shows a GPR profile across the southern end of Station Dune (profile SD1), which is oriented perpendicular to the dune crest. The topography of the dune is gently undulating with three rounded crests. The morphology indicates a complex or composite form but from study of the external geometry it is not clear if this is due to dune stacking (e.g. three dunes separated by low-angle accretion surfaces), vertical aggradation or superimposition of different types of dunes. The GPR profile allows the morphological evolution of the dune to be interpreted. The GPR profile (Fig. 3a) is dominated by reflections dipping from right to left (east to west) with a continuous reflection at the base of the dune. The continuous subhorizontal reflection at the base of the dune comes from the interface between the dune sand and the top of the underlying Tsondab Sandstone, a carbonate-cemented aeolian sandstone of predominantly Miocene age (Kocurek *et al*. 2000). The reflections within the dune include gently dipping inclined reflections and curved concave tangential reflections. The inclined and tangential reflections are interpreted as sets of cross-stratification and bounding surfaces. Bounding surfaces between sets of cross-stratification can be identified using radar sequence stratigraphic interpretation of the GPR profile as shown in Figure 3b. Reflection terminations have been identified and are marked with arrows showing truncation and downlap. Truncation indicates an erosive contact and minor unconformity between sets of cross-stratification. Downlap indicates burial of an older dune surface by a younger set of cross-stratification. From the cross-cutting relationships and superposition, a relative chronology can be established for the sets of cross-stratification (Fig. 3c). This has been used to construct a chronostratigraphic diagram (Fig. 4), which emphasizes the gaps in the stratigraphy represented by the bounding surfaces and shows that most of the units have time-transgressive conformable bases that correlate with conformable or downlapping reflection terminations, whereas the tops of the units are mostly marked by erosional truncation. The erosional truncation is attributed to erosion during wind reversal and erosion in the lee of superimposed dunes. The oldest set of cross-stratification shown on this profile is at the right-hand (eastern) end of the profile, whereas the youngest sets are at the left-hand side of the profile and at the top of the dune. Units 20, 21 and 22 are all believed to be of similar age, representing the most recent sand deposition on the western dune flank and on the superimposed dunes on top of Station Dune.

The westerly dipping reflections (Fig. 3a) show that the dune has migrated from east to west and is accreting on its western side. The dipping bounding surfaces within the dune are interpreted as reactivation or redefinition surfaces formed when the lee face has been periodically eroded (Kocurek 1996). The abundance of these surfaces indicates that the dune has had a relatively complex history with repeated episodes of migration, accretion and erosion. This complex history is attributed to frequent dune crest reversals and changes in dune morphology owing to changes in the wind direction, which is known to be variable and bimodal in this area (Lancaster 1983; Lancaster *et al*. 1984). In addition, bounding surfaces with more concave erosional truncation of underlying reflections (e.g. units 4, 9, 16 and 19) may be superposition surfaces produced by scour in the lee of superimposed dunes, although this is difficult to determine on the basis of the GPR profile alone. Thicker packages of reflections are interpreted as thicker sets of cross-stratification, which probably formed when the easterly winds were most active. The relative chronology derived from the radar stratigraphy clearly shows that the dune has migrated from east to west. This history could not have been determined from the dune morphology, because the dune morphology lacks distinct asymmetry and does not give any clear indication of a preferential migration direction. Even so, the youngest units are probably those on the highest point of the dune where the GPR profile shows low-angle dipping reflections that are interpreted as recent reworking. The GPR profile along the dune crest (not illustrated) shows bounding surfaces dipping gently towards the south with low-angle sets of cross-stratification dipping towards the north. Reconstructing the true dips from the apparent dips where the profiles intersect it is apparent that profile SD1 is close to a true dip section with sets of cross-stratification dipping slightly towards the north and bounding surfaces dipping gently towards the south.

Luminescence ages

Using the relative chronology derived from the GPR profile, a sampling programme was designed to select sample locations for optical dating. Sand samples were obtained using a percussion auger mounted on the back of a four-wheel-drive vehicle. During drilling a hollow steel core barrel with an inner rod with pointed tip was hammered into the sand by percussion and hydraulic pressure. When the target sampling depth was achieved the inner rod was removed and replaced by a 1 m long black-painted plastic core liner. Drilling then continued for 1 m to fill the core barrel, which was then withdrawn from the hole. The core liner was extracted from the steel drill casing under opaque black polythene to prevent any exposure to daylight. Sections of the core were cut and sealed in the field and wrapped in black plastic for transport.

Sample points were selected based on the GPR profiles. Thicker sets of cross-stratification, units 1, 11 and 17, were selected for dating for three reasons.

(1) The thicker sets of cross-stratification are believed to have been formed when the dune was most active.

(2) Selecting thick sets of cross-stratification avoids bounding surfaces, which by definition represent periods of non-deposition or erosion.

(3) By targeting thicker sets of cross-stratification there is greater confidence in sampling a specific stratigraphic unit, thereby reducing uncertainty surrounding depth/velocity calculations to the sample depth on the GPR profiles and any errors in measured drilled depth and compaction during coring. (In this case a 100 MHz GPR pulse with a velocity of 0.15 m ns^{-1} in dry sand should have a vertical resolution of around 0.375 m).

The age of the stratigraphic units defined on the basis of the GPR profile has been established using optical dating of samples obtained by percussion drilling. The parameters used in the calculation of optical ages are shown in Table 1. Unit 1 has been sampled in borehole SD250, sample 72 SD250-4, at a depth of 3.11 ± 0.20 m and has an OSL age of 1.57 ± 0.07 ka. Unit 11 has been sampled in borehole SD150, sample 72 SD150-1, at a depth of 4.8 ± 0.20 m and has an OSL age of 0.99 ± 0.05 ka. Unit 17 has been sampled in borehole SD100, sample 72 SD100-1, at a depth of 3.34 ± 0.02 m and has an OSL age of 0.34 ± 0.02 ka (Table 1). These ages are equivalent to calendar ages of AD 432, 1012 and 1662. The OSL ages correspond to the relative chronology derived from the GPR interpretation, confirming the stratigraphic relationships within the dune.

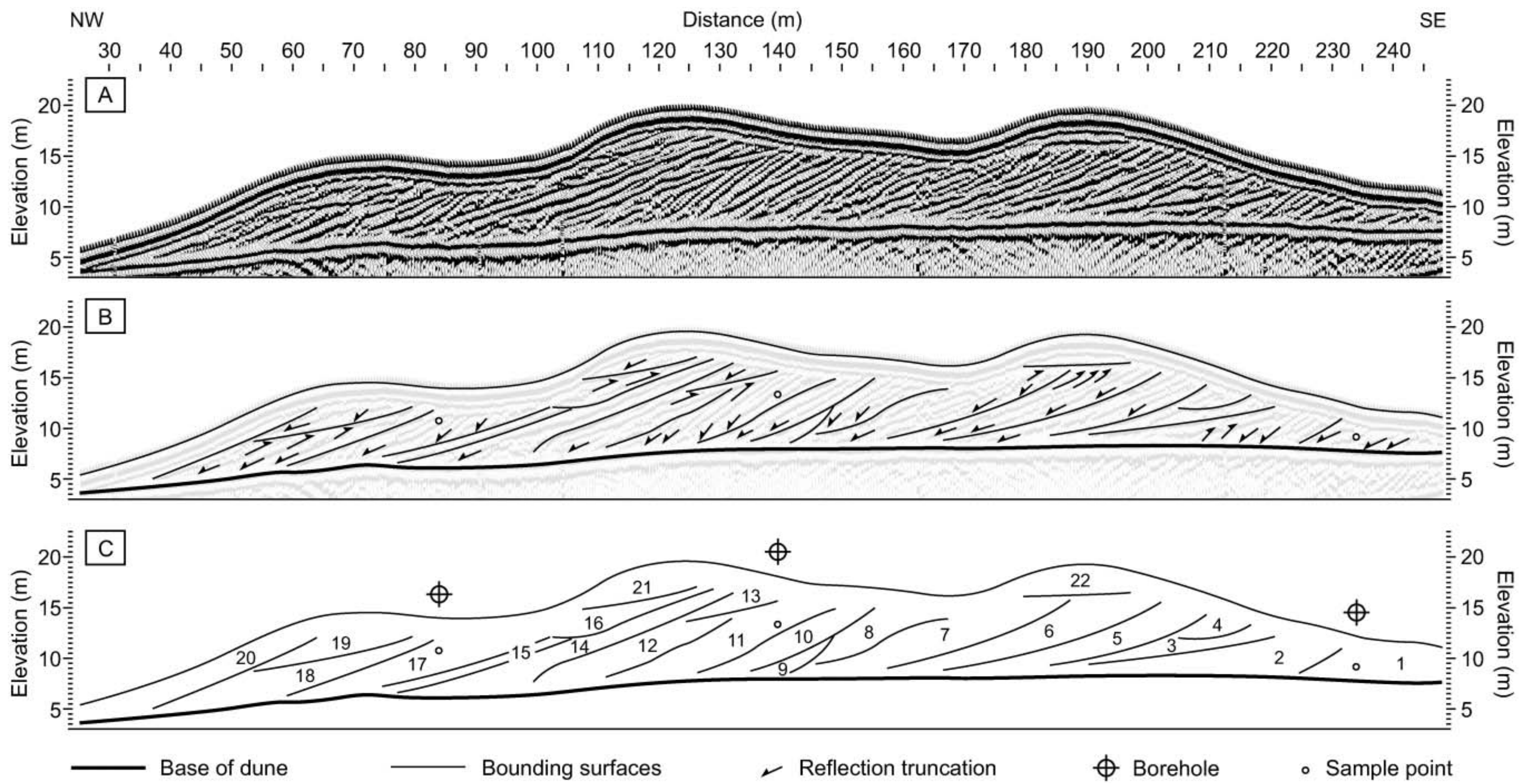

Fig. 3. (**a**) GPR profile SD1 across the southern end of Station Dune, showing the undulating topography of the dune and the complex internal structure dominated by sedimentary dips from east to west. (**b**) Radar stratigraphic interpretation of (**a**), showing bounding surfaces picked at reflection terminations. (**c**) On the basis of the radar stratigraphic interpretation (**b**) the dune can be divided into up to 22 stratigraphic units interpreted as sets of cross-stratification bounded by second-order bounding surfaces. The relative chronology of the sets has been established from cross-cutting relationships with 1 as the oldest and 20, 21 and 22 as the youngest.

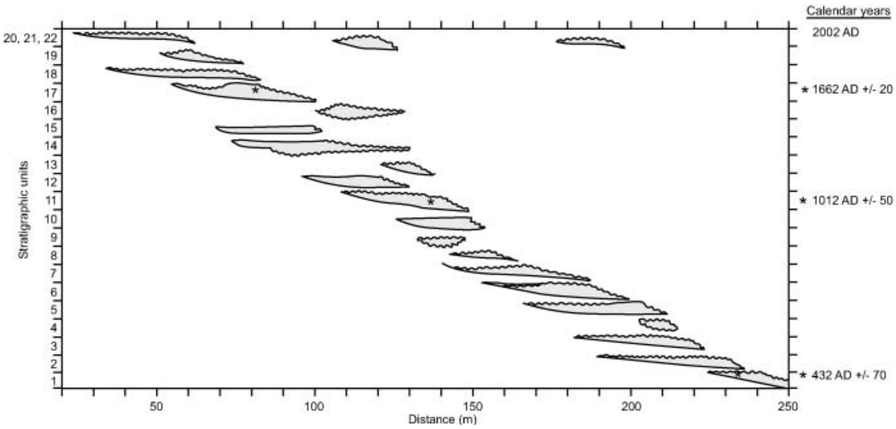

Fig. 4. Chronostratigraphic diagram constructed from the GPR profile, showing many erosional gaps in the dune stratigraphy marked by erosional unconformity bounding surfaces. Most units have time-transgressive conformable bases indicated by downlapping reflection terminations and erosional unconformable tops indicated by truncated reflection terminations.

Table 1. *Luminescence age data from Station Dune, Namibia*

	Aberystwyth laboratory number		
	72 SD100-1	72 SD150-1	72 SD250-4
Depth (m)	3.34 ± 0.20	4.80 ± 0.20	3.11 ± 0.20
Material used for dating		Quartz	
Grain size (μm)		180–211	
Preparation method		Heavy liquid separation (sodium polytungstate); 40% HF etch 45 min	
Measurement protocol		SAR; OSL 470 nm; detection filter 7.5 mm Hoya U-340	
Equivalent dose D_e (Gy)	0.73 ± 0.04	2.03 ± 0.09	3.50 ± 0.12
Number of aliquots, *n*	23	22	18
Water content (% dry mass)	3 ± 2	3 ± 2	3 ± 2
Unsealed α count rate (counts ks^{-1} cm^2)	0.330 ± 0.006	0.228 ± 0.004	0.235 ± 0.004
U (ppm)	1.48 ± 0.17	0.85 ± 0.12	1.07 ± 0.11
Th (ppm)	4.38 ± 0.56	3.60 ± 0.38	3.05 ± 0.37
Sealed/unsealed	1.05 ± 0.04	1.03 ± 0.04	1.04 ± 0.04
Infinite β dose rate (Gy ka^{-1})	1.51 ± 0.02	1.53 ± 0.02	1.63 ± 0.02
Calculated K (%)	1.50 ± 0.05	1.65 ± 0.05	1.79 ± 0.06
Layer removed by etching (μm)	10 ± 2	10 ± 2	10 ± 2
External β dose rate 'wet' (Gy ka^{-1})	1.28 ± 0.04	1.29 ± 0.04	1.38 ± 0.04
External γ dose rate 'wet' (Gy ka^{-1})	0.71 ± 0.04	0.65 ± 0.04	0.70 ± 0.05
Cosmic dose rate (Gy ka^{-1})	0.14 ± 0.01	0.12 ± 0.01	0.14 ± 0.02
Total dose rate (Gy ka^{-1})	2.13 ± 0.05	2.06 ± 0.06	2.22 ± 0.07
OSL age* (ka)	0.34 ± 0.02	0.99 ± 0.05	1.57 ± 0.07

SAR in single aliquot regenerative dose.
*Ages are expressed as thousand years (ka) before AD 2002.

Rates of migration

Using the OSL ages for samples 72 SD250-4, 72 SD150-1 and 72 SD100-1 from units, 1, 11 and 17 (Fig. 3), and their distance apart, a linear rate of dune migration can be calculated (Fig. 5). OSL sample 72 SD250-4 has an age of 1.57 ± 0.07 ka, which is equivalent to AD 432 in calendar years. Sample 72 SD150-1 has an OSL age of 0.99 ± 0.05 ka, which is equivalent to AD 1012; the difference in age between these two samples is 580 years and the horizontal distance between them is 95 m, giving an end-point migration rate of 0.16 m a^{-1}. OSL sample 72 SD100-1 has an age of 0.34 ± 0.02 ka, which is equivalent to AD 1662 in calendar years, making it 650 years younger than sample 72 SD150-1. The horizontal distance between them is 55 m, giving an end-point migration rate of 0.08 m a^{-1}. Projecting horizontally from sample 72 SD100-1 to the present dune face at the same elevation gives a distance of 34 m. This indicates that the dune has advanced by 34 m during the past 340 years, an end-point migration rate of 0.1 m a^{-1}. In the longer term, the average end-point migration rates between samples 72 SD250-4 and 72 SD100-1, and 72 SD250-4 and the present dune face are both 0.12 m a^{-1}.

The rates calculated are end-point rates; they do not take into account the discontinuous nature of dune migration, the erosional truncation and stratigraphic gaps shown in the chronostratigrahic diagram (Fig. 4) attributed to annual and seasonal variations in the local wind regime, and temporary crest reversal. However, the rates calculated are remarkably consistent, varying between 0.08 and 0.16 m a^{-1}, with an average of 0.12 m a^{-1}, and the sets of cross-stratification show a consistent dip towards the west and the GPR profile is perpendicular to the dune crest and close to the true dip direction. The OSL ages correspond to the relative chronology derived from the GPR interpretation, confirming the stratigraphic relationships within the sands. The OSL ages also show that the southern end of the Station Dune is relatively young, as all the ages shown here are less than 1600 years. The ages suggest that the sand dunes are actively migrating and sand has been deposited during the past 1600 years. The rate of dune migration is relatively slow at 0.12 m a^{-1}. This is consistent with observations of recent dune activity, which show active dune crests but little or no net migration of the crest line position (Livingstone 1993), and with the measured rates of dune

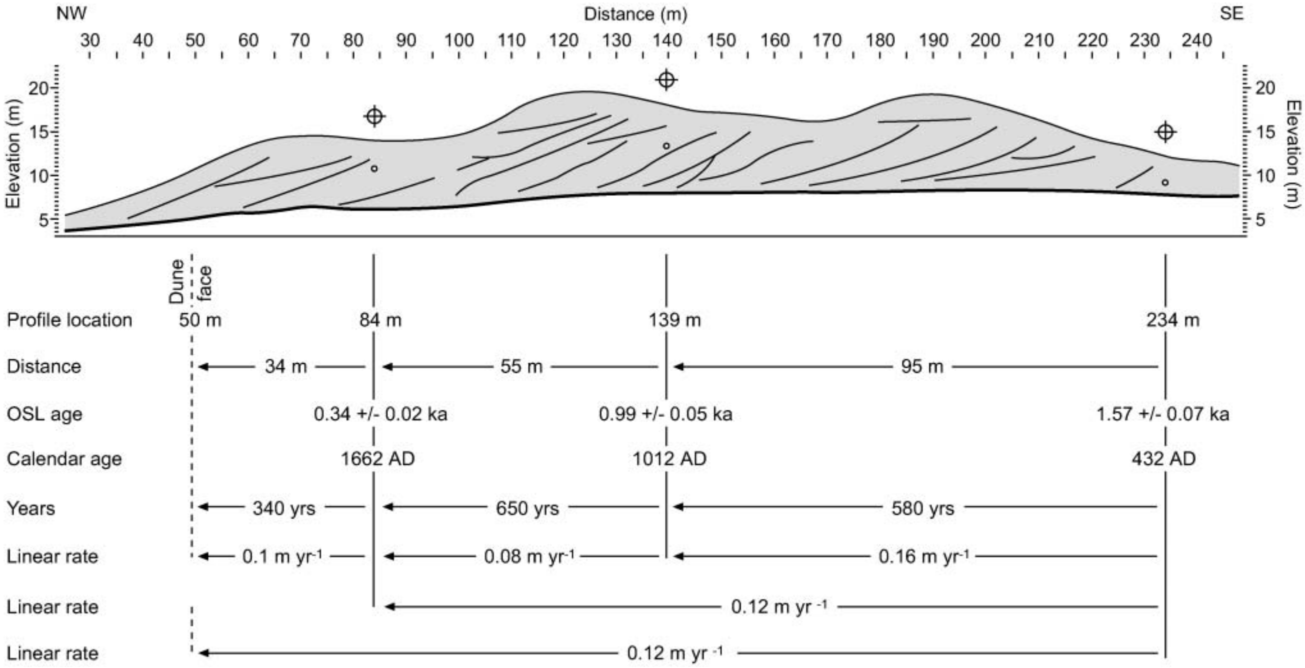

Fig. 5. Profile across Station Dune showing sample location for OSL dating in units 1, 11 and 17. The distance between the sample points and the dune face at a similar elevation is shown beneath, together with the luminescence age, calendar age and the years between them. The distance between the samples and the years between the calendar ages are used to determine an average linear migration rate of 0.12 m a^{-1}.

migration in the area (Bristow & Lancaster 2004). The westerly dune migration direction is probably driven by the easterly berg winds, which are dominant in the winter. This is different from the majority of measured dune migration directions in the area, which tend to be towards the NE (Ward & von Brunn 1985), but agrees with the net westerly movement of a small linear dune SW of Gobabeb (Besler 1975).

It is generally agreed that the linear dunes in the Namib Sand Sea have extended from south to north. Therefore the southern end of Station Dune should be the oldest part of the dune, yet the OSL ages indicate that it is less than 1600 years old. The relatively young ages reported here and the consistent migration direction suggest that the southern end of Station Dune is being reworked. Indeed, the modern resultant sand transport direction at Gobabeb is towards the WSW, consistent with the migration direction interpreted in this paper, adding further support to the hypothesis of reworking of an older dune form.

The westerly migration described here could be interpreted to indicate that the linear dune is migrating sideways. However, it is equally possible that the westerly migration is due to the migration of superimposed dunes around the southern end of an older large linear dune. The westerly dipping sets of cross-stratification and the low-angle southerly dip to the bounding surfaces support the superimposed dune hypothesis, and the OSL and GPR data reported here further support the hypothesis that the linear dunes of the Namib Sand Sea are relicts of a previous wind regime (Lancaster 1991). Further dating and 3D GPR surveys are required to fully resolve these outstanding issues.

Conclusions

This paper shows the advantages of combining geophysical and geochronological techniques to investigate the age, migration and accumulation of aeolian sand. Ground penetrating radar (GPR) provides an image of the subsurface showing the internal structure of dunes. At Station Dune, the surface morphology and dune topography do not provide a clear indication of the dune migration direction. However, sets of cross-stratification and bounding surfaces imaged by GPR clearly show that the dune has been migrating from east to west. Furthermore, stratigraphic relationships can be interpreted from GPR reflections to establish a relative chronology within dune sands. Once major bounding surfaces and depositional units have been identified, a sampling strategy can then be implemented for dating using OSL. Thus sampling can be targeted at specific horizons, to bracket erosion surfaces or stabilization surfaces, and sample the larger or more significant depositional units. This provides a significant improvement on the dating of sand accumulation and dune migration through sampling at arbitrary depths, in vertical profiles through pits or boreholes. In this study, large sets of cross-stratification were targeted for dating because they are interpreted as being formed when the dune was actively migrating in a downwind direction. In addition, sampling the larger and thicker sets of cross-stratification reduces errors in picking sampling depths from GPR profiles and compaction during drilling.

Radar stratigraphic analysis provides a relative chronology that should be used as a framework for selecting sampling points in aeolian sediments for optical dating. This combination of GPR and optical dating has been successfully employed in the Namib Sand Sea and shows that Station Dune has been actively migrating during the past 1600 years, with an average end-point migration rate of 0.12 m a^{-1}. The combination of shallow geophysics and geochronology has the potential to improve greatly studies of the chronology of dune migration and sand accumulation, and to provide a better constraint on episodes of sand movement and phases of dune activity. Indeed, sedimentary structures within dune sands imaged using GPR may be used to determine palaeodune morphology and orientation, thus allowing the reconstruction of palaeowind directions. Such observation may then be integrated with palaeoclimate models to investigate the forcing factors involved in dune migration.

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