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The Zambezi Society and The Biodiversity Foundation for Africa are working as partners within the African Wildlife Foundation's Four Corners TBNRM project. The Biodiversity Foundation for Africa is responsible for acquiring technical information on the biodiversity of project area. The Zambezi Society will be interpreting this information into user-friendly formats for stakeholders in the Four Corners area, and then disseminating it to these stakeholders.

THE BIODIVERSITY FOUNDATION FOR AFRICA (BFA is a non-profit making Trust, formed in Bulawayo in 1992 by a group of concerned scientists and environmentalists. Individual BFA members have expertise in biological groups including plants, vegetation, mammals, birds, reptiles, fish, insects, aquatic invertebrates and ecosystems. The major objective of the BFA is to undertake biological research into the biodiversity of sub-Saharan Africa, and to make the resulting information more accessible. Towards this end it provides technical, ecological and biosystematic expertise.

THE ZAMBEZI SOCIETY was established in 1982. Its goals include the conservation of biological diversity and wilderness in the Zambezi Basin through the application of sustainable, scientifically sound natural resource management strategies. Through its skills and experience in advocacy and information dissemination, it interprets biodiversity information collected by specialists like the Biodiversity Foundation for Africa and uses it to provide a technically sound basis for the implementation of conservation projects within the Zambezi Basin.

THE PARTNERSHIP between these two agencies was formed in 1996 as a result of mutual recognition of their complementarity. They have previously worked together on several major projects, including the biodiversity component of IUCN's Zambezi Basin Wetland project and the evaluation of biodiversity in Tete province described in detail in the first Four Corners TBNRM Biodiversity Information Package.

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CHAPTER 2. THE GEOMORPHOLOGY OF THE FOUR CORNERS AREA

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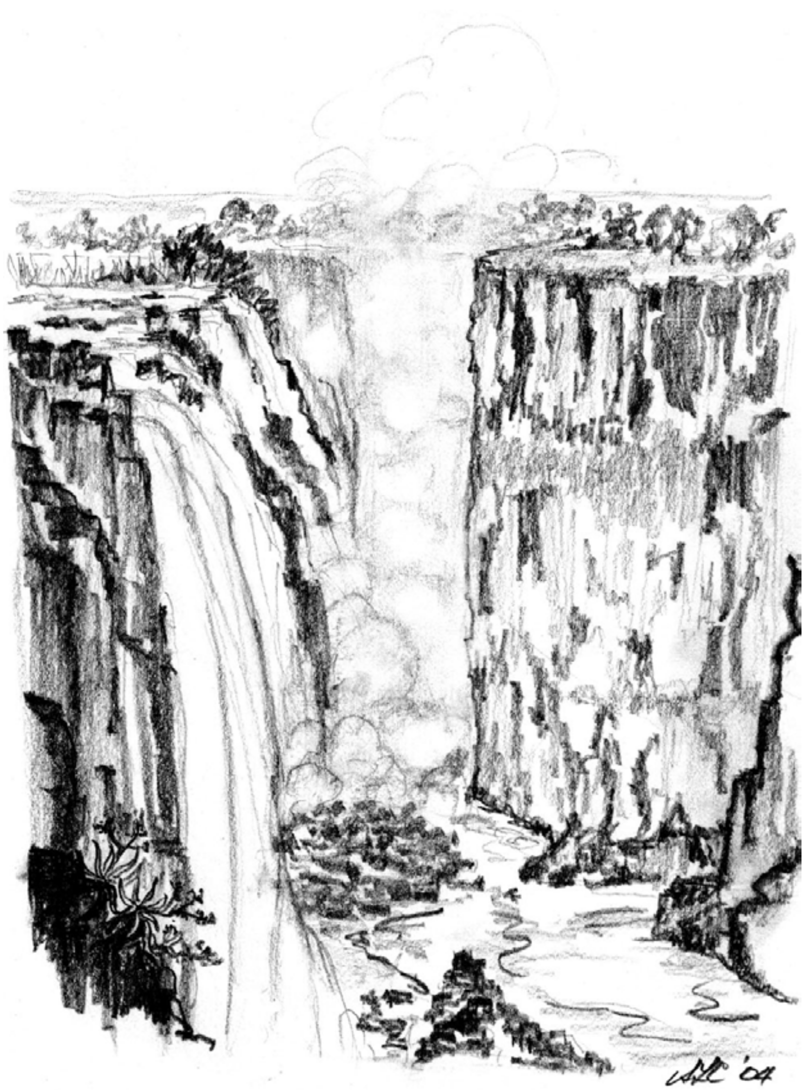
Andy Moore



Mosi-Oa-Tunya/The Victoria Falls

CHAPTER 2. THE GEOMORPHOLOGY OF THE FOUR CORNERS AREA

Andy Moore

ABSTRACT
A summary is presented of the geology of the Late-Cretaceous to Holocene Kalahari Group of sediments that blankets most of the Four Corners area. These sediments are interpreted to have been deposited in a fluvio-lacustrine environment, where inland draining rivers terminated in an inland lake system. Studies on the texture of Kalahari sands in the central Kalahari, to the south-west of the Four Corners area, show systematic grainsize and heavy mineral variations that are also consistent with fluvial deposition. Linear dune systems reflect reworking of the superficial sand during a number of late Pleistocene-Holocene arid periods.

Plant communities in the central Kalahari can be correlated with changes in the coarseness of the Kalahari sand. The microphyllous community favours areas of coarse sand, near the margins of the basin. This may reflect species' ability to tap sub-Kalahari aquifers, but further research is required to determine whether coarse-textured sand is associated with higher nutrient contents, which may be the ultimate determinant. Broad-leaved savanna species favour areas of finer sand in the central parts of the basin, which may reflect either lower nutrient contents associated with finer sand, or rooting strategies to exploit shallow-penetrating water following rainfall. The principles developed for accounting for variations in plant communities in the central Kalahari can be applied to the Four Corners area, although it is expected that there will be differences in detail.

This review also looks at drainage development across southern Africa, with particular focus on the Four Corners area. Active tectonism along dominant NE-SW lines is interpreted to reflect the present-day extension of the East African Rift system across the courses of major SE-draining rivers. This, coupled with the low relief of the area, resulted in marked changes in configuration of the river system in the Four Corners area during the Pleistocene-Holocene, in turn leading to the recent development of important wetland areas such as the Barotse floodplain, the Kafue Flats, the modern Okavango Delta fan and the Chobe-Linyanti floodplain. During the mid-Pleistocene a major inland lake (Lake Palaeo-Makgadikgadi) formed in northern Botswana, and subsequently dried out. The Okavango wetlands will ultimately be lost as a result of the capture of this river by the Upper Zambezi. The development and destruction of wetlands in the Four Corners area is thus the result of ongoing tectonic processes. Unfortunately, the timing of many of the recent geomorphological changes in the area cannot yet be established with great confidence. This important question should be addressed to refine our understanding of the evolution of ecological changes to the whole area.

2.1 INTRODUCTION

The aim of this review is to provide a background to the surface geological processes that have been responsible for shaping the geomorphological evolution of the Four Corners area, the region surrounding the point of contact of the borders of Botswana, Namibia, Zambia and Zimbabwe. In turn, this forms the basis for outlining the areas' geomorphological history, with particular focus on changes during the Quaternary (2.0 million years ago [Ma] to present). The Quaternary is subdivided into the Pleistocene (2.0-0.01 Ma) and Holocene (<10,000 years).

Table 2.1 shows the age ranges of the different geological Eras and Periods.

Table 2.1. Geological time scale for Mesozoic and Cenozioc eras.

Era	Period	Epoch	Age (Ma)	Intervals (Ma)
Cenozoic	Quaternary	Holocene	0.01	
		Pleistocene	2.0	2.0
	Tertiary - Neogene	Pliocene	5.1	
		Miocene	24.6	22.6
	Tertiary - Paleogene	Oligocene	38.0	
		Eocene	54.9	
		Paleocene	65.0	40.4
Mesozoic	Cretaceous		144.0	79.0
	Jurassic		213.0	69.0
	Triassic		248.0	35.0

Ma - million years

Virtually the entire Four Corners area is covered by a veneer of sediments of variable thickness referred to as the Kalahari Group or, more informally, as Kalahari Sand. As these sediments have a profound influence on both the geomorphology and biology of the area, they will be reviewed in some detail.

2.2 KALAHARI SAND

2.2.1 Geology

The central part of southern Africa is covered by continental sediments of the Kalahari Group, covering an area of some 2.5 million km^2 stretching from the Orange River in South Africa to the Democratic Republic of Congo in the north (Haddon 2000) (Figure 2.1a). They cover much of the eastern sector of Namibia and Angola, the west of Botswana and Zambia, and extend into NW Zimbabwe. Their distribution includes virtually the entire Four Corners Area (Figure 2.1b).

Despite the wide distribution of the Kalahari Group sediments, they have until recently been poorly investigated, as access has been limited by lack of roads, exposures are generally poor and confined to the margin of the outcrop, and fossils are rare. Much of our current knowledge of the group comes from few recent studies.

Haddon (1999) compiled a Kalahari isopach map (showing Kalahari sand thickness) based on available borehole data, illustrated in Figure 2.2. A more detailed Kalahari isopach map is available from the South African Council for Geoscience (Haddon 2000), together with a map showing sub-Kalahari geology (Haddon 2001). Haddon's isopach map shows that the thickness of the Kalahari Group varies considerably over its extent, and defines a number of sub-basins (Figure 2.2) in which thickness exceeds 300 m in places. The age of the lowermost Kalahari units is not well constrained, but is generally considered to be mid to upper Cretaceous (80-90 Ma) (Mabbutt 1955, Miller 1992). However, given the wide distribution of the sediments, it is possible that the lower units are not necessarily contemporaneous over the entire area of outcrop, and in particular in the different sub-basins. It is also worth noting that the processes responsible for initiating basin formation are poorly understood.

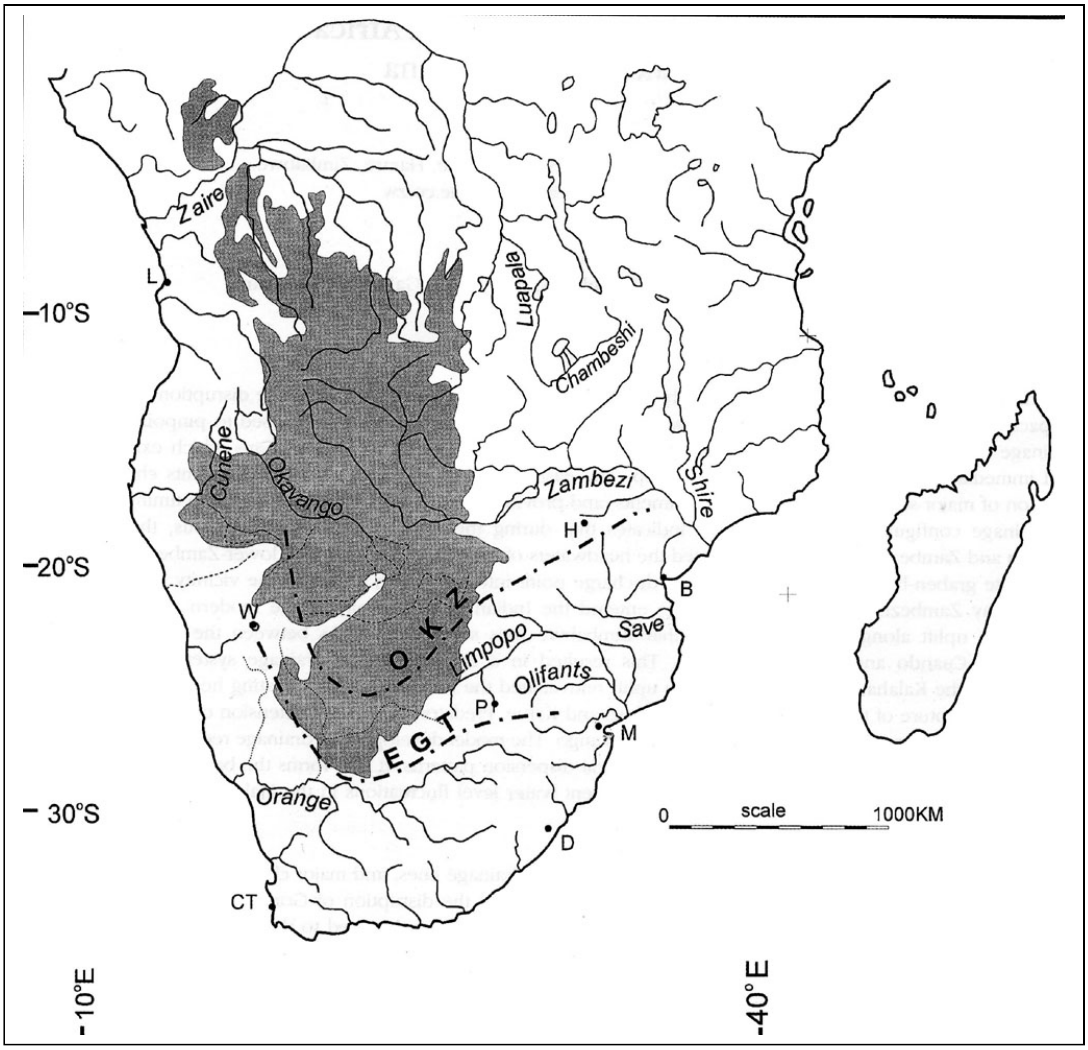


Figure 2.1a. Major drainages in Southern Africa (solid lines). Dotted lines show ephemeral and fossil drainages. Shaded area shows distribution of the Kalahari sediments. EGT Etosha-Griqualand-Transvaal axis and OKZ Okavango-Kalahari-Zimbabwe axis.

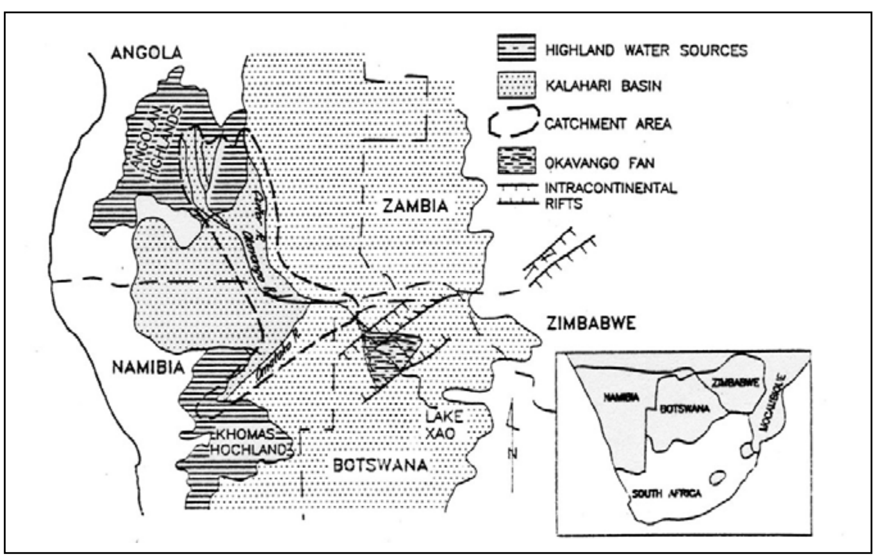


Figure 2.1b. Geological and geomorphological setting of the Four Corners area.

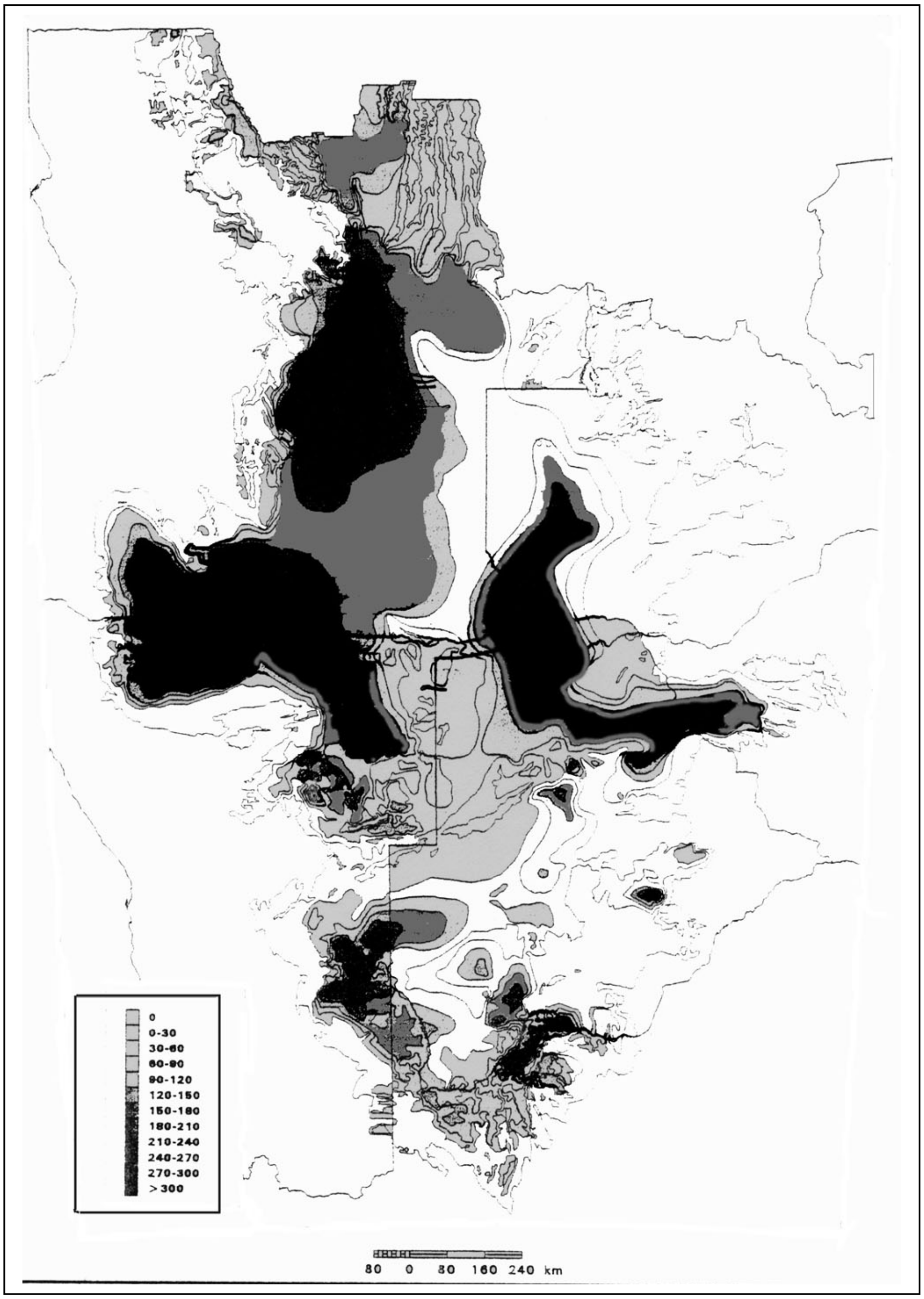


Figure 2.2. Isopach map of the Kalahari Group. excluding the portion of the basin in the Democratic Republic of Congo (thicknesses in metres).

The Kalahari succession in SW Zambia has been summarised by Thomas and Shaw (1991), based largely on the earlier work of Money (1972). The latter author divided the Kalahari in this area into a lower Barotse Formation (divided into Lower, Middle and Upper units) and an upper Zambezi Formation. The lower Barotse Formation consists of a basal conglomerate overlain by sandstone with pipe structures. The middle Barotse is comprised of ferruginous sandstones and quartzites, with bedding that was interpreted to indicate an aeolian origin. The upper Barotse Formation consists of units of massive pink quartzites, sandstones and conglomerates that are feebly cemented with calcium carbonate. The overlying Zambezi Formation consists of unconsolidated sand, duricrusts and clays associated with pans.

The only detailed study of the Kalahari Formation of NW Zimbabwe appears to be is a PhD study of the surface Kalahari sands in the Hwange area that has recently been completed. As yet, it has not been possible to access this work.

In northern Botswana, the stratigraphy of the Kalahari has been described by du Plessis (1993) based on studies of outcrops along the eastern edge of the sequence, which he terms the Kalahari Group (as opposed to Kalahari Formation). He notes that at this eastern extremity of the Kalahari, the sediments represent a condensed (compressed) sequence. The lowermost unit, the Orapa subgroup, consists of impersistent conglomerates overlain by sandstones, often characterized by tubular structures formed by the trace fossil *Thalassinoides*. This sedimentary unit is interpreted to represent fluvial (river-lain) and lacustrine (lake) deposits. Interlayered cherts and sandstones at the top of this unit are interpreted to have been deposited in a highly saline closed lake system. The Orapa subgroup would correlate with Money's Barotse Formation in SW Zambia, and the Pipe Sandstone which forms the base of the thin Kalahari sequence in the Victoria Falls area. The sediments of the Orapa subgroup are interpreted to have been deposited in basins formed by horst and graben faulting, with displacements up to 60 m. Du Plessis (1993) suggested that the basal Kalahari sediments may be 70-75 Ma in age. However, he subsequently reported a late Miocene (15-5 Ma) pollen age from basal Kalahari sediments in northern Botswana (du Plessis, pers. comm.).

The Orapa subgroup is overlain by a gravel, termed the Letlhakane Stoneline Formation (KSF). This unit reflects an intra-Kalahari period of erosion when the surface was lowered by some 25-50 m. Du Plessis (1993) notes that the KSF has a very wide lateral distribution, making it an important marker horizon. The KSF is overlain by calcretes followed by unconsolidated sand, which du Plessis (1993) correlates with the Gordonia Formation in South Africa. This would be equivalent to Money's Zambezi Formation in SW Zambia.

2.2.2 Kalahari Dunes

Degraded dune systems occur over much of the area covered by the Kalahari Group (Figure 2.3). In the Four Corners area, these include major relict dune fields in NW Zimbabwe, SW Zambia, northern Botswana, and NE Namibia (Lancaster 2000). In the past this has been put forward as evidence for an aeolian (wind-blown) origin for the Kalahari cover sands, but, as discussed later, these dunes are now considered to represent aeolian reworking of fluvial sediments during episodic arid episodes in the late Quaternary (Moore & Dingle 1998, O'Connor & Thomas 1999). In western Zimbabwe, periods of dune development have been dated at 115-95 ka, 46-41 ka, 26-20 ka and 16-9 ka (i.e. late Pleistocene and Holocene) on the basis of optical luminescence dating techniques (Stokes, Thomas & Washington 1997). Some 500 km to the north, in western Zambia, episodic late Quaternary episodes of dune construction were dated at 32-27 ka, 16-13 ka, 10-8 ka and 5-4 ka. This lack of correlation in the ages of dunes in different areas of the Kalahari suggests either regional variations in the timing of the main phases of dune building (Thomas *et al*. 2000), or problems associated with the dating technique. A particular problem is that bioturbation is probably responsible for continuous overturn of the surface sands, and could lead to spurious ages.

It should also be noted that samples used to date the dune systems in the Kalahari have generally been derived from shallow depths (<1.5 m). The Pleistocene (i.e. the past 2 million years) was a period of major global climatic oscillation, with at least four main glacial advances separated by intervening periods of warmer climatic conditions. Such climatic oscillations may have triggered episodes of Pleistocene aridity and dune building in the Kalahari earlier than those recognized to date.

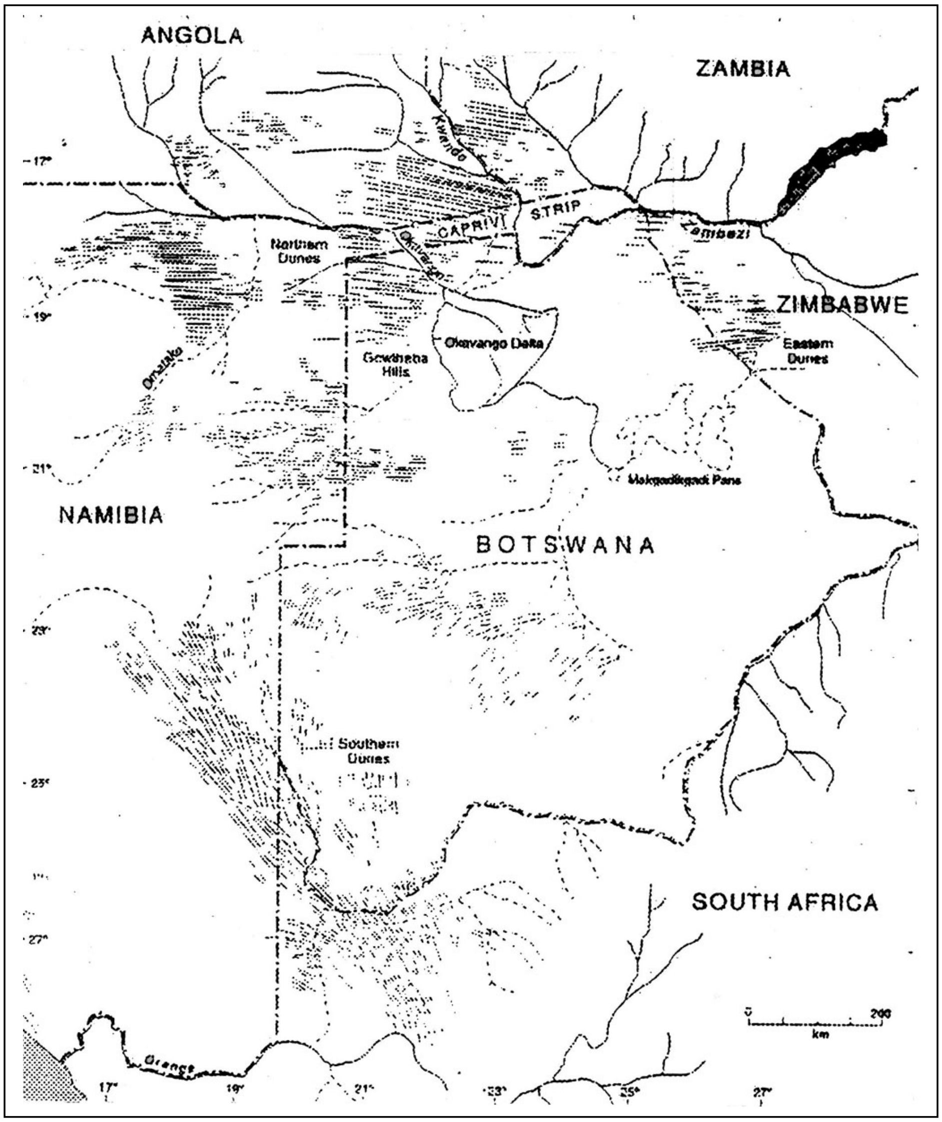


Figure 2.3.
Dune systems of the Mega Kalahari

2.2.3 Kalahari Sand Texture

Apart from the afore-mentioned recent PhD of the cover sands in the Hwange area of NW Zimbabwe, little systematic work has been carried out on the textures of the surface Kalahari sands in Four Corners area. As a result, it is necessary to draw on studies from peripheral areas.

A reconnaissance study of sand textures of the Kalahari surface sands over the whole of Botswana was carried out by Ballieul (1975). This study was hindered by poor access to much of the central Kalahari at the time the work was carried out, and the very broad sample spacing. He divided the Kalahari within Botswana into four broad areas, and argued that the texture (grainsize) of the surface sands closely reflected that of the underlying bedrock, in other words that the sand was very locally derived from disaggregated bedrock.

Moore and Dingle (1998) subsequently showed that the surface sands in the central Kalahari (immediately to the southwest of the Four Corners area) show very systematic grainsize and heavy mineral distribution patterns, with higher proportions of coarse (>425μm) sand and heavy minerals (such as tourmaline) concentrated in the area of high ground along the basin margin, while greater proportions of the finer sand fractions characterize the central basin. They noted that these patterns are not readily explained in terms of aeolian deposition, but pointed rather to fluvial deposition by low gradient drainages with headwaters in the high ground surrounding the central Kalahari basin. This is consistent with the conclusion reached by du Toit (1927) that the Kalahari cover sands in central Botswana are fluvial (i.e. laid down by rivers). The coarse sand and elevated concentrations of heavy minerals associated with the margin of the Kalahari basin were interpreted as a lag, that is material that has experienced minimal transport away from the source rocks at the basin margin. Finer sand fractions, which are more readily transported by low gradient fluvial systems, were selectively concentrated in the deeper parts of the basin. The dune features that characterise much of the Kalahari sands in the Four Corners area may therefore reflect aeolian reworking of sands previously deposited in a fluvial environment (Moore & Dingle 1998, O'Connor & Thomas 1999).

Circumstantial evidence for fluvial deposition of the Kalahari sand cover in Zimbabwe comes from the Kalahari outlier near Mvuma, on the central Zimbabwe watershed (Moore 1996). Borehole evidence shows that in this area the Kalahari consists of a series of upward fining sequences that fill a broad sub-Kalahari valley. Each sequence typically commences with basal gravels, and grades upwards through coarse to fine sand and clay. Such upward-fining sequences are characteristic of deposition by mature meandering river systems. This could, in turn, have supplied sediment to the NW Zimbabwe Kalahari basin.

It should be noted that while there is evidence from several areas for fluvial deposition of Kalahari sand, further research is required to establish whether this is true over the entire area blanketed by it, particularly in the Four Corners area, where there is a dearth of sand textural data.

2.2.4 Factors Controlling Vegetation Distribution across the Kalahari

Rainfall is clearly a major factor influencing vegetation distribution in areas of Kalahari sand cover. This is well illustrated by the systematic change in plant communities in Botswana from the northeast to the southwest (Weare & Yalala 1971). Dry deciduous forest, with *Baikiaea plurijuga* as the dominant tree species, occurs in the extreme northeast of the country. To the southwest, this deciduous forest is replaced by a broadleaved savanna community, where *Lonchocarpus nelsii, Terminalia sericea, Ochna pulchra* and *Bauhinia petersiana* subsp. *serpae* are characteristic, sometimes associated with mixed *Acacia* species. This savanna community extends over much of the central Kalahari, but to the southwest it is replaced by a microphyllous savanna, with the woody component dominated by *Acacia* species. These vegetation changes broadly track to the rainfall gradient from over 650 mm in the northeast to less than 250 mm in the southwest.

While precipitation is clearly the dominant factor affecting vegetation distribution, there are a variety of factors that appear to play a subordinate role. These are discussed here, as comparable controls may influence vegetation patterns in Kalahari sand areas.

Moore and Attwell (1999) investigated the relationship in the central Kalahari between variations in grainsize of the Kalahari sand and the distribution of plant communities and individual plant species.

The method of Cole (1949) was applied to test whether there is a statistical correlation between sand grainsize and the distribution of the broadleaved and microphyllous savanna communities. The test indicated that the broadleaved community shows a significant correlation with areas of finer sand, characterized by <5% of the coarse (>425 μm) sand fraction (r=0.36 at the 1%

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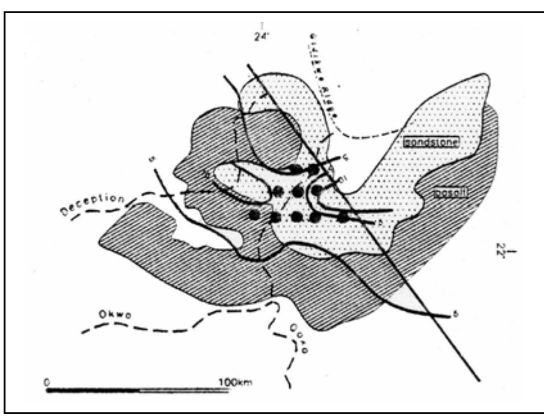
confidence level). It was demonstrated that individual woody species characteristic of the broadleaved savanna community also show a positive correlation with areas of relatively finer sand. On the other hand, the microphyllous community was positively correlated with areas of coarser sand (r=0.60 at the 1% confidence level). These correlations suggested that sand grainsize, either directly or indirectly, represents a secondary influence on vegetation distribution in the Kalahari superimposed on the dominant effect of rainfall.

Moore and Attwell (1999) noted that the isoline marking >5% of the coarse (>425µm) sand fraction, reflects shallowing of the Kalahari basin towards a gentle rise known as the Kalahari Schwelle, where exposures of basement rocks protrude through the Kalahari sand cover. They proposed that the ecotone between broadleaved and microphyllous savanna communities is not controlled by grainsize as such, but it is the decreasing sand thickness that is the ultimate determinant. In other words, the steep sand grainsize gradient, and marked increase in the numbers of heavy minerals, are merely monitors of shallowing bedrock. Areas of shallow sand would favour the deep-rooting microphyllous community, which is able to tap aquifers in sub-Kalahari formations or faults and fractures in the basement rocks. In areas of deeper sand cover, plants are not able to tap sub-Kalahari aquifers, and are therefore reliant on rainfall. Personal observations by the author, based on pits dug following severe showers (50 mm downpours), suggests that in the finer-grained areas of the central Kalahari, water seldom penetrates more than a few metres beneath the surface - these sands appear to act as a sponge. However, deeper penetration probably occurs in areas of coarser, more porous cover sands. Areas of fine sand cover and limited water penetration would therefore favour broadleaved species (e.g. *Terminalia sericia* and *Bauhinia petersiana*) with well-developed lateral root systems.

Further evidence for the influence of bedrock in controlling vegetation distribution is illustrated by *Colophospermum mopane*. The distribution of this species extends an embayment into the east of the area investigated by Moore and Attwell (1999), and corresponds closely to the sub-outcrop beneath the Kalahari sand cover of the Karoo-age Ntane Sandstone Formation, which is often a good aquifer (Figure 2.4a). (The Ntane Formation is the equivalent of the Clarence Formation in South Africa, formerly known as the Cave Sandstone). The correlation between the distribution of *C. mopane* and a sub-Kalahari aquifer suggests that the western extent of this species is determined by the ability to tap this aquifer (Figure 2.4b).



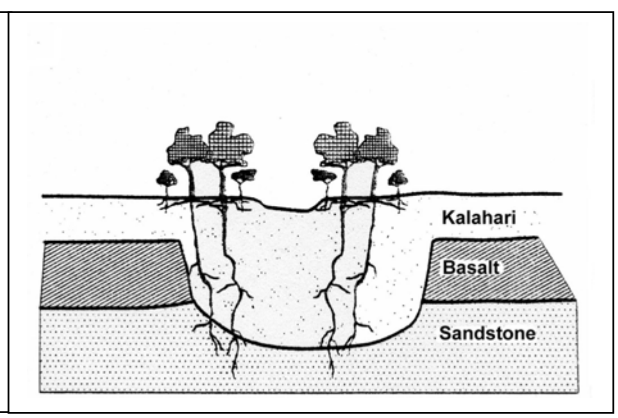


Figure 2.4a. Filled circles show localities where *Colophospermum mopane* was found. The diagonal (northwest-southeast) line is the eastern boundary of the Central Kalahari Game Reserve. Narrow diagonal lines show where the Kalahari sand is underlain by Karoo basalt. Stippling denotes areas underlain by Karoo sandstone.

Figure 2.4b. Section showing the inferred relationship between the distribution and structure of *C.mopane* and the sub-Kalahari geology.

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Albizia anthelmintica is another species with a distribution in the central Kalahari that appears to be related to the ability to tap basement aquifers. It is the dominant species fringing some of the fossil drainage lines in the Kalahari, which, in turn, show a close correspondence with the location of fractures and faults in the underlying sub-Kalahari bedrock. This suggests that *A. anthelmintica* is able to access sub-Kalahari aquifers related to such structural features. The species also occurs as mono-species "tree islands" in areas of extensive grassland. The precise factors favouring the preservation of such islands is speculative, although it may be related to local access to sub-Kalahari groundwater, possibly in areas of shallow bedrock. Moore and Attwell (1999) tentatively suggest that such "tree islands" are relics of a former more extensive distribution range, related to an earlier climate regime during the Quaternary. A number of authors (e.g. Scholes 1990, Scholes & Walker 1993) have proposed that soil nutrient content is a major determinant controlling savanna vegetation, and that microphyllous communities favour areas with higher nutrient content. This conflicts with the conclusion reached by Moore and Attwell (1999) that in the central Kalahari, the ecotone between the broadleaved and microphyllous communities is determined essentially by rooting strategies, and the ability to access different water resources. However, their study did not include chemical analysis of surface Kalahari sands. It is therefore necessary to consider whether areas of coarser sand in the central Kalahari are associated with elevated nutrient concentrations. While further work is required to resolve this issue, Moore and Attwell (1999) noted that areas of coarse sand are characterized by the presence of greater proportions of sand grains bonded by a ferruginous cement - in other words, by incipient ferricrete development. They pointed out that precipitation of insoluble iron oxides would be favoured in areas of coarser, more porous sand, where water would be drawn to the surface by capillarity effects. In the oxidising surface environment, relatively soluble ferrous ions would then be converted to the insoluble ferric state, and precipitated as ferric oxide. Precipitation of insoluble iron oxides is generally associated with the leaching of more soluble salts. Areas of coarse sand associated with the microphyllous savanna community in the central Kalahari would therefore be expected to be poorer in nutrients that the finer-grained sands.

Moore and Attwell (1999) demonstrate that within their central Kalahari study area, vegetation structure can be correlated with sand grainsize. They envisage that in areas of finer, less permeable sand, water penetration during rains is restricted, favouring shallow-rooting grasses and shrubs. Deeper water penetration in areas of coarser sand on the other hand favours deeper-rooting trees.

Kalahari topography also appears to play a local role in influencing plant distribution. Thus, in the Deception Pan area of the Central Kalahari, *Terminalia prunioides* favours the crests of sand dunes – an association that is highlighted when the species is fruiting. In northern Botswana, *Baikiaea plurijuga* also appears to favour dune crests. However, the ultimate factors determining such distribution patterns are not well understood (see Robertson, Chapter 3 and Childes, Chapter 4).

It should be stressed that the question of whether plant communities in the Kalahari environment are influenced primarily by soil nutrient content, or rooting strategies and the ability to tap differing water sources, remains contentious, and more work is clearly required to resolve this issue.

2.3 GEOMORPHOLOGICAL EVOLUTION OF THE FOUR CORNERS AREA

2.3.1 Concepts of River Evolution

Rivers erode their courses to an ultimate *base level* where they enter the sea. When a drainage system is initiated on any newly emergent land surface, rivers will initially flow to the lowest position (consequent drainage), and the energy so derived will develop the valleys by rapid downcutting. During this initial stage of incision, rivers will have steep gradients and eroded material is transported downstream, where it will be temporarily deposited, until ultimately it is transported to the ocean. This leads to a progressive decrease of the gradient of the lower sections of the river, until a stage of equilibrium is reached where, on average, there is a balance between erosion and deposition along the lower sections of the river course, which is now said to be *graded*. Given time and continued river evolution, the graded section of the river will extend headwards, ultimately producing a smooth *long profile* when river altitude at any point is plotted against distance from the sea. In practice, few rivers ever become continuously graded over their entire length. Sharp breaks in profile, marked by rapids or waterfalls, occur where they cross resistant rocks such as quartzites or dolerites, forming *knickpoints* along the river course. The Victoria Falls is a spectacular example of such a knickpoint. These knickpoints can act as *local base levels* for the higher stretches of the river - in other words, the upper section of the river is graded to the knickpoint, and the lower sections to a different base level, such as the sea. Lakes that form on a river course may also form temporary local base levels, although these will ultimately be filled with river sediment and eliminated from the river profile. These principles are illustrated in Figure 2.5.

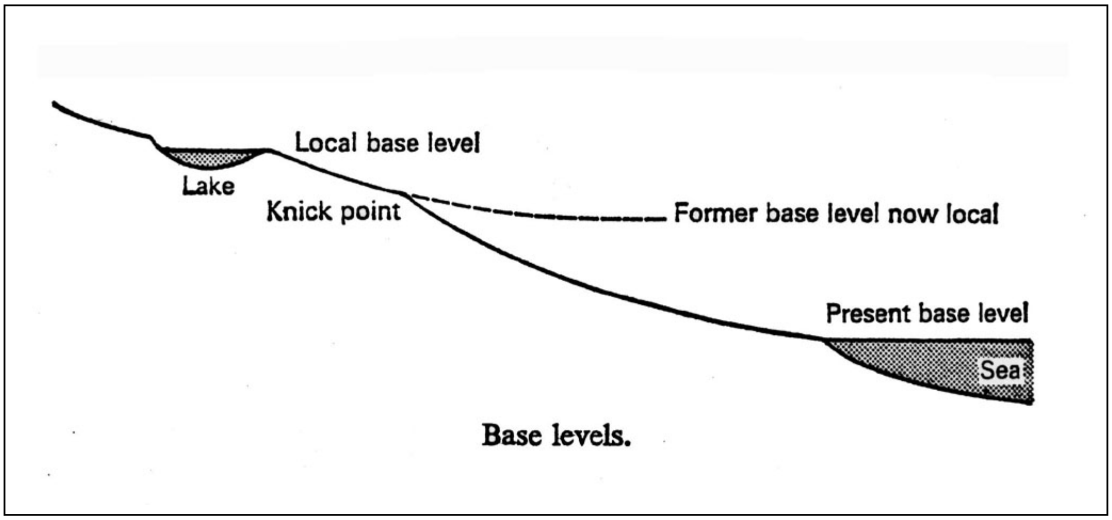


Figure 2.5. Changes to base levels through the process of erosion.

The idea that rivers evolve from an early stage of rapid incision to one of equilibrium between erosion and deposition led to the concept of a cycle of erosion from a *youthful* stage, involving rapid incision, to a stage of *maturity,* and finally *old age or senility*, when the landscape was reduced to a plain of low relief, traversed by well-graded meandering streams. At any stage in this cycle, if there was either a drop in sea level or a rise of the continent, the river base level would effectively be lowered. This will initiate a renewed episode of downcutting, resulting in *rejuvenation* of the lower sections of the river. Note that such rejuvenation will not influence stretches of the river above a temporary base level such as a waterfall or lake.

2.3.2 Factors that Modify Drainage Systems

River systems are not static, and have clearly undergone major changes over geological time. Moore and Larkin (2001) provide a discussion on the evolution of river systems in south-central Africa since the disruption of Gondwana. A variety of different processes contribute to modifying drainage patterns; some of the more important of these are discussed below.

River erosion is often held to result in the headward extension of the upper reaches of the drainage basin (although the processes involved are currently the centre of considerable debate). Youthful streams, associated with active incision, will extend their headwaters more rapidly than mature or senile streams. This can ultimately result in an aggressive drainage system extending its course, or that of one of its tributaries, across the line of a river in an adjacent drainage basin. The result is *river capture* or *river piracy*; the more aggressive drainage will capture the upper reaches of the adjacent river. The point of capture is often marked by an abrupt change in the direction of flow, referred to as a *capture elbow*. An example, discussed in greater detail in following sections, is the sharp change in direction of flow of the Kafue from a N-S to a W-E course in the Kafue Flats area (Figure 2.6). A further example is the change in course of the Luangwa from NE-SW to NW-SE direction immediately above its confluence with the Zambezi. It should be noted that while a sharp change in a river course highlights a possible point of river capture, it does not, on its own, prove that capture has taken place. Independent evidence is required to support such a possibility.

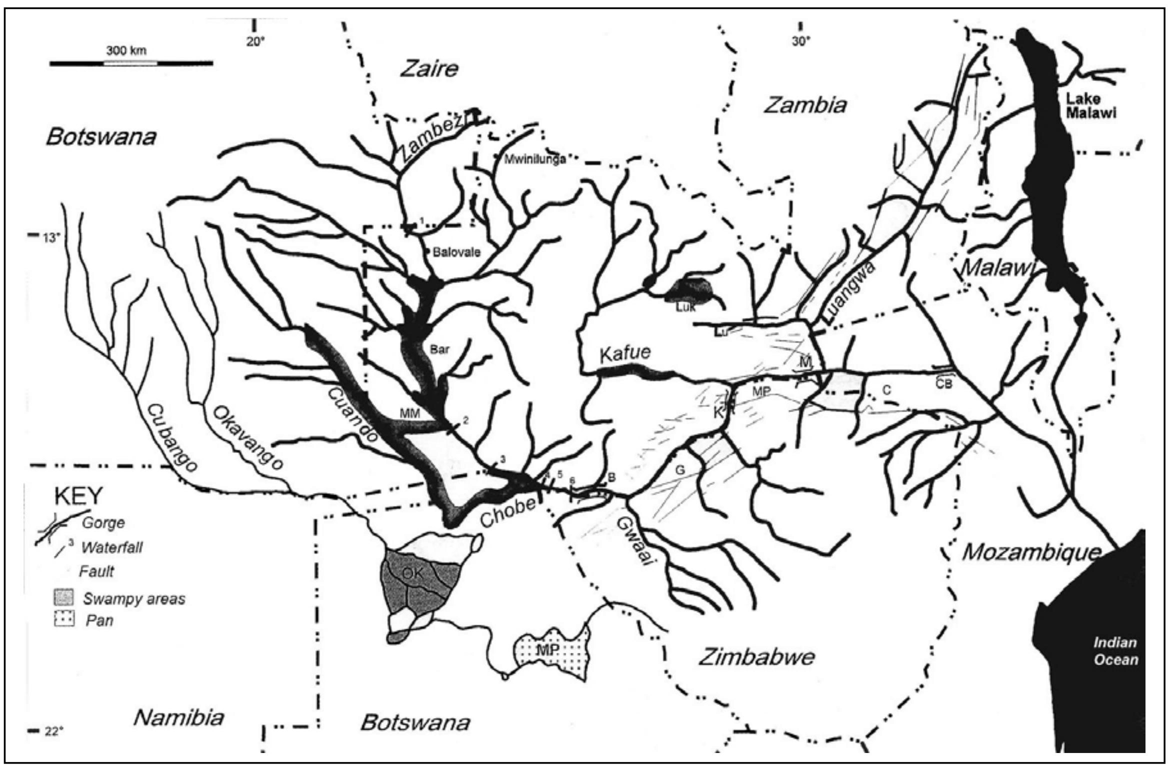


Figure 2.6. Detail of the Zambezi drainage system (adapted from Nugent, 1990).

Rift basins: G Gwembe trough (Mid Zambezi basin); MP Mana Pools basin; C Chicoa trough (Lower Zambezi basin).
Gorges: B Batoka; K Kariba; M Mupata CB Cabora Bassa.
Rapids and Falls: 1 Chavuma; 2 Gonya; 3 Katima Mulilo; 4 Mambova; 5 Katombora; 6 Victoria Falls.
Rivers: Lu Lunsemfwa.
Swamps and Marshes: Bar Barotse floodplain; Luk Lukanag; MM Mulonga-Matabele floodplain; OK Okavango.
Pans: MP Makgadikagadi Pans.

A variety of tectonic processes (earth movements) can also lead to marked changes in drainage systems. Thus, faulting across the line of a river will act as a dam, diverting the flow of water. A fine example of this is provided by the Linyanti fault which developed across the original course of the Cuando River. This deflected the river from an earlier southeast course, across eastern Botswana, to the northeast, to link with the Zambezi via the Chobe River (Moore & Larkin 2001) (Figure 2.7). The sharp change in course of the Cuando River, from southeast to northeast, is a further example of a capture elbow. In this case, however, river capture was initiated by faulting which disrupted an earlier drainage line, rather than headward erosion.

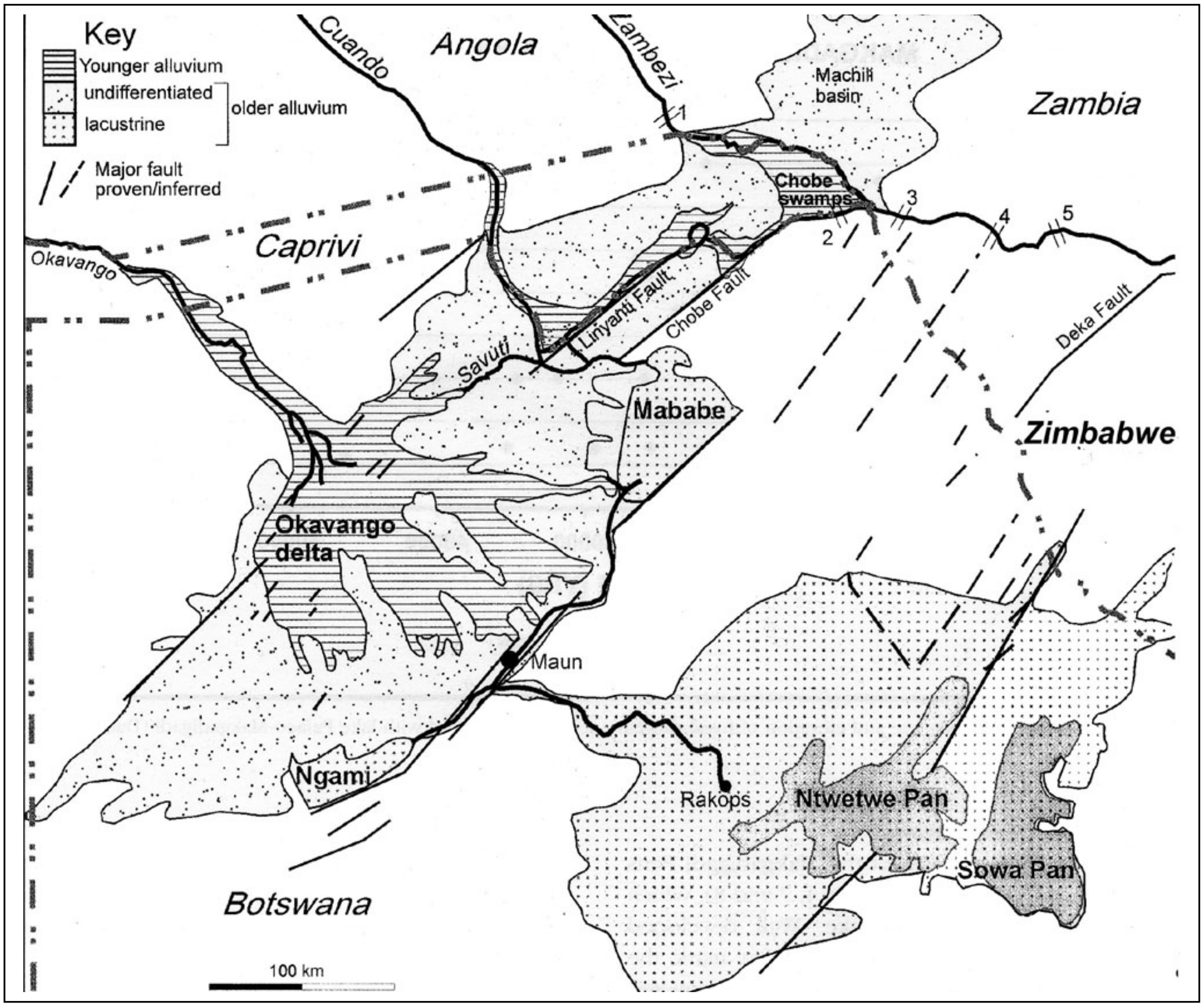


Figure 2.7. The distribution of alluvial and lacustrine sediments in north-eastern Botswana and southern Zambia.

The alluvium of the Machili basin possibly extends further to the north-east as far as the Kafue River. Limits of the older alluvial deposits reflect the possible extent of Lake Palaeo-Makgadikgadi associated with the highest recognised shoreline of 945 m (Thomas and Shaw, 1991). This formed two subsidiary basins, linked via a narrow neck along the Boteti valley. Note that the southwest-northeast trending basin which crosses the modern Okavango delta is strongly fault-controlled.

Rapids and Falls: 1 Gonya; 2 Katima Mulilo; 3 Mambova; 4 Katombora; 5 Victoria Falls.

In a remarkable paper published in 1933, the great South African geologist, Alex du Toit, recognized earth movements of a different character, which affected large areas of the sub-continent, and played a profound, but still poorly appreciated role in shaping its geomorphology. He proposed (Du Toit 1933) that the divides separating the major southern African river systems reflect axes of relative broad-scale uplift or flexuring of the continent. These were associated with the concomitant development of major depressions or basins.

Of particular importance for the Four Corners area, is the divide between the Zambezi and Limpopo systems, which forms the central watershed spine of Zimbabwe. This divide swings to the south-southwest in eastern Botswana, separating the Limpopo from fossil drainage lines that originally emptied into the Makgadikgadi Pan complex. Du Toit (1933) interpreted this watershed to be an axis of relative crustal uplift, which he designated the Kalahari-Rhodesian (now Kalahari-Zimbabwe) axis. He proposed that uplift along this line of flexure was associated with the development of a major basin to the west, to form the Makgadikgadi-Okavango depression. Du Toit (1927) recognized that the axis of uplift that now defines the eastern Botswana drainage divide was responsible for disrupting the former link between the Okavango and Limpopo rivers.

On the basis of a variety of recent lines of evidence, Moore (1999) proposed a revised configuration of the major flexure axes recognized by du Toit (1933). He envisaged that both the Kalahari-Zimbabwe and Griqualand-Transvaal axes curved to the northwest, and thus, with the Escarpment Axis, formed three roughly sub-concentric lines of relative uplift, broadly parallel to the modern coastline (Figure 2.8). These revised axes were termed the Ovamboland-Kalahari-Zimbabwe (OKZ) and Etosha-Griqualand-Transvaal (EGT) axes, respectively. Moore (1999) noted that the EGT axis crosses the fossil line of the channel that originally linked the Molopo River to the Orange. Disruption of this former link between the two rivers was ascribed to the uplift along the EGT axis. He also concluded that the three sub-concentric axes were of different ages. Formation of the Escarpment Axis was ascribed to break-up of Gondwana during the period 150-120 Ma, an upper Cretaceous (approximately 80 Ma) age was inferred for the EGT Axis, and a late-Cretaceous-early Tertiary age (approximately 65 Ma) was tentatively ascribed to the OKZ axis, although this is not well constrained.

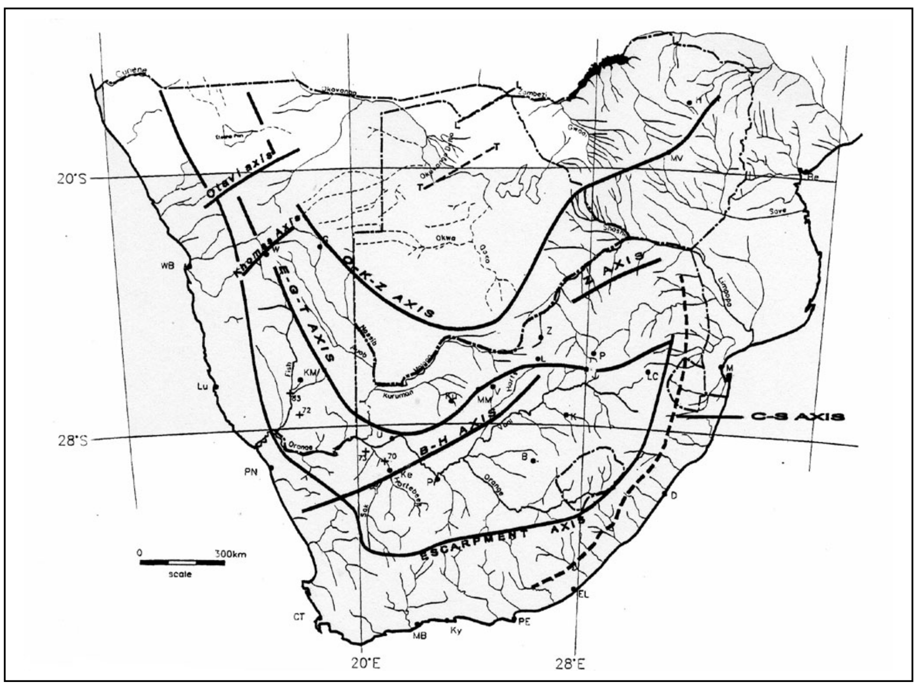


Figure 2.8.
Revised epeirogenic flexure axes.
B-H = Bushamanland-Harts axis;
C-S= Ciskei-Swaziland axis;
E-G-T= Etosha-Griqualand-Transvaal axis;
O-K-Z = Okavango-Kalahari-Zimbabwe axis;
Z = Zoutspansberg axis;
T-T = Thamalakane fault;
L-L = Linyanti fault.

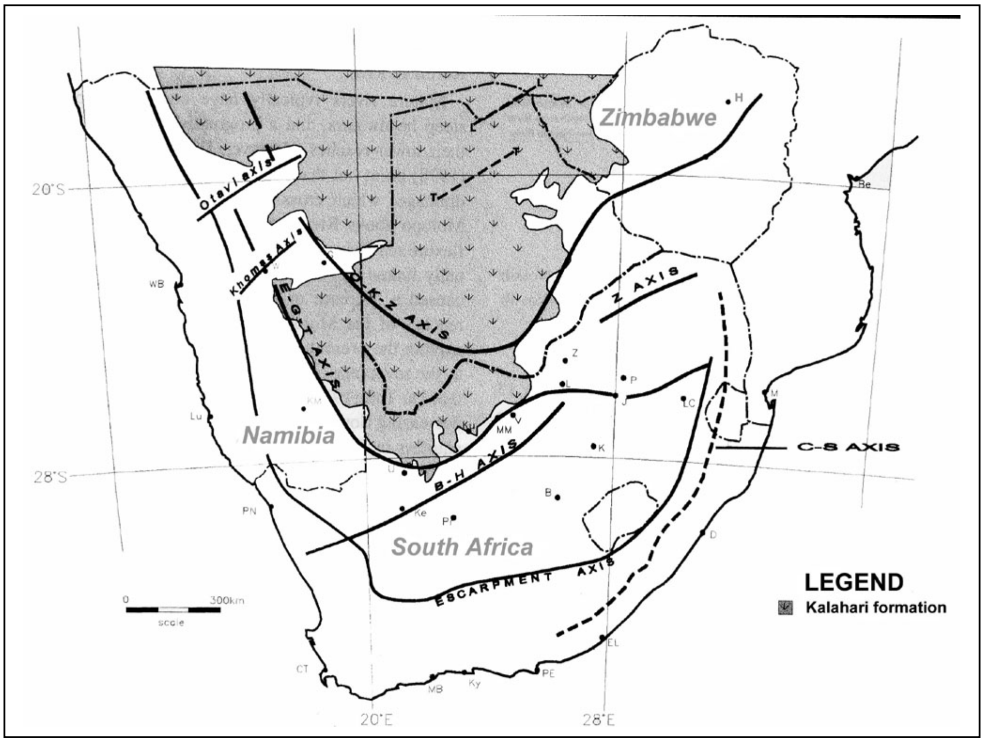


Figure 2.9. Location of the epeirogenic flexures axes in relation to the main Kalahari formation. Abbreviations as for Figure 2.8.

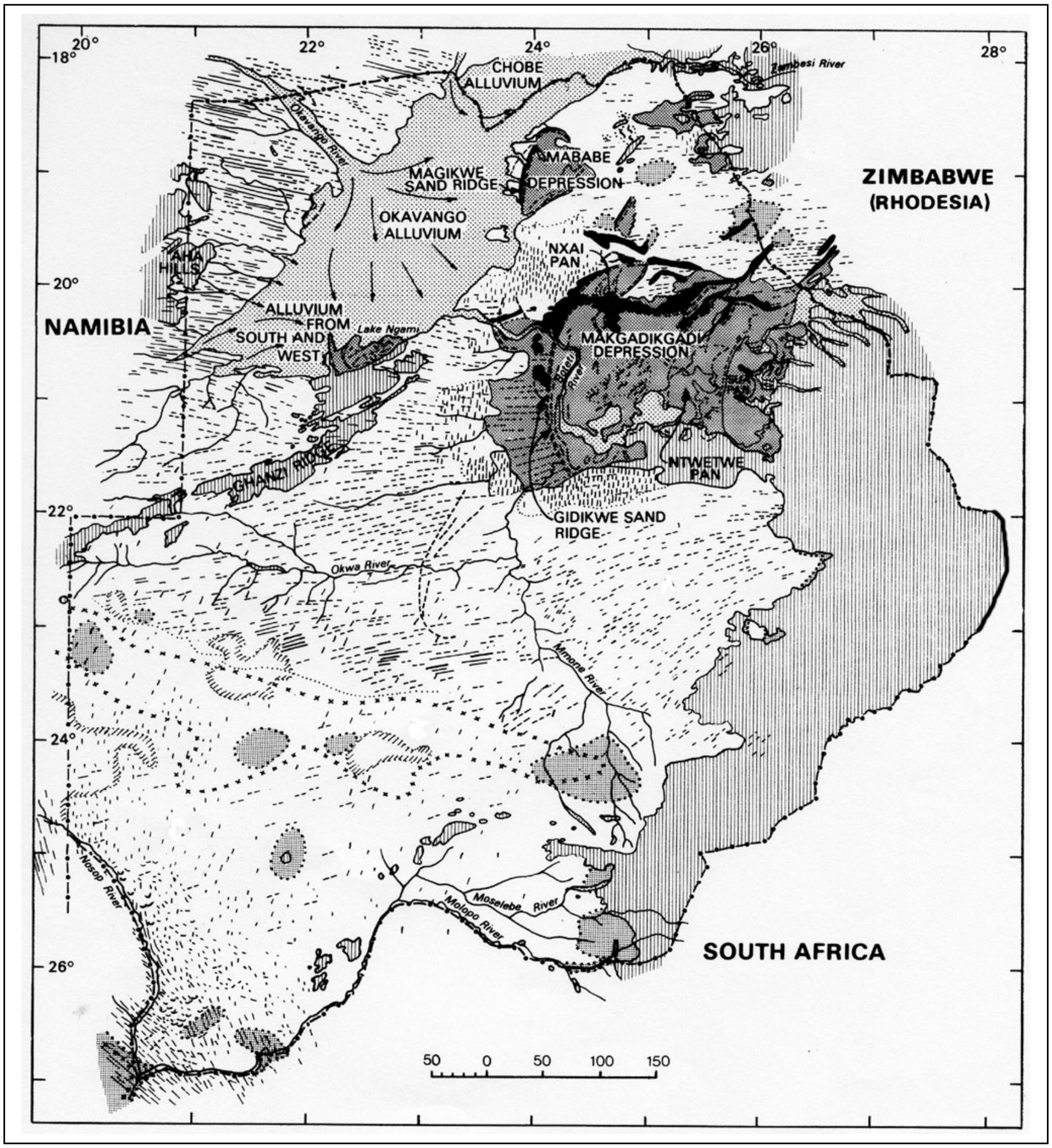
Moore (1999) noted that the line of the EGT axis closely follows the southern margin of the Kalahari sand. Further north, the eastern boundary of the Kalahari sand cover is closely associated with the OKZ axis (Figure 2.9). It was proposed that uplift along these lines of flexure disrupted old drainage lines such as the Okavango and Molopo, causing them to terminate in internal drainage basins. The result was the deposition of sediment carried by these rivers within these basins to form the widespread sand cover of the Kalahari Formation. This is consistent with the conclusion of du Toit (1927), Mabbutt (1955) and Moore and Dingle (1998) that the Kalahari sand cover is fluvial (i.e. river-lain) rather than aeolian (deposited by wind).

2.3.3 Factors Controlling River Evolution in the Four Corners Area

Two factors have been of specific importance in shaping the geomorphology of the Four Corners area:

a) Firstly, this is an area of low, gently rolling relief, with an altitude largely bounded by the 900 m and 1100 m contours. The country is traversed by a number of large mature rivers, with very low gradients. For example, over a distance of some 340 km from the Ngonye Falls in Zambia to the Victoria Falls, the Zambezi has an average gradient of 1:4250, but the 160 km stretch of the river below Victoria Falls, as far as the confluence with the Gwayi, has a steep average gradient of 1:380 m, characteristic of a youthful drainage line. (Gradients calculated from data presented by Nugent 1990.) The Okavango River in Botswana is similarly characterized by low gradients, varying from 1:3400 to 1:5570 (McCarthy *et al*. 1997, Gumbricht *et al*. 2001).

b) Northern Botswana is traversed by a number of major faults, with a general NE-SW strike (Figure 2.7). These truncate late Pleistocene to Holocene age dunes (Figure 2.10) (Mallinck, Hapgood & Skinner 1981) indicating that they are of relatively young age. Recent sieismic activity in northern Botswana, along a broadly NE-SW axis (Scholz, Koczynski & Hutchins 1967, Reeves 1972), indicates that at least some of the faults are



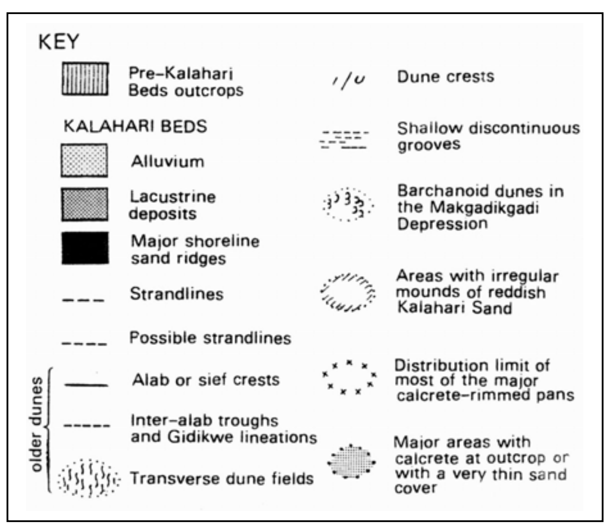


Figure 2.10 The post-Karoo deposits of the Kalahari Desert area of Botswana.

probably still active. Major faults, also with general NE-SW strikes, have been recognized in SW Zambia. In this area, east bank tributaries of the Zambezi (e.g. the Lui, Lumbe and Njoko) have remarkably straight courses, also with a NE-SW orientation, strongly suggesting that they are structurally controlled, and probably fault-related. The major NE-SW fault system recognized in northern Botswana therefore probably extends well to the north into SW Zambia. It is generally considered to represent an extension of the Great Rift System of East Africa (Scholz *et al.* 1967, Reeves 1972). This system of active faulting runs transverse to major rivers in the Four Corners area, such as the Kavango, Cuando and Zambezi, which have predominantly NW-SE courses. Given the exceptionally low relief of the area, uplift along a fault traversing these drainages would potentially disrupt their courses.

The sharp change in course of the Cuando River from southwest to northeast, becoming the Linyanti at the Botswana border, is a striking example of the disruption caused by faulting across a drainage line (Figure 2.7). This diverted the river from an original southeasterly course across Botswana to the northeast to link with the Zambezi. The damming effect of the fault also caused the Cuando to drop its sediment load, and to produce the shallow Linyanti floodplain now extensively colonized by reed beds.

A further striking example of tectonic disruption of a drainage line is provided by the Okavango. Uplift along the Thamalakane and Kunyere Faults across the river course initiated the formation of the modern deltaic fan. The damming effect of the faults resulted in the Okavango depositing its sediment load, enhancing the low gradients of the area. This has had a major influence on sedimentation patterns and channel development in the Okavango Delta (McCarthy *et al*. 1986, Cairncross *et al.* 1988) (Figure 2.11).

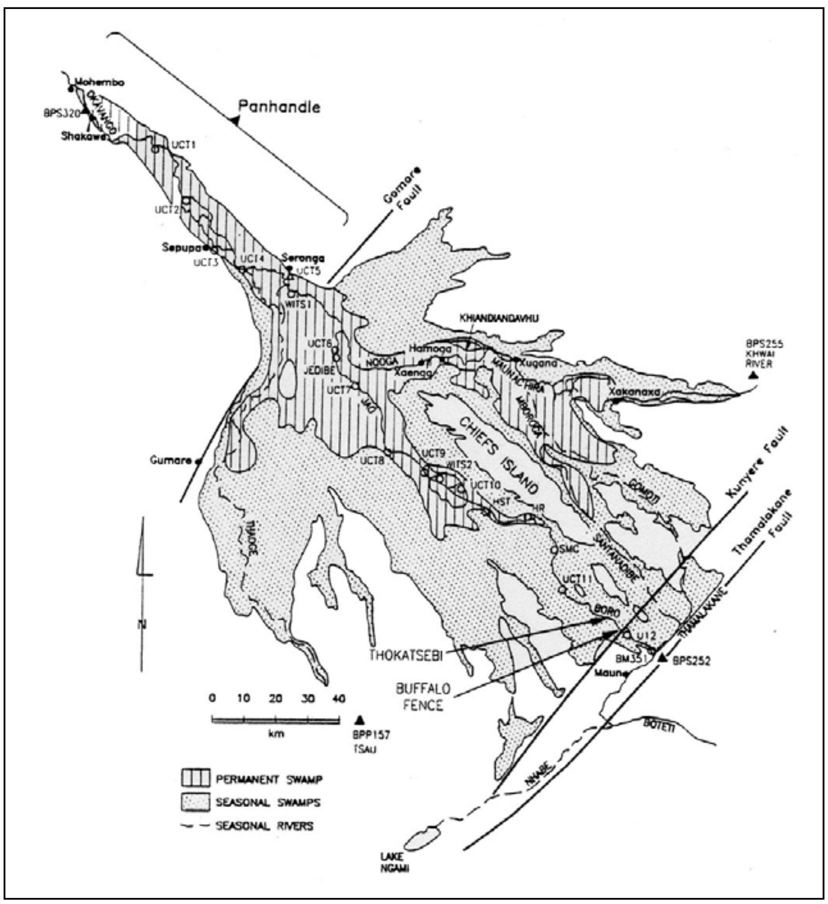


Figure 2.11. The Okavango fan showing location of fault lines

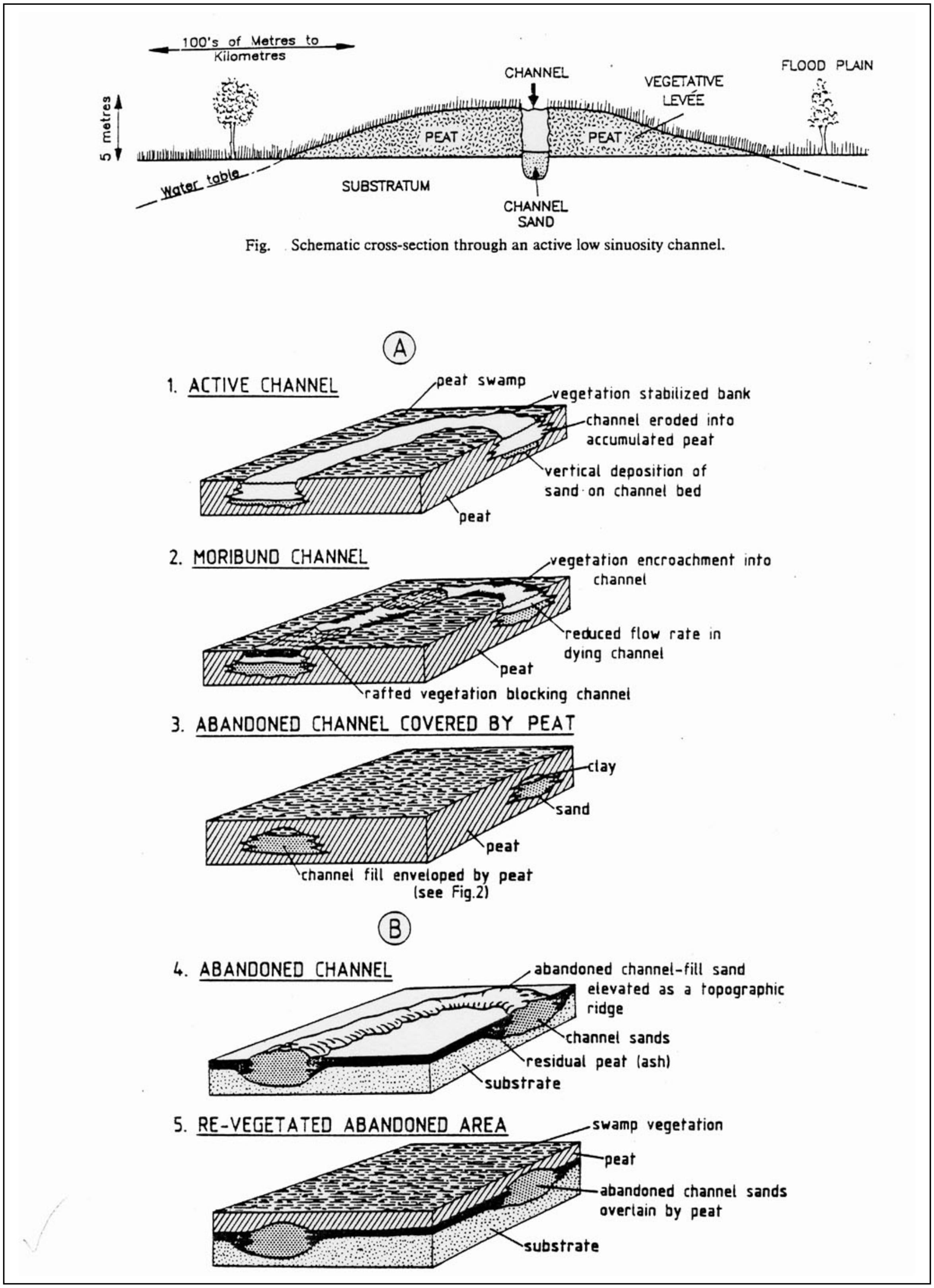
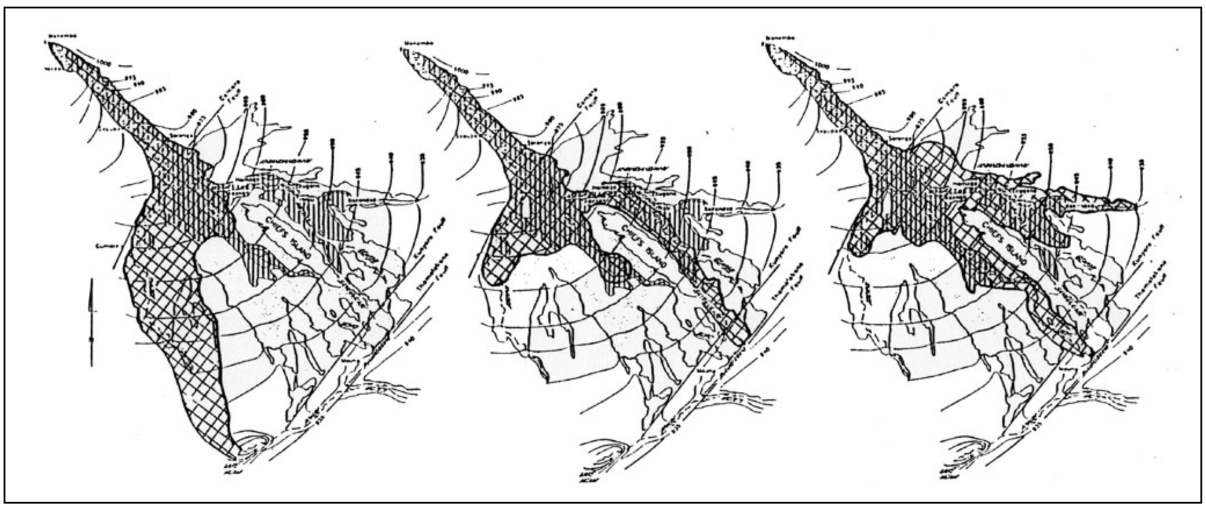


Figure 2.12. Modern analogues from the Okavango Delta of stone-rolls associated with the Permian coals. (A) Abandoned channel-fill sand becomes completely enclosed by peat to produce an in-seam stone-roll. (B) Abandoned channel-fill sand overlain by peat and re-vegetated.

In the sandy terrain traversed by the Okavango, the low gradients have resulted in the formation of a network of ephemeral channels which progress through a characteristic cycle before being abandoned (shown in Figure 2.12). Reed beds fringing the poorly incised Okavango channels will, over time, lead to the build-up of a peat deposit bounding the river channel. Sandy sediment carried by the river would be deposited on the floor of the river channel, and gradually aggrade (build up), keeping pace with the formation of the enclosing peat deposits. Eventually the higher reaches of the river would become blocked by vegetation, diverting the water into a new channel. Channel diversions might also be accomplished by movement along fault lines, although the relative importance of such tectonic factors remains conjectural. Blockages in the upper reaches of a channel would cut off water supply to the lower reaches, leading to desiccation of the bounding peat bed. This would eventually ignite spontaneously and be reduced to a thin layer of ash, leaving the former line of the channel standing proud as a low sandy ridge, built up of the sediment deposited within the original bounding peat deposits. McCarthy *et al.*(1986) estimate that the time scale for aggrading and ultimately abandonment of a channel may be relatively short, of the order of 100 years.

The processes of channel blocking and switching described above has resulted in major changes in water distribution within the Okavango delta over historic timespans (Shaw1984, McCarthy *et al*. 1986). Thus, in the early 1800s, one of the main distributary channels in the Okavango was the Thaoge (Figure 2.13), which supplied water to Lake Ngami. Flow in this channel was obstructed by a papyrus blockage in the 1880s, and the blockage proceeded steadily upstream over succeeding years (Shaw 1984). Flow switched to the Nqoga channel, which then became the main Okavango distributary in the early part of last century, causing a marked contraction in the size of Lake Ngami. The lower reaches of this channel began to block with vegetation in the 1920s, and over the next 50 years the blockage affected progressively higher reaches of the channel. As a consequence, flow has mainly shifted to the Maunachira and Jao/Boro channels (Figure 2.13) (McCarthy *et al*. 1986)



to 1880 1880 – 1930 1930 to present

Figure 2.13. The distribution of water in the Okavango Delta at various times during the 19th and 20th centuries. Vertical lines and stippled areas indicate the present distribution of permanent swamp and seasonal swamp respectively; cross hatching indicates the approximate areas of main flow in the periods shown.

Ellery, Ellery & McCarthy (1993) and McCarthy, Ellery & Ellery (1993) note that the areas surrounding the sandy ridges that mark former channel lines may subsequently become flooded, with the ridge standing proud as an island. This will become colonised by vegetation, with a riparian woodland developing along the island margins. They suggest that this riparian woodland plays a major role in influencing the evolution of the island vegetation over time. Ellery *et al.* (1993) demonstrated that islands in the Okavango are characterized by a major diurnal change in groundwater level over a 24 hour period. The groundwater table drops during the day, with the most marked fall near the island margin in the late afternoon, a fall ascribed to drawdown of the groundwater by transpiration of the riparian woodland marginal to the island. Recharge from the surrounding flooded areas occurs during the night. This process ensures that salts are flushed from the woodland-covered island margins. However, a build-up of insoluble salts, particularly Mg and Ca carbonates, occurs inland of the riparian forest fringe. Such precipitation will produce a raised rim to the island close to the margin of the riparian woodland. In the central interior, diurnal changes in groundwater will be much less marked, and capillarity action coupled with evaporation will lead to a gradual build up of more soluble salts such as Na-carbonates (trona) (Figure 2.14). This results in the die-off of tree species (typically *Acacia* species), that were originally present in the central parts of the island, and their replacement by shallow-rooting grasses. Eventually, the surface precipitation of salts forms a trona crust in the central parts of the island that is now barren of vegetation. McCarthy *et al*. (1993) estimate that this sequence of events occurs over a time period of around 200 years, although this will obviously vary with the size of the island.

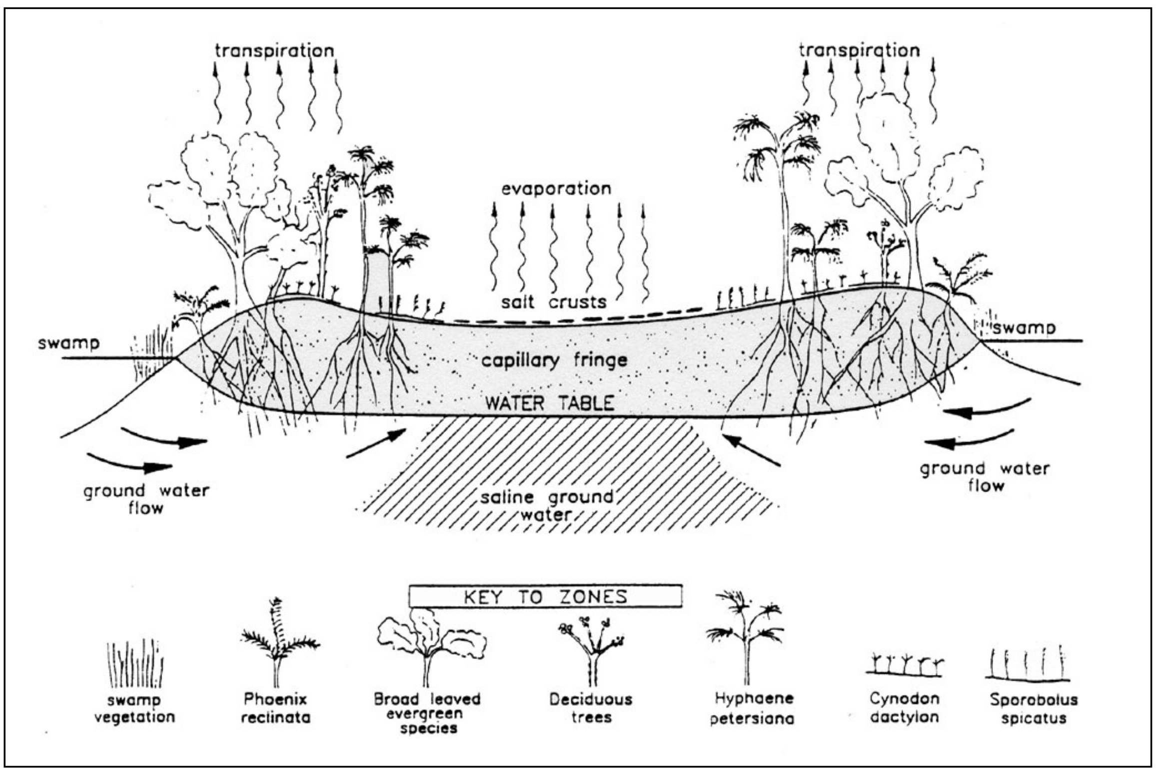


Figure 2.14. Diagrammatic cross section of an island in the permanent swamps illustrating ground water flow, transpiration and evaporation.

2.4 RIVER EVOLUTION IN SOUTHERN AFRICA

Until some 160 Ma ago, Africa formed the centre of a supercontinent known as Gondwana (originally referred to as Gondwanaland), comprising what are now the southern continents (Africa, South America, Australia, Antarctica and India). Gondwana began to fragment between 160-140 Ma ago with the opening of the Indian Ocean, followed by opening of the Atlantic at approximately 120 Ma. Rifting was associated with a major episode of basaltic volcanism which terminated the cycle of deposition that formed the rocks of the Karoo Group (White & McKenzie 1989).

Prior to the disruption of Gondwana, the area that now forms southern Africa is generally accepted to have been a plain of low relief traversed by sluggish meandering streams - in other words, with all the characteristics of old age. The disruption was associated with epeirogenic uplift along the continental margins and a marked lowering of river base levels, initiating rapid erosion of the continent and a radical change in the configuration of river systems. Factors that played the major role in controlling the development of drainage systems are discussed by Cox (1989) and Moore and Blenkinsop (2002), while detailed evidence for the subsequent evolution of river systems is presented by Moore and Larkin (2001). As changes in drainage systems over the past 2 Ma (Quaternary) are probably the most relevant in influencing biodiversity in the Four Corners area, river evolution during this period is discussed later in some detail.

2.4.1 Drainage Evolution Since the Break-up of Gondwana

The following summary of the main stages of drainage evolution in south-central Africa is based on the model developed by Moore and Larkin (2001), and summarized in Figure 2.15 (see also Table 2.2).

Following the opening of the Atlantic in the Lower Cretaceous (around 120 Ma), the proto-Limpopo was the main river system draining into the Indian Ocean, with the Okavango, Cuando and Upper Zambezi forming the major headwater tributaries. The Luangwa and Kafue were important west bank tributaries of the Zambezi. The Lower Zambezi formed a separate river system with the Shire as a major north bank tributary (Figure 2.15a). The courses of the lower proto-Limpopo and Lower Zambezi were both controlled by major rift faulting.

In the upper Cretaceous (80-90 Ma), uplift along the Etosha-Griqualand-Transvaal Axis severed the link between the Orange River and former north bank tributaries such as the Molopo-Nossob-Auob system. The latter rivers began to deposit their sediments in an inland basin, marking commencement of the Kalahari Group sediments (Moore 1999).

The early Limpopo drainage system was disrupted by uplift along the Ovamboland-Kalahari-Zimbabwe (OKZ) axis, which beheaded the headwaters of the proto-Limpopo (Figure 2.15b). Moore (1999) tentatively suggests an early Palaeogene age (~65Ma) for this uplift, although the timing is not well constrained. It should also be noted that the major rivers may have been able to incise their courses into the OKZ flexure for some uncertain time during or following uplift. The age of final severance of the headwater rivers from the lower Limpopo is therefore not well established, and possibly post-dates the OKZ flexure. Once the link to the lower Limpopo was severed, the former headwater tributaries of this river also began to deposit their sediment load in the Kalahari basin.

The Lower Zambezi extended its course inland, and ultimately captured the upper Luangwa (Figure 2.15c). The timing of this capture is not well established, although Moore and Larkin

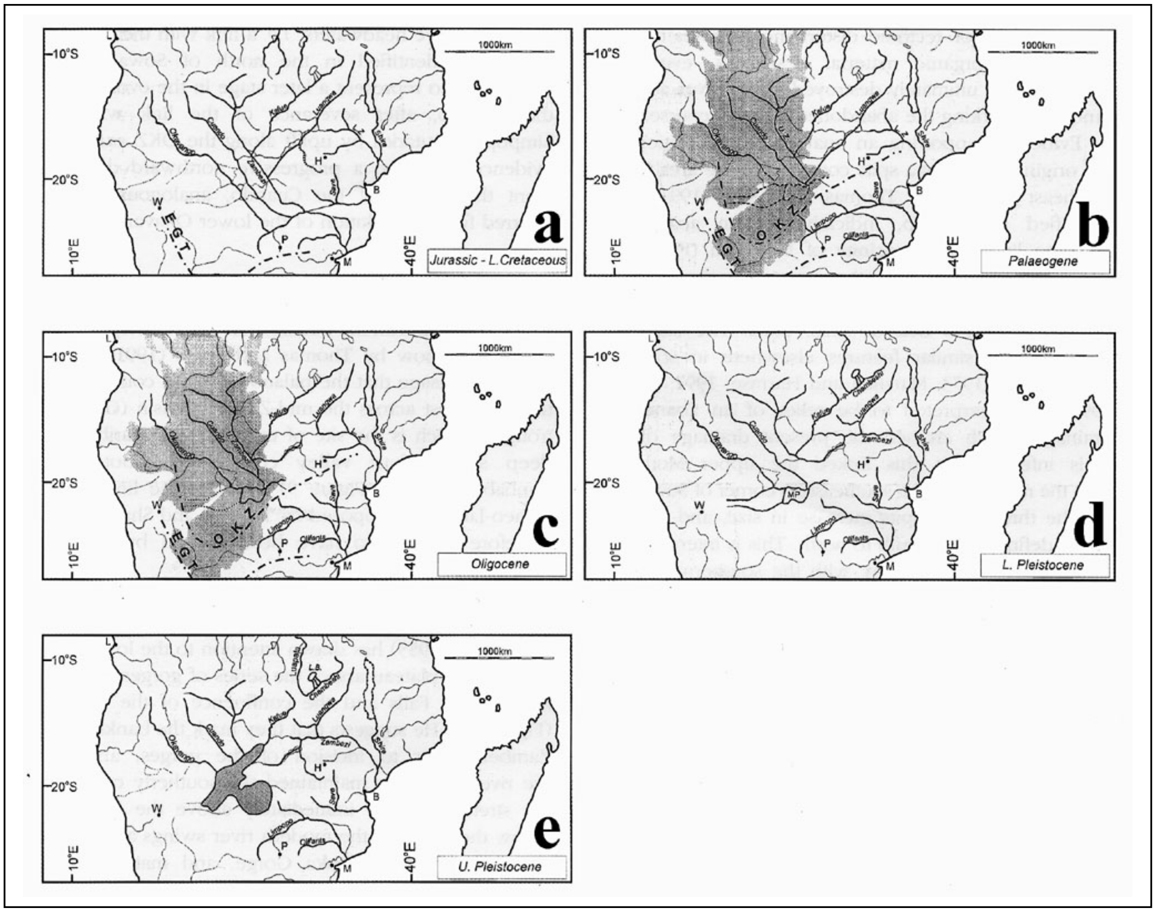


Figure 2.15. Successive stages in drainage evolution in south-central Africa.

- **a)** Faint lines: modern drainages. Heavy lines: Jurassic to Cretaceous system. The major eastward draining river was the Limpopo. The Cubango-Okavango, Cuando and Upper Zambezi (with the Kafue and Luangwa as major left bank tributaries) formed the original Limpopo headwaters. The Chambesi formed the Kafue headwaters. The Shire-Lower Zambezi and Save formed a separate drainage system. LZ = Lower Zambezi.
- **b)** Grey tone shows distribution of the Kalahari sediments. End – Cretaceous to early Tertiary crustal flexuring along the OKZ axis led to the severence of the link between the Limpopo and the Cubango-Okavango, Cuando and Upper Zambezi – Luangwa - Kafue. During the Palaeocene and Eocene, the latter three rivers formed an endoreic system, which drained into the Kalahari basin, and contributed to the deposition of the Kalahari Group sediments.
- **c)** Headward erosion of the Lower Zambezi, initiated by crustal flexuring along the OKZ axis, resulted in the capture of the upper Luangwa. The resultant lowering of the Luangwa base level, coupled with increased flow in the Lower Zambezi, initiates headward erosion from the point of capture, and incision of the Cabora Bassa gorge.
- **d)** Continued headward erosion of the Lower Zambezi, led successively to the capture of the Mana Pools basin and the Gwembe trough. These captures initiated incision of the Mupata and Kariba gorges respectively. Incision of the Batoka gorge was initiated once the Mid Zambezi beheaded the Upper Zambezi in the Lower Pleistocene.
- **e)** Grey tone shows Palaeo Lake Makgadikgadi. Displacement along the major northeast trending Linyanti and Chobe faults temporarily severs the link between the Upper and Mid-Zambezi, and diverts the flow of the Cuando and Zambezi headwaters into Palaeo-Makgadikgadi, which is filled to around the 945m level. Diversion of the headwaters of these rivers is reflected by a break in erosion of Batoka gorge. This cannot be accurately dated but is estimated to be mid to late Pleistocene (Derricourt, 1976). Major variations in the level of the Makgadikgadi Pans complex within the past 50 000 years, suggest that the link between the Zambezi and Makgadikgadi has been breached and re-established on a number of occasions.

Table 2.2. Summary of the major geomorphological events responsible for environmental change in the Four Corners area.

Epoch	Age (Ma)	Event	Notes
Holocene	Present	Initiation of capture of Okavango by Upper Zambezi	
Late Pleistocene - Holocene	0.15-0.01	Episodic arid periods result in formation of major dune fields. Desiccation of Lake Palaeo-Makgadikgadi	Uncertain whether there was progressive desiccation of Lake Palaeo-Makgadikgadi, or whether there was episodic expansion & contraction
Late Pleistocene	(?)	Faulting associated with Ngonye Falls initiates Barotse floodplain	
Late Pleistocene	(?)	Faulting across Cuando leads to capture by Zambezi and formation of Linyanti-Chobe floodplains. Faulting across Okavango initiates development of modern Delta fan	Faulting across Okavango probably leads to further desiccation of Makgadikgadi
Late Pleistocene	(?)	Capture of Kafue by mid-Zambezi tributary	Link between Kafue and upper Zambezi severed. Formation of Kafue Flats floodplain
Late Pleistocene (?)	(?)	Link between Chambeshi and upper Kafue severed	
Mid-Late Pleistocene	0.460 to 0.315	Link between Upper Zambezi re-established	Desiccation of Makgadikgadi initiated
Mid-Pleistocene	± 0.7 to 0.315	Diversion of Upper Zambezi-Kafue into central Botswana to form Lake Palaeo-Makgadikgadi	Chinamba Rapids in Batoka Gorge reflect break in erosion
Lower Pleistocene	± 1.25	Capture of the Upper Zambezi by mid-Zambezi	Link between Upper Zambezi and Indian Ocean re-established. Initiation of headward erosion of Batoka Gorge
Oligocene-Pleistocene		Capture of the Mana Pools & Gwembe basins of mid-Zambezi by headward erosion of the Lower Zambezi	Incision of the Mupata & Kariba Gorges by headward erosion to capture the Mana Pools & Gwembe basins
Oligocene (?)	± 38-25	Lower Zambezi captures Luangwa	Cabora Bassa Gorge cut by rapid headward erosion following capture of Luangwa

Epoch	Age (Ma)	Event	Notes
Early Tertiary	65 (?)	Continental flexuing along OKZ axis beheading link between Zambezi, Cuando & Okavango and the Limpopo	Zambezi, Cuando & Okavango now terminate in inland Kalahari basin, and supply sediment. Rejuvenation of Lower Zambezi, initiating headward erosion
Upper Cretaceous	± 90-70	Continental flexuring along EGT Axis, beheading of drainages such Molopo-Orange link	Initiation of Kalahari sedimentation by inland terminating river systems in horst/graben basins
Lower Cretaceous	120	Opening of Atlantic Ocean (Africa-S. America)	Major drainage reorganisation
Jurrassic	140-160	Opening of Indian Ocean (separation of Africa from Antarctica/Australia	Major drainage reorganisation

EGT - Etosha - Griqualand - Transvaal
OKZ - Ovamboland - Kalahari - Zimbabwe

(2001) tentatively suggest that this took place in the Oligocene age (38-28 Ma), to account for increased sedimentation rates at this time along the east coast.

Capture of the Luangwa would have triggered rapid downcutting of the Lower Zambezi, which in turn would have promoted inland extension of the headwater tributaries and ultimately, capture of the Upper Zambezi, with the Kafue still a north bank tributary (Figure 2.15d). Derricourt (1976) has tentatively suggested that this capture took place in the lower Pleistocene (approximately 1.25 Ma.).

Capture of the Upper Zambezi initiated a period of rapid headward erosion to form the Batoka Gorge. Derricourt (1976) infers that the Chinamba Rapids mark a break in this erosive cycle during the mid-Pleistocene (the exact age is uncertain, but tentatively 700,000 to 315,000 years BP). Moore and Larkin (2001) propose that this break in erosion was initiated by uplift along the Linyanti and Chobe Fault lines, which diverted the Zambezi into northern Botswana to form the Greater Makgadikgadi Pan (marked by the 945 m shoreline). Derricourt (1976) infers that the link between the Batoka Gorge and the Upper Zambezi was re-established some time in the interval 315,000-460,000 years BP, initiating erosion of the section of Batoka Gorge above the Chinamba Rapids to the modern Falls.

This renewed phase of erosion of the Batoka Gorge implies that the Upper Zambezi was able to breach the barrier formed by the Linyanti and Chobe faults, and largely ceased to flood the Makgadikgadi basin in northern Botswana. However, it has been noted that the older alluvium in northern Botswana (associated with the 945 m lake level) post-dates late Holocene dune systems. This suggests that the Zambezi has been diverted into central Botswana relatively recently, presumably as a result of renewed uplift along the Linyanti and Chobe faults. It is therefore possible that faulting still periodically disrupts the link between the Lower and Upper Zambezi, diverting the river into northern Botswana, and that this could recur. This has potentially complex geopolitical ramifications, and requires further urgent study. Detailed optical luminescence dating of the 945 m shoreline may be able to provide more reliable dates for periodicity of recent diversions of the Zambezi into central Botswana.

The sharp change in course of the Kafue from a north-south to west-east course in the Kafue Flats area is interpreted to be a capture elbow, resulting from headward erosion of a mid-Zambezi tributary. Headward erosion by this tributary is in turn ascribed to lowering of the base level (the confluence with the main river) caused by accelerated erosion in the Zambezi triggered by sequential river captures. In an area of low relief, during the initial stages of capture, the linking channel would be poorly incised and blockages analogous to those found in the Okavango Delta would be expected to trigger switches in course. The floodplain in the Kafue Flats area may therefore reflect the incipient stages of river capture; in other words it is a very recent event. This process differs from the essentially tectonic controls (i.e. faulting across drainage lines) that gave rise to the Okavango and Linyanti floodplains.

It should be noted that the modern upper Chambeshi formerly constituted the headwaters of the Kafue (Figure 2.1a). The sharp change in course of this river from southwest to north marks the point of capture by the Congo drainage system. The age of this capture is not well constrained, although is tentatively ascribed to the Lower Pleistocene by Moore and Larkin (2001). Genetic studies of fish species common to the Kafue and Chambeshi may provide evidence for its timing.

It is most probable that the predatory Zambezi is still in the process of extending its headwaters by further river capture. Figure 2.16 shows the postulated sequence of events that could result in the capture of the Okavango. The timing of the stages envisaged by Wellington (1955) is conjectural, but there is evidence that major changes have occurred over relatively short periods (of the order of thousands of years). It has been noted that the 'Older Alluvium' in northern Botswana (Figure 2.7) post-dates late Holocene dunes (20-10 ka). The younger alluvium, deposited by the Okavango Delta following disruption of the river by uplift along the Thamalakane and Kunyere Faults, must therefore be even younger. Within the Delta, there has been sequential change in the main distributionary channels from the Thaoge in the west to the Nqoga and finally the Boro-Jao during the past 200 years (Figure 2.13).

2.5 GEOMORPHOLOGICAL EVIDENCE FOR DRAINAGE REORGANISATION IN SOUTH-CENTRAL AFRICA

2.5.1 Shorelines Associated with the Makgadikgadi Pans

The Makgadikgadi Pans complex in northern Botswana provides several key lines of evidence for major changes in the drainage system of the Four Corners area during the Quaternary. This complex is composed of two major pans - Ntwetwe in the west and Sowa (formerly spelled Sua) in the east - and a number of minor pans (Figure 2.17).

Today, Ntwetwe Pan receives minor inflow, via the Boteti (formerly spelled Botletle), of water that is ultimately derived from the Okavango River. This is channelled, at the distal end of the Delta, into the fault-controlled SW-flowing Thamalakane River (Figs. 2.11 & 2.17). This river is unusual because, as a result of the extremely low gradients characteristic of northern Botswana, its flow bifurcates, with some feeding into Lake Ngami via the Nghabe, and the remainder into the western portion of Ntwetwe via the Botete River (Figure 2.11). This flow has been negligible during the late 1980s and 1990s. To the west of Ntwetwe Pan, three fossil drainage lines - the Okwa, Deception and Passarge (Figure 2.17) - mark former rivers that once emptied into the pan. It has not been established when these rivers were last active, although this was presumably associated with more humid climates during one or more of the Pleistocene pluvial periods. Sowa Pan receives sporadic inflow via the Nata River, which has its headwaters on the central Zimbabwe watershed, and a number of smaller seasonal drainages to the east. A shallow body of standing water may develop in the north of Sowa pan after heavy rains.

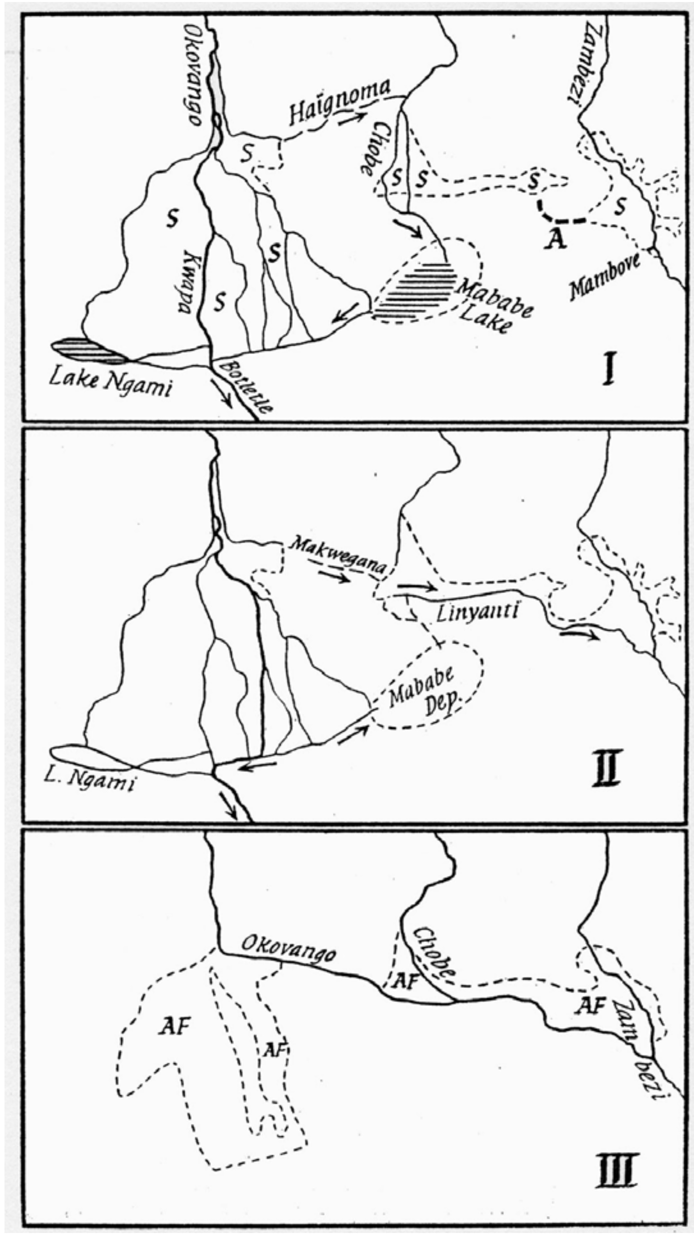


Figure 2.16. Probable recent and future evolution of the Zambezi-Chobe-Okavango relationships (after Wellington, 1955).

I. The three rivers flowing through their own swamps (*S*), the Chobe forming a lake in the Mababe Depression which overflows into the Thamalakane. An overflow channel from the Chobe to the Zambezi swamps is becoming established at***A***.

II. Diversion of the Chobe to the Zambezi. Development of the Makwegana Spillway (present conditions).

III. Future developments. Diversion of the Okavango along Makwegana channel; deepening of main and tributary courses; draining of alluvial flats (***AF***).

Although the Makgadikgadi Pans complex is largely desiccated today, it is surrounded by a variety of fossil shoreline features, including relict boulder beds (often associated with a distinct break in slope) which occur consistently at altitudes of approximately 945 m, 920-925 m and 910-912 m (Figure 2.17). These abandoned shorelines record the former existence of a major inland lake, which fluctuated in size over time. A particularly striking landform, to the west of the Makgadikgadi Pans is a broadly curving ridge (the Gidikwe Ridge) over 200 km in length, with a crest at an altitude of approximately 945 m). This has been interpreted as a relict offshore sand bar associated with the 945 m lake level.

Fossil boulder beaches are best developed to the south of the Makgadikgadi Pans (Grey & Cooke 1977), and are ascribed to formation by high-energy storm waves, concentrated on the southern shoreline, generated by easterly to northeasterly winds, comparable to the present day prevailing

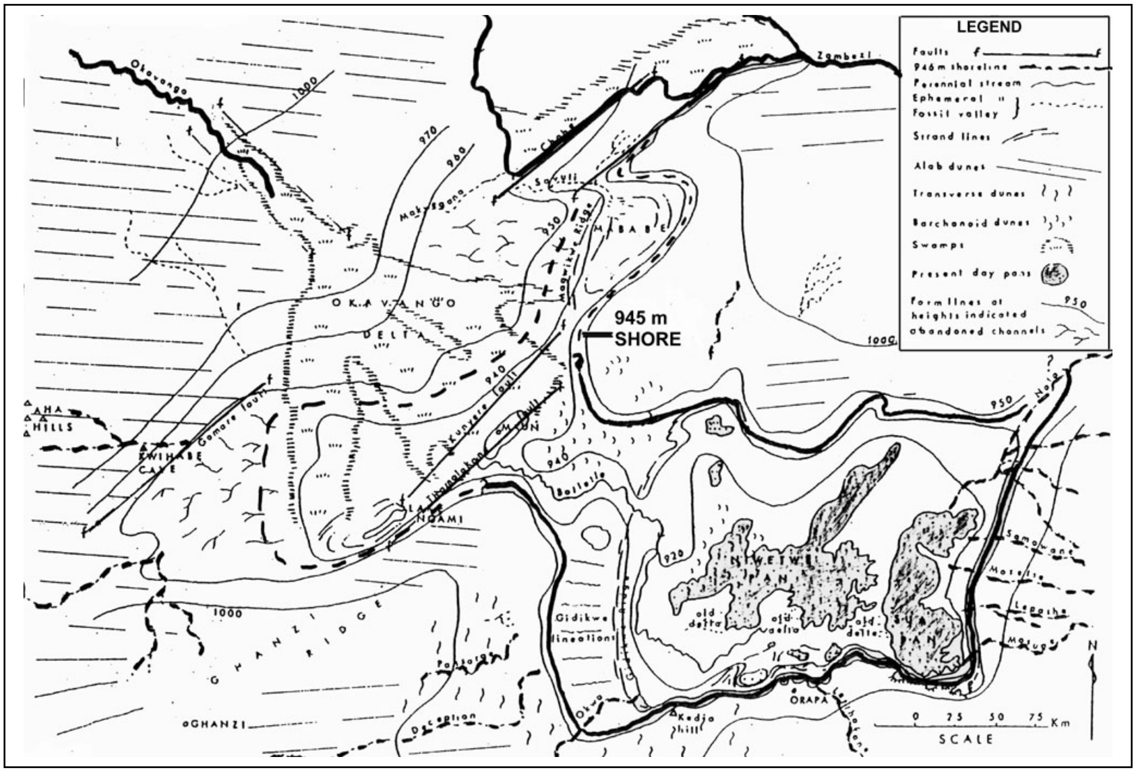


Figure 2.17. Main geomorphological features of northern Botswana (from Grey & Cooke, 1977).

wind system. The amplitude of waves developed on a standing body of water increases with wind strength and the fetch, the extent of the body of water affected by the wind. The 945 m shoreline would have surrounded a body of water in excess of 140 km parallel to the prevailing wind direction, which approaches the limiting conditions of an effectively infinite wind fetch.

Shaw and Thomas (1988) document evidence for fossil shorelines at a consistent elevation of 936 m in the Mababe depression and Lake Ngami. Shoreline features at this elevation are not found in the Makgadikgadi, and provide evidence for the existence of a much more restricted lake, termed Lake Caprivi (Shaw & Thomas 1988), with an area of some 2000 km^2, that included the Mababe and Ngami basins and the distal extremity of the modern Okavango Delta. Thomas and Shaw (1988) infer that this lake was formed by ponding of the Zambezi behind the Mambova Falls, located immediately downstream of the confluence with the Chobe (Figure 2.7). They note that there would have been outflow from Lake Caprivi into the Makgadikgadi via the Boteti channel, and speculate that such outflow could have been responsible for maintaining either the 920 m or 912 m Makgadikgadi lake stand.

^{14}C dating has been carried out on shells and calcretes associated with the major shorelines by Thomas and Shaw (1991). All three major shorelines show a range in ages extending to 50,000 years BP, the upper limit of the ^{14}C dating technique. Taken at face value, this points to major fluctuations in lake level over at least the past 50,000 years, and probably extending back over a greater period. However, calcretes are inherently difficult to date as they often show evidence of multiple stages of carbonate crystallization, making interpretation of the ages problematical. It is therefore questionable whether the ^{14}C dates do in fact record ages of former shorelines. Efforts are currently underway to apply optical luminescence techniques to dating the shorelines (Bill Downey, University of Botswana, pers. comm.), but no ages have yet been published. It should be noted, however, that problems inherent in this dating technique raise questions as to the interpretation of the results, and thus the reliability of the dates.

McFarlane and Segadika (2001) report the discovery of Early Stone Age artefacts beneath 1.5 m of overburden between the 945 m and 920 m lake levels northeast of Gweta, in the north of the Makgadikgadi Pans. This indicates that the lake must be older than the end of the Early Stone Age (approximately 200,000 BP), and thus considerably older than indicated by the calcrete ^{14}C ages.

The Quaternary was a period characterized by marked climatic fluctuations with periods characterized by much higher rainfall than at present. Nevertheless, in a remarkably prescient study, Grove (1969) pointed out that, given the high evaporation rates in northern Botswana, it is impossible to account for the 945 m level of the former Makgadikgadi lake on the basis of any realistic increase in rainfall associated with the Pleistocene pluvial (high rainfall) episodes. He calculated, on the basis of water volumes carried by major rivers in the Four Corners area, that this lake high stand would only have been possible if it received inflow from the Zambezi River. The implication was that the Zambezi was at some stage diverted from its modern course, into central Botswana.

2.5.2 Alluvial Deposits in Northeast Botswana

The development of the major Lake Makgadikgadi at the 945 m level was responsible for the deposition of extensive alluvial deposits in northern Botswana, providing further evidence for major changes in drainage in the Four Corners area during the Quaternary.

A soil classification study of Botswana has identified extensive alluvial deposits of two different ages in the northeast of the country (Figure 2.7, De Wit & Bekker 1990). The older suite is represented by lacustrine sediments of the Makgadikgadi Pans, Lake Ngami and the Mababe depression, and a broad SW-NE belt of 'Older Alluvium'. The latter extends across the Zambezi River and into Zambia (Figure 2.7), possibly as far as the floodplain where the Kafue swings abruptly from a southerly to an easterly course (Figure 2.2) (Mallink *et al*. 1981, Thomas & Shaw 1991). The older alluvial deposits together cover the inferred area of the maximum extent of the Makgadikgadi associated with the 945 m shoreline (Thomas & Shaw 1991). A narrow neck along the Boteti valley linked the Makgadikgadi basin with the NE-SW trending basin of this former major inland lake, which Thomas and Shaw (1991) term Lake Palaeo-Makgadikgadi (Figure 2.17). They estimate that the combined area of the two basins was approximately 120,000 km^2.

The belt of Older Alluvium is bounded by a set of major faults, which appear to have controlled sedimentation (Figure 2.7). Relict east-west trending sand dunes, located to the west of the Okavango Delta (Figure 2.10) (Mallinck *et al.* 1981) terminate close to the faults bounding the Older Alluvium. As discussed in an earlier section, the dunes show a range in ages extending from the late Pleistocene to the Holocene (20-10 ka; Stokes *et al*. 1997, Thomas *et al*. 2000). Termination of the dune field close to the faults bounding the older alluvium suggests that these faults were active subsequent to dune formation, which is consistent with present-day seismic activity that has been recorded in the Okavango area (Reeves 1972, Scholz *et al*. 1967). However, note that *initiation* of the faults may have commenced at an earlier date.

The abrupt change in course of the Kafue from N-S to W-E in the Kafue Flats area is typical of a capture elbow. The extension of the Older Alluvium into Zambia as far as the Flats, indicates a former link between the Kafue and Lake Palaeo-Makgadikgadi, and Thomas and Shaw (1991) postulate that the river originally continued on a south-westerly course to link with the Zambezi considerably above the modern confluence of the two rivers. It is therefore proposed that the Kafue and Zambezi at one stage flowed to the southwest into Botswana, providing the source for the northeast-southwest belt of older alluvium, and also the volume of water required to maintain the 945 m shoreline of the Makgadikgadi (Grove 1969). Diversion of these rivers into northern Botswana could be explained by uplift along the NE-SW trending Chobe Fault across the line of the Zambezi (Figure 2.7).

The Older Alluvium is not covered by the Late Pleistocene to Holocene dunes to the northwest, indicating that it is younger than these aeolian features. This in turn indicates that the greater Lake Palaeo-Makgadikgadi was in existence within the last 20-10 ka, which is consistent with the calcrete shoreline ages. In turn, this requires that the Zambezi, and probably also the Kafue, were diverted into northern Botswana in the last 20-10 ka (to maintain the 945 m lake level). As will be discussed in more detail in a following section, diversion of the Zambezi into northern Botswana may have been episodic, and could, in principle, recur.

The younger deposits of alluvium are associated with the modern Okavango, Linyanti and Chobe rivers. The Okavango Delta forms a fan that overlies a broad NE-SW trending belt of older alluvium, deposited in a fault-bound trough, that blankets the northeastern corner of Botswana (Figure 2.7). This younger alluvial fan was initiated by the development of major faults (the Thamalakane and Kunyere Faults, Figure 2.11) across the line of the Okavango River, which originally continued on a southeast course to link with the Limpopo (du Toit 1927, Moore & Larkin 2001).

2.5.3 Landforms and Sedimentation Patterns Around Sowa Pan

Sedimentation patterns and landforms in Sowa Pan and the surrounding area are evidence for the location of a number of abandoned drainage lines, providing further evidence for the configuration of earlier drainage systems in the Four Corners region. These are discussed under the major rivers involved.

2.6 GEOMORPHOLOGY OF SELECTED RIVERS AND FEATURES

2.6.1 Palaeo-Cuando

A drilling programme was carried out in the north of Sowa Pan by Selection Trust to investigate the economic potential of brines associated with the pan sediments (Ballieul 1979). This defined a sequence of alternating sand and clay beds above a prominent sandstone horizon, identified as either the Karoo Ntane sandstone or part of the Kalahari Formation. The geometry of the isopachs (i.e. the sediment thickness contours) of the pan sequence above this marker horizon suggests that they represent a major delta, fed by a river that entered the pan from the north-west. Mallinck *et al*. (1981) have identified a minor photofeature to the north-west of Sowa Pan (Figure 2.18), which they interpret to be an abandoned delta associated with one of the high lake shorelines.

In the northern portion of Sowa Pan there is a prominent sandy spit, oriented SE-NW, which projects from the eastern shoreline across almost three-quarters of the basin width (Figure 2.18). An analogous feature, with similar orientation, although smaller and not as clearly defined, occurs to the south, between the Mosetse and Lepashe rivers. In the southeastern corner of the pan, there is a third relict sandy spit, also oriented approximately SE-NW, and a linear sandy island with a similar orientation is located immediately to the north.

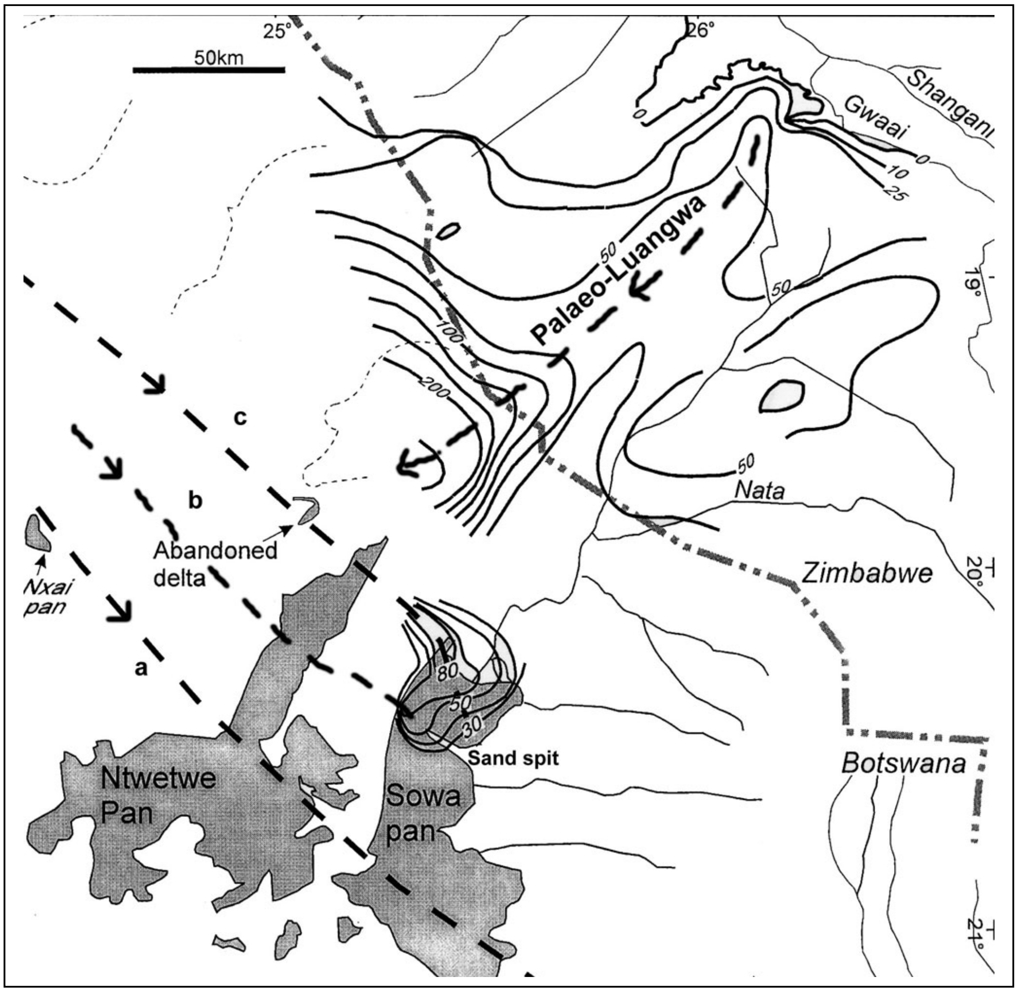


Figure 2.18. Kalahari sand isopachs straddling the Botswana-Zimbabwe border.
These are interpreted to reflect a major sub-Kalahari valley with headwaters located to the north-east. A photo-feature to the north of Ntwetwe Pan has been interpreted to represent an abandoned delta (Mallinck *et al*., 1981). a, b, c are inferred as progressively younger drainage lines of the palaeo-Cuando. Line b is defined by the major sand spit.

The three sand spits which project from the eastern shoreline are intriguing topographical features which have not yet been satisfactorily explained. They are unlikely to have formed as a result of longshore currents, which typically give rise to sand bars parallel to the coastline. Their orientation is oblique to a major W-NW trending post-Karoo dolerite swarm which traverses the pan (Botswana 1:1 million geological map), arguing against an origin linked to these intrusions.

Moore and Larkin (2001) propose that they are relict fluvial channels, formed in an area of low relief by processes analogous to those advanced by McCarthy *et al*. (1986) to explain linear sand ridges in the Okavango delta. The three Sowa spits increase in size and become better defined from south to north, which is interpreted to reflect an age progression, with the southernmost spit being the oldest and most degraded by wave action and currents. This evidence argues that the abandoned drainage that originally traversed Sowa Pan was displaced progressively northward.

Moore and Larkin (2001) also propose that the river course represented by the southernmost, most degraded spit was linked to the Limpopo via the Motloutse River (Figure 2.19). The more northerly course, marked by the northern sand spit, joined the Limpopo via the Shashe River.

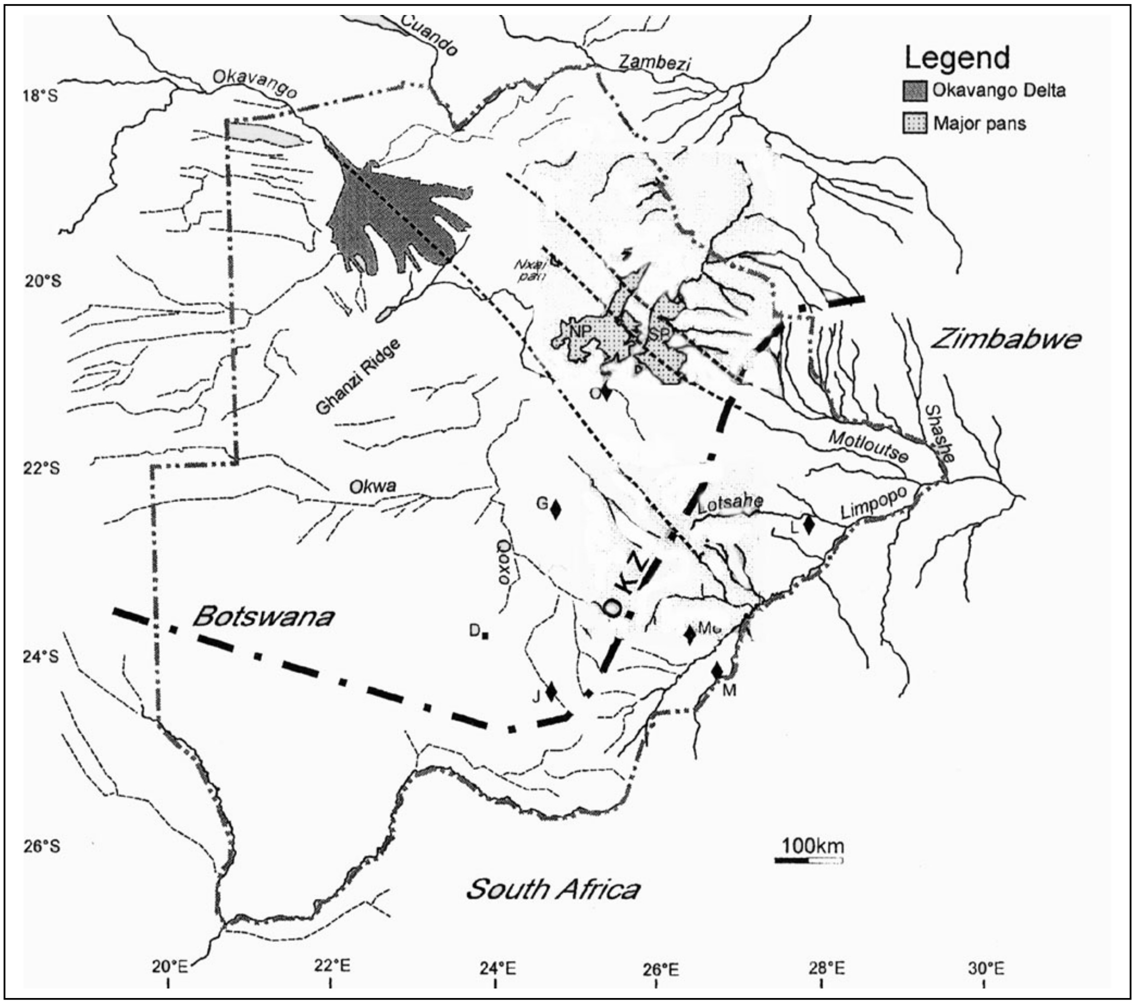


Figure 2.19. Reconstruction of palaeodrainages in Botswana and Zimbabwe.
Solid black lines: modern active drainages; stippled lines: fossil / ephemeral drainage lines; heavy dashed lines: inferred palaeodrainages.
OKZ = Okavango-Kalahari-Zimbabwe axis (Moore, 1999).
Solid diamonds denote kimberlite fields in eastern Botswana. G Gope; J Jwaneng; L Lerala; M Mochudi; Mo Mosemane; O Orapa; D Dutiwe heavy metal anomaly.
Note that the Cuando had former links to the Limpopo via both the Motloutse and Shashe rivers.

These links to the Limpopo were ultimately severed by uplift along the OKZ axis, which is tentatively dated at early Tertiary (65 Ma) (Moore 1999) but not well constrained. It should also be noted that the rivers may have incised and maintained their courses across the line of flexure for some time following uplift. The timing of the final severance of the link to the Limpopo River is therefore not clear.

A major drainage - the Cuando (or Kwando) - is located to the northwest of Sowa Pan. The upper reaches of the river follow a straight NW-SE course, but it swings abruptly to the northeast along the Linyanti Fault at the Botswana border (Figures 2.6 and 2.19). This change in direction is typical of a major capture elbow, and Moore and Larkin (2001) suggest that prior to uplift along the Linyanti Fault, the Cuando originally maintained the southeast course of the headwaters into Botswana, crossing Sowa Pan. Uplift along the Linyanti Fault thus severed the link between the Cuando and Sowa Pan, and therefore post-dated the formation of the delta in the north of Sowa Pan.

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2.6.2 Okavango

Moore and Larkin (2001) present evidence to show that the Okavango originally maintained a southwest course across Botswana to link with the Limpopo via the Bonwapitse River (Figure 2.19). This link was severed by uplift along the OKZ axis, while a much younger uplift along the Thamalakane and Kunyere Faults (Figure 2.11) initiated the formation of the modern Okavango Delta fan.

In summary, disruption of the Cuando and Okavango rivers occurred in stages. Initially their links with the Limpopo were severed by uplift along the OKZ axis; their courses were subsequently further disrupted by faults crossing the river channels.

2.6.3 Palaeo-Luangwa

Borehole data (assembled and made available by Vince Atkinson of Rio Tinto Zimbabwe), show that the thickness of the Kalahari sequence straddling the Botswana- Zimbabwe border (Figure 2.18) exceeds 200 m. The Kalahari isopachs (thickness contours) define a major sub-Kalahari valley, sloping from the northeast to the southwest. These data are broadly consistent with the regional study of the Kalahari sediments of Thomas and Thomas (1990). The abrupt change in course of the Luangwa just above its confluence with the Zambezi has been interpreted as a capture elbow (Thomas & Shaw 1991), and it is envisaged that the palaeo-Luangwa continued to the south-west across the mid-Zambezi basin (Gwembe trough), the site of modern Lake Kariba. The deep sub-Kalahari valley crossing the Botswana-Zimbabwe border (Figure 2.18) straddles the line of the palaeo-Luangwa proposed by Thomas and Shaw (1991), and is therefore inferred to have been incised by this old drainage. The reconstructed palaeo-course of the Luangwa is illustrated in Figure 2.20.

2.6.4 Zambezi

Figure 2.21 illustrates the stretch of the Zambezi River in the vicinity of the Victoria Falls (from 1:50,000 topographical sheet 1725 D4) where the river is incised into an extensive plateau of Karoo age Batoka basalts. Above the Falls, the Zambezi flows in a shallow meandering channel, in places over 2 km wide, but below the Falls the Zambezi follows a zig-zag sequence of narrow gorges oriented approximately W/NW - E/SE and E/NE - W/SW, before swinging to a roughly north-south course about 2 km above the confluence with the west bank Songwe tributary.

Wellington (1955) has drawn attention to the low scarps cut into the plateau above the series of gorges between the Victoria Falls and the confluence of the Songwe. He suggests that they mark the banks of the Zambezi prior to incision of the gorges, and that the river originally maintained the southerly course of the stretch of river immediately above the Falls.

Just below the Songwe, the modern river swings abruptly to the east into the Batoka Gorge, and maintains this general bearing for a distance of some 100 km as far as the confluence with the Gwayi River (Figure 2.21). Wellington (1955) interpreted this abrupt change in course to represent a capture elbow, marking the point where the mid-Zambezi beheaded the Upper Zambezi. Prior to this, the Upper Zambezi maintained its southerly course to join the Luangwa as a north bank tributary. Headward erosion and incision of the major gorge below the Falls can be ascribed to the marked lowering of the erosion base level following capture of the Upper Zambezi by the mid-Zambezi. The orientation of the series of zig-zag gorges reflects structural control by two major joint sets.

Gravels deposited by the Zambezi before and during regression of the Falls are preserved at heights of 110 to >250 m above the modern river bed. They contain artefacts which can be ascribed to the Magosian and earlier industries of the Middle Stone Age (Derricourt 1976).

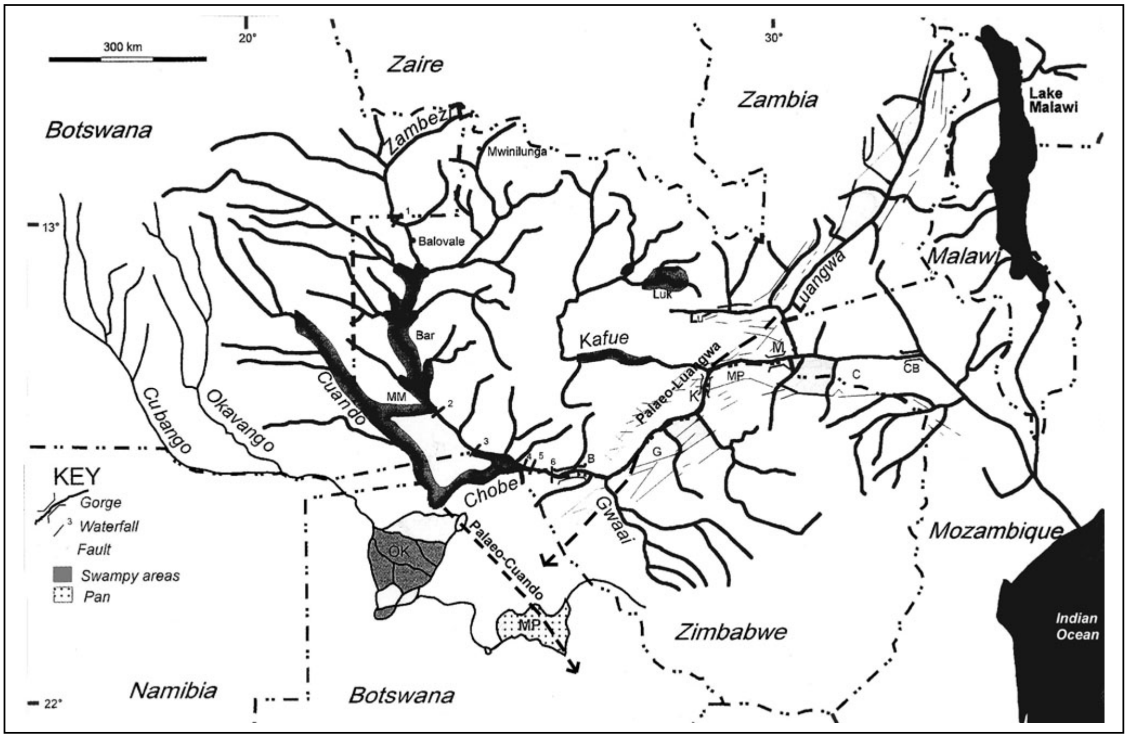

Figure 2.20. Detail of the Zambezi drainage system (adapted from Nugent, 1990).
Rift basins: G Gwembe trough (Mid Zambezi basin); MP Mana Pools basin; C Chicoa trough (Lower Zambezi basin).
Gorges: B Batoka; K Kariba; M Mupata CB Cabora Bassa.
Rapids and Falls: 1 Chavuma; 2 Gonya; 3 Katima Mulilo; 4 Mambova; 5 Katombora; 6 Victoria Falls.
Rivers: Lu Lunsemfwa.
Swamps and Marshes: Bar Barotse floodplain; Luk Lukanag; MM Mulonga-Matabele floodplain; OK Okavango.
Pans: MP Makgadikagadi Pans.

Dashed lines indicate the possible drainage routes for the palaeo-Cuando and palaeo-Luangwa.

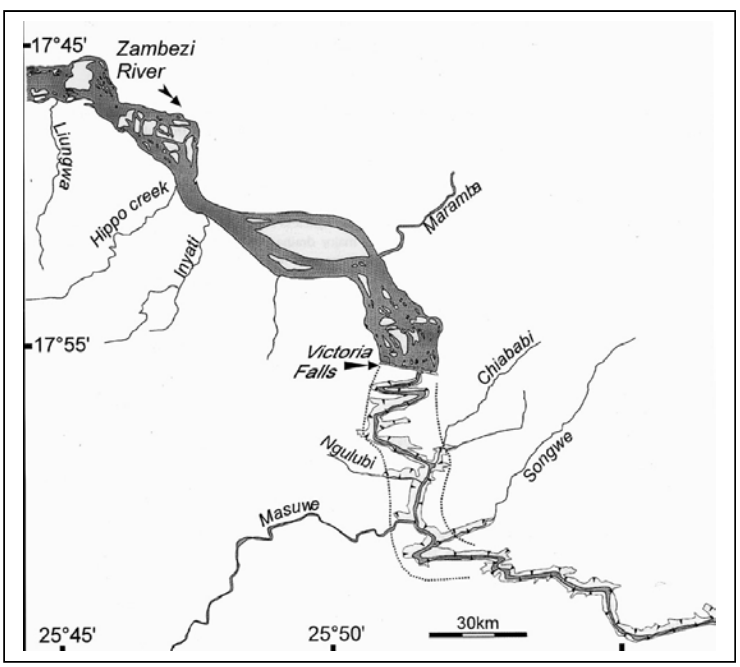

Figure 2.21. Geomorphology of the Zambezi river in the vicinity of the Victoria Falls.

Dashed line on either side of the gorge below the falls marks a low escarpment, interpreted to reflect the original bank of the Zambezi prior to river capture (following Wellington, 1955). The sharp deflection of the Zambezi from a southerly course to an easterly course immediately below the confluence with the Songwe is inferred to mark the capture elbow where the Mid-Zambezi beheaded the Upper Zambezi (Wellington, 1955).

Despite the uncertainty in dating of the stone age artefacts, they do provide broad constraints on the timing of erosion of the stretch of river below the Victoria Falls. The archaeological evidence discussed by Derricourt suggests that a major set of rapids (the Chimamba Rapids) on the Zambezi, 30 km below the Songwe confluence, reflects a chronological break in erosion of the Batoka Gorge. The geomorphological unity of the lower 70 km of the gorge to the confluence with the Matetsi, is consistent with this conclusion. Derricourt (1976) suggests that incision of the lower stretch of the gorge (between the Matetsi confluence and the Chimamba rapids) commenced within the Lower Pleistocene at least 1.25 Ma BP and was eroded over a period of between 540,000 and 790,000 BP. He infers that erosion of the upper section of the gorge, above the rapids, commenced in the middle Pleistocene, between 315,000 and 460,000 BP, while Moore and Larkin (2001) proposed that the mid-Pleistocene break in erosion of the Batoka Gorge reflects the period when the course of the Upper Zambezi was diverted into northern Botswana.

2.6.5 Barotse Floodplain

In western Zambia, the Zambezi enters the extensive Barotse floodplain just upstream from the point where it is joined by the west-bank Lungwebungo tributary (Figure 2.22). The floodplain extends southwards over a distance of some 180 km to terminate at the Ngonye (Gonye) Falls (Figure 2.6). This stretch of the river floods annually between January and June, attaining a width that in places exceeds 30 km, and links, via the Matebele-Mulonga plain, with the floodplain of the Cuando (Figure 2.20; Wellington 1955, Thomas & Shaw 1991).

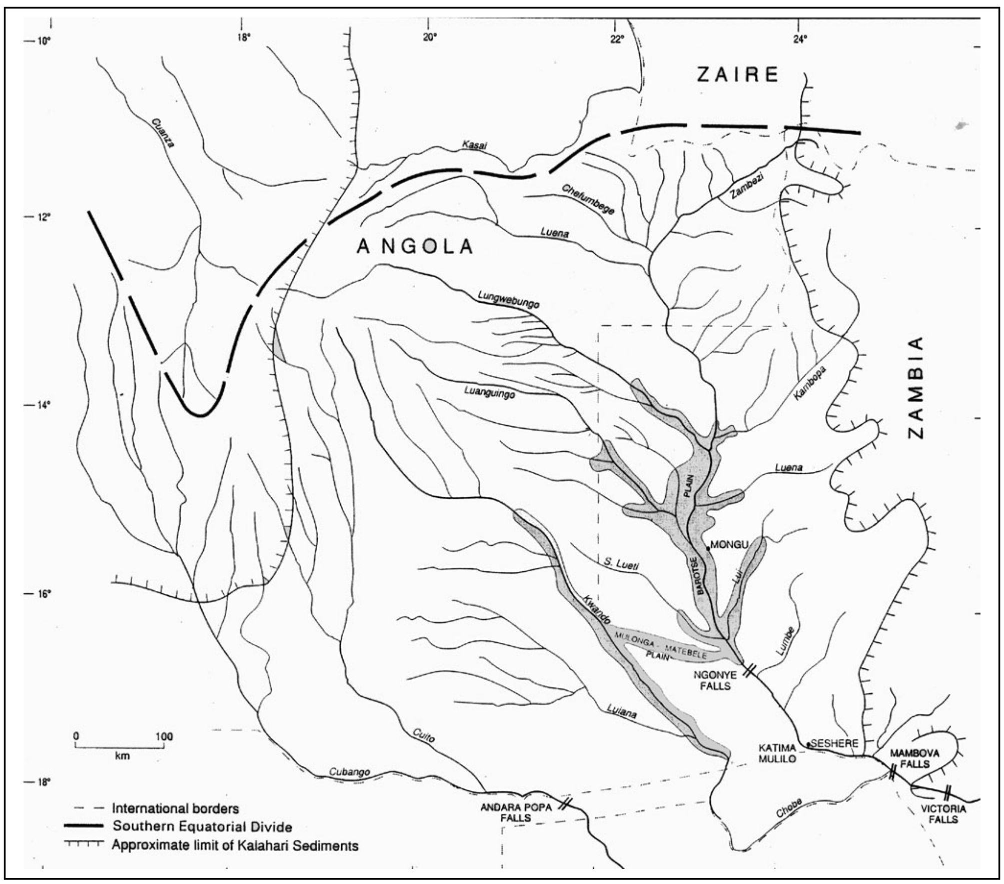

Figure 2.22. The drainage of the northern Kalahari.

The origin of the Barotse Floodplain is not well understood, but Williams (1986) suggests that it is linked to tectonic uplift. In an earlier section, it was noted that many of the east bank Zambezi tributaries to the south of the Ngonye Falls (e.g. the Lumbe and Njoko) have very linear NE-SW flowing courses, which may follow basement fault lines, parallel to those in northern Botswana. It is possible that the Ngonye Falls also mark a fault line responsible for damming the higher sections of the river, initiating a senile system that would dump the sediment load and lead to the formation of the Barotse floodplain. The link between the Zambezi and the Cuando along the Matebele-Mulonga plain may mark the incipient stages of the capture of the upper Cuando by the Zambezi, triggered by the Pleistocene to present-day seismic and tectonic activity that characterizes the Four Corners area.

2.6.6 Barotse Panveld

The area to the east of the Barotse floodplain, in the vicinity of the town of Mongu, is characterized by the development of numerous pans (permanently or seasonally inundated, enclosed depressions) and dambos (generally linear, seasonally inundated bottomlands, some of which are exploited by streams). The pans in some cases define lines, which may be collinear with the dambos. Both are important because seasonal water from springs at their margins makes them important sites for agricultural activity (McFarlane 1995). Water supplied by the springs not only provides irrigation but leads to seasonal flooding, which has permitted the build-up of fertile beds of peat, suitable for growing crops.

There is still very little consensus as to the origin of pans and dambos, or whether the same processes are responsible in different areas. Similar pans, occurring in relatively more arid areas of South Africa and Botswana, have been interpreted as representing relics of abandoned drainage systems (Wellington 1955, Mayer 1973, Marshall & Harmse 1992, Moore 1999). However, McFarlane (1995) infers that the pans to the east of the Barotse floodplain are essentially silicate karst depressions, formed by leaching of silicate minerals (quartz and clay) and contingent subsidence of the landsurface at sites of facilitated infiltration, linked to fluctuating groundwater tables associated with Quaternary climatic change. McFarlane (1995) interprets the dambos as representing the "surface expression of contemporary integrated sub-surface water movement rather than ancient river valleys infilled with alluvium…".

The springs at the margins of the dambos and pans are fed by groundwater flows, and the level of the groundwater table shows marked seasonal variation. Permanent water occurs in the more deeply inset pans, but many have historically only received water from marginal springs during the rainy season. Low rainfall during the 1990s and the resultant lowering of the groundwater table caused some of the pans that previously had permanent water to dry out, while there was a sharp decrease in the amount of water supplied to the seasonally inundated pans. This in turn led to the desiccation of the peat beds, and in some cases their complete destruction when they were burned (McFarlane 1995).

It is not clear whether the dramatic decline in water supply to the pans and dambos in the 1990s is a cyclical phenomenon, or the reflection of a long-term decline in the watertable with a progressive decline in precipitation. It is further not clear as to the timescale of the progression of changes. However, McFarlane (1995) points out that it is important to continue to monitor the process with the view to planning sustainable landuse practices. She notes in particular that the practice of burning peat deposits could render the pan soils too infertile to continue supporting agriculture. Further, she suggests that more efficient water utilisation (e.g. canalisation of water provided by marginal springs) could in part compensate for the declining supply related to the long-term decrease in rainfall.

2.7 INFLUENCE OF GEOMORPHIC FACTORS BEYOND THE FOUR CORNERS AREA ON BIODIVERSITY

An important conclusion of this study is that there have been major changes in river configuration in the Four Corners area during the late Pleistocene and Holocene. In some cases, severance of drainage lines would have resulted in the isolation of river species (e.g. fish and riverine plants), providing the opportunity for speciation to occur. However, the associated river captures would have led to mixing of species from river courses that had previously been isolated.

The changes in configuration of the river systems have been strongly influenced by tectonic activity (faulting) in an area of low relief. Major wetlands such as the Barotse floodplain, the Okavango Delta fan, the Kafue Flats and the Linyanti and Chobe floodplains have all formed in the Pleistocene. However the continued active tectonism means that this is a dynamic system. There have been marked changes in the Okavango system during historic times, leading to, for example, the desiccation of Lake Ngami. On a longer, but not yet quantified timescale, it seems most likely that the Zambezi will eventually capture the Okavango system. The Pleistocene (i.e. past 2 million years) has also seen the development and subsequent dessiccation of the major inland Makgadikgadi lake. Unfortunately they have not yet been accurately dated, so it is difficult to quantify changes in the proportion of the ecologically important wetlands during the Pleistocene. However, given the active tectonic activity in the area, it seems likely that there will be ongoing changes in the configuration of wetlands in the Four Corners area. The study raises the intriguing possibility that the Zambezi may in future be deflected back into central Botswana, to flood part or all of the area of the former Lake Palaeo-Makgadikgadi.

Dunefields in the Four Corners area also show that there were major climatic variations superimposed on the ecological changes resulting from river captures, and consequent changes in wetland systems.

This report has attempted to provide a background to the geomorphological evolution of the Four Corners area with the view to providing a framework for understanding the development of its biodiversity. It should be noted however, that species diversity has also been influenced by geomorphic factors beyond its boundaries, illustrated by two examples.

a) The Upper Chambeshi originally formed the headwaters of the Kafue, as illustrated in Figure 2.15d. Capture of the Upper Chambeshi by the Congo drainage network (Figure 2.15e) provides an explanation for the presence of common fish species in the Zambezi and Congo drainage basins. Research currently being carried out by F. Cotterill (pers. comm.) indicates that river captures and beheadings have important implications for speciation of water dependent species such as lechwe antelope.

b) Skelton (1994) has noted that a high proportion (55%) of the fish species recorded in the Cunene and the Okavango are common to both rivers. This might be considered counter-intuitive, given the fact that the Cunene empties into the Atlantic, while the Okavango terminates in an inland delta. However, Moore and Larkin (2001) postulate that the headwaters of the Cubango were originally linked to the Cunene via the Colui, as illustrated in Figure 2.23. Thus, minor river captures in the headwaters of the two main rivers have provided a pathway for fish migration.

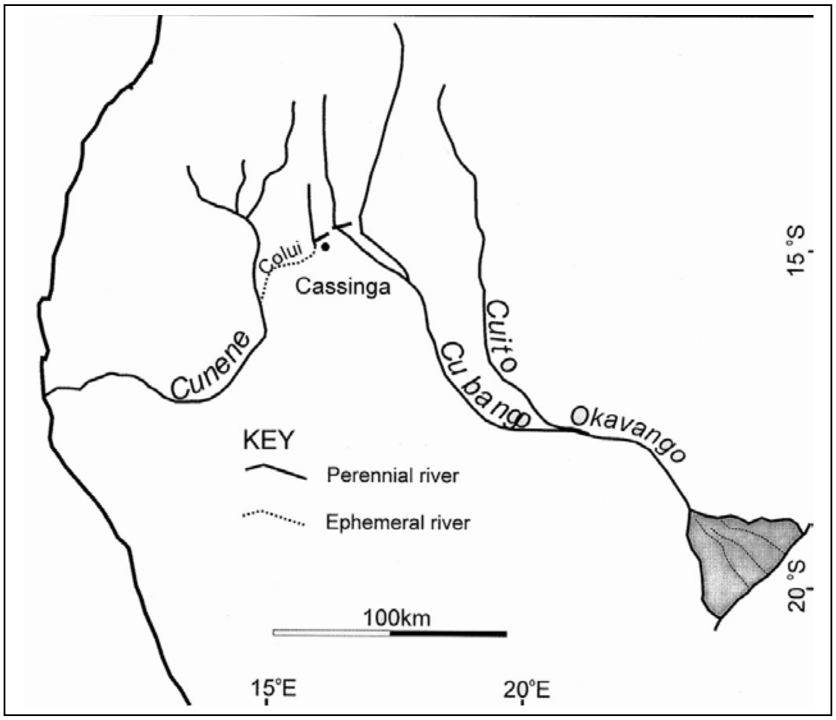

Figure 2.23. Headwaters of the Cunene and the Okavango-Cubango. Solid lines are perennial drainages, dashed lines denote the ephemeral course of the Colui.

2.8 FURTHER RESEARCH

Two lines of further research to improve our understanding of the dynamic factors responsible for modifying ecological environments within the Four Corners area are highlighted:

1. More refined dates are required to establish the timing of river captures and the ages of shoreline features in the Makgadikgadi palaeo-lake, as well as the timing of major episodes of dune formation. This is a problematic area given the inherent difficulties in interpreting both thermo-luminescence and ^{14}C ages, which potentially cover the important late-Pleistocene and Holocene. Nevertheless, there is progress. The archaeological evidence presented by McFarlane and Segadika (2001) has demonstrated that the Makgadikgadi is considerably older than implied by the ^{14}C ages. Further, genetic studies currently being carried out by Cotterill of water-dependent species such as lechwe that were isolated by river captures, provides a potential feedback mechanism that will place stronger constraints on the timing of drainage disruptions.

2. Data provided by Moore and Dingle (1998) on grainsize variation of the central Kalahari cover sands provides a potentially valuable framework for selective sampling to test correlations between textural variations and nutrient content. This would help resolve the question as to whether plant distribution is primarily a function of nutrient content, or related rather to rooting strategies to access available water resources.

2.9 CONCLUSIONS

The Four Corners area has been an area where profound drainage organizations have occurred during the Quaternary (i.e. over the last 2 million years). This has been controlled by a combination of low relief and active tectonic activity (faulting). River captures provide pathways for fish migration between river systems, but, on the other hand, such captures will isolate fish populations leading to speciation. This will also apply to other water-dependant species such as lechwe antelope (F.Cotterill, pers. comm.). Genetic studies offer potential tools to refine the dating of the broad sequence of changes to the river systems discussed in this study. We should also recognise, however, that species diversity will also be affected by geomorphic events beyond the immediate boundaries of the Four Corners area.

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