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Kalahari field trip
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FIELD GUIDE

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Background to the field trip

The Mega Kalahari

Much of southern Africa is dryland, with the Namib Desert, the Kalahari Desert and the Karoo being the principal distinct dryland regions. The Kalahari is the largest, extending from South Africa in the south to the Congo in the north, and Namibia in the west to Zimbabwe in the east.

The Kalahari can be defined in many ways, and has never been defined consistently in the scientific, let alone popular, literature. Only its south western extremities, in southern Botswana, south eastern Nambia and the Northern cape of South Africa -which we will visit- can it truly be described as a desert, receiving 100- 200mm of rainfall on average per year and with a very high (65%) inter-annual rainfall variability. The term Kalahari however describes in a geological sense an extensive sediment-filled basin extending north from Upington, through Botswana and Angola, to the banks of the Congo River on the equator. This area, *in toto* called the *Mega Kalahari* (Thomas and Shaw 1991), covers some 2.5 million km^2 (Cooke 1958) and is characterised by:

- representing the downwarped interior of southern Africa, developed by the splitting up of Gondwanaland from 180-80Ma and subsequent flexure of the passive margins of the African Plate.
- being infilled with Cretaceous and younger *Kalahari Group* sediments, comprising fluvial gravels and marls at the base and a mixture of lacustrine, aeolian and duricrust deposits above. Total thickness ranges from over 450m beneath the Etosha Basin (Haddon 1999) to a few metres around the margins;
- having experienced progressive drainage capture of an early endoreic system that contributed to sediment in-fill during the Tertiary. The Okavango is the last remaining major endoreic system;
- a notable absence of organised surface drainage in its southern half (from the Okavango south). Dry valley systems are however present in many areas and may occasionally flow locally
- a generally flat surface at 900-1200m a.s.l. that today largely comprises lacustrine, duricrust and wind re-worked deposits, which contain within them evidence of Quaternary environmental changes.

Terminology

With the above general setting in mind we can attempt some degree of clarification of Kalahari terminology, though it can be noted that even today in the literature there is considerable variance of use! *Therefore:*

Mega Kalahari: The area coincident with the structural basin in which Kalahari sediments have accumulated, and which extends from the Orange River to the Congo River.

Kalahari Group: Sediments, Cretaceous to Recent in age, that have accumulated in the structural basin. These are exclusively continental in origin and comprise sediments initially derived from erosion of the rim mountains around the basin, and deposited in the interior basin. These have subsequently been redistributed by various processes including aeolian, lacustrine and fluvial, and have also experienced internal modifications through the development of duricrusts.

Kalahari Sand: Over much of the Mega Kalahari the dominant surface expression of sediments displays aeolian characteristics, and in some areas has been shaped into aeolian depositional landforms.

Northern, Middle and Southern Kalahari: The terminology of Siegfreid Passarge, the German geologist who provided the first comprehensive attempt to describe and explain the geology of the Kalahari (Passarge 1904). The Northern Kalahari referred to areas north of 20°S (approximately North of the Okavango Delta), the Southern Kalahari the area south of approximately 22°S (and therefore includes the area we visit) and the Middle Kalahari the area between, embracing the Makgadikgadi and Etosha basins and the Okavango Delta.

Kalahari Desert: A vaguely used term for many synonymous with the western two-thirds of Botswana, but also covering the Northern Cape and parts of SE Namibia.

Sandveld: Synonymous with the Kalahari Desert but really comprising only those areas covered by aeolian deposits.

Hardveld: A colloquialism for peri-Kalahari areas where soil development from underlying (usually igneous or metamorphic) rock has taken place.

Climate

The Kalahari as a whole, however defined, has a climate influenced by five main factors:

- its relatively high altitude;
- the subtle seasonal fluctuations in position of the South African anticyclone, part of the subtropical high pressure belt;
- seasonal fluctuations in position of the ITCZ over southern and central Africa;
- the drawing in of moist air from the Indian Ocean over southern Africa, behind the ITCZ. This occurs predominantly during summer months and leads to strongly convective rainfall events.
- The occasional passage of low depression cells from the southern Atlantic over the region. This occurs during the winter months and usually results in bitterly cold, clear days since the actual depression usually passes to the south. However, a few times each winter this may result in grey, wet weather lasting up to 2-3 days.

The result of these factors is a strongly seasonal climate with hot summers (October-April) in which most rainfall occurs, and cool, mainly dry, winters (June-August). A steep rainfall gradient results from the nature of controlling factors, such that the southwest of the Kalahari is driest (with less than 200mm of rainfall on average per year) and the northeast wettest (e.g 750 mm p.a. on average at Victoria Falls in Zimbabwe). Droughts are frequent and linked in part to El-Nino cycles. Tyson (1986) has analysed southern African summer rainfall zone climates and has identified a quasi-18-20 major drought cycle.

Mean daily summer (wet season) temperatures are high in the SW Kalahari, averaging c.32°C at Upington and other stations in the region. Highs of 50°C have been recorded. Daily summer (dry season) minima are around 15°C. In the winter daily means are max. 23°C and min.4-8°C. Frosts are common on winter nights and in July night time temperatures commonly drop below zero, with temperatures down to –10°C not uncommon in locations such as the Kuruman valley. On many occasions during fieldwork in July your guides have found their beers frozen in their cans at 3 in the afternoon!

Soils, vegetation and animals

With the exception of local pockets close to bedrock outcrops and some channel systems, the Southern and Middle Kalahari does not possess proper soils: just sand, and even then 'sand with low fertility' (Sims 1981). Levels of essential nutrients (phosphorus, potassium and nitrogen are exceptionally low (e.g. ppms of 4.3, 41 and 40-100 from multiple samples, according to Buckley *et al.* 1987). Nonetheless, much of the Kalahari is well vegetated, indicating and efficient plant-litter-soil cycling system. The diversity and biomass of Kalahari vegetation, which is dominated by a range of savanna systems (Weare and Yallala 1971) generally increases in a northeasterly direction in line with rising mean precipitation values. Superimposed on this pattern are variations relating to geomophological and sedimentary criteria, and at shorter timescales to the occurrence of droughts, natural fires and ever growing human influences.

In Weare and Yalala's (1971) classification the SW Kalahari comprises Arid Shrub Savanna. Under natural conditions this comprises a dominant grass understorey of mainly clumped perennial grasses such as *Eragrostis, Stipagristis* and *Aristida* species, with the annual *Schmiditia kalahariensis,* and dotted bushes and shrubs of *Acacia* spp, *Boscia albitrunca*, and others including *Grewia flavia, Terminalea* spp and *Rhigosum trichotomum.* 35% ground cover or less is common. Droughts and fires create a patchy matrix of vegetation such that marked changes in cover and species make-up can occur over short distances, since this as a 'disequilibrium system' in modern ecological parlance. The expansion of pastoral farming has added a further layer of influences, with decreases in perennial grasses in favour of less palatable annuals and zones of bush encroachment, resulting in some areas. Van der Walt and le Riche (1999) provide a good general introduction to the plants of the southwest Kalahari.

The Kalahari is famous for its animals. By far the most dominant large mammals are cows, goats and sheep. It is easy to spot these lovely creatures, which dominate the agricultural lands that extend from the hardveld into the dune desert. The dominant large wild mammals are various forms of antelope; notably springbok, gemsbok, wildebeest and smaller duiker. Eland and hartebeest are less common. Game farming is now occurring in the Kalahari since these indigenous species are more environmentally friendly and drought-adapted than cattle and goats, and gemsbok and eland in particular are being introduced for farming. All these indigenous species, plus carnivores, are present in the extensive Trans-Frontier Kalahari Park whose boundaries our trip will take us to.

People in the SW Kalahari

Contrary to some views, the Kalahari was not, prior to European interventions, occupied simply by isolated bands of hunter-gatherer 'bushmen' living some form of idyllic lifestyle (cf Van Der Post 1958). There is ample archaeological evidence that demonstrates interactions occurred between hunter-gather groups (more correctly called Khoisan or San) and pastoralist groups over at least the last 2000 years (Denbow and Wilmsen 1986). It is likely however that the arid southwestern Kalahari to the north of Upington experienced minimal pastoral use, even during wet years, because of its predominant dryness. It should also be borne in mind though that the Orange River at Upington is perennial and this will have influenced its importance even prior to European arrival. Similarly the spring at Kuruman not only made it attractive to Robert Moffat as a site for a mission station, but was already occupied by Batswana people because of its perennial water supply. Since springs were also noted in the upper Nossop in the mid 19th century (Andersson 1857), it is likely that occasional flows reached lower reaches too, facilitating the movement of people and probably livestock along water courses when in flow.

The Gordonia and Mier areas were divided into farm blocks for European use in the late 19th century, partly through the judgement of a remote British cartographer who saw rivers on maps and assumed that they represented permanent water. Early farm blocks have Scottish names, many of which remain today. Even with boreholes, these farm units are not highly productive, and over the years many have been affected by consolidation to give the larger land units necessary for supporting herds. The establishment of these farms undoubtedly created conflict with hunter-gather groups. On the Botswana (Bechuanaland) side of the Molopo/Nossop border the British appointed a single policeman whose duties including rounding up roaming native groups when suspicion of poaching existed (Hodson 1912). He described the Kalahari as a dreary place (perhaps because there were not enough large animals to suit his hunting appetite), but on the whole his memoirs provide a clear representation of early 20th century European repression of indigenous groups.

Some farm blocks, especially in the Nossop region, were given over to coloured rather than British farmers. When the Kalahari National Park was established in South Africa in 1938 (its Botswana component is younger) several farms as well as remaining San groups were displaced. New farms were established outside the park boundaries in both South Africa and Bechuanaland, and small settlements at Welkom and Struizendam. Many San became labourers on European farms in the region. With the advent of the new South Africa in the 1990s, the whole region has been subject to various land claims and settlements. Today there is an on-going San claim to lands in the (recently renamed) Kalahari Transfrontier Park, and San groups can be seen along the road leading up to the park entrance. .

Tar roads have only arrived in the north parts of our trip area in the last few years, and today this is an area coming to grips with its lost isolation. The journey from the Kalahari National Park to Upington used to take, until the 1960s, several days (or several weeks on the camels of the local police). Upgrading of sand tracks to calcrete roads reduced this travel time to 4-5 hours. In the last four years the route has mostly been tarred: the journey now takes two hours or so.

General field excursion outline

The field trip will encompass two distinct sub-regions, the southwest Kalahari dunefield, and the peri-Kalahari region of Gordonia, with its ancient planation surfaces, scattered linear dunes and patches of Kalahari sand sheet. On the Gordonia leg, to the east of Upington, we will visit the **Moffat Mission** on the Kuruman River, an important site in the history of European colonisation of the region, and **Wonderwerk Cave**, a key site in stone age archaeological investigations and preserving a record of human adaptations to both drier and wetter times. We will visit the reserve at **Witsand**, a large and very untypical white sand dune famous for its 'singing sands'. We will also have the opportunity to visit an impressive deep sediment section through the entire Tertiary-Holocene Kalahari sedimentary sequence, in the open cast Bauxite mine at **Mamatwan**. The exposures present include impressive basal Kalahari fluvial sequences, linked to the late Tertiary drainage development of the region, and upper sand sheet deposits. Some of the units have recently been dated.

Moving north of Upington into the **linear dunefield** we will visit important locations that have been investigated in palaeoenvironmental studies, including **pans** and **dry river valleys**, and we will consider the late Quaternary climatic history of the region. We will also see locations where human disturbances have caused recent dune reactivation, and will see experimental **dune stabilisation** methods. Here we will have the opportunity to enjoy the Kalahari sunset and sleep out under the stars, amidst the red dunes of the Kalahari. The return journey will take in the lunette dune at **Witpan**, with its active crest and gullied flanks.

Itinerary

Date	**Purpose**	**Overnight**
Mon 3 Sept	Dept. Upington c 8a.m. Kuruman lunchtime (Moffat mission) p.m. Wonderwerk Cave (archaeology, Kalahari seds)	Kuruman Oasis Motel
Tue 4	a.m. Mamatwan Mine (Kalahari sediment sequence inc. basal deposits) p.m. to Witsand- large dunes outside Kalahari.	Witsand chalets
Wed 5	a.m. To Kalahari, via Upington, across linear dunefield and pans. Lunchtime: Molopo Valley. Duricrust exposures. p.m. North up Nossop Valley. Kalahari sediment exposures, destabilised dunes, bushman land claims	Bush camp
Thur 6	Dune variability. Linear dune stabilisation projects and ecology. High dunes and large pans.	Bush camp
Fri 7	a.m. to Witpan, lunettes, dunes, pan sediment cycling, lunette dune chronologies. Return to Upington pm, in time for those who need to catch late afternoon flight to Johannesburg.	

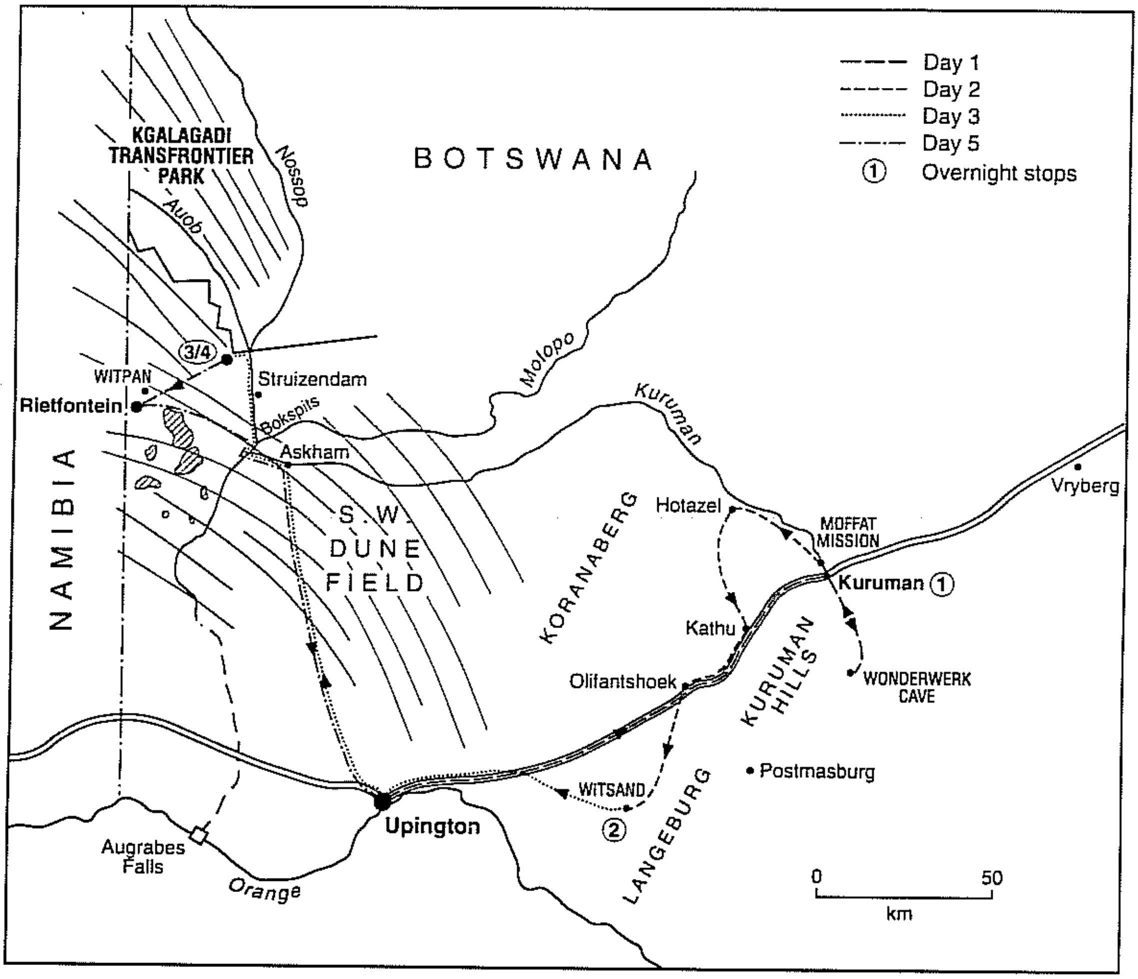


Figure 1 Field trip route map

Day 1: Monday 2 September

Kuruman, Moffat Mission, Wonderwerk Cave

The first day follows the tar road east from Upington to Kuruman, passing through an empty 'tableland' landscape of ancient Proterozoic rocks, dotted with isolated linear and ramp dunes and pans representing peripheral Kalahari sediments. At 159 km we pass through the small 'dorp' of Olifantshoek, before moving on to an outlier of the Kalahari sandsheet, readily identifiable by a change in vegetation, and, at 183 km, the twin mining towns of Kathu and Sishen. The area to the north of the road has been mined for iron and manganese since the 1950s and is estimated to have the world's largest manganese reserves. At 245 km we arrive at Kuruman.

Kuruman and the Moffat Mission Station

Kuruman is a small town at the foot of dolomite Kuruman Hills, servicing the local cattle-raising and mining industries. It owes its presence to the 'Eye' (pronounced 'Oog'), a natural spring which yields a constant 20 million litres of water per day, sufficient to provide for local needs (including the excessive watering of lawns in the town), and feeds the upper, perennial, reaches of the Kuruman River.

The area was originally settled by a branch of the Tswana, the Batlhaping, who, in 1816, invited the London Missionary Society to settle amongst them. The first missionaries, the redoubtable Scots Robert Moffat and his wife Mary, built the Moffat Mission downstream of the Eye in an area where irrigated cultivation was possible. From 1817 until the retirement of Robert Moffat in 1870 the mission became the focus of both missionary and exploration activity on the Kalahari periphery and a symbol of European values in the 'Dark Continent'. David Livingstone worked here briefly, marrying Mary Moffat jnr, before moving north on his expedition to Lake Ngami in 1849 and his own mission station in Kolobeng, Botswana.

Although the role of the mission declined after the passing of the Group Areas Act in 1950, which forbade multiracial gathering, it has been restored as a retreat and conference centre. Amongst the surviving buildings is the 800 seater church, completed in 1838, the village school and the Moffat homestead.

Wonderwerk Cave

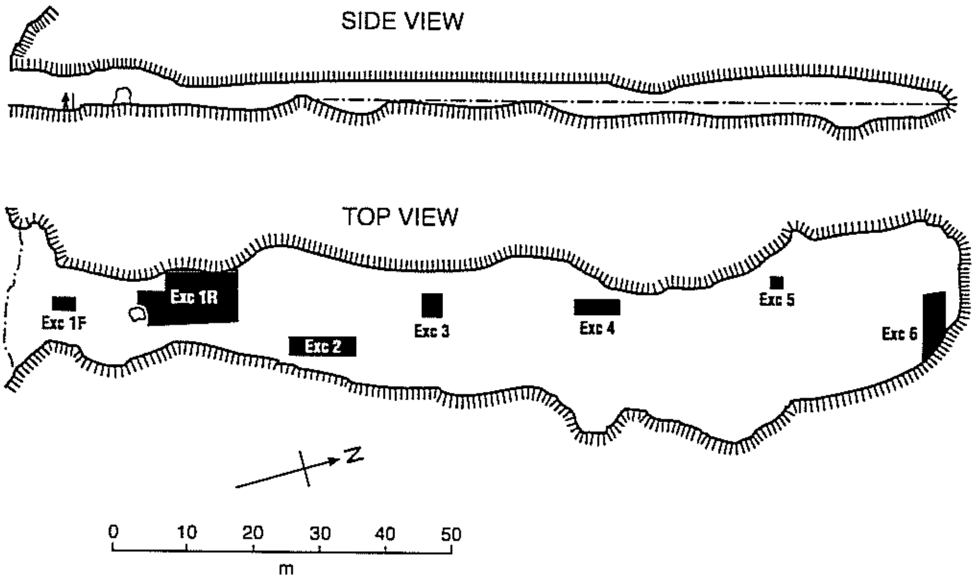


Figure 2 Plan of Wonderwerk Cave

The extensive Ghaap dolomite plateau is bounded on its southeastern margin by a 275km long escarpment that faces the Vaal and Hartz rivers. Spring deposits, tufas and solution cavities in the Ghaap escarpment and plateau have for several decades provided rich sources of archaeological and palaeoenvironmental data for the interior of southern Africa (e.g. Butzer *et al* 1978, Butzer 1984). 40 km south of Kuruman and at an altitude of 1680m asl, the Wonderwerk Cave is set into the side of the Kuruman Hills, near to the highest point of the Ghaap plateau. A horizontal 140 m solution cavity in the Ghaap Plateau Dolomite Formation, (Figure 1) the cave contains a record of human habitation back to 0.8 million years B.P. Today there is no permanent water at the site, the nearest source being a seep 5km to the south. Habitation of the cave ceased in the 1920s, since the first white farmer at Wonderwerk used the cave as a residence from 1907-17. Some of his children continuing to reside in it for a further ten years.

For four years from 1940 the cave was exploited for bat guano, which excavated the cave up to 35m from the entrance. Archaeological investigations commenced under B.D. Malan at the same time, finishing in 1948. Karl Butzer recommenced scientific interest in 1974, conducting excavations up to 1978. J. and A Thackeray conducted work in 1979, focusing on Holocene deposits and mammal content (Thackeray 1984).

Peter Beaumont of the McGregor Museum, Kimberley, has been excavating at the site since 1978, and will guide our visit to Wonderwerk.

Summary of the archaeological record

The cave deposits comprise washed in and aeolian sediments, precipitates and cultural horizons. The upper metre of deposits in the cave have been dated back to 300,000BP, and it has been postulated that the total suite of sediments spans c 800,000 years. While much detail is excluded, the excavations in Wonderwerk reveal overall six cultural groupings:

Earlier Stone Age: 6 strata with subdivisions, containing refined hand axes and cleavers and unrefined, unsophisticated flake tools. These represent the earliest human occupation of the cave after solutional opening of the cave mouth. C 800k years BP?

Earlier Stone Age: 3 levels with often degenerated hand axes but also refined points, blades and cores. These span 350k-200k BP.

Middle Stone Age: 2 strata with refined blades, segments and points. Dated by inference from other localities to 120-90k BP.

Later Stone Age: 1 level at the cave rear with some amorphous tools and perfectly preserved floral and faunal remains, including remains of extinct antelope species. Cold, late/post glacial conditions, dated to 13k BP

Later Stone Age: 6 strata with high artefact contents (ostrich shell beads, arrow points, stone arm rings, engraved stones. Age range 12,500-1500 BP. Early Holocene (10,000-7500 BP levels also include bones of now extinct antelope species (Thackeray 1984). High ungulate:carnivore ratios and low degree of bone damage suggest humans were principal agents of accumulation. Linked to San hunter groups

Ceramic Later Stone Age: A thin zone with stone artefacts, pot sherds, and fat-tailed sheep hairs. Suggests occupation by khoi—herders, c 1000BP.

Day 2: Tuesday 3 September

Mamatwan- Kalahari Group sediments, Witsand

In the morning of the second day we drive north out of Kuruman on the R31, passing the mission station and driving towards the border with Botswana. To the west the Koranna Hills rise above the Kalahari plain, which here is divided into farms largely use for extensive livestock rearing. 60 km northwest of Kuruman we reach the appropriately named Hotazel, a mining town (coal, iron, manganese) which is also the administrative centre for two manganese mines owned by Samancor- one at Wessels, the other Mamatwan. From Hotazel we drive c 25 km SW to Mamatwan, which is located in a topographic low within the Molopo sub-basin of the Kalahari. Our principal purpose for visiting Mamatwan is to view the excellent exposures of Kalahari Group sediments including basal fluvial deposits. A brief explanation of mining activities is however useful.

Mamatwan Mine

This large open-cast mine was initially developed in the 1950s to supply high grade manganese to the regional ferro-alloy industry, but world exports began in 1964. C.300,000 tonnes of manganese are exported annually, leaving the mine after treatment and sintering (for partial reduction) by rail. The manganese ore is located within Voelwater Formation sediments, part of the Cox Group of the Griqualand West Sequence (previously classified as part of the Transvaal System of dolomites and sandstones with ferous and manganiferous jaspers and lavas: SACs 1980). These sediments are 2300Ma old Proterozoic deposits, with the Voelwater Formation attaining a total thickness of 220-450m. These deposits lie in a syncline, with the manganese bodies extending for about 40 km north-south and 5-15km east-west. At Mamatwan the ore body attains a thickness of c45m of which c20m are economic to process. This is overlain by up to 25m of uneconomic manganese and banded ironstone, overlain unconformably by 40-50m of Kalahari Group sediments (Figure 3).

Mining at Mamatwan is by blasting and clearing on a series of benches cut into the overburden and the economic ore. Back filling occurs in areas that have been exploited. Waste and ore are removed in giant trucks for storing and sintering on site before dispatch. Production levels vary according to demand and world market prices. While open cast mining creates a large hole in the Kalahari (which because of the general flatness of terrain is not visible from a distance) it does also provide excellent exposures through the Kalahari Group sediments to their base.

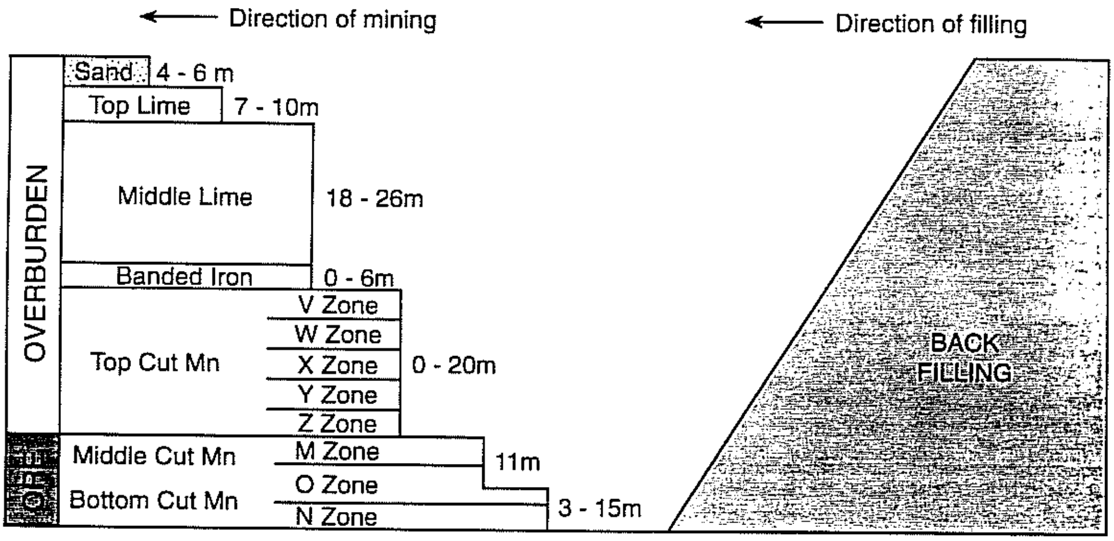


Figure 3 Schematic section through the Mamatwan Mine benches (from SAMANCOR mine guide)

Kalahari Group sediment sequence at Mamatwan

Williams (1993) described the Kalahari sediments exposed in the northern part of the mine, with Bootsman (1998) revisiting deposits in his PhD study of the evolution of the Molopo drainage. Other units have also now been dated at Sheffield by OSL, including the upper sand unit and sandy-calcrete units below.

There are three mine benches cut into the Kalahari sediments: a sand bench, a top lime bench and a mid lime bench (Figure 4). Bootsman (1998) notes that there was a lower lime bench in the south of the mine but, being underlain by slippery red clay deposits, this has broken up by rotational slumping.

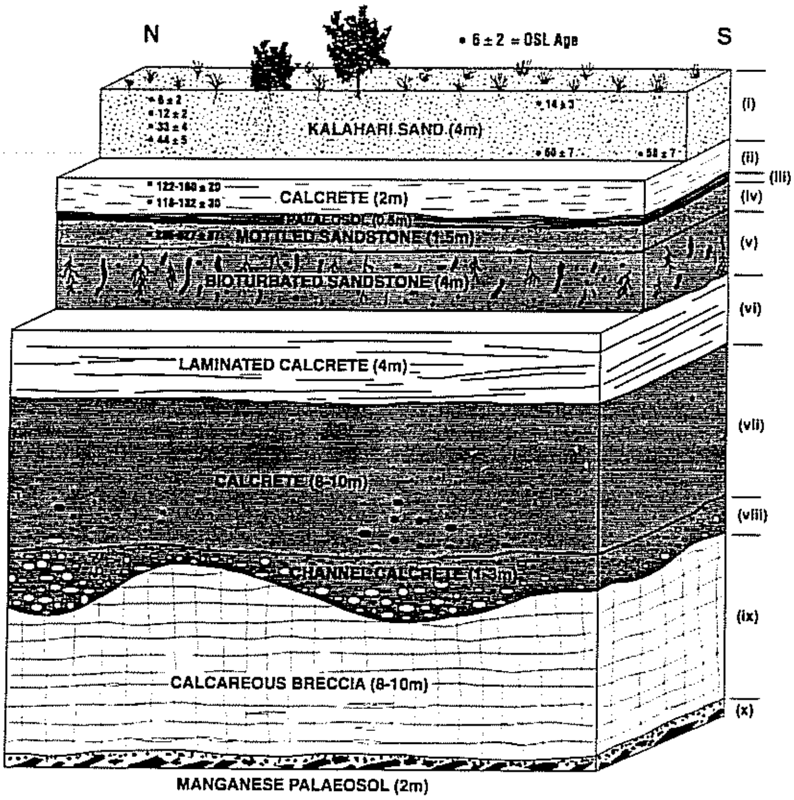


Figure 4. Kalahari Group sediment sequences exposed in the Mamatwan Mine (after Williams 1993.

The sediments shown in figure 4 are as follows, after Williams (1993) with additional notes from Bootsman (1998) and personal observations

Sand bench

i. **Kalahari Sand** c3-4m thick, comprising loosely compacted medium grained orange-red quartz rich sand. Some carbonate cementing, increasing with depth. Sampled in 1996 by David Thomas and Kees Bootsman for OSL dating.

Samples CT96//11/1 and 11/2 at 3m depth colour 5YR 5/8 (yellow-red) yield ages of 60.2 +/- 2.5 ka and 58.6 +/- 2.3 ka. (Mark Bateman, SCIDR dating lab). Further sampling in 1998 (Bateman and Thomas) yielded five additional ages, all chronologically sensible and indicating last glacial cycle accumulation (Fig. 4)

These include the oldest sand ages from the SW Kalahari (compare with ages from dunes, considered in day 3 and 4 sections of this guide). It can be noted that in this eastern part of the southwest Kalahari, dunes are not widely present (as observed from the mine observation platform, this is a sand sheet area). This may suggest that environmental / climatic conditions conducive for dune development and reworking during the LGM and early Holocene did not extend this far east. It can be noted in this respect that the climatic/rainfall gradient in this area is very steep, and this differential may have occurred in the past.

Top Lime Bench

ii. **Calcrete** 2m of largely homogenous featureless cream calcrete, according to Williams (1993). In fact this calcrete is blocky and massive in structure, grading up into fine powdery / nodular calcrete that grades into the overlying sand. Some red sand inclusions and manganese nodules occur within the blocky elements of the calcrete. OSL ages of quartz grains in the deposit have high errors but are within the 160-118 ka ago range (Fig 4).

iii. **Palaeosol** A 0.5m thick brown/orange palaeosol or iron pan (Williams 1993). Contains contorted horizontal laminations, contortions explained as resulting from water table fluctuations.

iv. **Mottled sandstone** 1.5m of fine-medium grained pale orange sandstone with carbonate cement. Matrix mottled by red-orange stained 'clasts' or patches of uncemented red sand. An unreliable age with a high error is shown on Figure 4.

v. **Bioturbated sandstone** up to 4m of fine grained orange sandstone, bioturbated by rootlets which have been replaced by pale pink-white calcrete.

Units iv and v as described above by Williams (1993) are not always distinct. Bootsman (1998) suggests that the units of the top lime bench could represent development under pan conditions. In fact they may represent the lower elements of the Kalahari sand, in which sil-calcrete emplacement has progressively occurred. Mottling and cementation may both result form a history of water table fluctuations and groundwater seepage of $CaCO_3$ in times past. It can however be noted that this is not pure calcrete and may more closely resemble silcrete or one of the composite forms commonly found within the Kalahari.

Mid Lime Bench

vi **Laminated calcrete** 4m of cream-pink calcrete with numerous narrow laminations of crystalline calcrete within a calc-arenite matrix.

vii. **Calcrete** 8-9m of thick cream calc-arenite with fine-medium quartz grains and occasional rounded clasts of banded ironstone. Laminations also occur as in vi.

viii. **Channel calcrete** Grading up to vi, a unit of 0.5-3m with a sharp erosional base. Contains a channel lag of medium-large rounded clasts of banded ironstone and manganese, initially clast-supported but now matrix supported due to calcrete development.

ix. **Calcareous breccia** Pale pink, 8-10m thick. Mainly comprises clay-silt size calcareous material altered to a soft low density rock. The matrix is brecciated by white calcareous veins. Small ironstone and manganese pebbles occur in the lower 2m of the unit. Clasts exibit concentric onion ring alteration. The low density and fine-grained nature of sediments is due to a high sepiolite clay content (Williams 1993). In parts of the mine the breccia is silcretised.

x. **Manganese palaeosol** A 2m unit directly overlying manganese deposits. Interpreted as a palaeo-weathering horizon or palaeosol, modified by later calcrete growth. Clasts with the deposit because more angular with depth.

Red clay unit (not shown on diagram) Unit x is not found in the SW of the mine, where a red clay unit occurs (Bootsman 1998). Under over burden pressure this seeps at a rate of 70mm/day . Borehole data shows that this unit thickens westwards and is 0.5-27 m thick in total

Bootsman (1998) interprets the red clay as a lacustrine deposit that resulted when the course of the proto-Molopo was affected by uplifting along the Griqualand-Transvaal axis. The lacustrine environment may have extended over 400km in the back tilted section of the proto-Molopo (Bootsman 1997). Unit x may be a lateral variant of the clay, with unit ix representing distal-end alluvial fan deposits. Since the proto-Molopo was the major pre-Kalahari river of this region, the disruption of its drainage may have been associated with the break up of Gondwanaland that ultimately led to the development of the Kalahari basin.

Witsand

Just outside Olifantshoek a good dirt track leads 71 km south to the Witsand Nature Reserve. This area gained nature reserve status in 1994 and is famous for its 'roaring sands'. Witsand is located on the northwest flank of the Langeberg Range, which comprise white, grey and pink quartzites of the Matsap Formation. These are Proterozoic deposits of the Olifantshoek Sequence, which lies above the Griqualand West sequence (as found at Mamatwan mine). The track from the main road passes through the steep Bergenaar's Pass (1:5), since the aeolian sands at Witsand have accumulated between the quartzite ridges of the Langeberg. The area occupied by the 3300 ha reserve was, up to the early 1990s, used as grazing land, and in some areas had experienced notable vegetation degradation. Witsand is at the convergence of three major vegetation types:

Kalahari/Karoo-Namib transition comprising sparse grasslands on dune crests with occasional trees, and better-grassed interdunes;
Kalahari deciduous acacia wooded grassland & deciduous bushland comprising dense bushland on stony soils and intervening sweet grasses
Bushy Karoo-Namib shrubland, composed of small bushy trees and large shrubs.

Aeolian deposits

It was originally suggested that the dune sands were probably derived from the northwest (i.e. from the Kalahari) during Quaternary arid phases (Lewis 1936), though local derivation has also been considered. Present mean annual rainfall at Witsand is c.340mm. Accumulation of this small sand sea has therefore been a function of topographic effects, and it can be noted that many hills in this area of the northern Cape have a sand drape on their windward side. Witsand dunes have therefore accumulated between the featureless sandy plain to the west of and the Langeberg to the east. The sediments of the plain are largely comprised fine sand (65-70% in the 0.02-0.2 mm size range) (Eloff and Bennie 1978). The sands at Witsand are somewhat coarser (Van Rooyen and Verster 1983: see below), and it is suggested that this is because they incorporate material weathered from the quartzite hills. Dunes at Witsand comprise compound features extending over an area 9km by 5km. Most notable are dune sand coloration differences, with white, yellow and red dunes present. It is generally considered that iron oxide coatings on Kalahari-derived sands have been leached in situ to generate the paler colours. Fulgurites are relatively common in the lower white sands, which being close to the water table are particularly susceptible to lightening strikes during the rainy season.

Roaring sands

On warm, dry days, movement on some of the dune sands causes a 'roaring' sound to be emitted from the sand surface. Lewis (1936) and Van der Walt (1940) published the first scientific papers referring to the roaring sands at Witpan. These authors attributed the resonance of the dunes to two characteristics; the marked roundness of sand grains and the absence of iron oxide coatings. They suggested that these properties allowed marked friction to occur between grains when moved, but only when dry since moisture between particles would both reduce friction and muffle sound.

Van Rooyan and Verster (1983) attempted to provide a thorough analysis of Witsand sediments to establish the reasons behind the noise-emitting properties, since they noted that not all well rounded white sands have this property, even within the Witsand area. They sampled roaring and non-roaring dunes and from lower aeolian deposits. Table 1 summarises their sedimentary data. They note that the roaring sands have a narrow size range (86% in 0.18-0.35 mm range), and are therefore very well sorted. These authors felt that the roaring dune sands were not sufficiently dissimilar from non-roaring sediments for these sedimentological factors alone to account for roaring properties, and that '*additional factors are therefore responsible for this apparent anomaly. Possible factors such as microclimatic differences or differences in the quantity of iron oxide coatings may be considered. These were not investigated.*' (Van Rooyen and Verster 1983, p221).

Table 1. Mean grain size parameters at Witsand, Folk and Ward statistics, phi units. From Van Rooyen and Verster (1983)

	Roaring dune sand	Non-roaring dune sand	Grey-white active dunes	Yellowish stable lower sands
n	4	3	5	15
Mean diameter	2.08 (0.24mm)	2.28 (0.21mm)	2.38 (0.19mm)	2.02 (0.25mm)
Median diameter	2.07 (0.24mm)	2.26 (0.21mm)	2.40 (0.19mm)	1.96 (0.26mm)
Sorting	0.32	0.37	0.69	0.34
Skewness	0.18	0.31	0.20	0.43
Kurtosis	1.10	1.02	0.87	1.14

Day 3: Wednesday 4 September
To the southwest Kalahari: valleys, dunes and pans

The route from Witsand follows the dirt road loop (102km) to tar road, then retraces the journey (89km) back to Upington. From here a new road goes north into the dunefield 196km to the Molopo Hotel at the junction of the Molopo and Nossop valleys. A further 50km up the Nossop River lies the gate to the Kalahari Gemsbok Park at Twee Rivieren, where we fork west along the park boundary to Andre van Rooyen's farm at 60km.

Southwest Kalahari

As the driest part of the mega-Kalahari, the southwest displays some of the best developed arid landforms related to both wind and water activity. It lies south of the *Bakalahari Schwelle*, the broad interfluve at 1000-1100m asl, hence nominally drains south and west into the Atlantic. Much of the area, particularly in the dunefield, has localised drainage into pans.

Valley systems

A major feature is the Molopo network of valleys, comprising the Molopo and Kuruman, with their tributaries, rising on the hardveld in the vicinity of Mafeking, and the Auob and Nossop systems, draining the rise of the Ghanzi Ridge in central Namibia. The four valleys converge in the field area, and drain, as the lower Molopo, to the Orange River west of Aughrabies Falls.

The Molopo has attracted much scientific interest since the early work of Du Toit (1907), largely because of diamondiferous deposits found in the Lichtenburg area, which may be associated with the course of an earlier palaeo-Molopo (see Dollar 1998 for discussion). It is an ancient drainage network, which has shifted alignment several times since the Cretaceous (Bootsman 1997) following the deepening of the Kalahari Basin and warping of the Griqualand-Transvaal and Kalahari-Zimbabwe axes. Depths of incision exceed 40 m in some parts of the Molopo Valley itself.

Although regarded as a 'fossil' network the valleys are not true '*mekgacha*' dry valleys of the type found in the endoreic Middle Kalahari, which can be largely attributed to groundwater weathering. All four valleys carry surface flow in their upper, hardveld, reaches (especially the spring-fed Kuruman) and may have intermittent fluvial activity in response to intense rainfall events. The Molopo may flow as far downstream as Water's End, between Werda and Tsabong. The Kuruman flowed throughout its length in 1891-2, 1894, 1896, 1915, 1917, 1918, 1920, 1974-77 and 1988-89, and the Nossop in 1806, 1963 and 1987. All four channels contained flow in 1934. Some of these flows are large – the 1934 Nossop flow, for example, was estimated at 450 feet wide, travelling at 6 mph.

Evidence of late Pleistocene, Holocene and recent flows are found within the valleys particularly the Kuruman, as a set of terraces, whilst the lower Molopo has abandoned waterfalls indicating ancient flow. The Auob and Nossop tend more towards broad, flat beds typical of flash floods. In all four valleys a suite of calcretes, silcretes and hybrid duricrusts form the valley sides, frequently with a rectilinear valley x-section. Thin-section and mineralogical studies of duricrust cements (Nash *et al* 1994) indicate that the Auob Valley may have incised through pre-existing duricrust horizons whereas the true *mekgacha* have duricrust profiles indicating progressive duricrust development downwards as groundwater weathering takes place.

Quaternary studies have been limited to radiocarbon dating of lower, Holocene, terraces in the Kuruman (Shaw *et al* 1992) and late glacial and Holocene flood deposits in Auob and lower Molopo valleys (Heine 1982).

Pans

Pans are small, closed basins, usually sub-circular or kidney-shaped, containing ephemeral lakes. They are common throughout semi-arid southern Africa, especially so in the southwestern Kalahari. They may occur solely within the Kalahari sediments (frequently with a grassed surface) or, where Kalahari sediments are limited in thickness, into the underlying bedrock. In the Molopo area most pans are of the latter type, having bare, alkaline clay surfaces which have been formed by the processes of shallow-water lacustrine deposition interrupted by periods of groundwater controlled aeolian deflation. Associated landforms frequently include duricrust suites – often a calcrete outer rim with silcrete formation on the pan surface, and one or more lunette dunes on the downwind side.

Pans of the scale 1-10 km^2 have been attributed to aeolian deflation (e.g. Lancaster 1978), based on the orientation of both pan and lunette dune. However, there is frequently a discrepancy in grain size between the pan surface sediment and that of the lunette, suggesting that the bare surface may act as an accelerating surface rather than as a sediment source. 3-dimensional geophysical and geochemical studies conducted on pans within the eastern Kalahari (eg Farr *et al* 1982) indicate groundwater convergence and deep weathering to 30 metres or more suggesting a strong chemical influence. This is particularly apparent in the bedrock based pans of the Molopo area with their saline surfaces. Arad (1984) suggested that many of these pans occupy pre-Kalahari drainage lines and may share a saline aquifer with the highly weatherable (and salt-rich) Dwyka Group strata. As such these pans are related to dry valleys. The relative influence of aeolian and groundwater activity on pans in general must be seen as a continuum based on climate and geology.

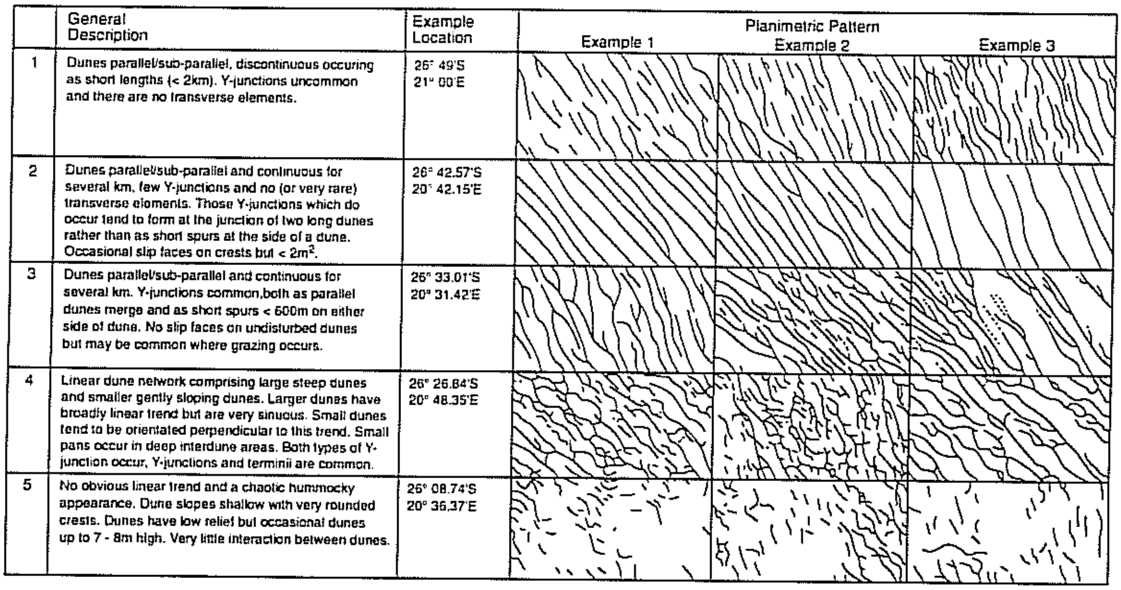
Aeolian sediments and dune activity

The southwest Kalahari dunes are predominantly linear in form, though pseudo-parabolic (Eriksson *et al.* 1989) and lunette (see day 4 section) also occur locally. Close to river valleys, topographic influences may have been marked on dune form and local orientation (Bullard and Nash 2000). The linear dunes generally trend from northwest to southeast across the region, with the 'upwind' end on the system bounded to the west by hills near Keetmanshoop in Namibia and in the north at c. latitude 23°S, by the watershed of the Nossop/Aoub river systems and channels running west to the Namib coast. The Orange River, near Upington, effectively marks the southern limit of the system. Today, despite being in the driest part of the Kalahari, the dunes display only localised and episodic aeolian activity, linked to 1) position on the dune body; 2) the occurrence of drought periods on a quasi-20 year cycle, and 3) the impact of land use activities in the region.

SW Kalahari dunes have rounded cross profiles with limited slipface development on the SW flank of dunes. The dominant linear dune forms actually display marked plan-form and sedimentary variability (Lancaster 1986, Thomas 1986). In the northern part of the dune field widely (c500m) spaced simple linear ridges 10-20m high tend to dominate (Lancaster 1986). Isolated widely spaced dunes occur at the southern extreme of the dunefield. In both these areas dune orientation tends towards being meridianal; in the centre of the dunefield, ridges take on a greater west-east component and spacing is reduced. Given that dune height and spacing is a function of sediment availability and wind regime, dunes in central areas tend to have lower mean heights (6-12m), and coalescing and merging of adjacent ridges, at Y junctions, becomes common. To some extent dunes in some areas therefore appear to be almost reticulate rather than linear. This is further borne out by up to 15% of Y junctions being open in a downwind rather than upwind direction (Thomas 1986) which is the 'norm' in dune fields. Where ridges do merge from an upwind direction, it is common for a new ridge to begin a short distance downwind, thereby maintaining mean dune spacing. Dune patterns have been analysed statistically by Thomas (1986) and Bullard *et al.* (1995), with the latter authors identifying a statistically-verifiable five-fold classification of forms in the SW Kalahari (Figure 5). Class 2 and 3 dunes are the most common patterns found in the areas visited on this fieldtrip, with class 1 dunes common close to Upington.

Compared to other dunefields, the SW Kalahari system is composed of relatively coarse sand (Table 2 after Lancaster 1986). While a general northwest to southeast fining (in the dominant direction of sand transport) has also been reported, this is complicated by local sediment inputs from weathered bedrock on pan floors and from channels, such that Livingstone *et al.*

(1999) found no systematic variations in parameters along a 28 km long profile in the central area of the dune field. Little or no significant cross-dune variations in grain size have been reported by Livingstone *et al.* (1999) except that crestal sands are invariability better sorted than plinth sands.



	General Description	Example Location
1	Dunes parallel/sub-parallel, discontinuous occuring as short lengths (< 2km). Y-junctions uncommon and there are no transverse elements.	26° 49'S 21° 00'E
2	Dunes parallel/sub-parallel and continuous for several km, few Y-junctions and no (or very rare) transverse elements. Those Y-junctions which do occur tend to form at the junction of two long dunes rather than as short spurs at the side of a dune. Occasional slip faces on crests but < 2m^2.	26° 42.57'S 20° 42.15'E
3	Dunes parallel/sub-parallel and continuous for several km. Y-junctions common,both as parallel dunes merge and as short spurs < 600m on either side of dune. No slip faces on undisturbed dunes but may be common where grazing occurs.	26° 33.01'S 20° 31.42'E
4	Linear dune network comprising large steep dunes and smaller gently sloping dunes. Larger dunes have broadly linear trend but are very sinuous. Small dunes tend to be orientated perpendicular to this trend. Small pans occur in deep interdune areas. Both types of Y-junction occur, Y-junctions and terminii are common.	26° 26.84'S 20° 48.35'E
5	No obvious linear trend and a chaotic hummocky appearance. Dune slopes shallow with very rounded crests. Dunes have low relief but occasional dunes up to 7 - 8m high. Very little interaction between dunes.	26° 08.74'S 20° 36.37'E

Figure 5 Dune classes and their characteristics (after Bullard et al. 1995)

Table 2. Averaged grain-size characteristics across SW Kalahari linear dunes (From Lancaster 1986, n = 22 dunes. Data in phi units)

		Mean	SD	Skewness	Kurtosis
Crest	x	2.16	0.49	0.14	0.52
	SD	0.20	0.12	0.09	0.03
NE flank	x	2.21	0.62	0.05	0.52
	SD	0.19	0.16	0.12	0.02
SW flank	x	2.26	0.59	0.07	0.53
	SD	0.18	0.15	0.09	0.04
Interdune	x	2.12	0.90	0.02	0.52
	SD	0.32	0.28	0.17	0.17

Southwest Kalahari dunes are partially vegetated, with spatial and temporal variations in dune cover dependent on antecedent rainfall conditions plus land use pressures (see day 4). High interannual rainfall variability can generate marked variations in crestal vegetation cover, giving the potential for episodic dune surface activity in the region (Livingstone and Thomas 1993). Lancaster (1987) developed and calibrated his dune mobility index in this region, indicating from climate data that most cross-profile components of SW Kalahari dunes are either stable or display only limited surface sediment transport. Research in the 1990s investigating the operation of aeolian processes in the region through field based studies and decadal scale analyses of climate data have demonstrated that currently both wind velocities and vegetation cover are the main limiting factors on aeolian activity (Wiggs *et al.* 1994a,b, 1995). During drought events in the 1980s, more optimal combinations of drought and higher wind velocities favoured dune surface sediment transport (Bullard *et al.* 1997, Figure 6). Even given high interannual climatic variability and the occurrence of droughts in the region, contemporary environmental conditions can favour episodic periods of marked dune surface aeolian activity, but are not sufficient in duration or magnitude for dune construction to occur. Specific local conditions, for example at Struizendam in Botswana, which we will see across the international border, can however prove exceptions to this rule!

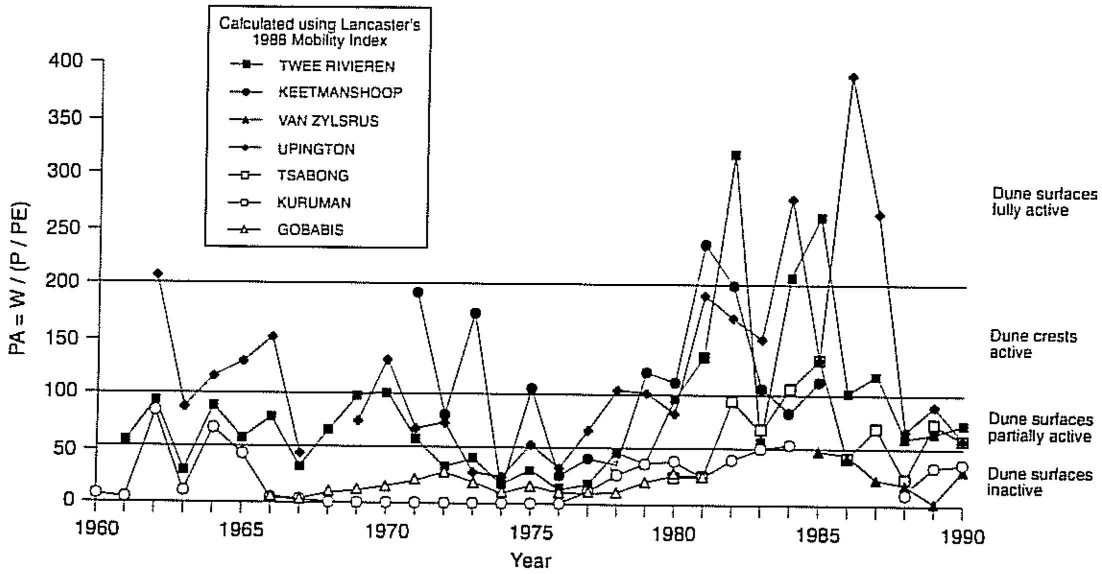


Figure 6. Temporal trends in potential dune activity (PA) values, 1960-1999. Thresholds derived from Lancaster's (1988) Dune Mobility Index. After Bullard *et al.* (1997).

Dune construction: the palaeoenvironmental record

Prior to the 1990s the timing of dune construction in the region was only estimated, based on windows within late Quaternary humid chronologies derived from dated fluvial, lacustrine and cave deposits. Kalahari wide, three general phases of linear dunefield construction were infered, each coincident with one of the region-wide subdivisions into northern, eastern and southern Kalahari dunefields (e.g. Lancaster 1981). Luminescence dating has subsequently provided an opportunity to directly date dune sediments, providing an opportunity to better place the dune record within Quaternary chronologies for the region. Thomas and Shaw (in press) provides a new overview and interpretation of available robust data for the Kalahari region as a whole It will appear in a special IGCP413 issue of *Quaternary Science Reviews* early in 2002, and is included here as Appendix 1.

Stokes *et al.* (1997 a& b) and Thomas *et al* (1997) provide a tentative chronology for the development of the southwest Kalahari linear dunefield based on 15 optical dates, mainly from sites in South Africa plus one in Botswana (Figure 7). These were based on multiple aloquot procedures which generate relative high errors (+/- 5-10%) and have not be re-dated using more refined single aloquot procedures. A number of other ages have been provided by the Sheffield (SCIDR) luminescence lab, but are as yet unpublished. In addition, lunette dunes have also been dated from within the same project (Thomas et al 1997 and Lawson 1998), while the German team of Bernhard Eitel and W.Blumel have dated dunes from the Namibia part of the southern Kalahari (Eitel and Blumel 1998) using TL.

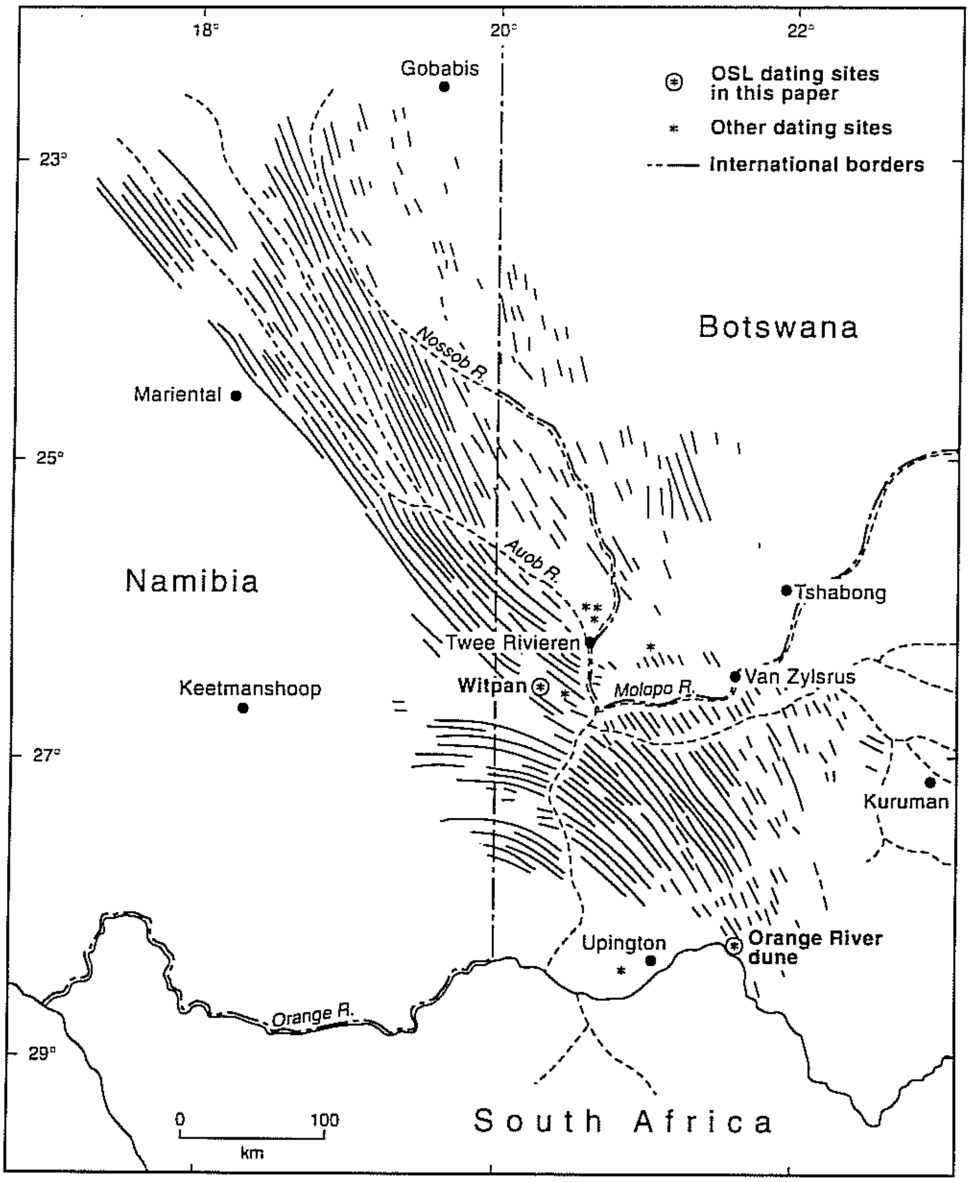


Figure 7 Location of sample sites for optical dating (From Stokes *et al.* 1997b)

Table 3 shows age data from Thomas *et al* (1997). It can be seen from Figure 8 that sample locations 945 and 948 include age determinations from basal dune deposits, immediately above gravels overlying the calcrete of Mabbutt's (1957) 'limestone surface'. This suggests that the oldest ages for dune construction are as recent as c 30 ka ago, which compares with ages in excess of 100 ka ago from the northern Kalahari.

The dune sediment ages from Stokes *et al.* (1997a) have been interpreted to suggest two phases of linear dune accretion in the southwestern Kalahari, at c 30-23 ka ago and 17-10 ka ago. This might even be interpreted as a single phase spanning the LGM. However Eitel and Blumel's (1998) ages also lend support to distinct phases, with their ages falling within the 17.5-8 ka range. Holocene activity appears to be limited to localised dune activity and the accretion of smaller dune forms such as pan margin lunettes (see day 5).

The absence of ages older than 30 ka from the SW Kalahari dunes is not interpreted as indicating no dune construction prior to this time, which is implausible for this aridity-prione region. Rather it is considered that this is a sediment-starved locality, where successive phases of dune construction are dependent on the reworking of pre-existing dune sediments (Stokes *et al.* 1997b).

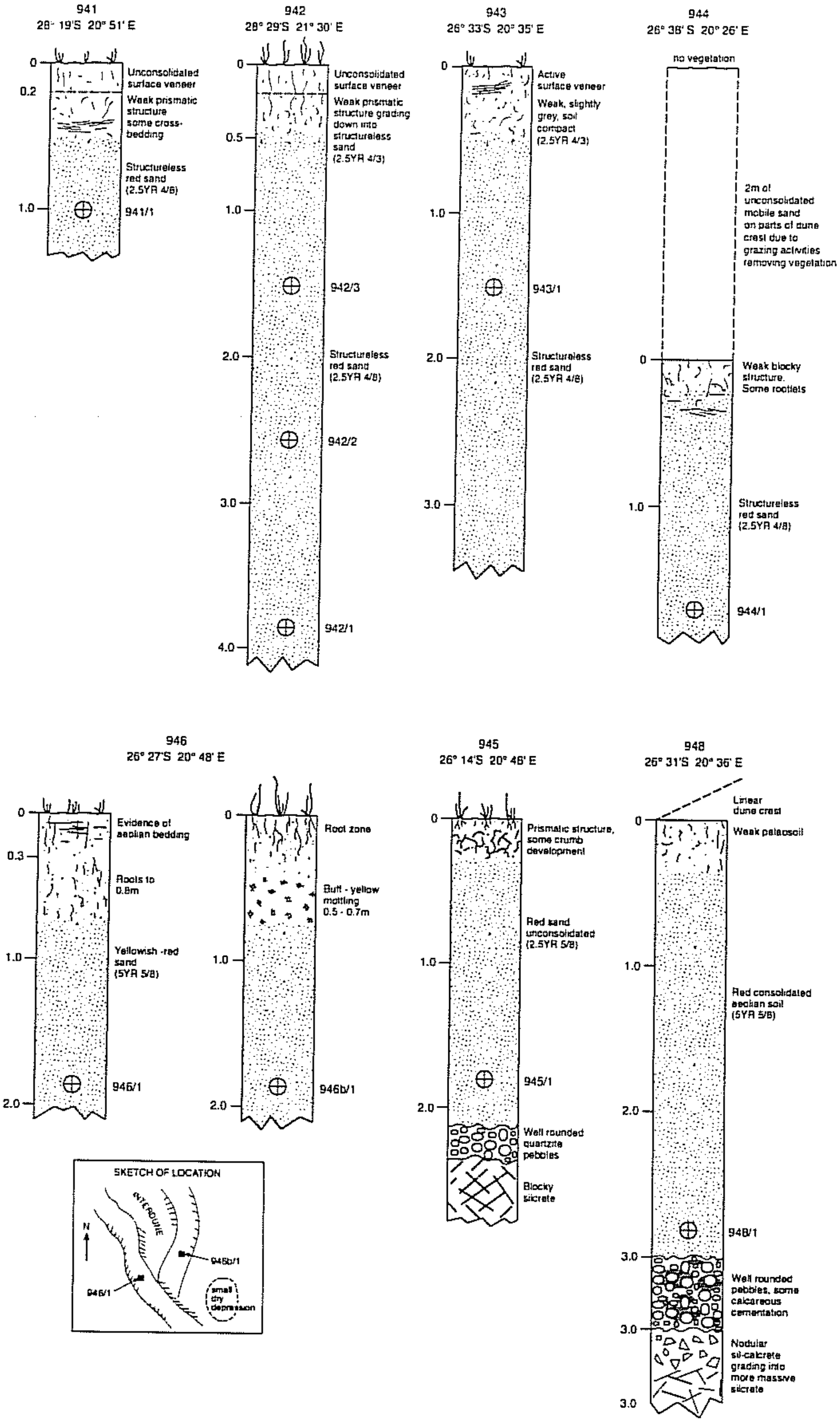


Figure 8 Stratigraphy of linear dune optical dating sites (after Stokes *et al. 1997b).*

Table 3.Data used in the calculation of OSL ages for aeolian samples from the southwest Kalahari Desert (From Thomas *et al.* 1997)

Sample	Lat.	Long.	Description	Sample depth (m)	Radioactivtiy data			D_{cosmic}	Dose rate	Palaeodose	Age
					K_2O (%)	Th (ppm)	U (ppm)	(Gy.ka^{-1})	(Gy.ka^{-1})	(Gy)	(ka)
942/1	28°24'S	21°30'E	linear dune	3.5	0.56 ±0.02	1.70 ±0.18	0.4 ±0.12	0.13	0.79 ±0.15	11.0 ±1.0	**14** ±3
942/2	28°24'S	21°30'E	linear dune	2.5	0.58 ±0.02	2.00 ±0.20	0.5 ±0.13	0.14	0.86 ±0.15	12.9 ±0.7	**15** ±3
942/3	28°24'S	21°30'E	linear dune	1.5	0.66 ±0.03	2.50 ±0.20	0.5 ±0.14	0.16	0.98 ±0.18	11.2 ±0.9	**12** ±2
943/1	26°33'S	20°35'E	linear dune	1.5	0.88 ±0.04	1.00 ±0.16	0.3 ±0.12	0.17	1.00 ±0.27	10.4 ±2.1	**10** ±4
944/1	26°39'S	20°36'E	linear dune	1.55	0.94 ±0.04	1.50 ±0.17	0.4 ±0.12	0.14	1.08 ±0.23	18.1 ±2.6	**17** ±4
945/1	26°14'S	26°14'S	basal linear dunefield sand	1.75	0.78 ±0.03	1.80 ±0.18	0.5 ±0.13	0.16	1.02 ±0.18	23.5 ±3.6	**23** ±5
946/1	26°27'S	20°48'S	recticulate dune overlying linear	1.8	0.73 ±0.03	1.40 ±0.16	0.5 ±0.13	0.15	0.94 ±0.17	5.2 ±1.5	**6** ±2
946b/1	26°27S	20°48'E	linear dune	1.5	0.78 ±0.03	1.80 ±0.17	0.4 ±0.12	0.17	1.01 ±0.20	26.8 ±5.3	**27** ±7
947/1	26°07'S	20°39'E	Hummocky dune patch	2.0	0.36 ±0.01	0.90 ±0.16	0.2 ±0.10	0.17	0.56 ±0.16	1.0 ±0.3	**1.7** ±0.7
947/2	26°07'S	20°39'E	Hummocky dune patch	1.0	0.51 ±0.02	0.90 ±0.15	0.3 ±0.11	0.17	0.71 ±0.16	1.0 ±0.3	**1.4** ±0.5
948/1	26°31'S	20°36'E	basal linear dunefield sand	1.0	1.09 ±0.04	2.60 ±0.23	0.6 ±0.15	0.19	1.37 ±0.24	37.9 ±6.4	**28** ±7
949/2	26°41'S	20°10'E	lunette	1.0	1.17 ±0.05	2.80 ±0.31	0.8 ±0.20	0.18	1.49 ±0.27	2.1 ±0.1	**1.4** ±0.3
949/3	26°41'S	20°10'E	lunette	1.0	1.11 ±0.04	3.20 ±0.23	1.0 ±0.19	0.22	1.56 ±0.20	2.1 ±0.1	**1.4** ±0.2
949/4	26°41'S	20°10'E	lunette	1.0	1.39 ±0.06	2.60 ±0.23	0.7 ±0.16	0.19	1.63 ±0.27	1.8 ±0.1	**1.1** ±0.2
949/5	26°41'S	20°10'E	lunette	1.0	1.25 ±0.05	2.50 ±0.24	0.8 ±0.18	0.23	1.58 ±0.25	1.7 ±0.1	**1.1** ±0.2

Day 4: Thursday 5 September
Dune stabilisation

Dune activity and stabilisation in the Mier Distict

The droughts that affect the Kalahari, particularly the southwestern parts, inevitably lead to temporal fluctuations in the levels of vegetation cover. The moisture retained within the sand of dune bodies does provide some buffering against the effects of individual dry years, but after an extended dry period even dune grasses are susceptible to moisture deficiencies. One effect of this is that cover diminishes to such and extent that aeolian sand transport can take effect, especially on the upper parts of dunes where vegetation cover and not wind velocity have been identified as the major constraint on sand transport (Wiggs *et al.* 1994a,b, 1995). Bullard *et al's (*1997) study showed, using the dune mobility index of Lancaster (1988), that *potential* dune activity was greatly enhanced during dry runs of years (see figure 6). A remote sensing based study of the Mier District (as yet unpublished) at Sheffield has shown how dramatically bare dune surfaces increase in dry periods. This study used a 14% cover threshold as a key mapping limit, since this was identified as a key vegetation cover level for inhibiting dune activity by Wiggs *et al.* (1994b). Many years of observations in the field indicate that during dry spells the limited slip faces on linear dunes in the area increase in extent, bare rippled surfaces expand, and undulating dune crest topography develops. The remote sensing study also showed that some areas in the dune field remain with less than 14% cover even in normal or wetter than normal periods. Inevitably these areas are in locations of marked grazing pressure, on intensively used farm units, around boreholes, etc.

The Mier has had a complex land use history in the 20th century. Today 125 fenced farm units are either privately owned or leased from the local administrative body, the Mier Transitional Council. Some farm units have been heavily used and the vegetation has become extremely degraded. This is marked principally by four characteristics:

1) The loss or reduction of perennial grasses. On the southwest Kalahari dunes clumped Kalahari dune grass (*Stipagrostis amabilis*) is the natural climax grass on dune crests, along with short (*Stipagrostis obtusa*) and long (*Stipagrostis ciliata)* bushman grasses on dune flanks and other locations. The root systems of these grasses help to bind the dune sediments and, being perennials, they are relatively deep rooted and therefore reasonably resilient to drought impacts.
2) An increase in annual grasses in areas that are not bare, notably Kalahari sour grass (*Schmidtia kalihariensis*). Not only is this less drought resistant, but it is also less nutritious.
3) Localised, but sometimes spatially extensive, bare dunes that develop active (sometimes high) crests and slip faces. In some cases the quasi-straight form of partially vegetated linear ridges is replaced by sinuous seif-like crests (Thomas 1988), a process observed in other linear dunefields around the world. It may be reversible, if pressures have not been too longstanding and are reduced (Tsoar and Moller 1986).
4) In very intensively pressured inter-dune areas, an expansion in the spiky *driedoring* shrub (*Rhygosum trichotomum).* In some areas this blankets inter-dunes and inhibits the growth of grasses, further reducing grazing potential.

While fires are a natural feature of this environment that periodically cause marked reductions in vegetation cover, they can trigger improved natural vegetation, whereas grazing tends to main pressures leading to the loss of natural characteristics.

The removal of grazing pressures alone, however, does not lead to recovery. Research by Andre van Rooyen and colleagues has been establishing why this is the case, and what can be done to redress the situation. The following points summarise the characteristics of degradation and restoration of the dune ecosystems.

Degradation

a. Once *Stipagrostis amabilis*, the most important crestal stabilising grass is removed, the morphology and functioning of the upper parts of the dune changes.
b. Bare dunes fail to provide safe sites for seeds, which are blown along the dune surface.
c. Mobile sand prevents seedling establishment by eroding/inundating the surface. Seeds also suffer physical scarring.
d. Even when seeds do germinate, sand transport removes nutrient-fixing micro symbionts, reducing the chances of seedling survival.
e. Water is not a limiting factor as bare areas appear to store more moisture than vegetated areas.

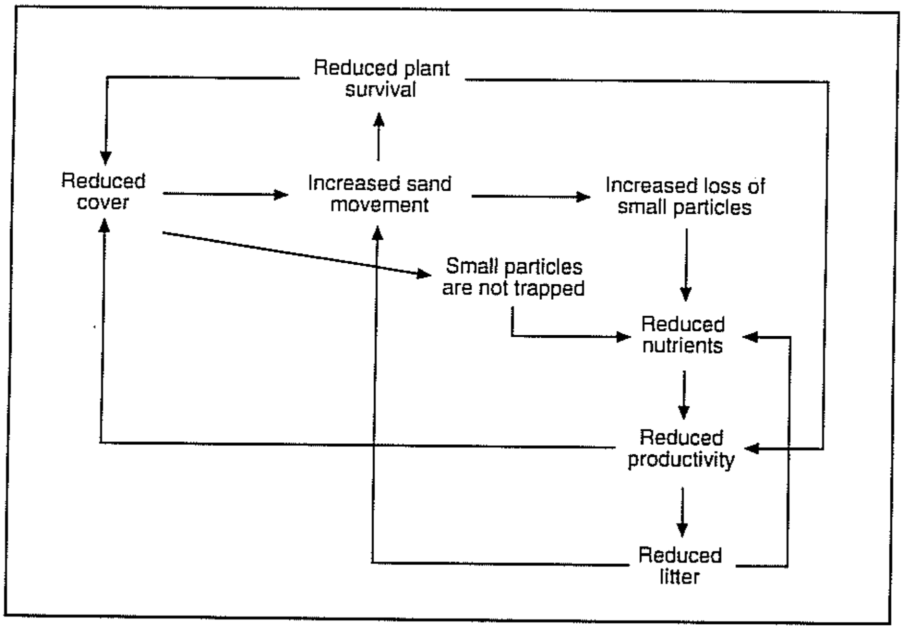


Figure 9 Links in the dune vegetation degradation process.

Restoration

a. The limiting factors on vegetation growth are: nutrient deficiency; substrate instability; sites for seed capture.
b. *Rhigozum trichotomum* is an increaser in interdune areas. It is cleared by hand and used to pack the dune crestal surfaces to provide locations with reduced sand transport, nutrient trapping ability, seed trapping and seedling safety.
c. The structures used to pack dune crests have been developed through local community involvement.
d. Project monitoring and evaluation also utilises local knowledge, expectations and expertise (van Rooyen 1998) and are part of the changing people-land relationships in the Mier.

The sustainability and transferability of the experimental programme is closely tied to changing land uses away from cattle, sheep and goats alone. Wildlife farming, commercial hunting and other tourist based livelihoods are all seen as offering marked environmental (and social) benefits over older practices that are dependent on borehole water and other unsustainable practices.

The farm block that we will visit and stay on is adjacent to the 38,000 km^2 Kgalagadi Transfrontier Park. We will have an opportunity to see into the park including at the vicinity of some of the highest dunes in the region.

Day 5: Friday 6 September
Witpan and return to Upington

Witpan

Witpan (meaning White Pan) and its neighbour Rooipan (Red Pan) are situated on the margins of the linear dunefield north of Reitfontein, close to the Namibia border. Although the pan features, such as the active saline surface, are similar to other pans in the region, Witpan possesses a distinctive active, bare, lunette crest (white in colour, unlike the deep red of the surrounding linear dunes), a cemented lower lunette pediment, and a highly active gully system on its lower flanks. Rooipan has a lunette dune, but it is stabilised by vegetation, as are most lunettes in the region

Sedimentological and chemical studies (Thomas *et al.* 1993) suggest that the entire dune is composed of 99% fine to medium sand-sized material, despite the presence of a significant proportion of fines and coarse sand on the pan floor. The lunette contains salts common to the pan floor (Na-CO_3-Cl-SO_4) sufficient to indurate the sediment. Whilst the pan surface may not be the source of the aeolian sediment at the present day it certainly provides air-borne salts, whereas the sedimentological evidence suggests that the dune sand may have originated from the pan under different hydrological conditions. At present the lunette is self-recycling, with sediment brought down by rainfall events returned to the crest by dry season aeolian activity (Figure 10).

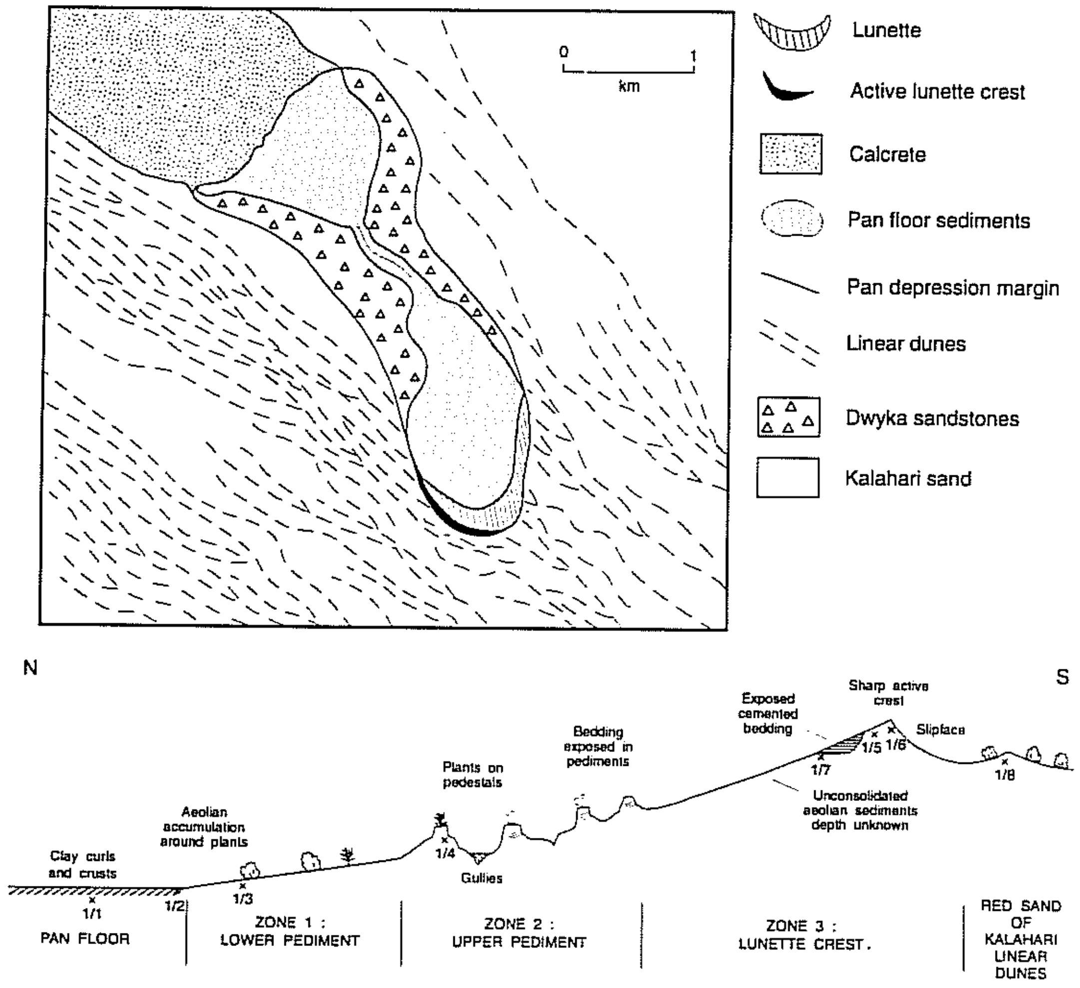


Figure 10. Witpan map and cross section

Four OSL dates (Thomas *et al* 1997: site 949 in Table 3) taken from cross-bedded units, separated by short-lived pedogenic hiatuses, in a 6 m gully face on the dune flank gives ages in the range 1.4 to 1.1 ka (Figure 11). The lunettes of three other pans in the area have been studied by Lawson (1998) - Koopan Suid, Soutpan and Luitenantspan- as part of a study of lunettes across the southern African climatic gradient. The 19 OSL ages obtained range from recent to 16 ka, but with no clear pattern of lunette formation within the sampling framework employed. Certainly the Holocene reworking at all 4 sites, which lies outside the episodes of linear dune reactivation, suggests changes in local conditions, particularly water tables, may be a primary factor in lunette dune reactivation.

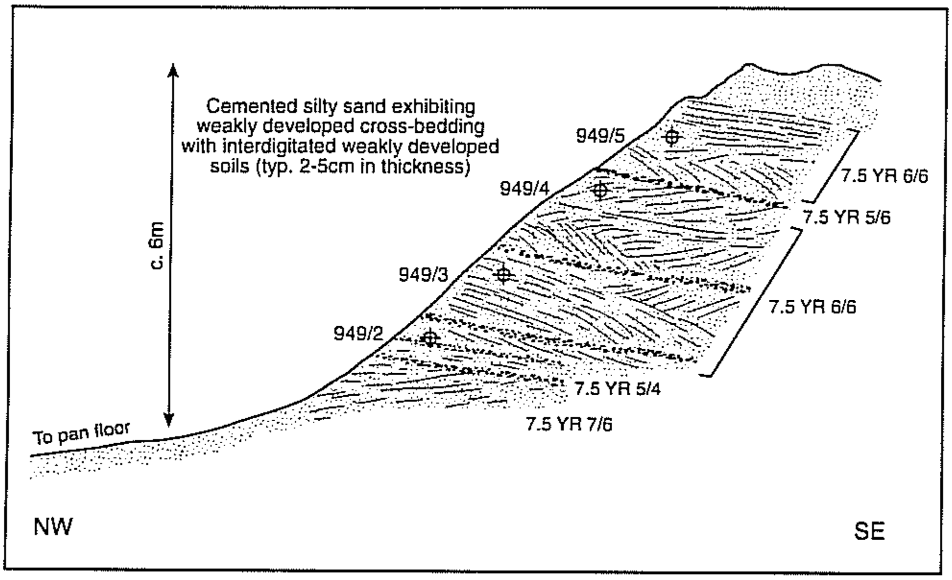


Figure 11. Witpan OSL site.

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APPENDIX 1: Paper in press, *Quaternary Science Reviews* March 2002

Late Quaternary environmental change in central southern Africa: new data, synthesis, issues and prospects

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Abstract

Much of the interior of central southern Africa is a sand sea, within which aeolian and lacustrine landforms and sediments of local and regional extent are preserved. Closed cave sites are restricted to very few locations, while fluvial systems traverse the margins of the interior. Until the early 1990s, chronologies of late Quaternary environmental and climatic changes developed for this region were based on only a limited number of proxy data sets, derived largely from lacustrine deposits and precipitates. In particular, directly determined ages from aeolian deposits, the most extensive suite of features in the region, were absent. The application of luminescence dating techniques to dune sediments, and the development of further detailed chronologies from cave precipitates, is now providing a more comprehensive record for the last 50 ka, with some chronologies extending back a further 100 ka. We present and review these data, assess their contribution to enhanced understanding of late Quaternary environmental changes in the region, and for the first time assess them against corrected radio carbon ages from lacustrine sites. It is concluded that there is now an enhanced understanding of the spatial and temporal complexity of climate changes affecting the region in the last glacial cycle, including a complex record of punctuated aridity, but that many issues, including data set integration and forcing mechanism controls, are imperfectly understood.

Introduction and background

Palaeoenvironmental investigations in the interior of central southern Africa have been hampered by issues of access, the paucity of closed sites, and geochronological diffficulties associated with establishing the timing of development of extensive geomorphic features. The pace of investigation has, however, increased substantially during the 1980s and 90s, both through improved mapping and field investigation of landforms and the application of enhanced dating methods. Since 1969 geomorphological and palaeoenvironmental studies have yielded approximately 300 14C, 80 Th/U and 150 luminescence ages, whose spatial distribution is shown in **Figure 1**. Here we concentrate on advances made since 1992 (Shaw & Thomas 1996), notably the growing luminescence-dating based chronology of aeolian deposition events, detailed cave speleothem studies and a calibration of existing key radiocarbon ages.

The sediments and landforms of the 2.5 million km^2 Kalahari sedimentary basin have long been widely recognised as a proxy record of climatic change (Livingstone 1858; Passarge 1904; Grove 1969; Deacon and Lancaster 1988). In the presently dry-subhumid to semi-arid Middle Kalahari (latitudes 19°-22°), river terrace sites around the eastern margins were investigated in detail over 50 years ago and palaeoclimatic changes, associated with contemporary archaeological chronologies, were inferred (e.g. Jones 1944, 1948). Lacustrine deposits in northern Botswana, including the Makgadikgadi Basin, and associated fluvial systems including the Okavango Delta, were subject to systematic palaeoenvironmental investigations 25 years ago (e.g Cooke 1976), with provisional chronologies of environmental change determined by the application of ^{14}C to calcretes in fluvial and lacustrine terraces. The potential of cave sediments, found in the few isolated hills that dot an otherwise flat landscape, was also recognised at this time by Cooke (1975a). Degraded, inactive sand dunes in western Zimbabwe were considered by Flint and Bond (1968) to provide evidence of two arid phases during the Pleistocene.

From 22°S to the Orange River at 29°S, the Southern Kalahari becomes progressively more arid in a southwesterly direction, but does not attain the levels of dryness reached in the coastal Namib Desert, to the west (Lancaster, this volume). Lewis (1936) described the extensive partially vegetated dunes found in western areas of the Kalahari, which he interpreted as evidence of even drier climates in the past. Lancaster (1976) generated the first systematic study and palaeoclimatic interpretation of the numerous pan depressions, many with fringing lunette dunes, that are found in the southwest. The dry valley systems of the Molopo River and its tributaries, with their ephemeral regimes, yielded shells and calcretes from which Heine (1978) derived a chronology of flow changes, and Cooke (1975b) highlighted the potential of cave speleothems at Lobatse, on the eastern edge of the southern Kalahari.

It was, however, the spring and tufa deposits developed on the Gaap Escarpment, the southeastern margin of the Kalahari, that provided the first comprehensive and long (Tertiary to Quaternary) record of moisture and temperature changes in the region (Butzer *et al.* 1978). The Northern Kalahari (north of latitude 19°S) has, by comparison, received little palaeoclimatic investigation. The terraces of the middle Zambezi River, above and below Victoria Falls, were investigated in early archaeological and geological studies (e.g. Maufe 1939), but the degraded linear dunes and pans of western Zambia, described by Williams (1982), and related features in Angola, have until recently received no attention. Although a number of overviews have been published, up to the mid 1990s, of palaeoenvironmental investigations in the region, progress in recent years warrants an assessment of significant dvelopments that includes a reappraisal of earlier radio carbon based chronologies and an integration of key outcomes with the findings of ongoing dune and cave-based research.

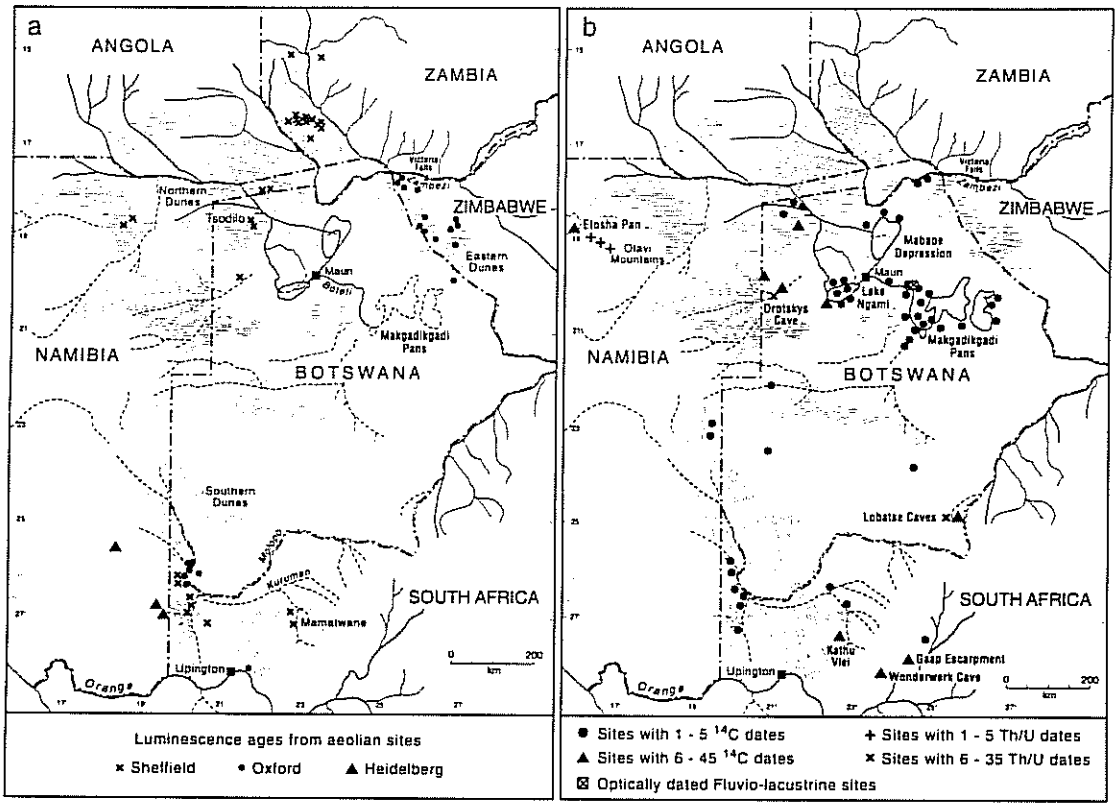

Figure 1. Distribution of numerically-dated sites in the Kalahari. a) Luminescence dated aeolian deposits. Samples dated in the Oxford and Sheffield laboratories are primarily optical ages, those from Heidelberg are TL ages. The majority of locations have at least two age determinations from a vertical sequence (see also Figure 3). b) Lacustrine, fluvial and cave sites that have yielded radiocarbon, Th/U and optical ages. For sources see figure 4.

The aeolian record

Dunes in central southern Africa are dominated by linear forms which are found across the modern SW-NE rainfall gradient in areas with mean annual precipitation values ranging from 150mm to over 1200 mm. The dunes today naturally possess a vegetation cover which ranges from sparse grasses in southern areas, where the features are morphologically recognisable as dunes, to dense deciduous woodland on degraded ridges in northern areas. A range of criteria allow the linear ridges to be diagnosed as relict forms (Heine 1981, Lancaster 1988; Livingstone and Thomas 1993) though not all criteria apply at all locations. In northern and eastern areas the dense plant cover, degraded ridge morphologies and sediment characteristics are all indicative of dune stability. In the semi-arid to arid south, aeolian sediment transport occurs today on the crests of sparsely grassed dunes. Dune process studies (Wiggs *et al.* 1995,1996) and assessment of decadal scale potential dune activity (Bullard *et al.* 1996,1997) indicate that while these dunes can experience episodic surface activity today, the interaction of low sand transport energy and the vegetation cover are not presently conducive to dune construction. These dunes too can therefore be regarded as palaeoforms.

In the past each of three separate linear dune systems developed in the Kalahari sand has been distinguished on the grounds of overall orientatation, and attributed to a distinct period of formation (Lancaster 1981, Thomas 1984). Lancaster (1989) subsequently attributed the northern dune system (Nambia, Zambia and Angola) to formation prior to 32 kyr BP, the eastern (Zimbabwe) to the LGM, 19-17 kyr BP, and the southern (SW Kalahari) to10-6 kyr BP with localised activity at 4-3 kyr BP. These periods were determined partially from a few isolated ^{14}C dates from materials within or under aeolian sediments, and from gaps within the humid chronology.

A systematic UK-based programme of optical dating (e.g Stokes *et al.* 1997a,b, 1998; Thomas *et al.* 1997a,b; Lawson 1998; O'Connor and Thomas 1999), supplemented by additional independent investigations by other researchers, is permitting a geochronometric reassessment of Kalahari aeolian landforms and sediments. Since linear dunes, the dominant dune type throughout the interior, are extending rather than migratory forms, they possess the potential to accumulate and store aeolian sediment that preserves a record of successive phases of dune construction and aridity (Thomas and Shaw 1991b). To date, 111 optical luminescence age determinations from aeolian features and sediments have been published of which 69 are from linear dune sites in the southwestern (Stokes *et al.* 1997b Thomas *et al.* 1997a), eastern (Stokes *et al.* 1998) and northern (O'Connor and Thomas 1999; Thomas *et al.* 2000) Kalahari. A further four thermoluminescence (TL) ages have been published from linear dunes in the southwestern Kalahari (Eitel and Blumel 1997). 42 optical ages from pan-margin lunettes and minor dune forms in the southwestern and eastern Kalahari have been presented by Lawson (1998), Lawson and Thomas (this volume), Stokes *et al.* (1997b) and Thomas *et al.* (1998), with TL ages from minor dune forms in the Etosha basin of northern Namibia presented by Buch *et al.* (1992). A further suite of age determinations from sand sheet and lunette dune sites in the southern interior and from lunette dunes in western Zambia are being prepared, with reference being made in this paper to those which are currently available.

The southern interior

A number of morphological and sedimentological contexts within the main area of linear dunes have been embraced in optical dating programmes in this area (Stokes *et al.* 1997a and b; Thomas *et al.* 1997, 1998) including ancillary forms that have developed on the principal linear features. Eitel and Blumel (1997) provide TL ages from three single linear ridges that traverse large deflation basins betwen Mariental and Aroab (25-27°S, 18-20°E) in southern Namibia, which extends the western limit of age data. To the east of the main dunefield, aeolian deposits are represented by an extensive, flat, sand sheet that extends to the eastern limit of Kalahari Group deposits. The sand sheet has been sampled (D.S.G. Thomas and M.D. Bateman). at Mamatwan for optical dating. Figure 1 shows that more northerly locations in the southern linear dunefield have not yet been dated, while Figure 3 identifies the optical ages and their locations from linear dunes in the southern and central parts of the dunefield, where secondary dune features have also been investigated. Thomas *et al.* (1998) dated the aeolian sediments exposed in the extensively gullied 6 m high lunette dune at Witpan, close to the South Africa-Namibia border. Lawson and Thomas (this volume) present new ages from a detailed investigation of lunette dune sediments in the vicinity of the Molopo valley in the southern Kalahari.

Previously unpublished eastern sand sheet optical ages of 60.2 +/-2.5 ka and 58.6+/- 2.3 ka (samples CT96/11/1 and 11/2; Thomas and Bateman pers comm.) from the 3m deep lower limit of yellow-red Kalahari Sand exposed in the Mamatwan mine (27°22'S, 22°58'E; **Figure 2**), represent t the earliest aeolian sand age determinations obtained so far within the southern Kalahari. All other ages fall within the last 30 ka, including those obtained from basal dune sands directly overlying non-aeolian beds in the main dunefield (Stokes *et al.* 1997a,b; Thomas *et al.* 1997). The suite of linear dune ages suggests two significant phases of dune construction, at 30-23 ka and 16-10 ka. Eitel and Blumel's (1998) Namibian linear dune ages range from 8 ka to 17.5 ka, and are compatible with this grouping, possibly indicating a more extended dune construction period in a westerly, drier, location.

The absence from linear dune sediments of ages older that 30 ka requires consideration. Dune construction in this area might not have occurred prior to this time, though this is unlikely given both the sand sheet ages and since this driest location on the SW-NE rainfall gradient will have been the first area to experience externally-forced regional aridity (Stokes *et al.* 1997a). Two possible explanations exist. First, despite sampling to the base of two dune bodies, older dune sediments preserved in isolated pockets (cf. Nanson *et al.* 1992a in the Simpson Desert, Australia) have been missed. Second, this is a sand starved environment with few sources of sediment for dune construction. It can be noted that dunes in the region are on average less than 12m high, frequently rising less that 6m above interdunes. Consequently, dune building episodes in the Quaternary may have resulted in the reworking of older dune forms, resetting luminescence signals and erasing proxy evidence of earlier arid phases (Stokes *et al.* 1997b). The potential for the preservation of a long dune construction record is therefore not simply a function of the appropriate climatic conditions having prevailed, but also the existence of a sediment supply allowing a stacked record to accumulate.

Lunette dunes in the southwest Kalahari have been optically dated at Witpan (Thomas *et al.* 1998), Luitenantspan, Soutpan and Koopan Sud (Lawson 1998). Fourteen of the 18 dates presented in Lawson (1998) are of Holocene age, and the three Witpan section ages all at 1.1 to 1.5 ka. Lawson (1998) presents four ages betwen 17 and 11 ka, all derived from outer lunettes where pans possess more than one fringing transverse dune. Minor dune forms within the southwest linear dunefield, including crossing dune forms and hummocky dune patches, all generate mid- to recent- Holocene ages (Thomas *et al.* 1997). It would appear that since the end of the last major linear dune construction period at 8-10 ka, opportunities for dune building have been localised rather than region-wide, as recorded in the lunette record and the hummocky dune patch at 26°27'S 21°48'E superimposed on, and reworked from, linear dune sediments. The total data set may, however, support the occurrence of a mid-Holocene dry event, witnessed in crossing-dune development at site 946 of Thomas *et al.* (1997). Both late Pleistocene and mid-Holocene dry periods have been independently identified from the cave sediment record at Wonderwerk, northern Cape Province, by Beaumont *et al.* (1984) and Thackeray & Lee-Thorp (1992).

Photo not included

Figure 2. Examples of dune and other aeolian sites that have yielded optical ages. a) site 948 at 26"31'S 20"36'E in the main linear dune field in the southwest Kalahari, showing cross section through the linear dune and underlying calcrete; b) The 3m thick upper sand sheet deposit exposed at Mamatwan mine, 27"22'S22"59'E; overlying duricrusts and Plio-Pleistocene age fluvial deposits; c) linear dune immediately south of Victoria Falls town, west of location in which site 896, at 18"00'S 25"50'E was excavated; d) low linear dune ridge, marked by the line of trees, in western Zambia; close to site am 95/24 at 16"28'S 22"51'E. a) is discussed in detail in Thomas *et al.* (1997); c) in Stokes *et al.* (1998), and d) in O'Connor and Thomas (1999).

The central and northern interior

Optical dating studies in western Zimbabwe (Stokes *et al.* 1997a, 1998) and western Zambia (O'Connor and Thomas, 1999) have focused on heavily degraded and well vegetated linear dune forms, with a total of 52 ages contributing to chronological assessments (Figure 2). A further 19 linear dune optical ages have been derived from linear dunes in northern Namibia (Thomas *et al*, 2000)

The record from western Zimbabwe includes two long linear dune sequences (Stokes *et al.* 1998; **Figure 3**). Site 952 located close to the Middle Zambezi River above Victoria Falls at 17°55'S 25°28'E provides a 4.5 m deep record from which three ages have been determined from the lower 2.5 m of the section, while 12 ages come from the 6m long record excavated in a dune at 19°23'S 26°45'E (site 1004) in Hwange National Park. Aeolian deposition is recorded at 52 +/-8 ka, 77+/-12 ka and 164 +/-32 ka at site 952. The length of recorded deposition, in contrast to the situation in the southern sites, is thought to be a function of greater sediment supply in this region when compared to the southern Kalahari. The chronology at site 1004 spans 18 ka to 112 ka (Figure 3) without obvious depositional breaks in the record. This potentially generates interpretive problems, since continuous deposition might be inferred throughout the last glacial cycle; analysis of the data set by Stokes *et al.* (1997a) and independently by Singhvi and Wintle (1999), indicates that deposition, and therefore conditions conducive to the effective operation of aeolian processes, was punctuated (see below). The absence of stratigraphic breaks in the record can be considered by recourse to an understanding of the processes of linear dune construction and to models of sediment supply in successive arid-humid phases. The onset of an arid phase leading to aeolian activity probably results in initial wind erosion of upper dune surfaces (including weak soils) at the onset of each new aeolian episode (cf. Kocurek 1998) which would erase stratigraphic breaks. This view is endorsed by the extremely weak and shallow pedogenesis that has affected the modern surfaces of the western Zimbabwe dunes that have not experienced aeolian construction for over 10 ka (see Stokes *et al.* 1998). Stokes *et al.* (1997a, 1998) propose three main dune building phases from the overall Zimbabwe record, at 115-95 ka, 46-41 ka and 26-20 ka.

The western Zambian record (O'Connor and Thomas 1999) presents some notable contrasts. South of the Mulonga Plain, to the west of the upper Zambezi River, dunes are no higher than 4-6 m (Figure 2d), but are nonetheless very distinct because of clear vegetation contrasts with the interdune areas. Dune construction is identified at 32-27 ka, 16-13 ka and 10-8 ka. The northern Namibian dunes

(Thomas *et al.* 2000) are very pronounced compared to those in western Zambia, individually extending for up to 100 km and rising up to 25m above interdune areas. Although these E-W orientated dunes are thought to be originally sourced with sediment from fluvial systems that traverse northern Namibia from north to south, just as the Zambian ridges appear to have been deflated from sediment in the Zambezi system, their great length indicates that they are not simply the result of local, seasonal deflation but have developed from aeolian transport under arid conditions. Thirteen optical ages have been derived from the upper 2m of dune sediments, with none more recent than 21 +/-2 ka, from sample Nam 95/43/3 at 18° 53'S, 18°51'E. Dune construction is suggested at 48-41 ka, 36-29 ka and 23-21 ka, while in both Zambia and Namibia, earlier phases of dune construction can be expected to be recorded in the, as yet, unsampled sediments below 2 m.

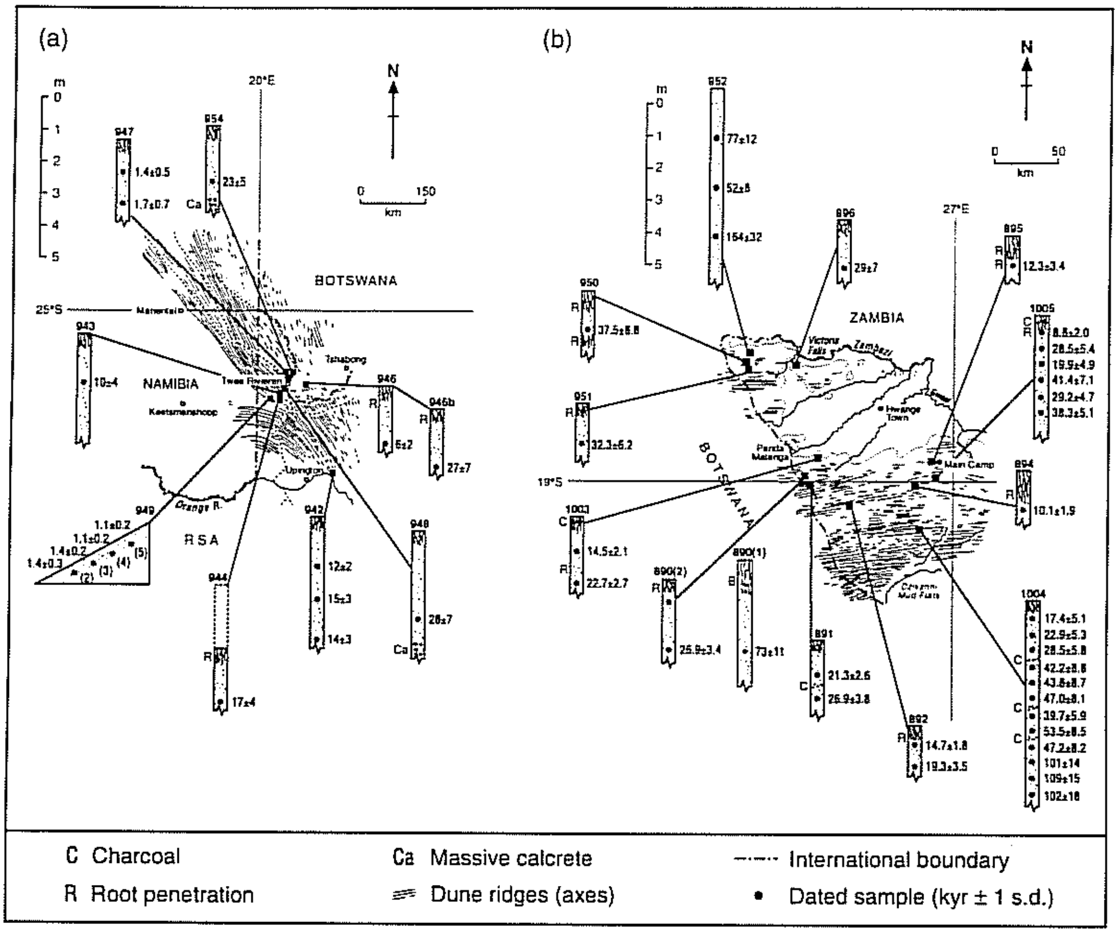

Figure 3. Samples sites and optical ages from linear dune sites in a) the Southern and b) the Middle Kalahari. (modified after Stokes *et al.* 1997a).

The lacustrine and cave record

Investigations have concentrated on palaeo-lakes, pans, dry valleys and cave sites, with reliance upon an uncorrected ^{14}C chronology of which nearly half the dates were derived from calcretes. In the Middle Kalahari two high stages of the massive palaeolake linking the Ngami, Mababe and Makgadikgadi Basins with the Okavango Delta and Zambezi system (Shaw 1988) have been identified, the lower 936m level dated to 17-13 ka BP and 2.5-2 ka BP. Although this may be attributed to greater inflow from the Angolan Highlands through the Okavango an equivalent local increase in precipitation from 17-12 ka BP has been indicated by shell deposits in the dry valleys such as the Okwa and Xaudum (Shaw et al. 1992). Initial work on Drotsky's (Gcwihaba) Cave suggested enhanced local rainfall at 45-37 ka BP, 34-9 ka BP and 16-13 ka BP, with shorter Holocene episodes at 6-5 ka BP, 4 ka BP and 2 ka BP. The high proportion of calcrete dates falling into the 12-10 ka BP bracket suggests that the widely evident late glacial wet period was followed by a regional decline in groundwater tables.

In the southern Kalahari the long-term Gaap Escarpment tufa record (Butzer *et al.* 1978) has been supplemented by fragmentary and frequently conflicting evidence from Equus, Wonderwork and Lobatse Caves (Beaumont *et al.* 1984, Butzer *et al.* 1984, Shaw & Cooke 1986), suggesting a moist, cold climate from 30-26 ka BP and 13-11 ka BP. In the Holocene initial cool, dry conditions were replaced by a warm moist optimum between 8-5 ka BP, gradually drying to 2.7 ka BP. Lancaster's (1979) study of Urwi Pan suggested a lacustrine phase at 17-15 ka BP, whilst Heine (1981, 1982) proposed perennial or semi-perennial flow in the Molopo network from 16-12.5 ka BP. Overall there is consistent evidence of Late Glacial humidity throughout the region, but discrepancies between individual sites, particularly in the southern Kalahari.

Recent work has sought to re-evaluate the radiocarbon chronology, including recalibration following the method of Bard *et al.* (1990), to provide compatability with other chronological methods, establish longer records for cave speleothems using Th/U dating and evaluate the use of luminescence techniques on lacustrine sites, with the eventual aim of establishing an optical chronology. Some syntheses have been published (e.g. Brook *et al.* 1996, 1997, 1998) which combine the first two approaches. Research has also been initiated on new environments, such as pan sediments (Holmgren & Shaw 1997) and the Okavango floodplain (Nash *et al.* 1997) using traditional ^{14}C methods.

Brook *et al.* (1996, 1997, 1998) have dated speleothems from Lobatse I, Drotsky's and Bone Caves and submerged speleothem material from five cenotes in the Otavi Mountain Land, east of the Etosha Basin. Additional analyses of incorporated clastic and organic sediments from stalagmite DC87 in Drotsky's Cave (Burney *et al.* 1994) have improved the Holocene record. In synthesis these indicate wetter conditions, suitable for stalagmite growth, at 200-186 ka, 133-131 ka, 111-103 ka, 93-83 ka, 77-69 ka, 50-43 ka, 38-35 ka, 31-29 ka, 26-21 ka, 19-14 ka, 12.5-11 ka, 8.2-7.9 ka, 6.9-2.6 ka and 1.6-0.5 ka. The Otavi stalagmites, conversely, are considered to have formed sub-aerially at times of low groundwater tables and therefore suggest comparative aridity in eastern Namibia at 130-111 ka, 103-93 ka, 83-77 ka, 69-50 ka, 35-31 ka, 30-27 ka, 10-6-8.5 ka and at 7.5 ka. Potential sources of error in these age brackets include, first, the use of spot samples from unrelated speleothems and sinters and, second, bracketing using only two dates.

Detailed analysis of a single stalagmite, LII4, from Lobatse II Cave (Holmgren *et al.* 1994, 1995), using parallel Th/U and ^{14}C dating alongside 400 ^{13}C and ^{18}O isotope measurements, has addressed these sampling problems. LII4 accumulated in a warm, humid period from 51 to 43 ka, associated with C_3 ground vegetation, and between 27-21 ka, during which temperatures fell by an estimated 2°C and C_4 plants became dominant. A depositional hiatus between 43-27 ka is ascribed to dry conditions, whilst the stalagmite ceased to grow after 21 ka. Although comprehensive stalagmite analysis is preferable to selective sampling is does raise the issue that the value of the analysis is ultimately controlled by the characteristics and environment of the stalagmite selected. For example, a core analysis of a large stalagmite, LII2, from the same cave, involving 17 U-series alpha spectometry age determinations and 225 stable isotope measurements has indicated rapid stalagmite growth between 26-22 ka (Holmgren & Shaw, in press).

The chronology of lake fluctuation has, as already noted, been heavily dependent on radiometric dating of shoreline and lake bed calcretes, which are ambiguous in both the dates they yield and in their environmental interpretation. However, more reliable ages of high stands have been obtained from the dating of shoreline mollusc assemblages and these, when paired against their calcrete matrices, have indicated that the calcrete is 15-25% younger over the Late Glacial range (Shaw & Thomas 1992). Organic materials are scarce, though, and refinement of the chronology will come from the application of luminescence techniques to the highly bleached sand of the Okavango Delta and its associated palaeo-lakes. An initial investigation into the the age and provenance of the 250 cm diatom bed at Moremaoto, on the Boteti River (Shaw *et al.* 1997), using optical dating, indicates shallow lacustrine conditions resulting from the ponding back of neutral to slightly alkaline waters in a meander loop inside the Gidikwe Ridge, upstream of the Makgadikgadi Basin, in two phases between 32-27 ka. These dates are older than, and consistent with, available ^{14}C dates for calcretes on the Boteti terraces and confirm the existence of a lake in the Makagadikgadi basin at this time. The research has also confirmed the applicability of the optical method to lacustrine sediments, for which a major programme of dating has now been initiated.

Synthesis and dating constraints

A synthesis of Quaternary data for the region is presented graphically in **Figure 4. Figure 5** provides time-slice maps of the provisionally determined distribution of drier and wetter conditions from 50-10 ka. Whereas earlier syntheses (eg Thomas & Shaw 1991) underlined the lack of data available for the timing of phases of enhanced aridity, here we place emphasis on the recently derived aeolian chronology. Evidence for more humid conditions derives from the more reliable sectors of the ^{14}C corpus, together with the results of recent cave and lake studies. All ^{14}C dates have been calibrated by the method of Bard *et al.* (1990). Discussion of dating constraints is limited here to the aeolian programme, as the limitations of the humid landforms and their dating methods are covered elsewhere (e.g. Shaw & Thomas 1996).

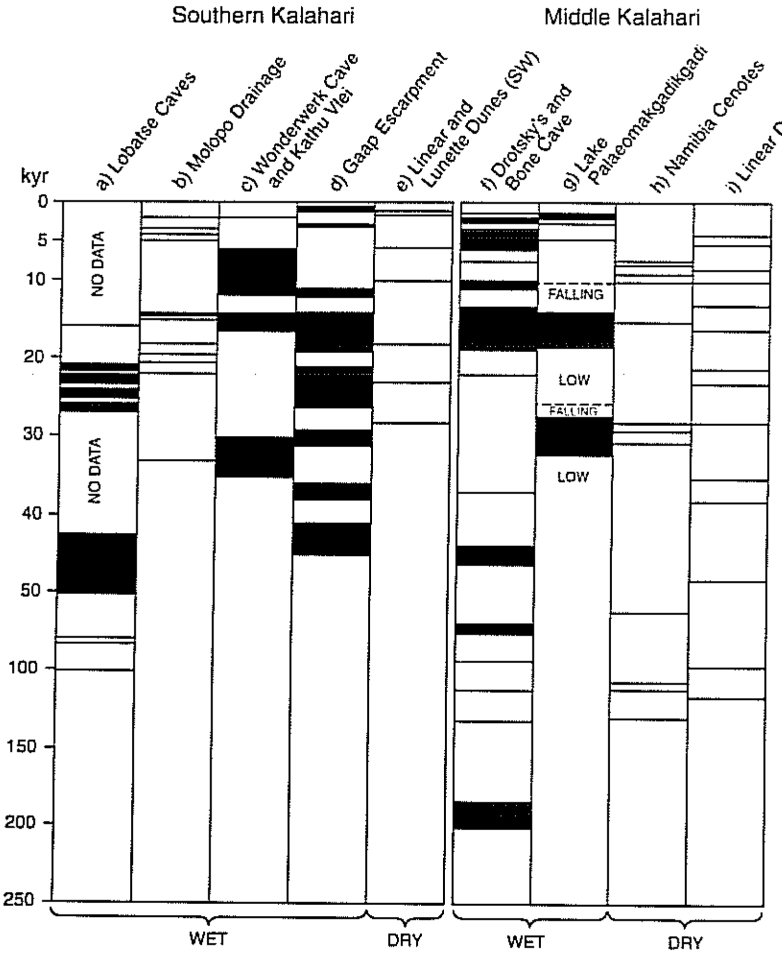

Figure 4. Summary of wet and dry chronolgies from the Middle and Southern Kalahari from 200 ka to present. Note the break in scale at 50 ka. Sources:A: Shaw & Cooke 1986; Holmgren *et al* 1994, 1995; Holmgren & Shaw (in press); Brook *et al* 1998. B Heine 1982,: Shaw *et al.* 1992; C: Beaumont *et al.* 1984; Butzer 1984, Johnson *et al.* 1997; D: Butzer *et al.* 1978; E: Thomas *et al.* 1997; Stokes *et al.* 1997a, 1997b; Thomas *et al.* 1998; F: Cooke & Verhagen 1977; Cooke 1984; Shaw & Cooke 1986; Thomas & Shaw 1991a; Burney *et al.* 1994; Railsbeck *et al.* 1994; Brook *et al.* 1996, 1998; G: Cooke 1984; Cooke & Verstappen 1984; Shaw 1985; Shaw & Cooke 1986; Shaw & Thomas 1988; Thomas & Shaw 1991a; Shaw *et al.* 1992; Nash *et al.* 1997; Shaw *et al.* 1997; H: Brook *et al.* 1996, 1997; I: Stokes et al. 1997b, 1998; O'Connor & Thomas 1999; Thomas et al 2000.

The suite of luminescence ages derived from dune sediments is enhancing understanding of the timing of aridity and dune development in the region, but a number of difficulties, in sampling and the interpretation of results, exist. The extensive nature of aeolian deposits can cause sampling problems, with the precise locations chosen in some cases determined by specific research questions or the occurrence of exposures. In many cases it is determined by the desire to achieve good lateral and vertical coverage, tempered by issues of access and the practicalities of achieving a good sampling depth. When a set of luminescence ages is analysed to provide a proxy record of dune activity, it is necessary to recognise the inherent limitations that might exist within a data set. For luminescence dating it is necessary to avoid sampling the upper 30-50 cm of a sediment body and to exclude sediments that have experienced either disturbance or excessive levels of cosmic radiation. Sediments below c 2m depth can prove difficult to sample when natural or artificial sections or cuttings are absent. Some researchers have drilled or augered below this depth, but in turn this generates other difficulties, including problems of sample contamination during auger or drill extraction.

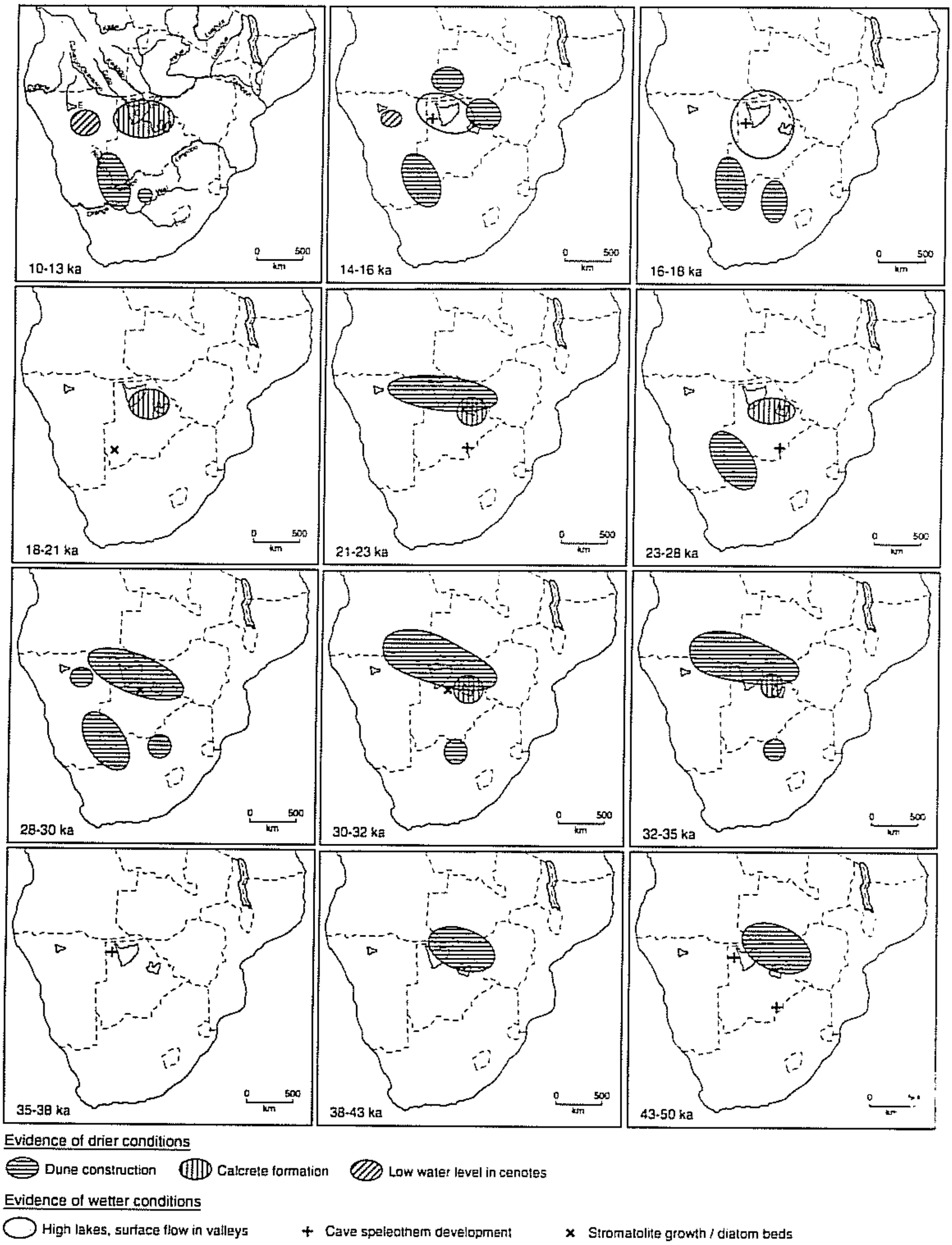

Figure 5. Summary maps of major dated geomorphic and sedimentary evidence of late Pleistocene environmental changes in the Kalahari 50-10 ka. Information is based on evidence described in the text and on the geographical extent of dated contiguous landforms. Palaeoclimates have not been extrapolated from the data in the construction of maps - it can be seen, for example, for the period 14-16 ka in the Middle Kalahari, that there are potential conflicts within evidence that may be interpreted as representing both arid and humid conditions.

The luminescence age determinations from dune sediments can be used to investigate the temporal and spatial distribution of aeolian activity and aridity in the region during the last glacial cycle. Nanson *et al.* (1992b) used frequency histograms to group TL and others ages suites in an analysis of long term (300 ka) aridity-humidity shifts in central and eastern Australia. To some extent this overcame problems associated with a data base where n was small, (20 TL ages in total from dune sands) but the 10 ka time intervals used to group frequencies would mask the subtleties of environmental change which the southern African interior record provides. **Figure 6** shows the frequency groupings of dune luminescence ages (taking age mid-points) by region in this paper, with a 1 ka frequency up to 30 ka, 5k frequency from 31 to 60 ka and 40 ka thereafter. It demonstrates a propensity for older ages to be derived from Middle and Northern Kalahari locations, and younger ages from the southwest of the region.

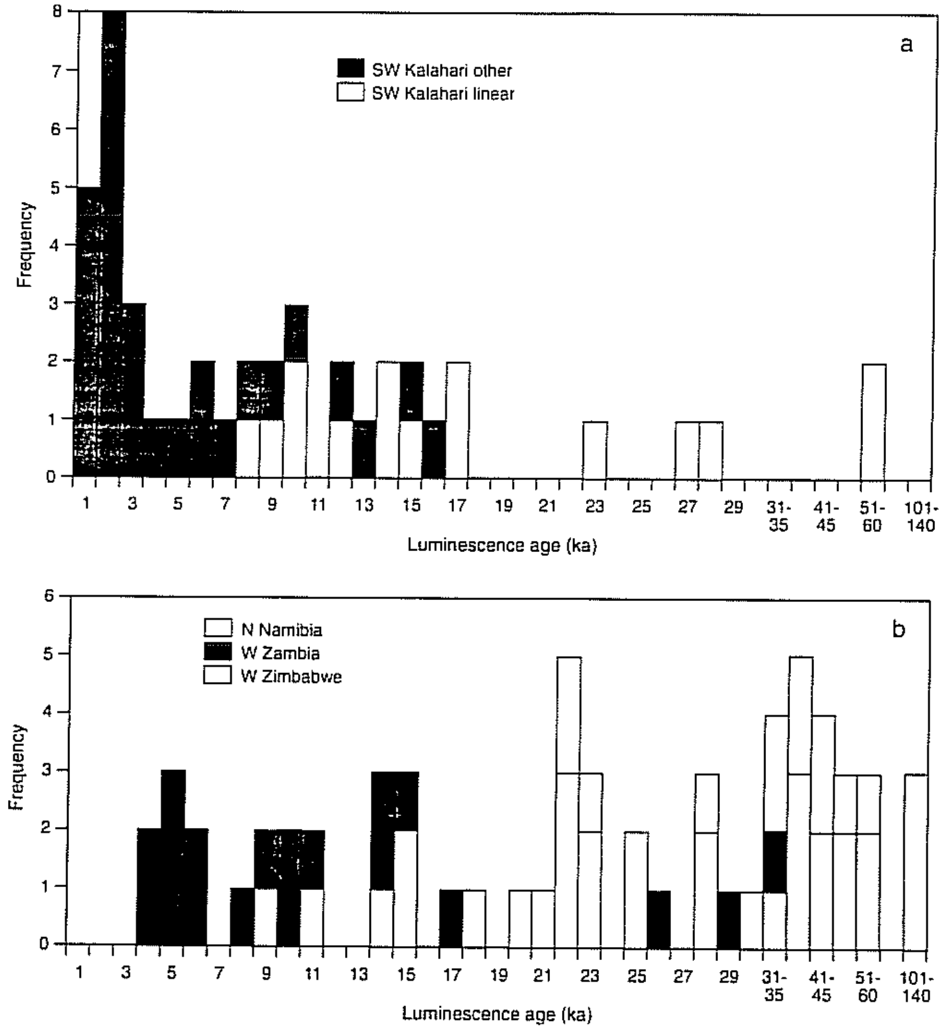

Figure 6. Histograms of dune and aeolian sediment luminescence ages derived from a) the Southern Kalahari and b) the Middle and Northern Kalahari. Central points on ages are plotted without the inclusion of 1 sigma deviations. The latter have been used by for example Stokes *et al.* (1997a) to assess age clusterings and also by Singhvi and Wintle (1999) to assess the probability of peaks of aeolian deposition within the record (see text)

An alternative approach, used by Stokes *et al.* (1997a), has been to group overlapping, statistically indistinguishable ages, and calculate mean weighted values for the ensuing groups. This approach can be applied to the total, region wide, data set, but more logically, given the spatial variability in present day environmental and climatic conditions in the southern Africa interior, should take account of the regional locations of sampling sites. Singhvi and Wintle (1999) have now provided an independent analysis of the data set of Stokes *et al.* (1997a), using a Gaussian probability analysis, which confirms the punctuated nature of dune construction through the identification of several peaks in the record of aeolian sediment deposition. When the dated records from western Zambia, western Zimbabwe and northern Namibia are considered together, a number of disparities are presently identified in the overall record of dune construction in the period c 48 ka-20 ka, which may be resolved by further field investigations or which may represent real spatial difference in the timing of dune construction.

The dated record preserved in the southwest Kalahari identifies two post-30 ka periods of linear dune construction, with isolated older ages from sand sheet deposits. The propagation of aridity, favouring the operation of dune construction if both conditions of sufficient windiness and sediment supply are satisfied, across the interior of southern Africa, has been proposed by Stokes *et al.* (1997a) to explain the general distribution of dune sand ages. The identification of extensive early Holocene age linear dunes in western Zambia (O'Connor and Thomas 1999) requires further explanation if this model is correct.

The humid chronology is still constrained by the incompatibility of the different lines of evidence, and the limitations of available dating techniques. In particular doubts must be raised about widely quoted records which have low environmental resolution, such as the springs of the Gaap Escarpment (Butzer *et al.* 1978, Figure 4 column D) or ambiguous climatic interpretations, such as the river bed deposits of the Molopo (Heine 1978, Figure 4 column B). Long term detailed speleothem records appear to offer great potential, with a caveat concerning the individuality of single stalagmites, but have so far proved difficult to integrate into regional scenarios (Figure 4 columns A & E). In particular the speleothem records proposed for 200-50 ka are based on few dated samples (Brook *et al.* 1996, 1997, 1998), and must be regarded as a preliminary attempt to establish a chronology.

Within the last 50 ka the high levels in the Boteti River and Makgadikgadi at 32-28 ka, preceded and followed by episodes of lake bed calcretisation (Shaw *et al.* 1997) are now at variance with aeolian and cenote evidence for aridity, and will require further research. There is widespread evidence for a cool, dry, LGM in the Kalahari, followed by wetter conditions in lakes and valleys throughout the Kalahari from 18-14 ka, in turn superseded by drier conditions in which calcretes formed by falling groundwater tables from 13-10 ka. The overlap between wet and dry evidence in the Middle Kalahari at around 14 ka is most probably due to lack of resolution in the current data set.

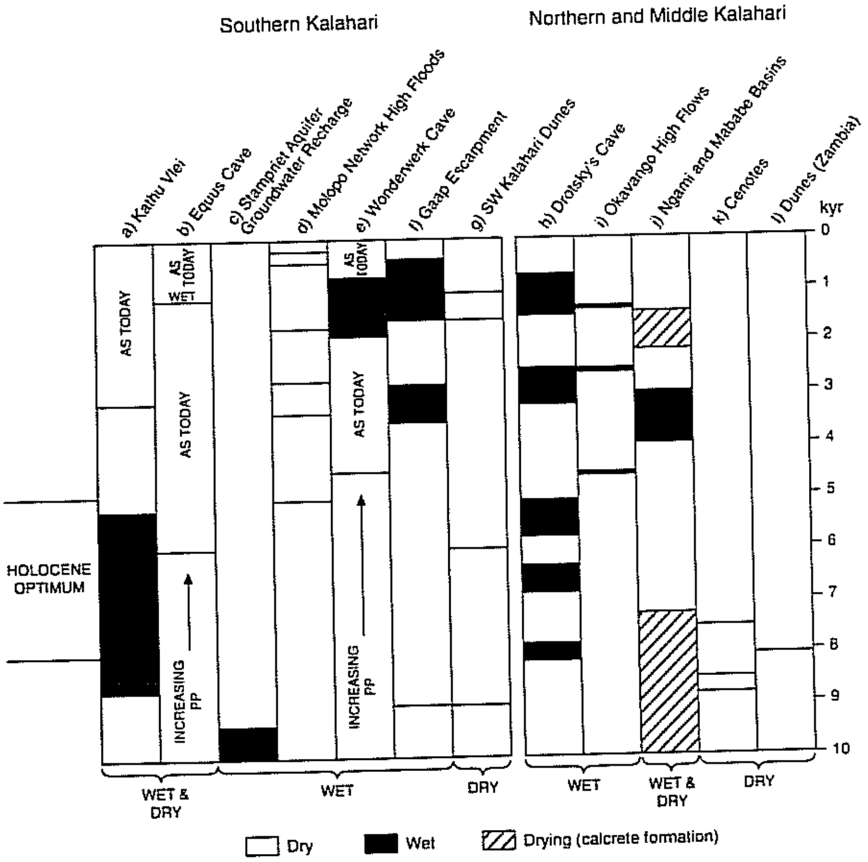

Figure 7. Summary of wet and dry chronologies from the Middle and Southern Kalahari for the Holocene. Sources: A: Beaumont *et al* 1984; B: Johnson *et al* 1997; C: Heaton *et al* 1983; D: Heine 1982, Shaw *et al* 1992; E: Butzer 1984; F: Butzer *et al* 1978; G: Thomas *et al* 1997; H: Brook *et al* 1996, 1998; I: Shaw & Thomas 1988. Nash *et al* 1997; J: Shaw 1985, Robbins *et al* 1998; K: Brook *et al* 1996, 1998; L: O'Connor & Thomas 1999.

The body of evidence for Holocene palaeoclimates, summarised in **Figure 7**, has not grown much in recent years and a number of conflicts remain between sites. Most indicate an increase in temperature and precipitation from 10 ka to the Holocene Optimum around 7 ka, although the conditions at that time were probably similar to the present, rather than the 10-20% increase in rainfall hypothesised by Partridge *et al.* (1999). Short term increases in precipitation in the Middle Kalahari are suggested from speleothems and Okavango channel sediments (Nash *et al.* 1997) at 3-2.5 ka and c 1.4 ka. In the southern Kalahari similar conditions appeared between 1.8 and 1.2 ka. A recently published high resolution speleothem record (Holmgren *et al.* 1999) from Cold Air Cave, Northern Province, South Africa, confirms that a warm, wet period was widespread throughout the summer rainfall zone at 2-1.6 ka. Although the optical dating programme has yielded a large number of dates for the SW Kalahari (Figure 6) these are mostly related to pan lunette dunes, suggesting that once linear dune mobility ceased around 9 ka, subsequent aeolian activity was localised to minor dune forms.

Forcing mechanisms of change

Dune construction in central southern Africa is inhibited today by both effective precipitation amounts (the climate is too wet) and wind strengths (conditions offer insufficient aeolian transport potential). Effective channel flow does not occur today either, except in the northern Kalahari where perennial rivers originate from wet tropical locations. Lakes are therefore dry too. Present day conditions would therefore appear to be 'sedimentation neutral' over much of the Kalahari summer rainfall zone. Aridity leading to dune building in the Northern Kalahari requires a reduction in effective rainfall equivalent to a c. 500-600 mm decrease from present day annual precipitation values. This could be achieved by a fall in absolute precipitation levels, an increase in potential evapotranspiration, or a combination of both. To replenish the Ngami and Mababe lakes to the 936 m asl Lake Thamalakane level would likewise require a 100 percent increase in regional precipitation, taking in to account the amplifying effect of the Okavango swamps (Shaw 1988). The Southern Kalahari would require a significantly lower reduction in rainfall (or increase in evaporation) for dune construction to occur, but present wind energy levels are insufficient for dune building even if precipitation levels were sufficiently reduced (Lancaster 1988; Bullard et al. 1997). What factors are likely to control windiness, precipitation or evaporation values in the southern African interior, which would appear to be the major controls on sedimentation in the region?

At deca-millenial Quaternary timescales, key debates presently revolve around the relative roles and impacts of high latitude ice volume and direct orbital procession, solar insolation, and forcing of African tropical and subtropical climates. If ice volume changes are a key driving mechanism, then northern and southern-hemispheric covariance in key cliamatic parameters, as recorded by proxy indicators of climate change, would be expected. If direct solar insolation is most important as a climate driver, then antiphase changes in key climate indicators may be expected between the two hemispeheres.

Following a complex analysis of sedimentary data from Pretoria Salt Pan, located c200 km to the southeast of the Kalahari periphery, Partridge *et al.* (1997) proposed antiphase variations in monsoon peaks (rainfall maxima) between the African north and southern hemispheres, over the last 200ka. Through a process of 'phase locking', the same authors linked the Pretoria Salt Pan rainfall maxima to 23ka –cyclicity summer insolation peaks, with a 15% increase in summer insolation at 30°S correlating with a 68% increase in precipitation. Partridge *et al.* (1997) therefore propose direct solar insolation variations as a primary mechanism for late Quaternary rainfall changes and ensuing changes in ecological, geomorphological and sedimentological processes, in central southern Africa It should be noted, though, that the relationship breaks down for the c20ka ago summer insolation maxima, which coincided with (last glacial maximum) low precipitaion levels.

In contrast, analysis by Little *et al.* (1997a, 1997b) of microfaunal remains in south eastern Atlantic sediment cores from 19°34'S 11°11'E and 23° 19'S 12°23'E has proposed a direct link between northern hemisphere ice volume changes and atmospheric circulation in the region. Precipitation in the summer rainfall zone of central southern Africa is closely linked to the seasonal movements of the inter-tropical convergence zone and the expansion of moist air bodies, derived from the Indian Ocean, over the sub-continent. It has also been shown by Tyson and co-workers (e.g Tyson 1986; Tyson and Lindesay 1992) that present day dry phases/droughts are closely linked to strengthened and expanded westerly circulation, associated with intensified blocking anticyclone conditions over southern Africa. This both inhibits the penetration of moist easterly airflows of the Indian Ocean and gives a relative increase in the westerly (Atlantic) moisture sources. This may provide an analogue for situations where aridity is enhanced in eastern areas at times when moisture increases occur in the west.

Sea surface temperature (SST) changes are a key factor linked to the circulation changes considered above, which Cohen and Tyson (1995) have modelled for the Holocene and which appear to correlate with proxy records of coastal conditions around the southern African coast. Warm SST anomalies off the south/southeast coast of South Africa are related to dry interior conditions and low SSTs with warm, wet periods.

Off the southwest coast, Little et al. (1997b) have produced a long (140 ka) record of SST changes related to changes in the upwelling of the Benguela current. Enhanced upwelling (lower SSTs) events are associated with stronger and more zonal trade winds, and are teleconnected to North Atlantic Heinrich events and Greenland ice cap Dansgaard-Oeschger cycles. These changes in the strength of the Benguela current upwelling appear to correlate with late Pleistocene arid events in the interior (Stokes et al. 1999), determined from the dune construction chronology. The role of teleconnections in explaining climate change processes in southern Africa has now been explored in consideration of windspeed changes across the region. Wind speed maxima in the southern Kalahari have been linked to Asian monsoon minima (Prell and Van Campo 1986; Stokes et al. 1999) both in modelled variations in the late Quaternary and observed variations during the last century. This is due to the development of ridged anticyclonic conditions in the southern Indian Ocean when the monsoon is weak.

The record of dune construction for the Kalahari based on luminescence dating shows a complex spatial and temporal record of aeolian construction during the last glacial cycle, that presently does not readily correspond to the predictions of low latitude insolation or high latitude ice forcing mechanism models. The reliable elements of the current humid proxy record from the Kalahari afford a further level of complexity in attempting to identify the forcing mechanisms of environmental change in the region. Whether climate changes in the southern African interior are driven by direct insolation variations or SST variations, linked to events in high latitudes, or whether the relative importance of these two possible mechanisms varies through time, establishing the climatic forcing mechanisms responsible for directly recorded environmental changes is presently complicated by limitations and uncertainties within the proxy record and difficulties in linking the millenia timescales of the records of environmental changes in the interior and the century or less scales of some of the climatic change mechanisms that are being proposed.

Conclusion

Regional palaeoenvironmental data bases have recently been employed by Jolley *et al. (*1998*)* and Partridge *et al. (*1999) to evaluate the nature of southern African climate at the LGM and mid-Holocene, and as comparators against modelled climates. The interior of southern Africa is poorly represented in these assessments, largely due to the absence of the long sedimentary cores and palynological evidence found elsewhere. Palaeogeomorphic and sedimentary evidence, along with isolated cave records, therefore remain the principal sources of data that are available for reconstruction in the Kalahari. In the last decade notable developments have occurred in deriving chronologically controlled records of regional-scale dry events and higher resolution records of precipitation events. Appropriate scaling, and gaining an improved understanding of the nature and controls of sub-regional climatic variations and the millenia scale, are amongst key issues that require continued investigation.

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