7 Geomorphological Processes, Environmental Change and Landscape Sensitivity in the Kalahari Region of Southern Africa

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ABSTRACT

Kalahari Group stratigraphy covers some 2.5 million km^2 of southern Africa. These sediments, of which the Kalahari Sand is the most ubiquitous, are of post-Cretaceous age, and have low fossil and organic contents — characteristics that have impeded geological interpretation in the past. In the last two decades geomorphological studies, focused on the semi-arid region (the 'Kalahari Desert') south of the Zambezi River, have provided contemporary and past geomorphological processes on the landscape. Research on caves, lakes, pans and fluvial links have indicated widespread humid episodes in the late Quaternary that are asynchronous with those in other sub-tropical arid regions, and which have been magnified, particularly in the Okavango Delta and adjacent parts of northern Botswana, by tectonic activity. Variations in groundwater recharge and chemistry have led to the formation of complex duricrust suites up to 100 m in thickness, many of which are associated with surface landforms. The most enigmatic landforms are vast 'fossil' linear dune fields, which cannot be related to present or past climatic parameters, and for which new explanations are being sought. Importantly, correct palaeoenvironmental interpretations require recognition and understanding of the sensitivities of individual landscape units to environmental changes. This in turn requires not just the application of modern analogues but recognition of regional hydrological complexities and responses to local, as well as more general, geomorphic controls.

INTRODUCTION

The postwar era has seen great advances in the understanding of tropical and subtropical landscapes at a variety of temporal and spatial scales. Significantly research has tended to concentrate on process studies, and on the reconstruction of past environments, mostly within the range of radiocarbon dating. In both directions there has been a tendency to emphasise erosional landscapes and well-defined climatic environments.

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Large areas of the low-latitude continents, however, experience semi-arid climates characterised by a range of temperature and precipitation conditions, including high inter-annual and intra-annual precipitation variability. Such regions are not only climatically unpredicatable, but also occupy positions between the tropical and temperate circulations that render them liable to dramatic change on the Quaternary timescale. Such environments require patient study; there is sufficient vegetation to mask surface landforms, while in process studies the wait for specific fluvial or aeolian events can be a frustrating experience.

The Kalahari is an extensive semi-arid depositional environment that has, over the past two decades, yielded much information on the rates and processes of landscape change. Some of these changes are specific to the Kalahari, while others have wider application. This paper summarises the results of this research.

THE KALAHARI

The initial impression of the Kalahari suggests that the landscape has recorded past episodes of both greater and lesser precipitation than the present mean, which varies from 250 mm year^{-1} in the south-west, to 700 mm year^{-1} on the Zambezi. Large dry valleys and extensive lake basins suggest the former, while massive linear dune fields covering most of the Kalahari Desert suggest greater aridity, based on the assumption that the dunes are now fixed by a vegetation cover. The problem then becomes one of identifying the extent and chronology of these climatic episodes, using a suite of sediments that are singularly unhelpful. Most of the Kalahari Group comprises sands, duricrusts, marls and conglomerates of Cretaceous to Recent age, which are non-fossiliferous and have, in the case of the ubiquitous sand, ambiguous sedimentary characteristics (Thomas, 1987). Attempts to define the stratigraphy of the Kalahari have been made since the beginning of the century (Passarge, 1904), but have been constantly thwarted by the inability to distinguish genuine strata from post-depositional alteration to duricrusts, which reach up to 100 m in thickness (Bruno, 1985). Although the interpretation problem has been recognised for some time (e.g. Rogers, 1936), there are still many geologists who persist in applying strict stratigraphic terminology to the Kalahari sequence, which, of course, varies spatially too (e.g. Wright, 1978; Malherbe, 1984).

The problem is compounded by the nature of the duricrust suite. Although research has covered many aspects of calcretes (Goudie, 1971) and silcretes (Smale, 1973; Summerfield, 1982, 1983), detailed site studies (e.g. Gwosdz and Modisi, 1983) show a bewildering range of intermediate duricrust forms over short distances, which could be termed sil-calcretes or cal-silcretes, depending on their major constituent. So great is this variety that Mazor *et al.* (1977) suggest the word 'crete' be used as a blanket term. Likewise, the thickess of the duricrusts has led to the assumption (e.g. Goudie, 1973, Summerfield, 1983) that they must be at least of Tertiary age. Such antiquity would render meaningless any climatic interpretation; Rust, Schmidt & Dietz (1984) suggest that climatic variability even within the last 20 000 years would render such an exercise pointless, though many attempts have been made (e.g. Heine, 1978, 1982).

From the tectonic viewpoint, the Kalahari Basin has been gradually evolving as a depositional setting since the break-up of Gondwanaland, with gradual epeirogenesis at the Kalahari rim. This stability has allowed Pickford (1990) to suggest, on the basis of the study of Pliocene cave floors, that the overall rate of rock erosion may be of the order of 0.1–0.2 mm year^{-1}. However, the extension of the East African Rift into the Middle Kalahari via the Gwembe

Trough and the Okavango Delta introduces an element of neo-tectonism that has had a profound effect on the geomorphology of the area (Cooke, 1980) and its sensitivity to climatic changes, and which persists in the year to year functioning of the Okavango Delta (Shaw, 1985).

'WET' LANDFORMS — CAVES, LAKES AND PERENNIAL RIVERS

The most persuasive evidence of greater precipitation comes from caves and lacustrine landforms in the Middle Kalahari (Figure 7.1). Drotsky's Cave in the Gcwihaba Hills of north-west Ngamiland has provided 26 ^{14}C dates from sinter deposits which represent periods in the late Quaternary during which local precipitation may have reached 300% of the present mean (Cooke and Verhagen, 1977; Cooke, 1984). Some of this carbon dating has been carried out in tandem with uranium/thorium dating on the same samples, while the latter method has recently been used to probe the environmental history back to 300 000 BP (Brook, Burney

Figure 7.1 Landsat mosaic of the Middle Kalahari, northern Botswana. The Okavango Delta can be seen centre left linked, by the Boteti River, to the Makgadikgadi basin in the bottom right. Over much of the area, vegetated linear dunes appear as parallel striping, especially to the north and west of both the Delta and Makgadikgadi

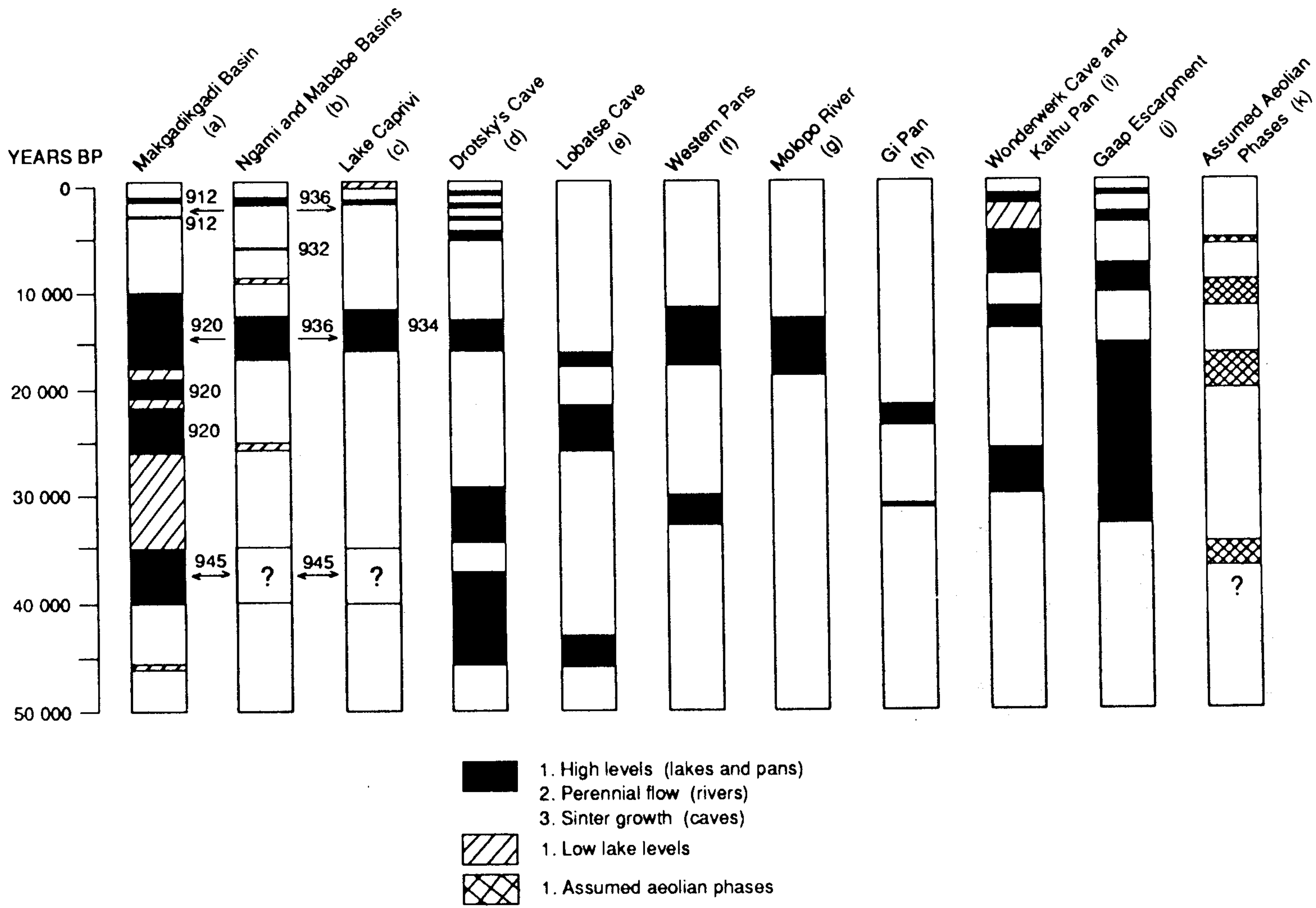

Figure 7.2 Summary of the palaeoclimatic data for the Kalahari. Sources — as per text

& Cowart, 1990). During the past 20 000 years wetter episodes are indicated at 16 000–13 000 BP, and on a number of occasions in the late Holocene (Figure 7.2).

The Okavango Delta is currently by far the most dynamic landform system in the Kalahari, with an annual flood cycle varying the inundated area from some 6000 to 13 000 km^2. Considerable variations have been noted in the distribution of floodwater throughout the Delta during the past 150 years (Wilson, 1973; Shaw, 1985), and on an inter-annual basis, depending on factors ranging from precipitation and tectonism through to fire and the activities of hippopotami! Approximately 400 000 m^3 $year^{-1}$ of bedload sediment is deposited within the delta (UNDP/FAO, 1977), while probably three times that amount of solutes are deposited, the salt precipitation contributing greatly to the micromorphology of the islands and terraces in the upper delta (McCarthy & Metcalfe, 1991).

On a larger scale the Okavango (including 22 000 km^2 of contemporary and fossil sediments) is joined laterally to the Zambezi and Chobe Rivers, and downstream to the Makgadikgadi, Mababe and Ngami lake basins by a series of fault-controlled fluvial links. The configuration and evolution of the stages of the resulting massive palaeolake (Figure 7.3) have been described in a number of papers (see Shaw, 1988, for a recent summary), while calcretes and associated shell deposits on strandlines have provided 48 ^{14}C dates on which a chronology can be based (Cooke, 1984; Shaw, 1985; Shaw & Cooke, 1986; Shaw, Cooke & Thomas, 1988; Shaw & Thomas, 1988).

Two major stages have been identified. The higher, Lake Palaeo-Makgadikgadi stage (Grey & Cooke, 1977), at 845 m asl, lies at the limits of radiocarbon dating, and, with a lake area covering at least 60 000 km^2, has a hypothetical hydrological budget that can only be satisfied by the diversion of the Zambezi into the lake. Its interpretation is thus problematic, but cannot be viewed solely in climatic terms. The Lake Thamalakane stage at 936 m asl, however, would have been a shallow lake of some 7000 km^2 overflowing to the Makgadikgadi, with inputs from both the Angolan Highlands via the Okavango, Chobe and Zambezi Rivers and from local precipitation. Revised estimates of the hydrological budget suggest that only a 100% increase in mean annual precipitation would be sufficient to maintain this stage, as the flat terrain, finely adjusted fluvial links between lake basins, and the amplifier effect inherent in the hydrology of the Okavango Delta would lead to a high degree of sensitivity in the system.

The lake Thamalakane stage seems to have been coeval with the wet periods indicated in Drotsky's Cave. The subsequent desiccation of the lake led to widespread calcification of adjacent sediments, probably associated with the fall in the lake-associated water-table. This can be inferred from sets of paired dates associated with the 936 m level, in which aquatic

Table 7.1 Paired radiocarbon dates for sites associated with the Lake Thamalakane stage (variation expressed as a percentage of the 'real-time' age)

Site	Material	Date (BP)	Lab. no	Variation (%)
Ngwezumba River,	mollusca	15 570 ± 220	GrN 14788	
Mababe (936 m)	calcrete	13 070 ± 140	GrN 12623	16
Serondela Terrace,	mollusca	15 380 ± 140	GrN 13192	
Chobe River (934 m)	calcrete	11 550 ± 110	GrN 13191	25
Gidikwe Ridge,	mollusca	14 070 ± 150	GrN 14786	
Makgadikgadi (~920 m)	CO_3 reed casts	11 980 ± 130	GrN 15536	15

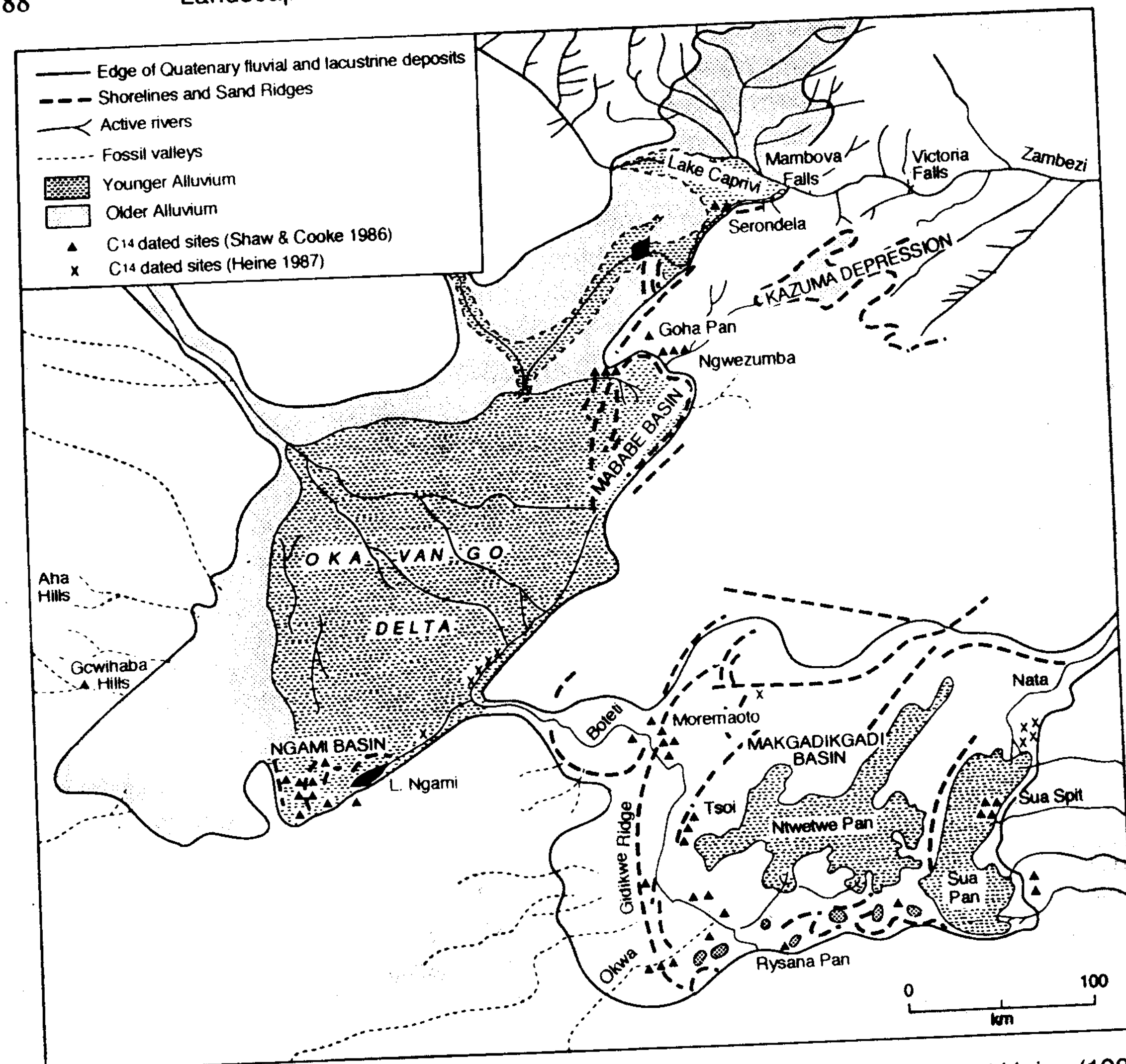

Figure 7.3 The drainage of the Middle Kalahari. After Shaw & Cooke (1986) and Heine (1987)

molluscs have been dated alongside their calcrete matrices, or associated calcareous forms (Table 7.1). Although the chances of cross-contamination between organic and inorganic carbonate are high, there appears to be a consistent variation between the 'real-time' indicator and the subsequent development of the matrix. This would suggest that much of the soft, alluvial calcrete associated with the palaeolakes is of recent origin, as are some of the duricrusts encountered on the lake beds, for example, the silcretes of Sua Pan (Shaw, Cooke & Perry, 1991).

GROUNDWATER LANDFORMS — PANS AND DRY VALLEYS

Pans and dry valleys (termed *mekgacha* in Botswana) are two major Kalahari landforms associated with extensive duricrust development. Until recently the evolution of the former has been associated with aeolian deflation of sediments, as suggested by the presence of fringing lunette dunes (e.g. Lancaster, 1978), while the latter have been attributed to fluvial action during periods of wetter climate. Detailed examinations of the morphology of both landforms, particularly in relation to underlying geological and hydrogeological conditions, suggests that both are a function of groundwater weathering and duricrust formation.

A detailed three-dimensional study of two pans in the south-east Kalahari (Butterworth, 1982; Farr *et al.*, 1982) indicates, in both cases, weathering and duricrust formation to the limits of drilling at 30 m, and a strong association with sub-Kalahari lineations. This link to zones of groundwater convergence has also been demonstrated in the southern Kalahari (Arad, 1984). Changes in the zonation of fresh and saline groundwaters in the pan, which would be significant in silcrete formation, have been explained by upward flushing of the less dense saline water during episodes of local recharge (Bruno, 1985).

Although lunette dunes are common on the leeward side of Kalahari pans, there are problems in linking them to pan evolution. Not least of these is the fact that the sediments comprising the lunettes are much coarser than those encountered in the pans themselves (Goudie & Thomas, 1986). Until this aspect has received further study it is essential to consider pans as polygenetic forms, with aeolian activity modifying pan morphology.

The dry valleys of the Kalahari can be divided into two categories: an endoreic system draining towards the Okavango Delta or the Makgadikgadi Basin, and a network of valleys associated with the Atlantic drainage of the Molopo River. The former, which includes the massive Okwa-Mmone network, with a potential catchment of 70 000 km^2, rise at the margins of the Kalahari Basin, where bedrock is either exposed, or lies close to the surface, and show a variety of distinctive valley forms, including an incised head-valley section associated with a wide range of duricrust types. Within the Kalahari itself the valley loses relief and adopts a dambo form of linked shallow depressions. The valleys lack active channels, and only a few records of sporadic flow exist, associated with high intensity rainfall events. Valleys of this type show deep weathering along pre-Kalahari (and in some cases, pre-Karoo) lineations, and Shaw & De Vries (1988) suggest that they are compatible with groundwater erosion along preferential flow paths, a hypothesis supported by the presence of near-surface groundwater levels until the early years of the 20th century.

The Molopo and its tributaries differ from these true *mekgacha* by displaying, in varying degrees, some of the characteristics of ephemeral hardveld rivers, including some active channel development. Floods have been recorded in all four major rivers (the Molopo, Nossop, Auob and Kuruman) at approximately 20 year intervals, while the Kuruman is perennial in its headwater section as a result of spring activity. These characteristics offer the opportunity to estimate the magnitude of past rainfall events by comparison of flood deposits, for the flood that extended the whole length of the Kuruman in February 1988 in response to a regional precipitation event of an estimated return time of 1 in 100 years is a useful measure of extreme conditions.

'DRY' LANDFORMS — THE KALAHARI ERG

The Kalahari erg is dominated by linear dunes, which, in the area south of the Zambezi, have been divided into three major dune fields on the basis of dune morphology and orientation. Linear dunes account for the vast majority of all dune forms in the Mega Kalahari and some 85% of dunes in the southern dunefield (e.g. Fryberger & Goudie, 1981), where annual preciptation is lowest. The pattern of the dunefields forms a 'wheelround' reflecting the anticyclonic circulation over the subcontinent (Figure 7.4). Less common dune forms include transverse dunes (barchans, barchanoid ridges) and parabolic dunes (lunettes, nested

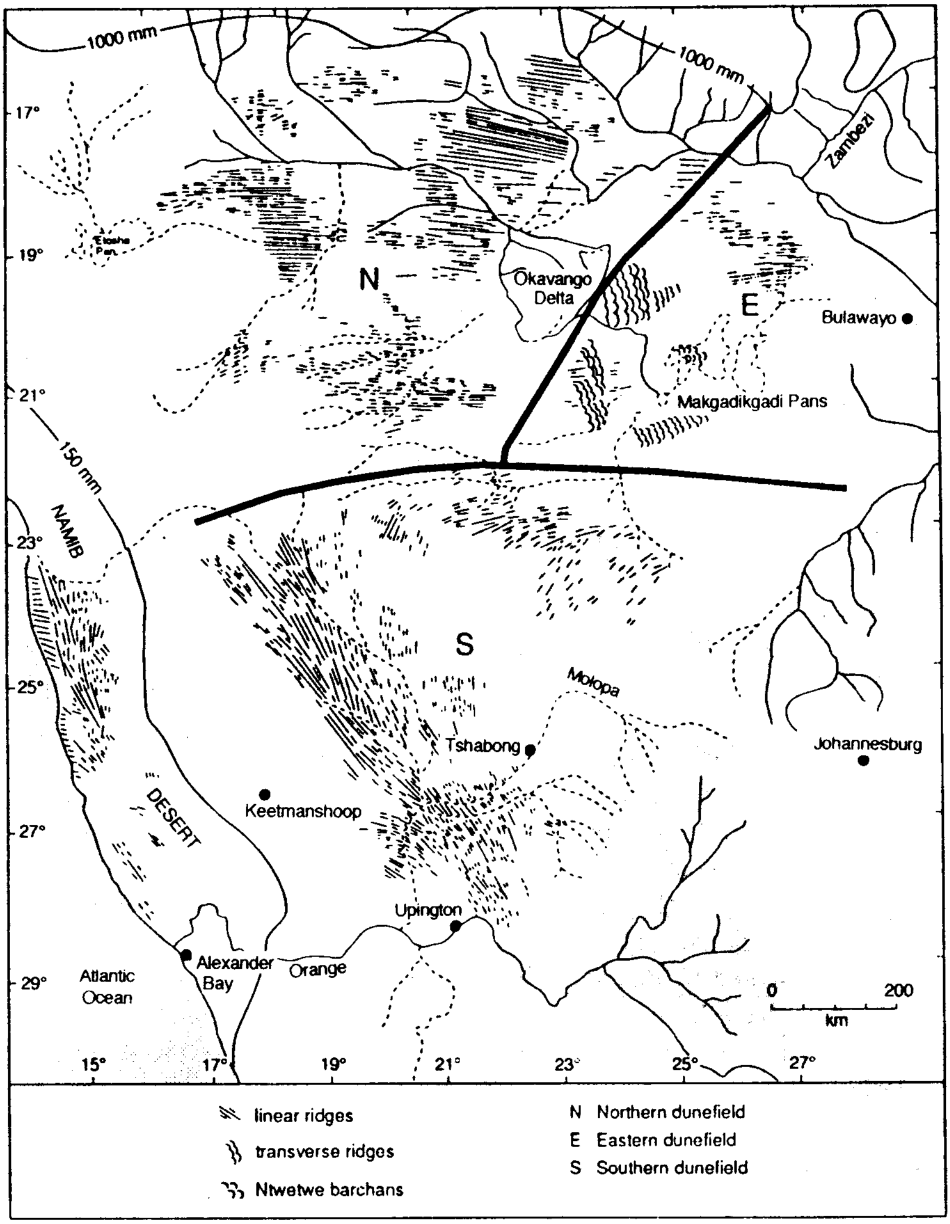

Figure 7.4 Desert dunefields of southern Africa, modified after Lancaster (1981)

parabolics). The morphometry and sedimentary characteristics of these dunefields have received detailed study (Lancaster, 1981, 1986, 1987, 1988; Thomas, 1984, 1988; Thomas & Martin, 1987).

The linear dunes have been hitherto regarded almost exclusively as relict landforms, representative of episodes of drier climate. Interpretations of the dune fields have been directed at the elucidation of the direction and strength of palaeo-wind circulations, and on identifying the extent of Quaternary aridity, based on the assumption that a maximum rainfall of 150–200 mm year^{-1} would permit dune mobility (Lancaster, 1980, 1981). Thomas (1984) pointed out that the application of this model to the erg north of the Zambezi would require an isohyet shift of 2300 km, and Lancaster (1988) has subsequently reassessed dune mobility against an index based on precipitation, potential evaporation and wind strength, concluding models that propose synchronous late glacial aridity throughout the sub-tropical arid zone (e.g. Nicholson & Flohn, 1980). Humidity in the Kalahari synchronous with glacial episodes has now been traced back to 300 000 BP (Brook, Burney & Cowart, 1990) and supports the view that the northern and southern hemispheres responded differently to changes in the earth's energy budget. Although the global glacial chronology may be revised as a result of recalibration of radiocarbon dates (e.g. Bard *et al.*, 1990), this conclusion will not be altered.

CONCLUSIONS — PROCESSES AND SENSITIVITY

The study of Kalahari geomorphology and Quaternary history has long been influenced by inferences and conclusions drawn from outside the region. Its very designation as a desert has tended to ignore its function as a depositional basin and its relatively high levels of precipitation. The undue emphasis placed on aeolian activity may not be warranted; the linear dune fields appear to be among the most stable and enduring of Kalahari landforms, for although there is evidence to suggest that sediment transport and duneform modification is taking place in southern parts of the region under a partial vegetation cover, the overall dune pattern changes little. The dune mobility often mentioned in relation to overgrazing and vegetation stripping in south-west Botswana probably relates to the local reshaping of linear dunes by blowouts once equilibrium conditions are removed. There is much to understand concerning the sensitivity of the climate–process–vegetation interactions of these forms before palaeoenvironmental certainties can be drawn from them.

The fluvio-lacustrine landforms of the Okavango–Makgadikgadi are the unique product of an unusual hydrological regime within a delicately adjusted tectonic framework. Both climatic and tectonic influences can be detected in the high degree of sensitivity revealed on Quaternary, historical and inter-annual timescales. The landforms of the swamps, and to a certain extent, of the adjoining lake basins, are the product of water volume rather than velocity. Chemical activity related to the transfer and evaporation of water has resulted in a regional suite of duricrusts and precipitates that are considerably younger than previously thought.

Influxes of groundwater and consequent chemical activity are also major long-term processes in the formation of Kalahari landforms, and in the modification of the Kalahari sediments. There has been lively debate over the past 80 years as to whether groundwater recharge of the Kalahari Group sediments has taken place *in toto* under contemporary climatic conditions. Two schools of thought exist: one (Boocock & Van Straten, 1961; Foster *et al.*, 1982) believes that recharge is limited to a capillary zone of 6 m; the other (Verhagen, Mazor & Sellschop, 1974; Mazor, 1982), based on isotope studies, suggests that recharge is uniform in neither time nor space, with concentration in zones of high infiltration (shallow sediment cover, faults, zones of vegetation penetration and bioturbation) and during years of prolonged excessive rainfall. Zones of preferential recharge (and hence a geological control) are expressed in the pan and valley landforms themselves. Experimental measurement of recharge as a function of rainfall intensity and duration has been undertaken in Botswana for the past four years and shows considerable promise (A. Gieske, 1992). Careful field mapping of duricrusts in the Kalahari should determine which are related to specific landforms, and which have formed in response to widespread groundwater inputs. The resolution of regional and localised duricrust formations would go far towards an understanding of Kalahari stratigraphy.

The palaeoclimatic pattern that has emerged for the past 50 000 years emphasises the models that propose synchronous late glacial aridity throughout the sub-tropical arid zone (e.g. Nicholson & Flohn, 1980). Humidity in the Kalahari synchronous with glacial episodes has now been traced back to 300 000 BP (Brook, Burney & Cowart, 1990) and supports the view that the northern and southern hemispheres responded differently to changes in the earth's energy budget. Although the global glacial chronology may be revised as a result of recalibration of radiocarbon dates (e.g. Bard *et al.*, 1990), this conclusion will not be altered.

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