# Desert landforms in Namibia – a Landsat interpretation

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## Abstract

*In the desert regions of Namibia there are various major largely undescribed landform types which have been studied by means of Landsat images. These include the sand dunes of the Cunene erg in northern Namibia, the yardangs developed in the coastal regions of southern and northern Namibia, aligned calcrete karst developed in the western Kalahari of southern Namibia and banded vegetation (brousse tigreé), also in the southern Kalahari. The Cunene erg consists of barchans, transverse and linear types. The mega-yardangs, which are developed in ancient metamorphic and igneous rocks, are moulded by sand laden, high velocity winds. The aligned drainage pattern of the Weissrand has been created by a combination of inter-dunal deflation and calcrete solution. The banded vegetation stripes occur in inter-dunal depressions, along ephemeral drainage lines, and on gentle slopes.*

KEY WORDS: *dunes, yardangs, calcrete, aligned drainage, Namibia*

## 1. Introduction

In recent years, Landsat imagery has become widely available by means of such platforms as Google Earth (earth.google.com) and the NASA Zulu site (https://Zulu.ssc.nasa.gov/mrsid/mrsidpl). The purpose of this paper is to use such imagery to describe previously largely undescribed desert landforms from the Kalahari and Namib Deserts in Namibia, landforms which are either difficult to identify on the ground or which are difficult to access. The paper describes four main landform types:

a) Sand dunes from the Cunene erg in northern Namibia
b) Yardangs from the southern and northern Namib
c) Aligned drainage on calcrete in the western Kalahari
d) Banded vegetation stripes (tiger bush or brousse tigrée) in southern Namibia.

Locations are shown in Figure 1.

## 2. Sand dunes from the Cunene Erg

The Cunene Sand Sea is located in the far north west of Namibia, and is bounded to the north by the Cunene River, to the west by the Atlantic Ocean, to the south by a

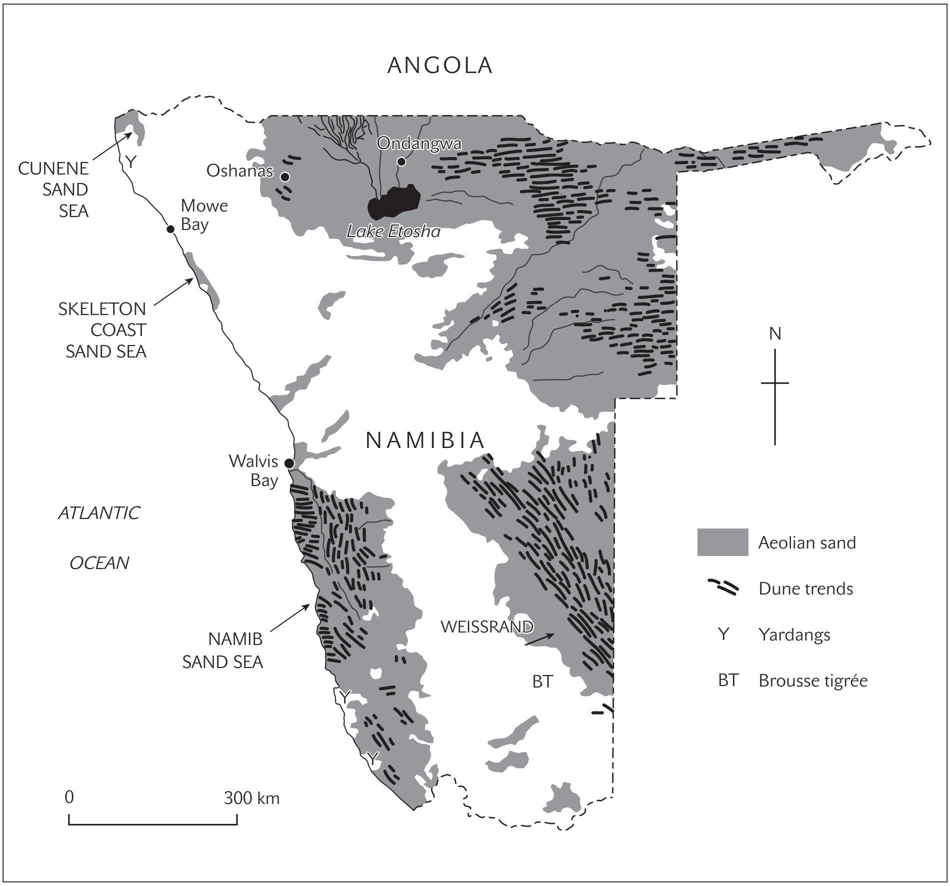

**Fig. 1** Location of the Namib desert landforms described in this paper.

large area of wind eroded bedrock in Kaokoland, and to the east by the Hartmann range of mountains. The sand sea (Figure 2) is relatively small in size (ca. 2,000 km$^2$ in area). Unlike the more southerly Namib Sand Sea (Lancaster 1989) and the Skeleton Coast Sand Sea (Lancaster 1982), its landforms have never been described. It is located in a hyper-arid area, and its climate is moderated by the presence of the cool Benguela current offshore. There are no climate stations within the immediate vicinity, but it is probable that the mean annual rainfall is less than 50 mm. The nearest climate station in Angola, at Tombua (Porto Alexandre), generally receives between 10 and 30 mm per annum. Much of the area is underlain by ancient igneous and metamorphic rocks belonging to the Swakop Group (570–900 Ma). Beetz (1934) noted that sand had filled valleys that had developed in an old land surface (peneplain) cut across these ancient rocks and had, in the Cretaceous and Tertiary, entered Angola. He observed sand thicknesses of 150 m in sections along the Cunene River.

## The dunes

Analysis of Landsat-7 imagery shows that three main types of dune dominate the Cunene Sand Sea: barchans, transverse and linear (Figures 3 and 4). Barchans, of simple and compound form, cover an area of 348.6 km$^2$, which is 17.4 % of the total area of the sand sea. They are largely located in the south west of the region and abut the zone of yardang development to their south. Transverse dune ridges are the most extensive dunes of the sand sea, covering ca. 525.1 km$^2$ (26.3 % of the area). They dominate the north western part of the region (Figure 3). To the east lies a field of seemingly subdued linear ridges which covers 403.6 km$^2$ (20.2 % of the area).

The barchans are oriented N-NE, have a mean length of 560 m, and a mean width between their horns of 193 m. Their orientation near the coast is much more north to south than it is further inland. The transverse dune ridges average 2.927 km in length. In general terms dunes in the west and south of the area have northerly orientations, whereas in the north and east of the area they swing round to have an orientation that has a greater west to east component. The linear dunes which average 7.08 km in length. (Figure 4) appear to be overlain by some of the transverse forms, and may, therefore, be of greater age. In the far north east of the sand sea they become increasingly west-east in their orientations. The Curosa-Bahia dos

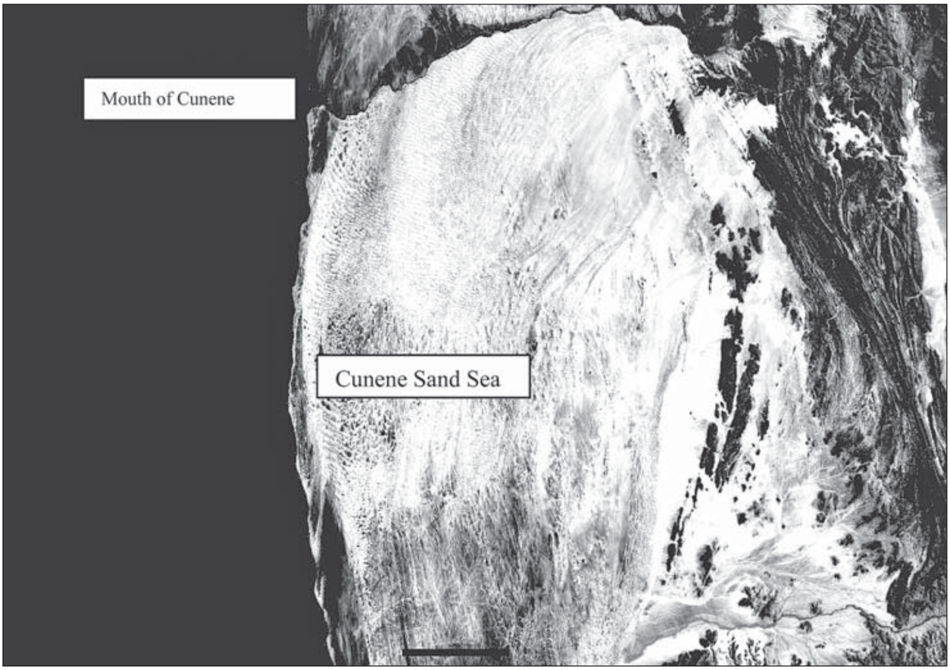

**Fig. 2** The Cunene Sand Sea, with the Atlantic Ocean to the west and the Cunene River to the north. *All images (fig. 2–13) are derived from NASA Zulu, and are oriented from north to south. Scale bars all equal ca. 10 km.*

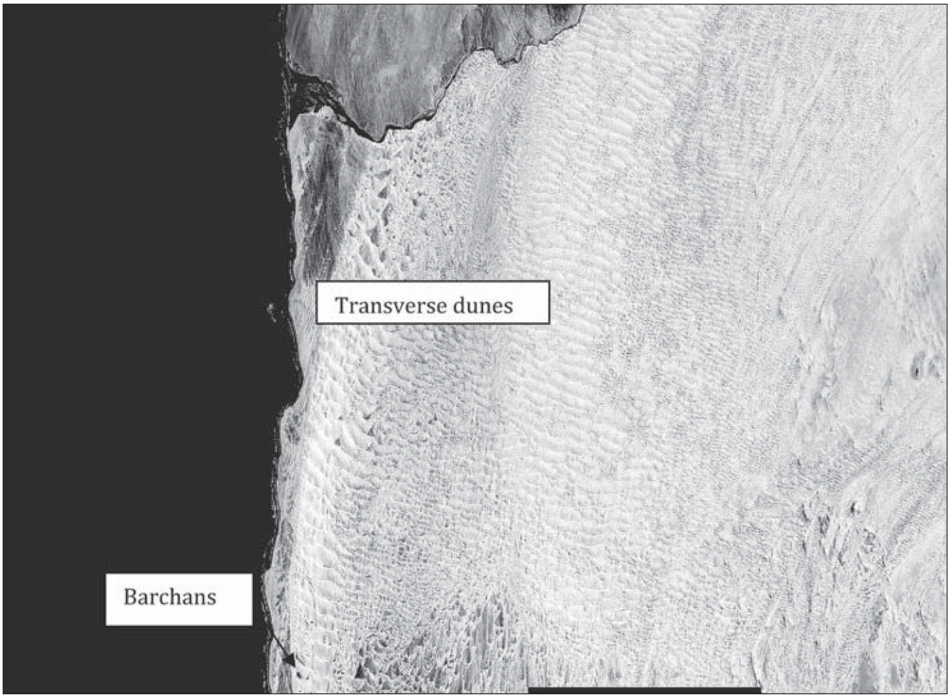

**Fig. 3** The western portion of the Cunene Sand Sea showing barchans and transverse types of dune.

Tigres dune field in Angola, on the other side of the Cunene, shows a similar swinging round of the linear forms as one moves eastwards. It also has transverse dunes overlying linears. The presence of barchans in the west of the region, in proximity to the ocean, mirrors the situation in the Namib and Skeleton Coast sand seas and may be related to a constancy of wind direction (a necessary prerequisite for barchan development) and also to a limited sand supply. Wind data for stations further south on the north Namibian coast, including Mowe Bay, show strongly unimodal winds coming from the south, whereas inland stations to the east, such as Ondangwa, show more variable wind regimes but with a clear tendency for winds to blow from the east (Table 1). It is this which probably explains the changing orientations of the dunes as one moves inland.

**Table 1** Wind directions (%) for a coastal and an inland station in northern Namibia for different degree classes.

| | 22.5 / 67.5 | 67.5 / 112.5 | 112.5 / 157.5 | 157.5 / 212.5 | 212.5 / 247.5 | 247.5 / 292.5 | 292.5 / 337.5 | 337.5 / 22.5 | Calm |
|---|---|---|---|---|---|---|---|---|---|
| Mowe | 0.64 | 1.17 | 8.36 | 62.53 | 8.70 | 2.51 | 1.70 | 0.34 | 14.04 |
| Ondangwa | 5.36 | 16.67 | 2.72 | 7.34 | 1.68 | 2.74 | 3.18 | 3.18 | 57.12 |

## The barchans

As table 2 indicates, the Cunene Sand Sea barchans are relatively large compared to the classic examples studied in southern Peru, but they are comparable in width to those from Saudi Arabia, Qatar, Egypt and the southern Namib. Data for dune heights are not available, but using the formula of Hesp and Hastings (1998) it is possible to calculate barchan slipface height from barchan horn width:

$$W = 8.82h + 7.65 \quad (1)$$

On the other hand, Finkel (1959) indicated the relationship was

$$W = 10.3h + 4.0 \quad (2)$$

If these formulae are applied to dunes with an average width between horns of 193 m, then the respective heights of those dunes are 29.53 and 22.74 m respectively. Alternatively, the barchan height/width relationship can be expressed as

$$H = W/2 \tan\Phi \quad (3)$$

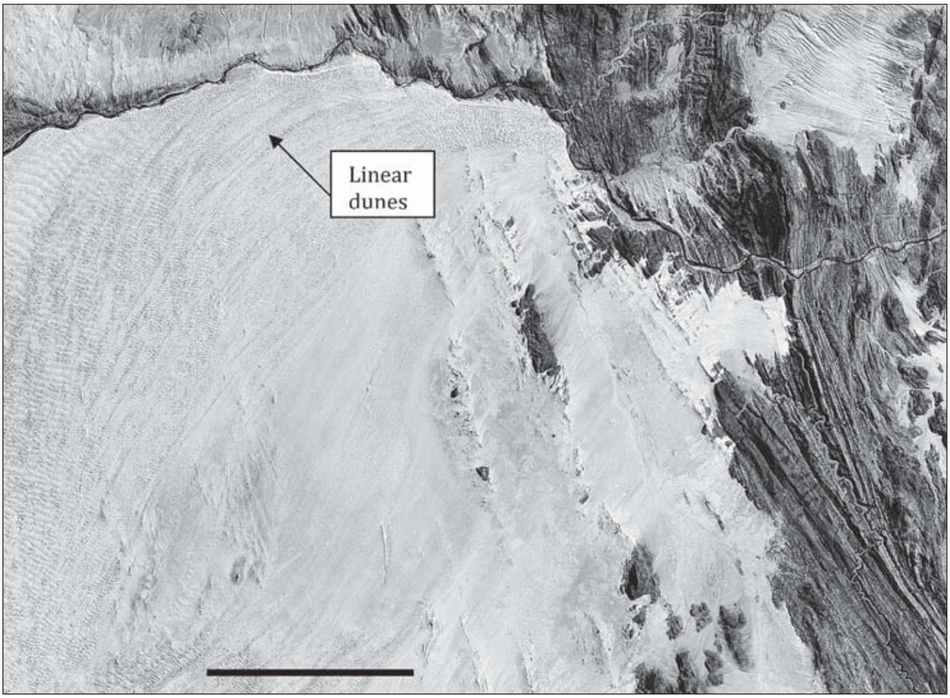

**Fig. 4** The eastern portion of the Cunene Sand Sea showing linear dunes gradually assuming a west to east orientation.

where $H$ is dune height, $W$ is the width between horns, and $\Phi$ is the average angle on one side of the dune. If, following Walmsley and Howard (1985), we take a slope angle of 11° as the typical mean for the side slope of a barchan, then this value can be incorporated into the equation

$$H = W/2 \tan 11^{\circ} \tag{4}$$

or

$$H = W/2C \tag{5}$$

where $C$ is a slope constant and is equal to 0.194.

On this basis the mean height of barchans in the Cunene Sand Sea would be 18.7 m.

Plainly different methods give different results, but using the range of height data developed in this way (18.7–29.5 m) it is possible to try and predict the speed at which the Cunene dunes may move. Previous studies have shown that rates of barchan movement decrease as dune size increases (e.g. Cooke *et al.* 1993, Figure 23.24). These tend to suggest that the Cunene sand sea barchans will tend to move at rates of less than 10 m per year, and probably around ca. 5 m per year.

**Table 2** Barchan widths (m)

| Cunene Erg | range 130–280, mean 193 m (this paper) |
|---|---|
| Arequipa, Peru | range 12–70 (Hastenrath 1967) |
| Southern Peru | range 11.4–66, mean 37.2 (Finkel 1959) |
| Jafurah, Saudi Arabia | range 230–450 (Shehata 1992) |
| Qatar, range 15–1000 m | mean 226.50 (Embabi and Ashour 1993) |
| Kuwait | range 12–78 (Al-Awadhi *et al.* 2000) |
| Walvis Bay | mean 155.27 (range 75.8–342.3) (Barnes 2001) |
| Imperial Valley, California | mean 125.6 (Long and Sharp 1964) |
| Kharga, Egypt | mean 155.5 (Embabi 1978) |
| Kharga, Egypt | range 89–485, mean 240.6 (Stokes *et al.* 1999) |
| Dakhla, Egypt | mean 173.6 (Embabi 1986/7) |
| Southern Morocco | range 30–100 (Sauermann *et al.* 2000) |

## 3. Yardangs of the Namib

### Northern Namibia

To the south of the Cunene sand sea there is a very large area of wind- fluted basement rock that shows a great expanse of narrow, linear yardangs that trend approximately from south south east to north north west (Figure 5), and appear to have

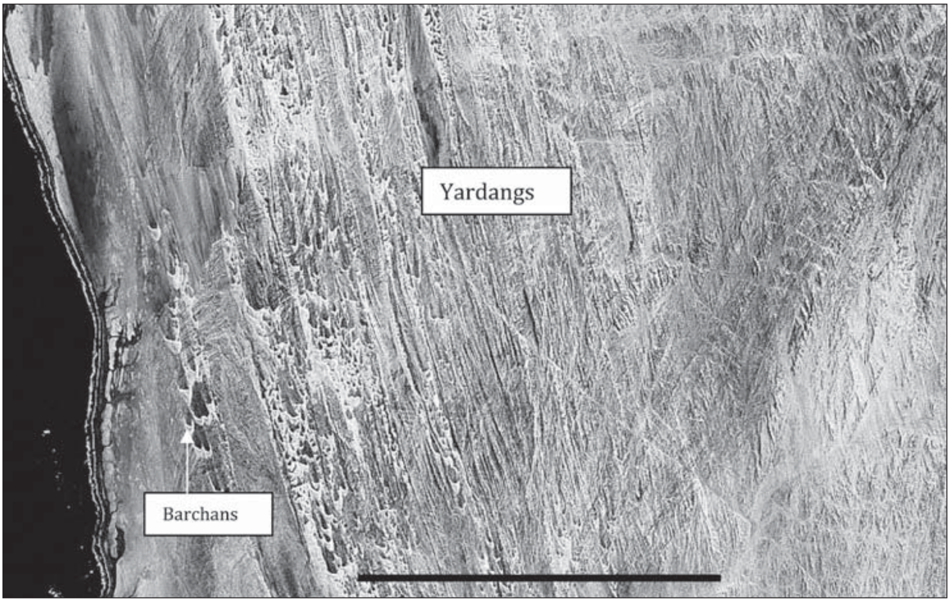

**Fig. 5** The yardang field of the northern Namib just to the south of the Cunene Sand Sea. Note the similarity in orientation between barchans and the yardangs.

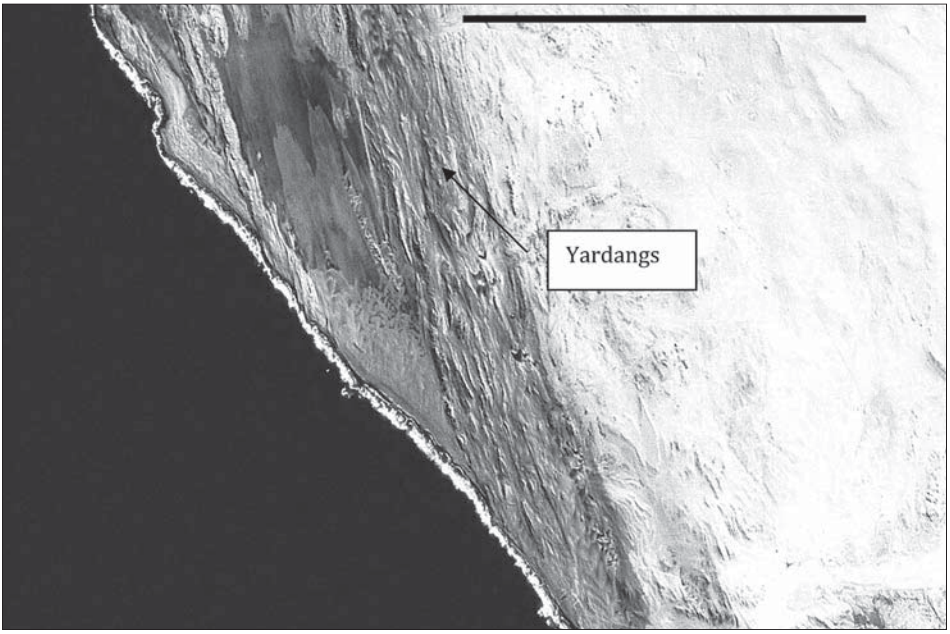

**Fig. 6** The yardangs of the southern Namib between Luderitz and the mouth of the Orange River.

similar orientations in that area to the barchans that move across their surface and to the orientations of the predominant sand streams that have been identified in the Skeleton Coast sand sea to the south. This also corresponds to the predominant wind directions recorded at Mowe Bay, where 62.5 % of winds blow from between 157.5 and 212.5°. The yardang area covers around 42 km by 25 km (ca. 1,311 $km^2$), with individual ridges running typically for distances of 8–10 km, and with a spacing of around 300–350 m.

### Southern Namibia

In southern Namibia, between the Namib Sand Sea and the Orange River, there is a hyper arid area with mega-yardangs developed in ancient crystalline and metamorphic rocks with complex structures (Figure 6). Many of the ridges are in excess of 20 km long and are ca. 1 km across. They run approximately SSE to NNW, which is the same as the trend of individual barchan dunes in the area. This also corresponds to the dominant annual sand transport directions for Alexander Bay, which lies on the coast to the south of the wind fluted zone (Lancaster 1989, p. 82). Some of the corrasional features near Pomona have previously been recorded as being 100 m high (Krenkel 1928, p. 668). There are at least four main areas where large yardangs occur: just to the south of Luderitz (ca. E 15° 07', S 26° 42'); near Pomona (E 15° 21', S 27° 03'; and E 15° 19', S 27° 09'), and inland from Chamais Bay (E 15° 37', S 27° 47').

## 4. Aligned drainage of the western Kalahari

### Introduction

Analysis of Landsat-7 images of southeastern Namibia shows that there is a large area of previously undescribed aligned drainage (Figure 7). It consists of broadly parallel drainage lines along which there are a multitude of small closed depressions, identification of which on the ground is far from easy, given the great subtlety of the relief.

The depressions have developed on the extensive calcrete deposits of the region, which cap Ecca (Permian) sedimentary rocks and Kalahari bed sediments. The spacing and alignment of the drainage lines implies (i) that they may have been superimposed onto the calcrete by a formerly more extensive dune cover and (ii) that the closed depressions may have developed along the drainage lines because of localized solution of the underlying calcrete, assisted perhaps by other pan-forming processes such as deflation and animal activity.

### Region of Interest

In southeastern Namibia, the area with the best developed aligned drainage occurs in a zone to the east of the Marienthal and Keetmanshoop and to the west of the Auob River, at ~26 deg S and 19 deg E. This area is known as the Weissrand. It covers a large tract of country that runs approximately 150 km from north west to south east and 50 km from south west to north east. On its western side, particularly in the north, it is bounded by a clear escarpment, though further to the south this becomes much less obvious. The Weissrand is a plateau with very limited slopes, most of which lies at an altitude of around 1,000–1,200 m above sea level. To the west it is bounded by a depression which drains to the Fish River and its tributaries, one of which, the Löwen, also forms the southern boundary to the plateau. To the east it is bounded by the Kalahari sandveld and the valley of the Auob. To the north, near Marienthal, there is a triangular outlier to the Plateau, separated from the main body by the drainage of Die Vlak.

Geological and topographic maps of the area indicate that the aligned drainage is developed where Kalahari beds and calcrete overlie Ecca sedimentary rocks, which include extensive mudstone and shale units. To the east lie the main linear dunes of the southwest Kalahari, most of which are ~10–20 m in height. Also in the area are some large pans (e.g. Koes, Gaibis, and Gammib), which are typically 2–5 km across and cut through into the softer Ecca beds. The floor of Koes Pan lies some 80 m below the plateau surface that surrounds it. These large pans sometimes have lunette dunes on their southeast sides, much like many other pans in the Kalahari (Goudie, Thomas 1985). They are much larger than the depressions that have developed in the calcrete alone.

The area is currently semi-arid, with a mean annual rainfall at Keetmanshoop of 148 mm per annum and at Marienthal of 180 mm per annum, with the bulk of the precipitation occurring during the summer months. There is sufficient rainfall to support a cover of savanna grassland and xerophytic trees and shrubs of the Nama Karoo biome, but the degree of vegetation cover, which influences dune mobility, shows considerable variability from year-to-year (Bullard *et al.* 1996).

The Kalahari sediments include calcretes (Nash and McLaren 2003), pan deposits, and aeolian sands of various ages (Thomas, Shaw 1991). The aeolian dunes are dominantly linear forms, many with tuning fork junctions, the morphology of which has been described by Grove (1969), Goudie (1969), Lancaster (1981), and Bullard *et al.* (1995; 1997). Their alignment is predominantly from north west to south east, and this is the alignment of the drainage developed on the calcrete surface of the Plateau. The dunes may have been more active in the Late Quaternary (Stokes *et al.* 1997a, b; Thomas *et al.* 1997).

The calcrete profiles (petric calcisols) of the southwestern Kalahari can attain considerable thicknesses – sometimes over 30 m (Goudie 1973). The age of the Weissrand calcretes is probably early Tertiary and they are associated with the development of the African Surface (Mabbutt 1955; Blümel, Eitel 1994).

Some of the calcrete contains fluvial pebbles, which form a scatter over the surface where they have been liberated from the calcrete congolomerate by weathering. Although cal-silcretes and sil-calcretes occur, most deposits are dominated by calcium carbonate, with average calcium carbonate contents comprising ~70–80 % (Goudie 1973, tables 51 and 9). Thick, pure calcretes, like other limestones, may therefore be susceptible to karstification (see, for example, Goudie 1973, Figure

12). Indeed, calcrete karst is known both from ancient sedimentary sequences (e.g. Balin 2000) and from Quaternary calcretes. In Australia, Twidale, Bourne (2000) have described calcrete hollows (dolines) from the Eyre Peninsula, while Lorenz (2002) has described them from the *tosca* deposits of Argentina.

## Morphometry of the depressions

The depressions occur in large numbers. There are approximately 2 per square kilometer. They tend to occur in lines running from north west to south east, with around 1.3 to 1.4 km between depressions. The alignments in which they occur are spaced at approximately 1 km intervals. The depressions themselves have long axis lengths that range between about 100 and 1,200 m, with the mean being around 460 m.

## The alignment of the depressions and the Kalahari dunes

There is a striking near correspondence between the alignment of the Weissrand drainage and the alignment of the linear dunes and inter-dunal depressions of the Kalahari (Figure 7). Both run from north west to south east. It is this near correspondence which suggests that the aligned drainage alignment has been imprinted

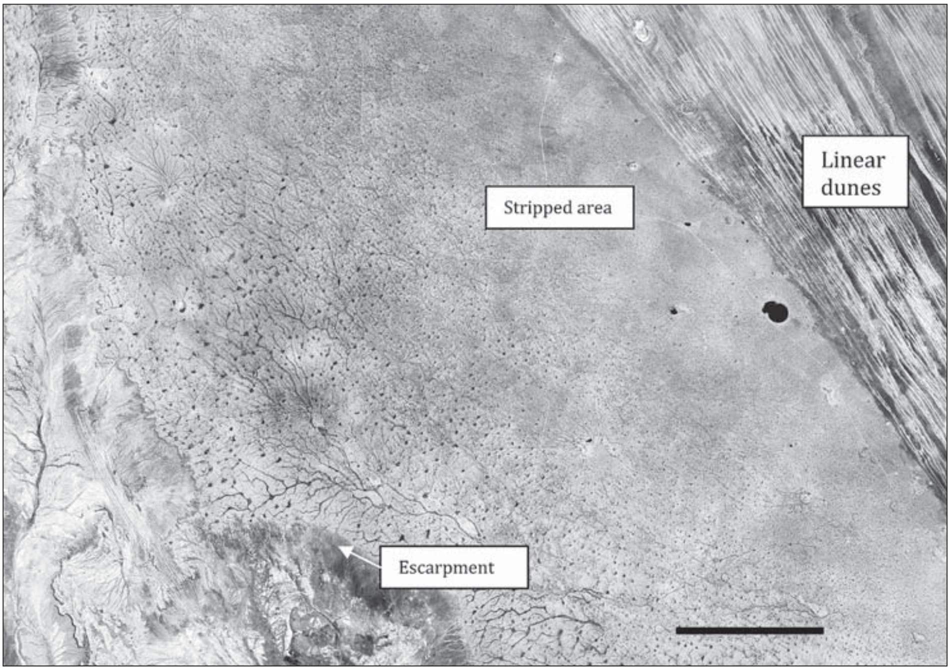

**Fig. 7** The calcrete covered Weissrand Plateau, with linear dunes of the Kalahari to the north east (Stage 1). Note the greater degree of depression development in the west of the Plateau (Stage 3).

from a former more extensive cover of Kalahari dunes. This cover formerly extended further west than it does today, and has now largely been stripped off, though small patches remain. Patches of linear dunes still occur on the downwind sides of depressions like that at Koes, and at the nearby salt pan at Vertwall.

### Evolutionary model

The nature of the depressions on the Weissrand Plateau and their spatial arrangement, suggests that they may have evolved through the following four stages:

1) In Stage 1 (Figure 7), there is an extensive calcrete surface over which there is a complete cover of branching linear dunes. Some very shallow depressions develop along the interdune swales either as a result of deflation or solution, or a combination of the two, but most of the calcrete is not directly exposed to the atmosphere.

2) In Stage 2 (Figure 8), the dune cover becomes stripped from the western part of the plateau, either because of a reduction in sand supply, or because of a shift in wind direction. This exposes the calcrete surface to the atmosphere. The depressions formed in the Stage 1 form an aligned pattern etched into the calcrete surface.

3) In Stage 3 (Figures 7 and 8), the depressions are developed further as a result of karstic processes, and themselves start to become foci for shallow drainage lines,

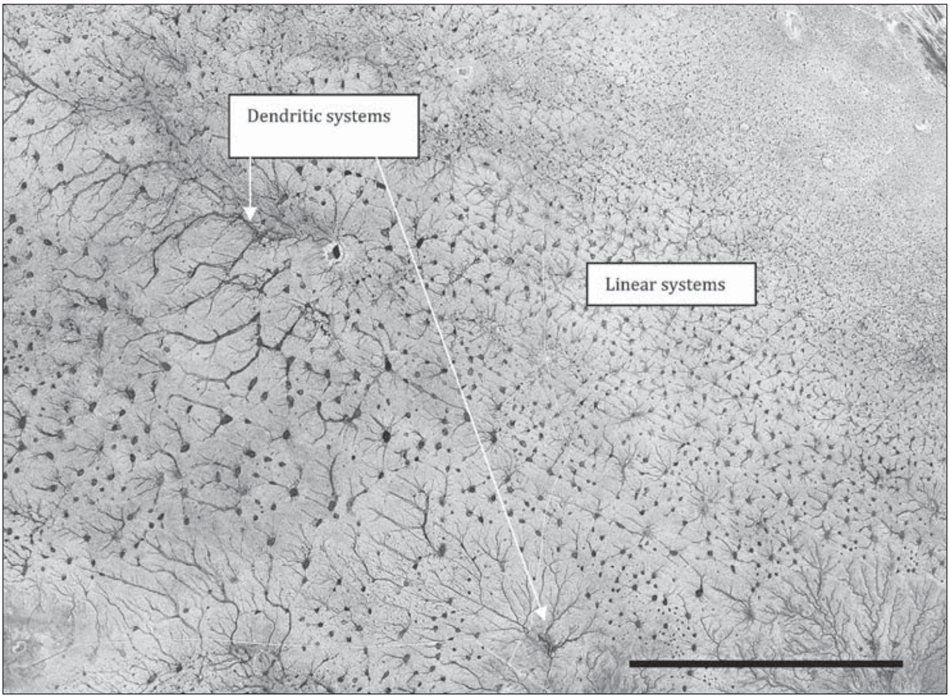

**Fig. 8** Well developed lines of depressions on the Weissrand Plateau. Note also the drainage that flows towards the depressions (Stage 2).

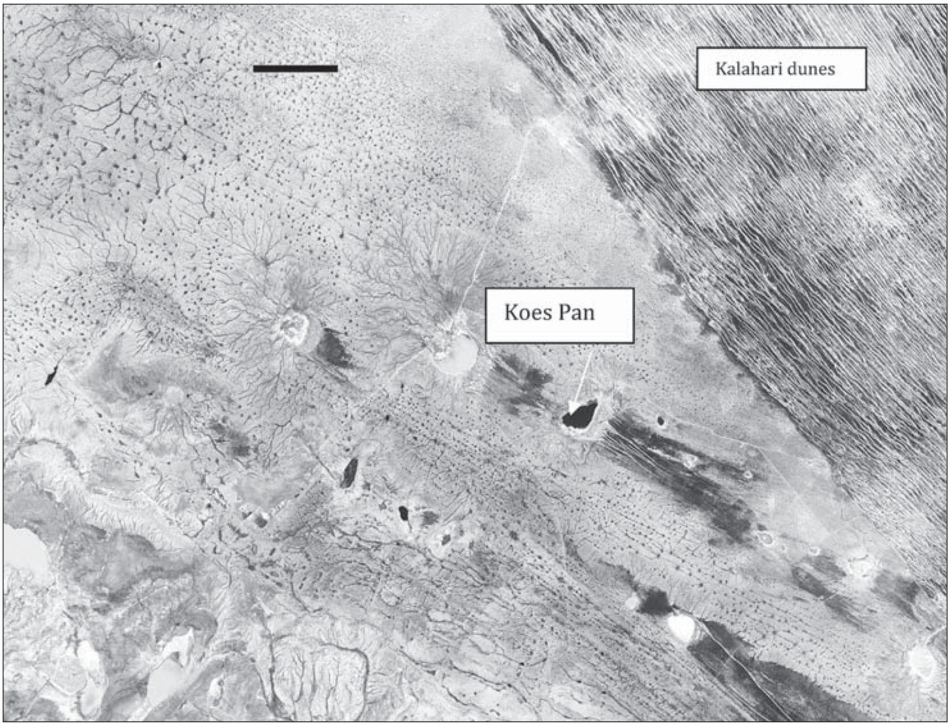

**Fig. 9** The development of a series of large pans into the Ecca surface (Stage 4).

which means that a more dendritic pattern develops. Such a dendritic pattern is accentuated near the escarpment edge, when drainage cuts back into the escarpment from the Fish River System, which lies to the west.

4) In Stage 4 (Figures 9 and 10), when the calcrete caprock becomes breached, the underlying Ecca shales are subjected to pan development by such processes as salt weathering and deflation, and eventually large, characteristically shaped pans evolve, some with lunettes on their lee sides, as shown by Koes Pan. A centripetal drainage pattern develops, focused on the pan.

## Analogues

Perhaps the closest analogues to the aligned calcrete depressions of southeast Namibia are the High Plains of the USA. There are very extensive areas of aligned drainages developed on shales in the northern High Plains (Russell 1929; Flint 1955), but in the southern High Plains of Texas and New Mexico, the aligned drainage and associated pans are developed on the calcrete (caliche) caprock surface of the Ogalalla Formation. The thick Ogalalla calcretes are probably of Late Tertiary (Pliocene) Age (Frye, Leonard 1957; Brown 1956), and various authors have attributed their pans to calcrete solution (e.g. Baker 1915; Judson 1950; Levings 1951; Nicholson,

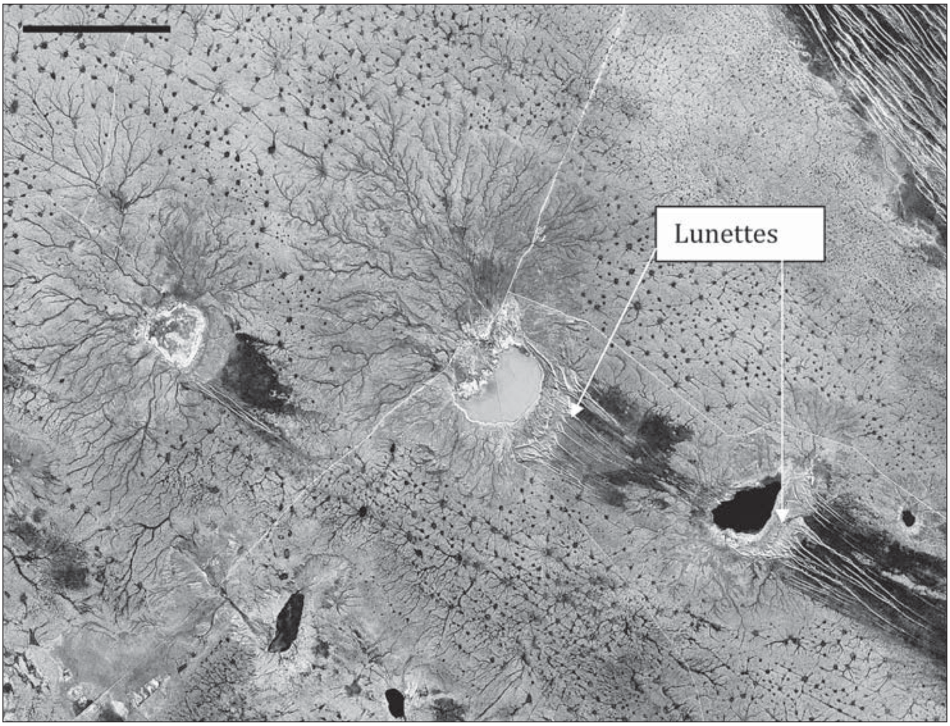

**Fig. 10** The pans at Koes, showing the development of lunettes on their lee sides (Stage 4).

Clebsch 1961; Havens 1966; Reeves 1971; Osterkamp, Wood 1987). Remote sensing studies by Wells (1992) demonstrated the presence of numerous basins showing clearly preferred alignments in Lea County, and around Lamesa, Texas (Goudie, Wells 1995). Wells argued that the great majority of basin alignments in the area were produced by the development of fields of parabolic dunes during episodes of aridity following the formation of the Ogalalla caprock. The dune ridges were subsequently removed by deflation and fluvial incision, leaving the pattern of aligned basins as a testimony to a former vast sand ridge desert. This follows from the ideas of Price (1944; 1958), Reeves (1971) and Bachman (1976) who believed that longitudinal dunes formed by northwesterly winds during the late Pliocene or Pleistocene created the oriented regional drainage when interdunal swales became etched into the calcrete caprock. Other notable aligned basin patterns occur surrounding the Portales Valley on the Texas-New Mexico border (Barnes *et al.* 1977).

## 5. Banded Vegetation Stripes

In the southern Kalahari there are extensive areas of banded vegetation stripes, which are generally called tiger bush or brousse tigrée. Such phenomena are ex-

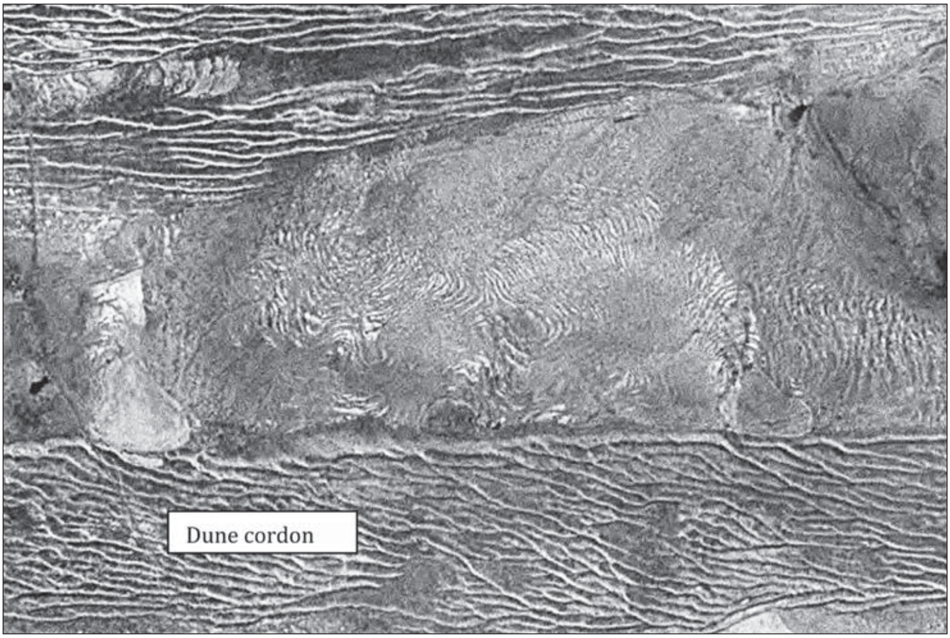

**Fig. 11** Banded vegetation in a depression between complex liner dunes with tuning fork junctions near the farm, Warte. The southern dune cordon is about 2.6 km wide and the interdunal depression is up to 3.5 km wide.

tensively developed in the world's drylands where there is between ca. 100 and ca. 600 mm of mean annual rainfall (Tongway *et al.* 2001; Valentin and Poesen 1999), but have only been very briefly described in Namibia by Stengel (2000). It is generally believed that they form where water flows as sheetflow over low angle slopes under conditions of patchy vegetation cover.

Tiger bush occurs in two isolated zones near Bullsport (24° 09' S; 16° 25' E) and Mara (24° 50' S; 16° 38' E) on the edge of the Naukluft Mountains, but the main zone occurs between latitudes S 24° and S 28° to the west and south east of the Weissrand Plateau between Marienthal, Keetmanshoop and the South African border. They have developed where the mean annual rainfall averages between 150 and 200 mm. They do not appear to occur in drier areas than this, probably because there is less sheetflood activity and a much sparser vegetation cover. They are present in three main geomorphological situations: in interdunal corridors (Figure 11), on low angle slopes developed on alluvium or outcrops of fine-grained Ecca and Dwyka sedimentary rocks (Figure 12), and along the courses of ephemeral streams (Figure 13). They do not occur on areas with a total aeolian sand cover (probably because this restricts overland flow), on the top of the Weissrand Plateauu (where drainage mostly seeps underground through the aligned karstic hollows described above), or on steep slopes in mountainous areas, where runoff tends to be more concentrated. The dark stripes tend to occur with a frequency of around 4–10 per km (i.e. the wavelength

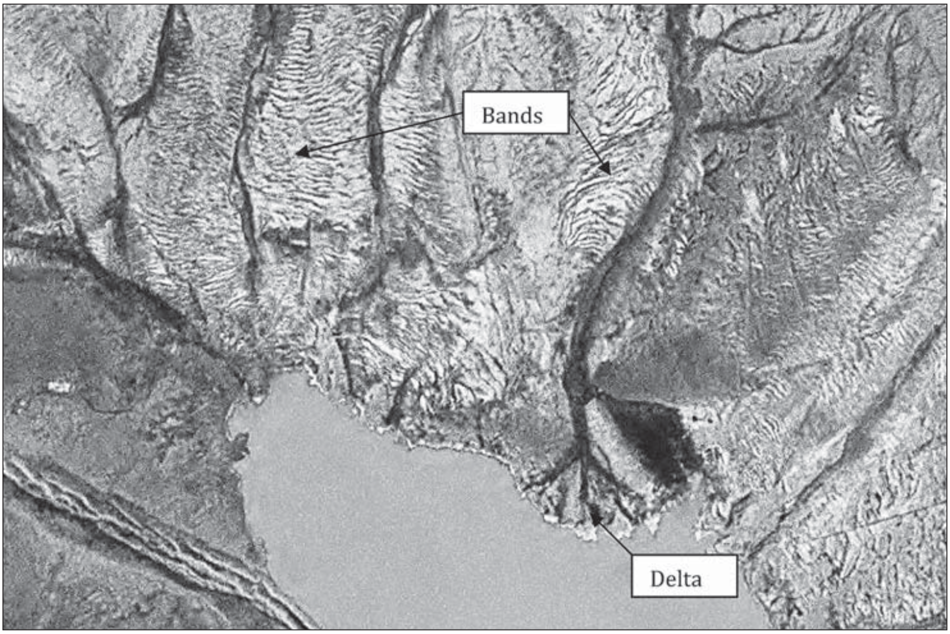

**Fig. 12** Banded vegetation developed on Ecca beds on the farm Kuubmaamsvlei. The delta developed in the pan is ca. 2 km wide.

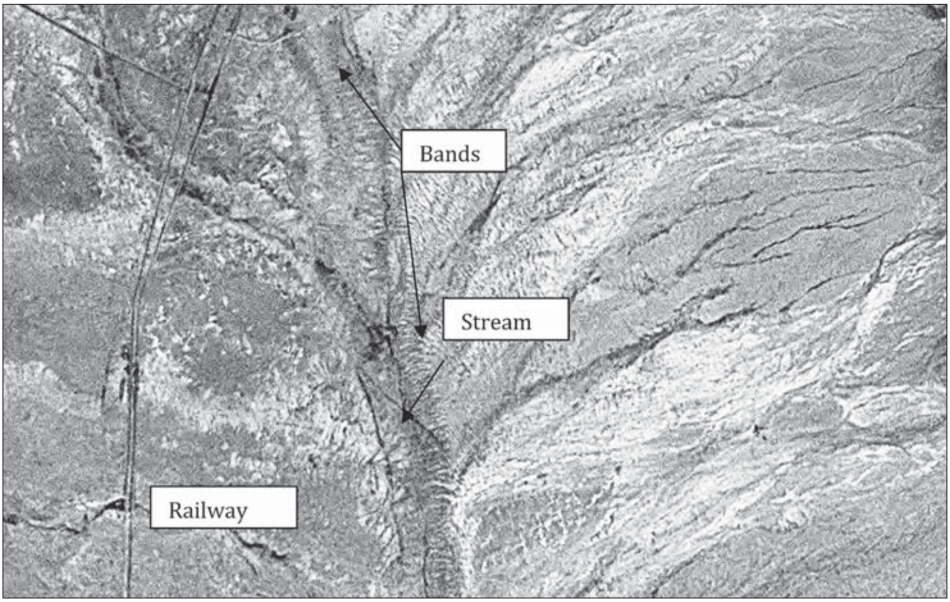

**Fig. 13** Banded vegetation running down an ephemeral drainage line developed in Dwyka shales between the Weissrand Plateau and Gibeon. The stream is ca. 0.6 km wide.

of a cycle including a band and an interband is around 100–250 m). This is broadly comparable to figures reported from other areas in Africa and in Australia (see, for example, Valentin and Poesen 1999, table 2, p. 7).

## 6. Conclusions

The free availability of Landsat imagery has enabled the mapping and description of a range of aeolian landforms in areas that are either difficult in terms of access or because on the ground the patterns are difficult to establish. There is considerable potential to extend this work to other landform types in Namibia to, for example, establish the significance of areas of drainage that have been impounded by dune systems between the Great Escarpment and the Atlantic coast in western Namibia.

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## References

Al-Awadhi, J.M., Al-Dousari, A., Al-Enezi, A. (2000): Barchan dunes in northern Kuwait. Arab J. Sci. Res., 18, 32–40.

Bachman, G.O. (1976): Cenozoic deposits of southeastern New Mexico and an outline of the history of evaporite dissolution. US Geol. Surv. J. Res. 4, 135–149.

Baker, C.L. (1915): Geology and underground water of the Llano Estacado. University of Texas Bull. 57 pp.

Balin, D.F. (2000): Calcrete morphology and karst development on the upper Old Red Sandstsone at Milton Ness, Scotland. Geol. Soc. Special Pub., 180, 485–501.

Barnes, J. (2001): Barchan dunes on the Kuiseb River delta, Namibia. S. African Geogr. J. 83, 283–292.

Barnes, V.E., Eifler, G.K., Reeves, C.C. (1977): Clovis sheet. Geologic Atlas of Texas. Austin, Texas: University of Texas Bureau of Economic Geology.

Beetz, P.F.W. (1934): Geology of South West Angola, between Cunene and Lunda axis. Trans. Geol. Soc. S. Africa, 36, 137–176.

Blümel, W.D., Eitel, B. (1994): Tertiäre Deckschichten und Kalkrusten in Namibia: Entstehung und geomorphologische Bedeutung. Z. für Geomorp. 38, 385–403.

Brown, C.N. (1956): The origin of caliche in the northeast Llano Estacado, Texas. J. Geol. 64, 1–15.

Bullard, J.E., Thomas, D.S.G., Livingstone, I., Wiggs, G.F.S. (1995): Analysis of linear sand dune morphological variability, southwestern Kalahari Desert. Geomorphology 11, 189–203.

Bullard, J.E., Thomas, D.S.G., Livingstone I., Wiggs G.F.S. (1996): Wind energy variations in the southwestern Kalahari Desert and their implications for linear dunefield activity. Earth Surf. Proc. and Landf. 21, 263–278.

Bullard, J.E., Thomas, D.S.G., Livingstone, I., Wiggs, G.F.S. (1997): Dunefield activity and interactions with climatic variability in the southwest Kalahari Desert. Earth Surf. Proc. Landf. 22, 165–174.

Cooke, R.U., Warren, A., Goudie, A.S. (1993): Desert geomorphology. UCL Press, London.

Embabi, N.S. (1978): Statistical relationships between barchan shape dimensions. Egyptian Computer J. 1, 1–15.

Embabi, N.S. (1986/7): Dune movement in the Kharga and Dakhla Oases Depressions, the Western desert, Egypt. Bull. Soc. de Géogr. d'Egypte, 59/60, 35–70.

Embabi, N.S., Ashour, M.M. (1993): Barchan dunes in Qatar. J. Arid Env., 25, 49–69.

Finkel, H.J. (1959): The barchans of southern Peru. J. Geol. 67, 614–647.

Flint, R.F. (1955): Pleistocene geology of Eastern South Dakota. US Geol. Surv. Prof. Paper 262.

Frye, J.C., Leonard, A.B. (1957): Studies of Cenozoic geology along the eastern margins of the Texas High Plains, Armstrong to Howard Counties. Report of Investigations University of Texas Bureau of Economic Geology 32. pp.

Goudie, A.S. (1969): Statistical laws and dune ridges in southern Africa. Geogr. J. 135, 404–406.

Goudie, A.S. (1973): Duricrusts in tropical and subtropical landscapes. Oxford: Oxford Univeristy Press.

Goudie, A.S., Thomas, D.S.G. (1985): Pans in southern Africa with particular reference to South Africa and Zimbabwe. Z. für Geomorph. 29, 1–19.

Goudie, A.S., Wells, G.L. (1995): The nature, distribution, and formation of pans in arid zones. Earth-Sci. Rev. 38, 1–69.

Grove, A.T. (1969): Landforms and climatic change in the Kalahari and Ngamiland. Geogr. J. 135, 191–212.

Hastenrath, S.L. (1967): The barchans of the Arequipa Region, Southern Peru. Z. für Geomorph., NF 11, 300–331.

Havens, J.S. (1966): Recharge studies on the High Plains in northern Lea County, New Mexico. US Geol. Surv. Water Supply Paper 1819-F. pp.

Hesp, P.A., Hastings, K. (1998): Width, height and slope relationships and aerodynamic maintenance of barchans. Geomorphology, 22, 193–204.

Judson, S. (1950): Depressions of the northern portion of the Southern High Plains of eastern New Mexico. Bull. Geol. Soc. Am. 61, 253–274.

Lancaster, N. (1981): Palaeoenvironmental implications of fixed dune systems in southern Africa. Palaeogeogr., Palaeoclim., Palaeoecol. 33, 395–400.

Lancaster, N. (1982): Dunes of the Skeleton Coast, Namibia (South West Africa): geomorphology and grain-size relationships. Earth Surf. Proc. and Landf., 7, 575–587.

Lancaster, N. (1989): The Namib Sand Sea: dune forms, processes and sediments. Balkema, Rotterdam.

Levings, W.S. (1951): Late Cenozoic erosional history of the Raton Mesa region. Colorado School of Mines Quarterly 46.

Long, J.T., Sharp, R.P. (1964): Barchan dune movement in Imperial Valley, California. Bull. Geol. Soc. Am., 75, 149–156.

Lorenz, W. (2002): The "Calcreta Principal" at the border of the provinces of La Pampa and Buenos Aires. Z. für Angewandte Geol. 48, 44–51.

Mabbutt, J.A. (1955): Erosion surfaces in Namaqualand and the ages of surface deposits in the south-western Kalahari. Trans. Geol. Soc. S. Africa, 58, 13–29.

Nash, D.J., McLaren, S.J. (2003): Kalahari valley calcretes: their nature, origins and environmental significance. Quat. Internat. 111, 3–22.

Nicholson, A., Clebsch, A. (1961): Geology and groundwater condition in southern Lea County, New Mexico. New Mexico State Bureau of Mines and Mineral Resources Ground Water Report 6. pp.

Osterkamp, W.R.,Wood, W.W. (1987): Playa-Lake basins of the Southern High Plains of Texas and New Mexico: Part I. Hydrologic, geomorphic and geologic evidence for their development. Bull. Geol. Soc. Am. 99, 215–223.

Price, W.A. (1944): Greater American Deserts. Texas Acad. Sci. Proc. and Trans. 27, 163–170.

Price, W.A. (1958): Sedimentology and Quaternary geomorphology of south Texas. Gulf Coast Ass. Geol. Societies Trans. 8, 41–75.

Reeves, C.C. (1971): Relations of caliche to small natural depressions, Southern High Plains, Texas and New Mexico. Bull. Geol. Soc. Am. 82, 1983–1988.

Russell, W.L. (1924): Drainage alignment in the western Great Plains. J. Geol. 37, 240–255.
Sauermann, G., Rognon, P., Poliakov, A., Herrmann, H.J. (2000): The shape of the barchan dunes of southern Morocco. Geomorphology, 36, 47–62.
Shaw, A.I., Goudie, A.S. (2002): Geomorphological evidence for the extension of the Mega-Kalahari into south-central Angola. S. African Geogr. J. 84, 182–194.
Shehata, W., Bader, T., Irtem, O., Ali, A., Abdallah, M., Aftab, S. (1992): Rate and mode of barchan dunes advance in the central part of the Jafurah sand sea. J. Arid Env. 23, 1–17.
Stengel, I. (2000) Brousse tigreé – Muster und Materialverspülung und Pflanzewuchs in Südnamibia. Petermanns Geogr. Mitt. 144 (2), 4–5.
Stokes, S., Goudie, A.S., Ballard, J., Gifford, C., Samieh, S., Embabi, N., Al-Rashidi, O.A. (1999): Accurate dune displacement and morphometric data using kinematic GPS. Z. für Geomorph. Suppl., 116, 195–214.
Stokes, S., Thomas, D.S.G., Washington, R. (1997a): Multiple episodes of aridity in southern Africa since the last Interglacial period. Nature 388, 154–158.
Stokes, S., Thomas, D.S.G., Shaw, P.A. (1997b): New chronological evidence for the nature and timing of liner dune development in the southwest Kalahari Desert. Geomorphology 20, 81–93.
Thomas, D.S.G., Shaw, P.A. (1991): The Kalahari Environment. Cambridge: Cambridge University Press.
Thomas, D.S.G., Stokes, S., Shaw, P.A. (1997): Holocene aeolian activity in the southwestern Kalahari Desert, southern Africa: significance and relationship to Late Pleistocene dune-building events. The Holocene 7, 271–279.
Tongway, D.J., Valentin, C., Seghieri, J. (eds.) (2001): Banded vegetation patterning in arid and semiarid environments. New York, Springer Verlag.
Twidale, C.R., Bourne, J.A. (2000): Dolines of the Pleistocene dune calcarenite terrain of western Eyre Peninsula, South Australia: a reflection of underprinting. Geomorphology 33, 89–105.
Valentin, C., Poesen, J. (eds.) (1999): The significance of soil, water and landscaping processes in banded vegetation patterning. Catena 37, 1–273.
Walmsley, J.L., Howard, A.D. (1985): Application of a boundary-layer model to flow over an aeolian dune: J. Geophys. Res., 90 (D6), 10631–10640.
Wells, G.L. (1992): The aeolian landscape of central North America from the Late Pleistocene. University of Oxford unpublished D. Phil thesis. 3 vols.