Drainage evolution in south-central Africa since the breakup of Gondwana

A.E. Moore
Somabula Explorations, Box CH399, Chisipite, Harare, Zimbabwe.
e-mail: andymoor@africaonline.co.zw

P.A. Larkin
Aqua Tech Groundwater Consultants, Box 10072, Gaborone, Botswana.

ABSTRACT

The drainage system in south-central Africa has undergone major reorganisations since the disruption of Gondwana. Isopachs of the Kalahari sequence and a variety of geomorphological features can be used to pinpoint abandoned drainage lines. Continental fluvial sediments of Mesozoic-Cenozoic age reflect river systems which existed prior to and immediately following continental break-up. The east coast sedimentary sequence documents changes in the location of major supplies of terrigenous sediments, and provides a framework for establishing the timing of changes in drainage configuration. This evidence indicates that during the upper Jurassic to Cretaceous, the Okavango, Cuando and Zambezi-Luangwa rivers formed the headwaters of the proto-Limpopo. The lower-Zambezi-Shire formed a separate graben-bound river system with a discharge point into the Indian Ocean in the vicinity of mouth of the present-day Zambezi. A third major drainage entered the Indian in the vicinity of the modern Save mouth. End Cretaceous uplift along the Okavango-Kalahari-Zimbabwe Axis severed the links between the Limpopo and the Okavango, Cuando and Zambezi-Luangwa. This resulted in a senile endoreic drainage system which supplied sediment to the Kalahari basin. However, the uplift rejuvenated the lower Zambezi, initiating headward erosion and progressive capture of the Luangwa, upper Zambezi and Kafue. Predatory headward extension of the Zambezi is still active, and this river will eventually capture the Okavango. The model developed for drainage reorganisation provides a framework for interpreting kimberlitic heavy mineral dispersion patterns. It also forms the basis for explaining fish and plant dispersion patterns, and understanding recent water level fluctuations in the Makgadigadi pans system in Botswana.

Introduction

The evolution of the modern drainage system in southern Africa has been controlled by the complex interplay of a variety of geological processes. For example, du Toit (1910) recognised that the upper Harts River follows exhumed Permo-Carboniferous valleys related to the Dwyka glaciation. The Vaal flows discordantly across the concentric ridges of Witwatersrand quartzite, which surround the Vredefort Dome, suggesting that it is a superposed drainage (King, 1963). White and McKenzie (1989) postulated that the Karoo volcanism, which heralded the disruption of Gondwana, was associated with updoming of the super-continent over major mantle plumes. Cox (1989) suggested that these domes played a major role in controlling the development of the post-Gondwana drainage system. Subsequent to the break-up of Gondwana, epeirogenic flexing of the sub-continent has disrupted drainage lines. Examples are the severance of the links between the Okavango and Limpopo rivers (du Toit; 1927; 1933) and between the Molopo and Orange rivers (Moore, 1999).

Three major eastward-flowing drainages in southern Africa the Zambezi, Save and Limpopo – enter the Indian via the Mozambique coastal plain (Figure 1). This study reviews the geography of these three rivers, and presents evidence, for the positions of major abandoned drainage lines, and major changes in river configuration since the disruption of Gondwana. Thus Kalahari sand isopachs can be used to define the former positions of major valleys. Surface alluvial deposits in the Kalahari and a variety of geomorphological features can also be related to fossil river systems. Continental fluvial sediments of Karoo-Cretaceous age reflect drainage systems, which existed prior to, and immediately following disruption of Gondwana. The east coast sedimentary sequence reflects progressive changes in the location of major fluvial discharge centres. Collectively, this evidence provides a framework to reconstruct and date successive stages in the evolution of the major rivers and tributaries in south-central Africa which drain towards the east coast, from the time of continental break-up to the present.

The Zambezi, Save and Limpopo river systems

The Zambezi system, illustrated in detail in Figure 2, is by far the largest of the three eastward-draining rivers in south-central Africa. It can be divided into three distinct sections, each with a distinctive geomorphic character (Wellington, 1955).

The Upper Zambezi extends from the headwater basin to the Victoria Falls (Figures 1 and 2). This section of the river traverses an area of low relief, which is largely underlain by Kalahari Group sediments. At the

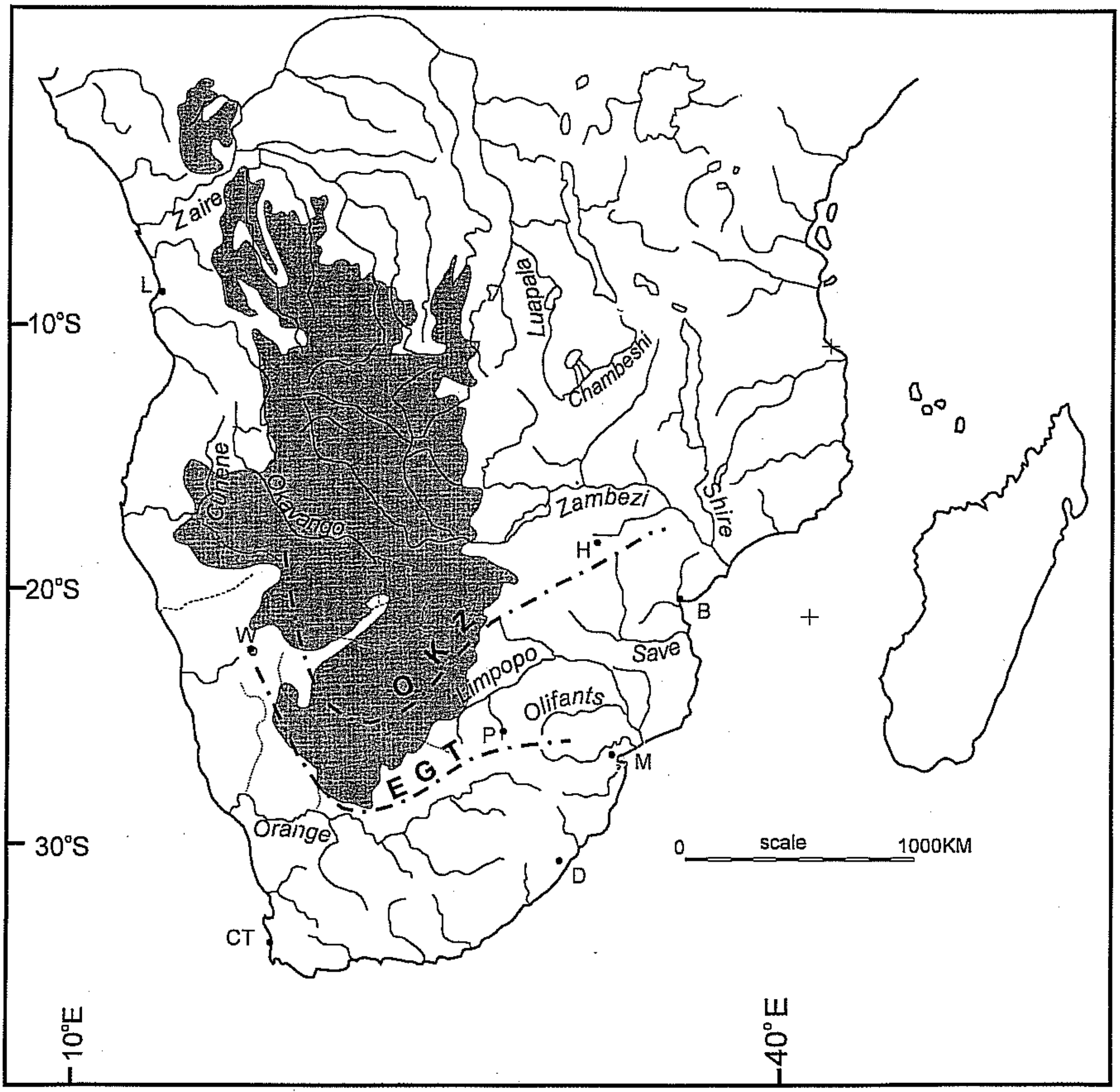


Figure 1. Major drainages in Southern Africa (solid lines). Dotted lines show ephemeral and fossil drainages. Shaded area shows the distribution of the Kalahari sediments. Dashed-Dot lines: Etosha-Griqualand-Transvaal (EGT) Axis and Okavango–Kalahari–Zimbabwe (OKZ) Axis (from Moore, 1999). Cities: B: Beira; CT: Cape Town; D: Durban; H: Harare; L: Luanda; M: Maputo; P: Pretoria; W: Windhoek.

border between Angola and Namibia, the course of the Zambezi veers from southeasterly to easterly. The Cuando, a major west bank tributary of the upper Zambezi, swings abruptly from a southeasterly to a northeasterly line, becoming the Chobe, just above the confluence of the two rivers.

The Mid-Zambezi, or Zimbabwe-Mozambique trough zone, extends in a broad arc from the Victoria falls to the Cabora Bassa gorge. This and three other major gorges on the Mid-Zambezi (in an upstream direction, the Mupata, Kariba and Batoka gorges) separate a series of subsidiary troughs or basins where the channel widens. These are, also in an upstream direction, the Chicoa (site of the Cabora Bassa dam), Mana Pools and Gwembe (site of Lake Kariba) basins (Figure 2). Over much of its length, the mid-Zambezi flows through a major rift zone, with a thick infill of Karoo-age sediments and lavas. The Luangwa and Kafue are major north bank tributaries of the Mid-Zambezi.

The Lower Zambezi extends from the Cabora Bassa gorge across the low-lying Mozambique plain. The Shire, with headwaters in Lake Malawi, is a major north-bank tributary. Both rivers are controlled by major rift bounding faults.

The Limpopo rises in the north of South Africa, and flows in a broad curve that is essentially parallel to the course of the Mid and Lower Zambezi (Figure 1). It enters the Indian Ocean in southern Mozambique, some 800km south of the Zambezi mouth. The Olifants is an important south bank tributary of the Limpopo.

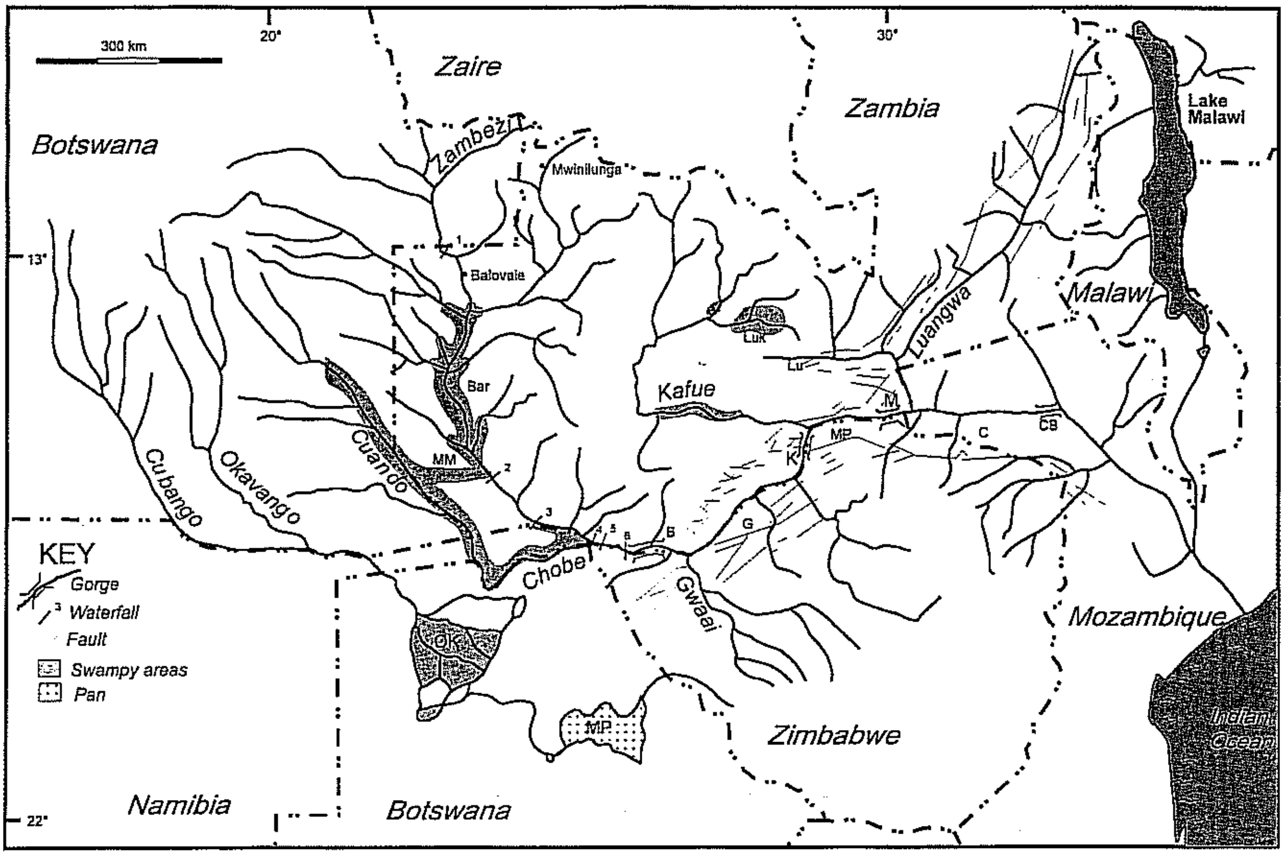


Figure 2. Detail of the Zambezi drainage system (adapted from Nugent, 1990).
Rift basins: G :Gwembe trough (Mid-Zambezi basin); MP: Mana Pools basin; C: Chicoa trough (Lower Zambezi basin).
Gorges: B: Batoka gorge; K: Kariba gorge ; M: Mupata gorge; CB: Cabora Bassa gorge
Rapids and Falls: 1: Chavuma;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

The Save flows southwards from its headwaters in Zimbabwe until the Mozambique border, where it swings abruptly to the east (Figure 1). It maintains this course until it enters the Indian Ocean, roughly midway between the mouths of the Zambezi and Limpopo rivers.

Evidence for disruption of the major east draining rivers

Previous research workers have drawn attention to a number of lines of evidence which argue for changes in the configuration of the major eastward draining rivers. The more important are summarised below:

Du Toit (1927; 1933) noted that the Okavango River is unusual in terminating in a major inland delta, and suggested that it was originally linked to the Limpopo, possibly via the Motloutse River.

The change in course of the Upper Zambezi from southerly to easterly at the head of the Batoka Gorge has

Table 1. Fish species Similarity Indices (SI) between selected southern African rivers. (From Skelton, 1994)

Rivers Compared	Combined number Of species	Species shared	Similarity Index (SI)
Upper Zambezi/Okavango	96	77	0.80
Upper Zambezi/Kafue	97	62	0.64
Kunene/Okavango	93	51	0.55
Save/Limpopo	59	28	0.48
Limpopo/Mid-lower Zambezi	88	36	0.41
Upper Zambezi/Middle-lower Zambezi	133	36	0.27
Upper Zambezi/Limpopo-Inkomaas-Pongola	122	23	0.19
Limpopo/Orange	48	6	0.13

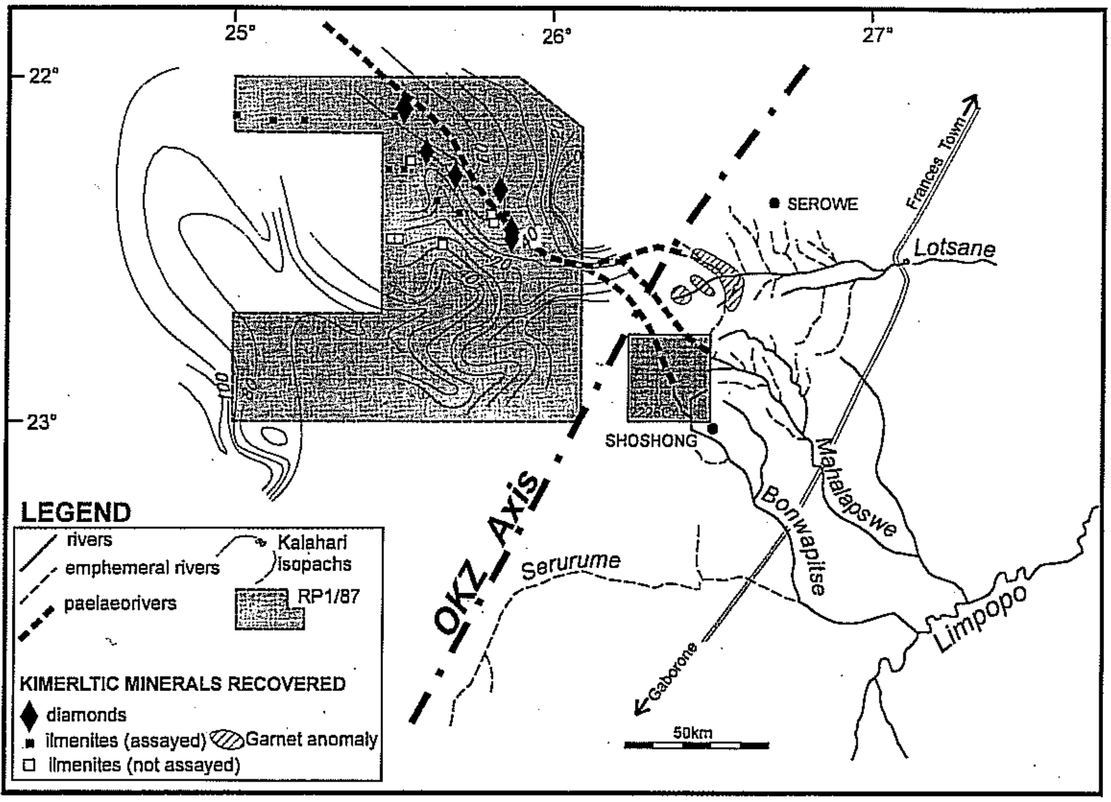


Figure 3. Kalahari isopachs (from borehole data) and prospecting results from RP 1/87. Dash-dot line is the Okavango-Kalahari-Zimbabwe (OKZ) Axis, (Moore, 1999). The heavy dashed lines show inferred palaeo-drainage lines. The river associated with the sub-Kalahari valley outlined by the Kalahari isopachs in RP 1/87 would have been linked to the Limpopo successively via the Bonwapitse, Mahalapswe and Lotsane. The area covered by Figure 6 (Quarter Degree Sheet 2226C4) is shown by the grey-tone rectangle.

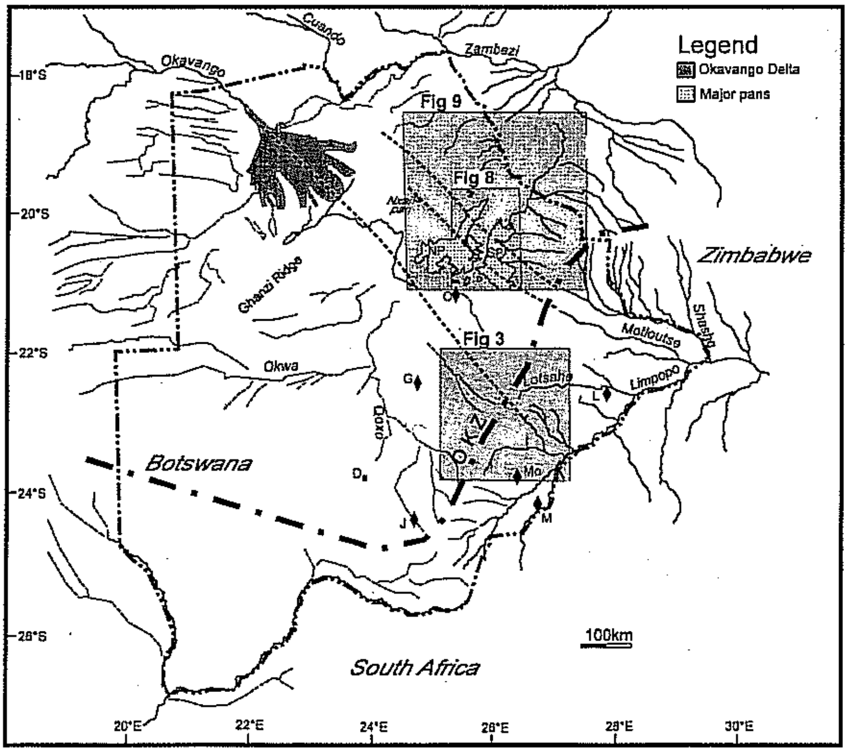


Figure 4. Reconstruction of palaeodrainges in Botswana and Zimbabwe. Rectangular grey-tone boxes show areas covered by Figures 3, 8 and 9. Solid black lines: modern active drainages; stippled lines: Fossil/ephemeral drainage lines; Heavy dashed lines: inferred palaeodrainages. OKZ = Okavango-Kalahari-Zimbabwe Axis (Moore (1999). Note that the Cuando had former links to the Limpopo via both the Motloutse and Shashe, as discussed in the text. Solid diamonds denote kimberlite fields in eastern Botswana: G: Gope; J: Jwaneng; L: Lerala; M: Mochudi; Mo: Mosemane; O: Orapa. D: Dutiwe heavy mineral anomaly.

been interpreted as a capture elbow (Wellington, 1955). A number of the Zambezi tributaries also show abrupt changes of course, which could indicate capture elbows. Thus, the lines of the Kafue and Save both swing sharply from southerly in the upper reaches, to easterly in their lower sections. The Luangwa flows to the southwest until just above the confluence with the eastward flowing Zambezi, where it veers abruptly to the south-southeast (Figure 2).

Several palaeo-shore line features can be recognised on the Makgadigadi pans in central Botswana (Figure 2). Grove (1969) infers the highest stand (945m) of the palaeo-lake cannot be explained by any realistic increases in precipitation associated with earlier climatic regimes. He suggests, rather, that this level could only have been maintained if the Makgadigadi Pan was fed by the Zambezi river. This requires a course considerably to the south of the modern drainage.

The occurrence of common fish species in different rivers provides compelling evidence for earlier links between these drainages (Gaigher and Pott, 1973; Bond, 1975; Bowmaker *et al.*, 1978; Skelton, 1993; 1994). The number of species common to two rivers divided by their total number of species provides a similarity index

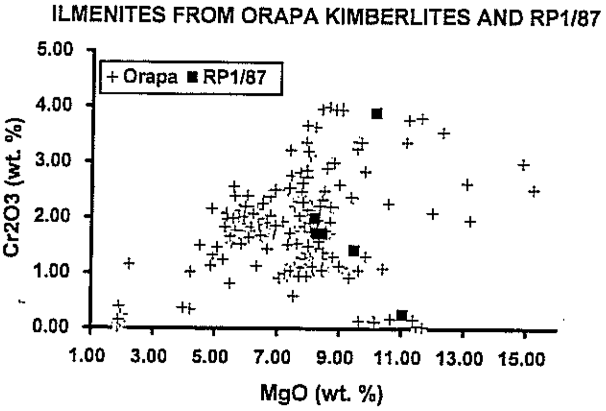


Figure 5. Compositions of ilmenites from RP 1/87 compared to the population from the Orapa kimberlites (data sources given in Table 2). Orapa ilmenites with very low Cr_2O_3 (<<0.5%) and between 9-12% MgO are from ilmenite-bearing eclogites from the Orapa (AK1) pipe that are described by Tollo (1982). Note that one ilmenite from a soil sample in RP1/87 falls within this sub-population. The ilmenites in this low-Cr suite are not included in the statistical analysis summarised in Table 2.

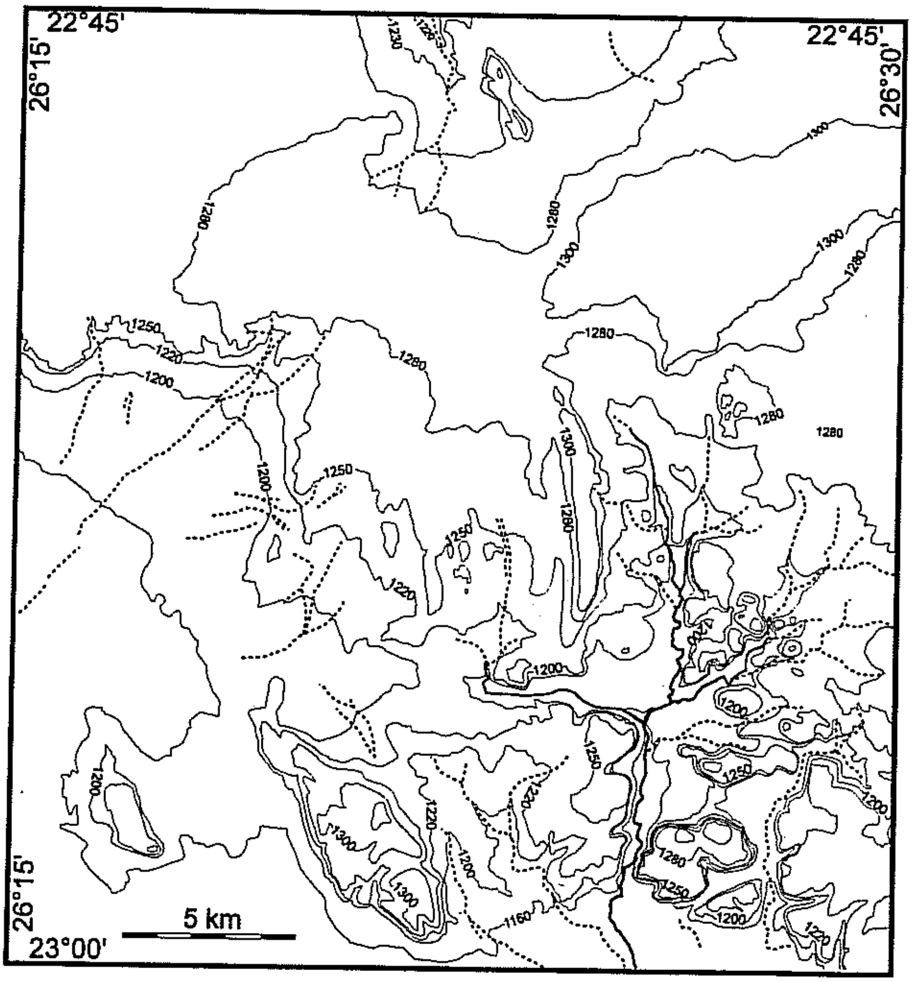


Figure 6. Topographical data (contours in metres) from quarter degree sheet 2226C4, illustrating the deeply incised ravine forming the headwaters of the ephemeral Bonwapitse River. The location of Quarter Degree Sheet 2226C4 is shown on Figure 4. Heavy black line shows the modern river channel. Dashed lines are minor channels.

Figure 7. Landsat image of Sowa Pan illustrating the three spits that project into the pan from the eastern shoreline. The southernmost (inferred oldest) spit is at the extreme south of the image. Attention is drawn to the linear sandy island located immediately to the north-west of this feature. (Landsat image acquired and processed by the Satellite Applications Centre, CSIR, Pretoria, South Africa, www.sac.co.za).

(SI). Selected Similarity Indices (from Skelton, 1994) are shown in Table 1. On the basis of the Similarity Indices, southern Africa can be divided into two major icthyofaunal provinces – designated the Southern (or Cape) and Zambezi provinces respectively. The former comprises the Orange-Vaal system (including the Molopo) and coastal drainages southwards from the Tugela. The Zambezi province is divided into western and eastern sub-provinces. The former comprises the Okavango, upper Zambezi and Kafue rivers, and also the Cunene, which empties into the Atlantic. The eastern Zambezi province comprises the Lower Zambezi and east coast rivers to the north of the Tugela (Skelton, 1994). Skelton notes while a high SI argues for a former link between two drainages, a low SI may in part reflect differences in river ecology.

The occurrence of paired, isolated populations of riverine plant species on the Zambezi and Limpopo has been ascribed to an earlier link between these two river systems (Moore, 1988).

Evidence for abandoned drainage lines

Several lines of evidence, chiefly from Botswana and Zimbabwe, make it possible to pinpoint the locations of abandoned drainage lines related to the Zambezi and Limpopo and their tributaries.

South-eastern Botswana

Seltrust Botswana Explorations (Pty.) Ltd. (Seltrust) identified a major southeast-northwest oriented sub-Kalahari valley within their former diamond exploration Reconnaissance Permit 1/87 (RP1/87) in southeastern Botswana (Figures. 3 and 4) (Davidson, 1988). It is located immediately to the west of the watershed between the Limpopo and fossil endoreic drainage lines in the central Kalahari. Kalahari sequence isopachs indicate that this valley drained towards the northwest. Note that the watershed to the east of the valley has been interpreted to represent a line of late Cretaceous – early tertiary crusted flexure, termed the Okavango-Kalahari-Zimbabwe (OKZ) axis (Moore, 1999)

Reconnaissance sampling in RP1/87 resulted in the recovery of diamonds and picro-ilmenites from the surface Kalahari sands just to the west (downwind) of the valley axis. Prospecting experience in Botswana has shown that anomalous concentrations of kimberlitic minerals in the surface sands may reflect the existence of underlying sub-Kalahari kimberlites (*e.g.* Lock, 1985; Lee, 1993). Such primary heavy mineral anomalies are typically displaced in a downwind direction of the source kimberlite (Lock, 1985). However, secondary anomalies have also been identified where the Kalahari sand overlies basal gravels deposited by a river system which drained upstream kimberlites. The best documented of these secondary surface anomalies occurs at Dutlwe in the central Kalahari (Figure 4). The kimberlitic heavy mineral suite associated with this anomaly is inferred to have ultimately been derived from the Jwaneng kimberlite field, located some 100 km to the south-east (Edwards, 1986; McGeorge, 1998).

Follow-up sampling within RP1/87 by Seltrust failed to locate any kimberlites. It was therefore concluded that the pathfinder heavy mineral suite was derived from a distal source, and concentrated in gravels associated with the sub-Kalahari valley (Davidson, 1988). The ground to the south–east of RP1/87 has been covered by a number of detailed prospecting programmes involving several different companies. The closest known kimberlites in this area are those recently discovered by the South African Minerals Corporation (SAMC) near Mosemane (Figure 4) (company press release dated 02-11-98). Two small kimberlites (designated AK-1 and AK-2) had previously also been discovered by de Beers Botswana Prospecting (Debot) further to the south-east near Mochudi (Figure 4).

Ilmenites from individual kimberlites typically define diagnostic compositional fields, which serve as geochemical "fingerprints" (Lee, 1993). Table 2 compares Cr and Mn concentrations in ilmenites recovered within RP1/87 with those in the kimberlites to the southeast (data for the Mosemane kimberlites supplied by SAMC, and those from Mochudi kindly provided by Debot). Compared with the grains recovered in RP1/87, ilmenites from all the kimberlites to the southeast are markedly depleted in Cr_2O_3, but strongly enriched in MnO. A statistical analysis shows that at the 5%

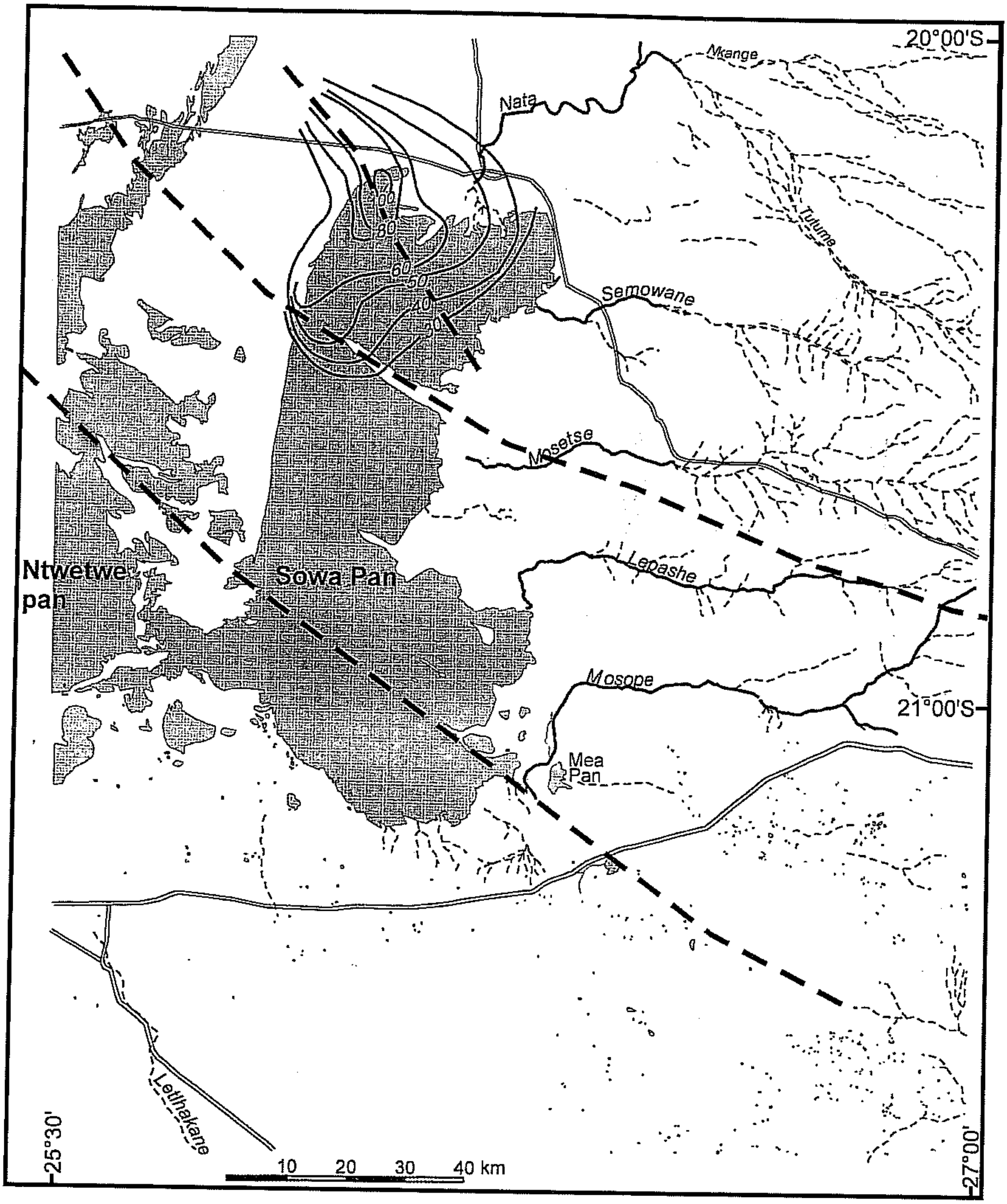


Figure 8. Geomorphology of Sowa Pan. Data taken from 1:250 000 Sheets 12 (Nata) and 17 (Letlhakane), Dept. of Surveys and Lands, Republic of Botswana. Note that the three northwest oriented spits projecting from the eastern shore of the pan become progressively more poorly defined from north to south. A belt of pans associated with relict drainage lines traverses the watershed separating southwestern Sowa and the headwaters of the Motloutse River. Contours in the very north of Sowa show isopachs of the pan sediments above a prominent sandstone marker horizon. These are interpreted to reflect a major delta, fed from a source to the northwest. Heavy dashed lines are two inferred fossil drainage courses, which formerly traversed Sowa Pan. The middle spit, and the "island" immediately to the north of the southern spit are also inferred to be relics of abandoned river channels.

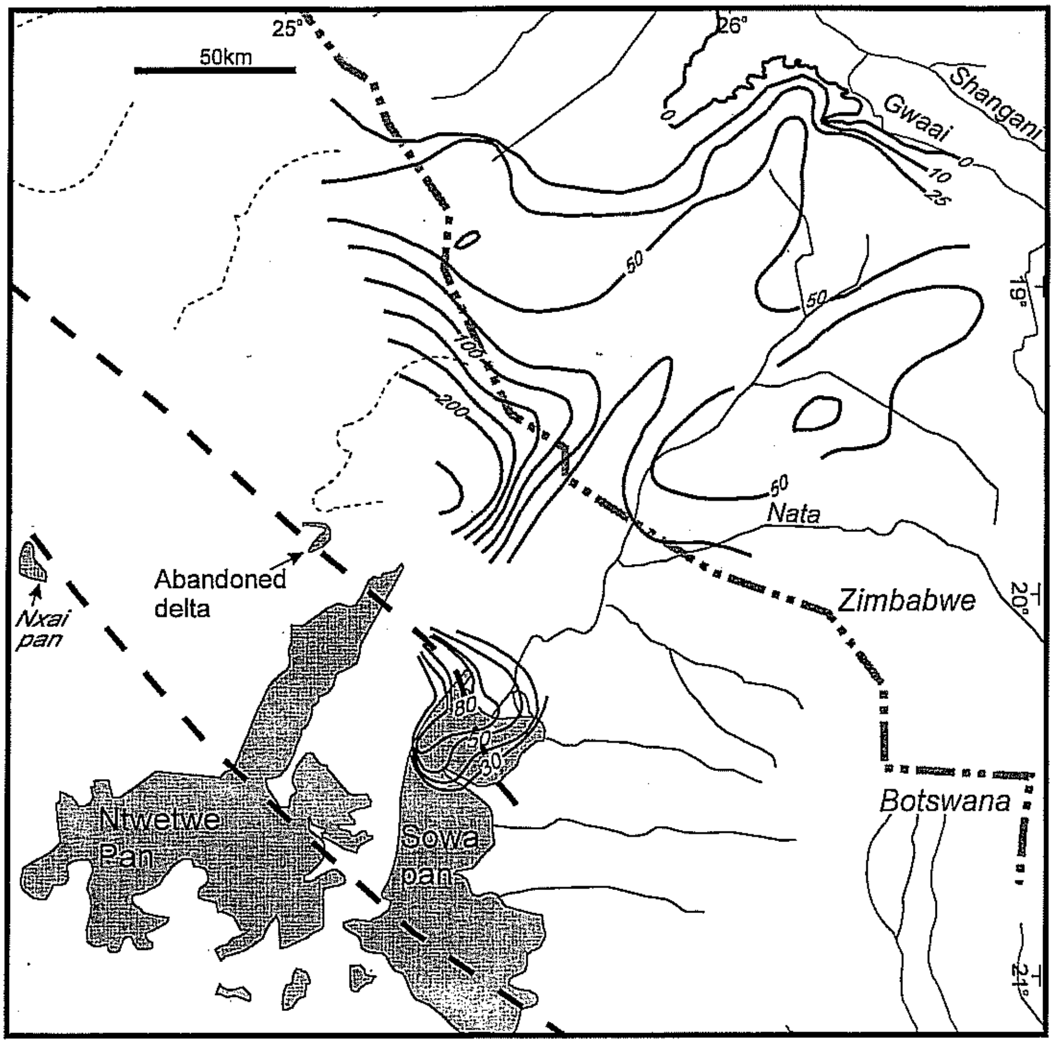


Figure 9. Kalahari sand isopachs straddling the Botswana-Zimbabwe border. These are interpreted to reflect a major sub-Kalahari valley with headwaters located to the north-east. Isopachs in the north of Sowa Pan are from Figure 8. A photo-feature to the north of Ntwetwe Pan has been interpreted to represent an abandoned delta (Mallinck *et al.*, 1981)

confidence limit, the ilmenites recovered in RP1/87 do not match, and thus cannot be derived from the known kimberlites located to the southeast. However, they plot within the very distinctive MgO-Cr_2O_3 chemical field defined by the suite from the Orapa kimberlite cluster (Figure 5). Average MnO and Cr_2O_3 contents of the two populations (Table 2) are indistinguishable at the 5% confidence limit. Such closely similar chemical fingerprints provide very compelling evidence that the Orapa kimberlite field was the ultimate source of the pathfinder minerals recovered in RP 1/87. Thus, while the Kalahari isopachs (Figure 3) show that the sub-Kalahari valley slopes towards the north-west, the chemistry of ilmenites recovered in RP1/87 indicates

Table 2.

			Mochudi Kimberlites		
	RP1/87	All Orapa Kimberlites	AK1	AK2	All Mosemane Kimberlites
N	5	208	980	174	145
Cr_2O_3 (Av)	2.14	1.81	0.26	0.37	0.54
Cr_2O_3 (SD)	1.00	0.85	0.46	0.30	0.49
MnO (Av)	0.30	0.28.	1.63	0.85	1.10
MnO (SD)	0.11	0.06	1.68	1.33	1.23

N = number of ilmenites analysed; Av = population average; SD = standard deviation

Note that Orapa data is for all kimberlite for which ilmenite analyses are available. Sources of data: Shee (1978); Tollo (1982); de Beers, unpublished data; Rio Tinto, unpublished data; South African Minerals Corporation (Ltd), unpublished data; Moore, unpublished data.

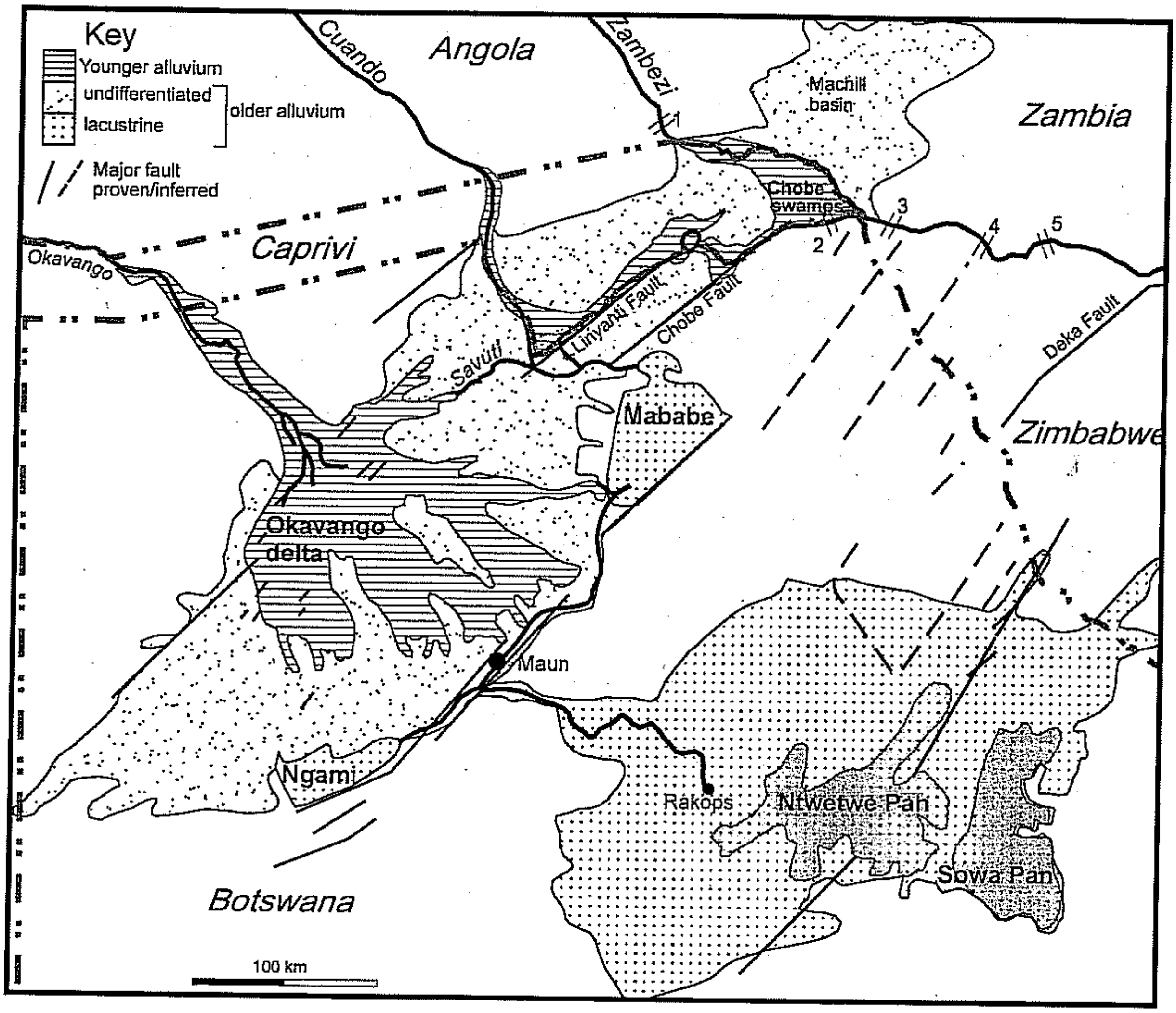


Figure 10. The distribution of alluvial and lacustrine sediments in north-eastern Botswana and southern Zambia. The alluvium of the Machili basin possibly extends further to the north-east as far as the Kafue River (Thomas and Shaw, 1991). Limits of the older alluvial deposits reflect the approximate the extent of Lake Palaeo-Makgadigadi associated with the highest recognised shoreline (945 m) (Thomas and Shaw, 1991). This formed two subsidiary basins, linked via a narrow neck along the Boteti valley (Thomas and Shaw, 1991). 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.

derivation from the Orapa kimberlite field, which is located to the north-west (Figure 4). This requires the reversal of a drainage which originally flowed to the south-east.

Three ephemeral Limpopo tributaries, which only flow following heavy rains, have their headwaters immediately to the east and southeast of the sub-Kalahari valley identified in RP1/87 (Figure 3).

The northernmost of these is the Lotsane, which flows in an easterly direction from the headwaters, located to the southwest of Serowe (Figure 3). Prospecting carried out by de Beers resulted in the recovery of pyrope garnets in the upper reaches of this river. However, despite further detailed follow-up, no kimberlites have been discovered, and the source of the pathfinder minerals remains unresolved.

Immediately to the south of the Lotsane is the Mahalapswe, which flows to the southeast. Where it crosses the main Gaborone-Francistown road, some 50 km downstream from its headwaters, this is a sand-choked river over 100m in width.

To the south of the Mahalapswe is the Bonwapitse, a minor ephemeral braided stream in the broad shallow Shoshong valley. The headwaters rise in a narrow steep-sided ravine located at the head of the Shoshong valley, illustrated in Figure 6 (topographical data digitised from 1:50 000 Quarter Degree topographical sheet 2226C4). The location of Figure 6 is shown in Figure 4. In the higher sections of the ravine, the channel of the Bonwapitse is sand-choked, but in the lower reaches there are pockets of poorly sorted polymict basal gravels with rounded clasts up to 100mm in diameter. The gravels are loosely cemented, and thus pre-date the modern sandy bedload. Exploration work carried out by Debot has identified an anomalous concentration of kimberlitic garnets in the vicinity of the Bonwapitse-Limpopo confluence (Andrew McDonald, Debot, personal communication)

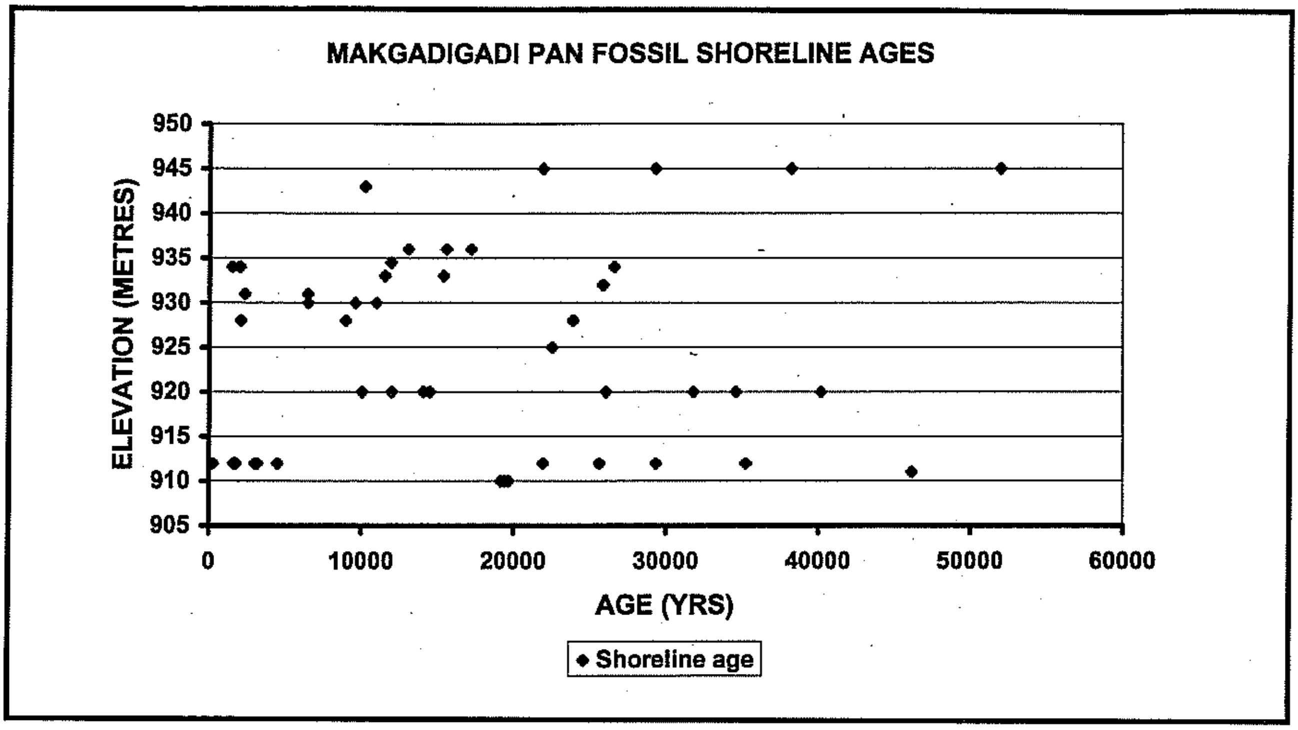


Figure 11. Relationship between age and elevation of fossil shoreline features associated with lake Palaeo-Makgadigadi (Data from Thomas and Shaw, 1991).

Sowa Pan, Central Botswana

Sowa Pan is the eastern basin of the Makgadigadi Pans complex in central Botswana (Figures 4, 7 and 8), which was formerly a major inland lake. Well developed shoreline features at an elevation of 945m mark the greatest extent of Makgadigadi basin, when it covered an area of between 60 000 to 80 000 km^2 (Cooke, 1980; Mallinck *et al.*, 1981). Relict shoreline features are also preserved at a number of lower levels. The most important of these occur at elevations of 935 to 930m, 920m and 911m (Thomas and Shaw, 1991). Today, the Makgadigadi basin only fills to any significant extent in the north of Sowa Pan, where the Nata River has built out a minor delta.

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 above a prominent sandstone horizon, identified as either the Karoo Ntane sandstone or part of the Kalahari Formation. Isopachs of the pan sequence above this marker horizon are shown in Figure 8. Their geometry suggests that they represent a major delta, fed by a river, which entered the pan from the northeast. Mallinck *et al.* (1981) have identified a minor photofeature to the northwest of Sowa Pan (Figure 9), which they interpret to be an abandoned delta, associated with one of the high lake shorelines.

In the north of Sowa Pan there is a prominent sandy spit, oriented south-east – north-west, which projects from the eastern shoreline across almost three quarters of the basin width (Figures 7 and 8). 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 southeast-northwest. A linear sandy island, with a similar orientation, is located immediately to the north of this spit.

Botswana-Zimbabwe border

Borehole data (assembled, and made available by Mr. Vince Atkinson of Rio Tinto Zimbabwe) show that the thickness of the Kalahari sequence straddling the Botswana-Zimbabwe border (Figure 9) exceeds 200m. The Kalahari isopachs 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 Shaw (1990).

Alluvial deposits in north-east Botswana

A soil classification study of Botswana has identified extensive alluvial deposits of two different ages in the north-east of the country (Figure 10) (Land Systems Map of the Republic of Botswana, 1990 (1:2 000 000); Soil Mapping and Advisory Services Project, AG:DP/BOT/85/011). The younger alluvial deposits are associated with the present-day Okavango, Linyanti and Chobe Rivers. The older suite is represented by lacustrine sediments of the Makgadigadi Pans, Lake Ngami and the Mababe depression, and a southwest-northeast trending belt of undifferentiated alluvium, which extends into southern Zambia, and may continue as far as the Kafue flats (Thomas and Shaw, 1991). This belt of alluvium is bounded by a set of major faults, which appear to have controlled sedimentation (Figure 10). Some of these faults truncate east-west trending dunes of Quaternary age, located to the west of the Okavango Delta (Mallinck *et al.*, 1981), indicating that they have been active very recently. This is consistent with the present-day seismic activity that has been recorded in the Okavango area (Reeves, 1972; Scholz *et al.*, 1976).

The older alluvial deposits together cover the inferred area of the maximum extent of the former Lake Makgadigadi associated with the 945m shoreline (Thomas and Shaw, 1991). A narrow neck along the Boteti valley linked the Makgadigadi basin with the northeast-southwest trending basin of this former major inland lake, which Thomas and Shaw (1991) term "Lake Palaeo-Makgadigadi". They estimate that the combined area of the two basins was approximately 120 000 km^2.

^{14}C dating of the of deposits associated with the 945m shoreline gives a range of ages varying from >52 000 BP (the limit of ^{14}C dating) to 10 230 BP. Ages for the 920m and 911-912m levels range from 40 200-10 070 BP and 46 200-235 BP. respectively (Thomas and Shaw, 1991) (Figure 11). This indicates that within the timeframe that ^{14}C dating is reliable, the lake has filled and contracted on several occasions.

Victoria Falls and lower gorges

Figure 12 illustrates the stretch of the Zambezi River in

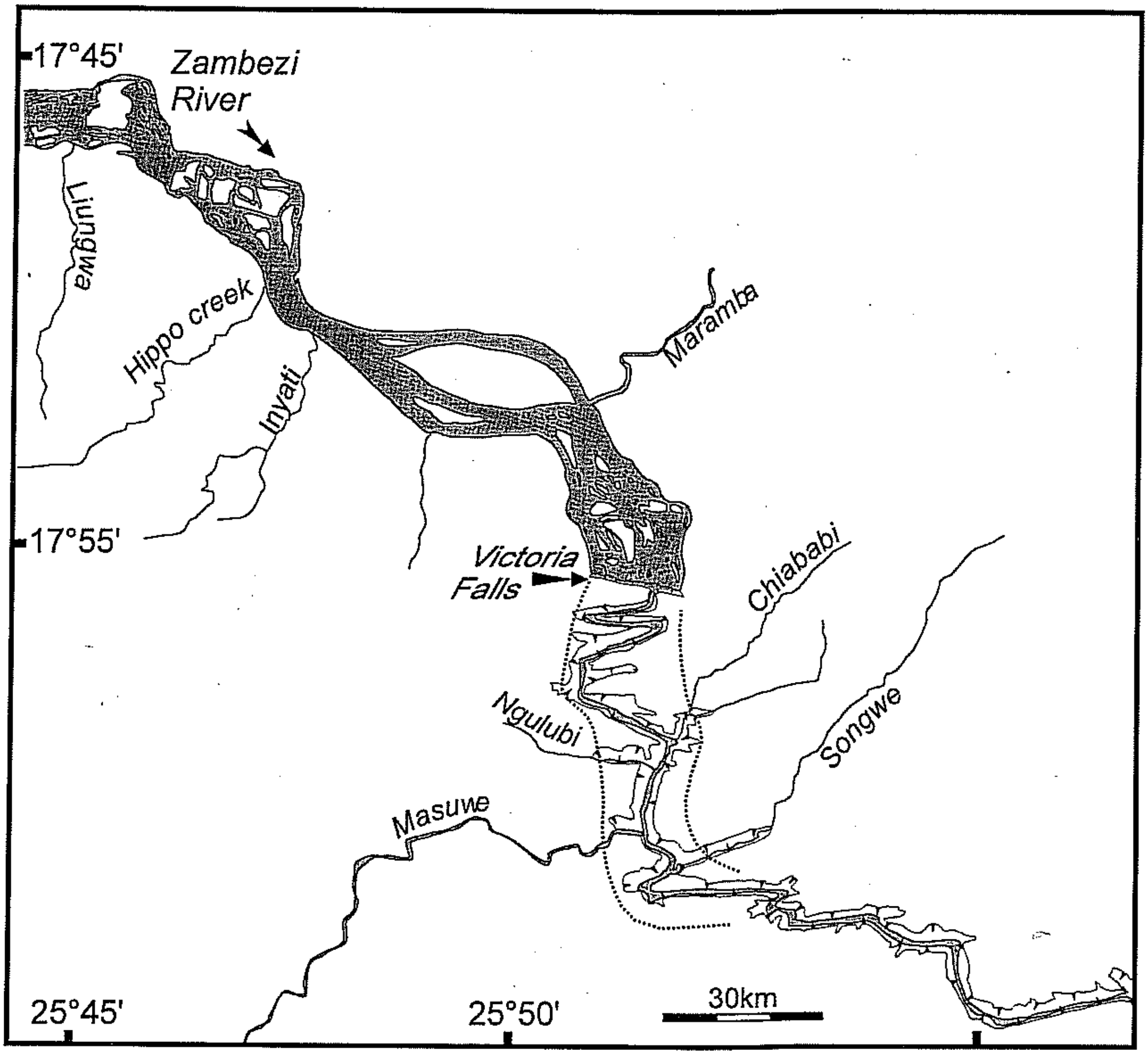


Figure 12. Geomorphology of the Zambezi River in the vicinity of Victoria Falls (from 1:50 000 topographical sheet 1725D4 (Victoria Falls)). Dashed line on either side of the gorge below the falls marks a low escarpment, interpreted to reflect the original bank of the Zambezi prior to river capture (following Wellington, 1955). The sharp deflection of the Zambezi from a southerly 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).

the vicinity of the Victoria Falls (from 1:50 000 topographical sheet 1725D4), 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 2km wide. Below the falls, the Zambezi follows a zigzag sequence of narrow gorges oriented approximately west-north-west – east-south-east and eastnortheast-westsouthwest, before swinging to a roughly north-south course about 2km above the confluence with the west bank Songwe tributary. Immediately downstream of this confluence, the Zambezi turns sharply to the east into the Batoka gorge, and maintains this general bearing for a distance of some 100 km. Wellington (1955) notes that on either side of the Zambezi gorge above the confluence with the Songwe, a low scarp has been cut into the surrounding flat-lying plain. This feature is shown by the dotted line in Figure 12.

Sedimentary evidence for drainage evolution

Continental fluvial sediments of Karoo-Cretaceous age reflect drainage systems, which existed immediately prior to, and following disruption of Gondwana. The east coast sedimentary record documents changes in location of major supplies of terrigenous sediment, and provides a framework for establishing the timing of major changes in drainage configuration. This sedimentological evidence is discussed below:

Continental fluvial sediments of Karoo-Cretaceous age

The Zambezi Valley is a major fault-bound Karoo depocentre. In the western Cabora Bassa basin of the lower Zambezi, the Karoo sequence is divided into upper and lower units, separated by an angular unconformity (Oesterlen and Millsteed, 1994). The Permian age Lower Karoo is divided into the basal Kondo Pools Formation, deposited in a glacial or post-glacial environment, and the overlying argillaceous Mkanda Formation, which is interpreted to reflect lacustrine sedimentation (Oesterlen and Millsteed, 1994). The Upper Karoo commences with Triassic fluvial sediments of the Angwa Formation and overlying Pebbly Arkose Formation. Palaeocurrent directions in these units indicate that flow was to the west. Eolian sands of the Forest Formation, dated as Upper Triassic to Lower Jurassic, overlie these fluvial sediments. The latter is conformably overlain by the post-Karoo, upper Jurassic to lower Cretaceous, Dande Sandstone Formation (Osterlen and Millsteed, 1994). This unit consists of fluvial sediments and an alluvial fan facies associated with the rift scarps. Between approximately 30°E and 32°E, palaeocurrent directions in the centre of the basin are consistently to the west (Shoko, 1998).

Outcrops of post-Karoo sedimentary rocks also occur in the Limpopo region where South Africa, Zimbabwe and Mozambique have common borders (Botha and de Wit, 1996). These were formerly known as the Malvernia Formation in South Africa and Zimbabwe, but have been renamed the Malonga Formation. Their equivalents in Mozambique are the Formacao de Sena and Formacao de Singuedeze/Elefantes. The most extensive outcrop occurs in southeastern Zimbabwe, straddling the border with Mozambique between the Limpopo and the point where the Save course swings abruptly from southerly to south-easterly (Figure1). More restricted occurrences are present to the south, along the South Africa-Mozambique border. The age of these sediments is not well constrained, but is commonly accepted to be mid-late Cretaceous. They are interpreted to represent taphrogenic sedimentation on the eastern margin of the continent following the break-up of Gondwana. Facies analysis shows that they were deposited in a braided stream system associated with coalescing alluvial fans on a piedmont land surface along the continental margin. In southeastern Zimbabwe, palaeo-current directions are consistently to the south. However, southeast and east-southeast transport components are recorded in the extreme northeast of South Africa (Botha and de Wit, 1996).

Sediments of the eastern continental margin

There is a prominent seaward bulge in the Mozambique coastal plain between Beira in the north, and Maputo in the south (Figure 1). The Zambezi enters the Indian just to the north of this coastal plain, and the Limpopo in the south. The mouth of the Save, which is a smaller but nevertheless substantial river, is located between the two major drainages (Figure 1). The coastal plain between Beira and Maputo is covered by sediments ranging in age from Jurassic to the Quaternary (Dingle *et al.*, 1983), which provide an important record of the evolution of the inland drainage systems.

Isopachs for the Jurassic to Lower Cretaceous strata are given in Figure 13a. A particularly thick sedimentary wedge (>2.4 km) is developed in the graben structure between the modern mouth of the Zambezi and Beira. Limited drillhole data indicate an extensive, but much thinner Jurassic-Lower Cretaceous sequence to the south, in the broad coastal bulge between Beira and Maputo, with a maximum thickness (in excess of 1.3km) recorded in the centre of the coastal plain. A thick (>2km) sequence of Jurassic to lower Cretaceous sediments was also deposited in the Natal valley, which extends from the modern Limpopo mouth to the southwest, parallel to the coast line.

During the Upper Cretaceous, continental sandstones and conglomerates of the Sena Formation were deposited at the inner margin of the modern coastal plain (Figure 13b). Marine sediments were deposited on the outer margin, with the main depositional basin in the vicinity of the modern the mouth of the modern Save River, where the sequence exceeds 1.5km. The geometry of this basin suggests that some of these sediments were derived from a source to the north, in the vicinity of Beira. A thick sedimentary sequence was also deposited in a narrow depositional trough to the south of the modern Limpopo mouth (Dingle *et al.*, 1983).

The Save depocentre was abandoned during the Palaeocene and Eocene (Figure 13c), and replaced by isolated basins to the north and south. The former, centred on the area between Beira and the Zambezi mouth, was the larger of these. The southern basin was located roughly midway between the mouths of the modern Save and Limpopo. The supply of sediment to the basin south of the modern Limpopo (active in the upper Cretaceous, Figure 13b) appears to have diminished markedly during the Lower Tertiary (Figure 13c).

In the Oligocene, the northern basin remained the major depocentre, while the southern basin was displaced towards the modern Limpopo mouth (Fig 13d). Evaporites of the Temane Formation were deposited in the vicinity of the modern Save mouth, indicting that this river was not a major source of terrigenous material at that time.

High rates of terrigenous sedimentation are recorded in a narrow trough (the Natal Valley) parallel to the coast to the south of the mouth of the Limpopo during the Miocene and Pliocene (Figure 13e). Carbonates were deposited in the vicinity of the modern Save mouth, indicating that the supply of terrigenous material from this river continued to be minor. Neogene rates of sedimentation are poorly known for the depocentre between Beira and the Zambezi mouth (Richard Dingle, personal communication)

Configuration of fossil drainage lines in south-central Africa

The evidence for abandoned drainage lines in south-central Africa forms the basis for reconstructing the configuration earlier river systems.

Okavango

Evidence from RP 1/87 in south-eastern Botswana, argues for a major sub-Kalahari valley that must at one time have flowed to the southeast, and drained the Orapa kimberlite field. The only major modern river to the northwest is the Okavango, which is unusual in terminating in a major inland delta (du Toit, 1927). A southwesterly projection of the course of the Okavango would pass close to the Orapa kimberlites, and link with the major valley identified in RP 1/87 (Figure 3), which is thus inferred to be a relict of the palaeo-Okavango.

The headwaters of the Bonwapitse are located immediately to the southeast of this sub-Kalahari valley. They rise in a deeply incised ravine (Figure 6), which contrasts strongly with the rolling topography, which characterises the upper reaches of typical mature streams. The lower reaches of the ravine open onto the broad Shoshong valley, where the Bonwapitse is a narrow ephemeral braided stream. This cannot adequately account for incision of the headwater ravine or the broad lower reaches of the valley, and argues for an originally more vigorous drainage. Basal gravels in the upper Bonwapitse, which indicate earlier higher energy conditions, support such an interpretation.

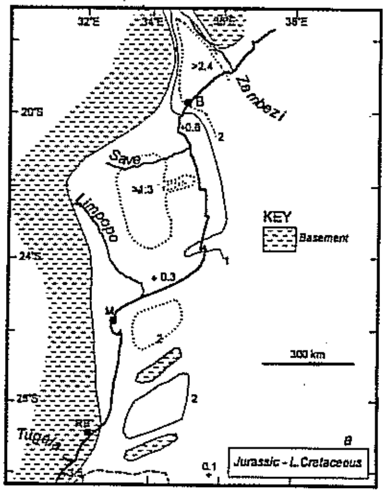
The Mahalapswe has a substantial (100m wide) channel only 50km downstream of the headwaters. However, this is sand-choked, and is thus aggrading rather than eroding under the present-day ephemeral flood regime. The underfit between the present-day flow regime and relatively wide river channel suggests that the Mahalapswe, like the Bonwapitse, was incised under originally higher energy conditions.

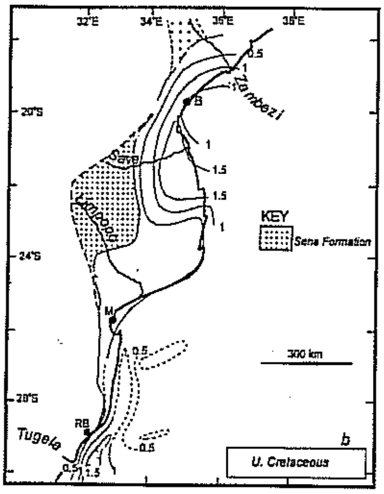
Earlier enhanced flow in these two rivers may reflect a previously more humid climate and higher precipitation. Alternatively, they may originally have had more extensive headwaters. The garnets recovered by de Beers in the lower Bonwapitse could be explained by link to the palaeo-Okavango (which drained the Orapa kimberlites, Figure 4), via the sub-Kalahari valley identified in RP1/87. This supports the second interpretation. No local kimberlite source has been discovered for the kimberlitic garnets recovered in the Lotsane. However, this heavy mineral anomaly can also be explained if the Lotsana was originally linked to the Palaeo-Okavango via the sub-Kalahari valley in RP 1/87 (Figure 3).

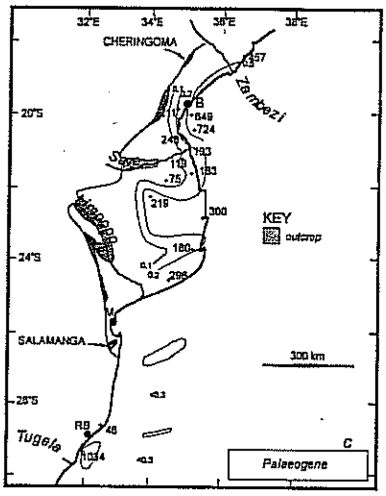
It is therefore concluded that all three Limpopo tributaries were at some stage linked to the Okavango. The deeply incised ravine at the head of the Shoshong valley is interpreted as a windgap which originally linked the Bonwapitse to the Okavango. The well-defined channel of the Mahalapswe indicates that it is younger than the drainage, which eroded the broad Shoshong valley, and thus beheaded the Bonwapitse headwaters. The Lotsane headwaters extend westward, across the line of the upper Mahalapswe, and are inferred to have subsequently captured the headwaters of the latter river. This interpretation implies a progressive northward displacement of the palaeo-Okavango prior to final severance of the link with the Limpopo tributaries. It is suggested that this river piracy was initiated by uplift along the OKZ axis. (Moore,1999) (See Figures 3 and 4).

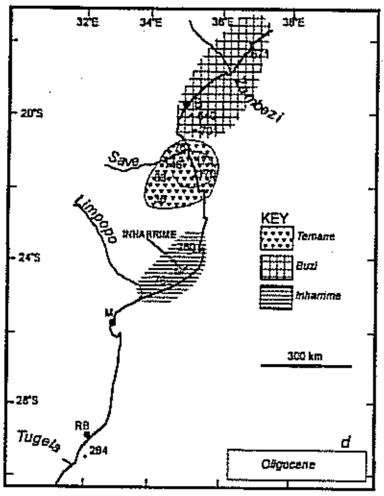
Cuando

The three sand spits which project from the eastern shoreline of Sowa Pan, 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 the major west-north-west trending post-Karoo dolerite swarm, which traverses the pan (Botswana 1:1 000 000 Geological map), arguing against an origin linked to these intrusions. We propose that the spits 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. These authors envisage that the dense fringe of reeds bounding active drainage channels in the delta develop into peat beds, and that the channel gradually aggrades between the enclosing peat deposits. This continues until it is abandoned as a result of blockage









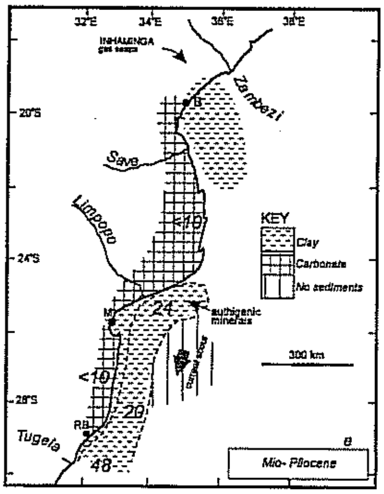


Figure 13a. Isopachs (in km) of Jurassic to lower Cretaceous strata. Jurassic lavas have been excluded, and sediments as young as Turonian (Domo Formation) are included. A narrow fault-bound basin with sedimentary infill in excess of 2.4 km is developed immediately south of the modern Zambezi mouth. There is a shallower, but more extensive basin on the coastal plain between Beira (B) and Maputo (M), and a separate basin (with over 2 km of sediment) to the south of the modern Limpopo mouth. RB = Richards Bay.

Figure 13b. Distribution and thickness (km) of Upper Cretaceous sediments in southern Mozambique and Zululand. Borehole data are in metres. Sena Formation is continental. The remainder of the sequence is marine. Major basins are developed in the vicinity of the mouth of the modern Save and to the south of the modern Limpopo. Abbreviations as for Figure 13a.

Figure 13c. Distribution and thickness of Palaeogene (Palaeocene and Eocene) strata. Borehole data in metres. The Upper Cretaceous basin centred on the Save has been replaced by separate basins to the north and south. Abbreviations as for Figure 13a.

Figure 13d. Distribution and thickness of Oligocene strata. Borehole thicknesses in metres. The occurrence of extensive evaporites of the Temane Formation in the vicinity of the modern Save mouth indicates that this river was not a significant source of terrigenous material. The southern depocentre has been displaced to the vicinity of the modern Limpopo mouth. Abbreviations as for Figure 13a.

Figure 13e. Variations in lithofacies and sedimentary rates (in mm/yr) during the Miocene to Pleistocene. Heavy dashed line shows accumulation rates >20 mm/yr. Abbreviations as for Figure 13a.

Figures 13a-e. Adapted from Dingle *et al.* (1983).

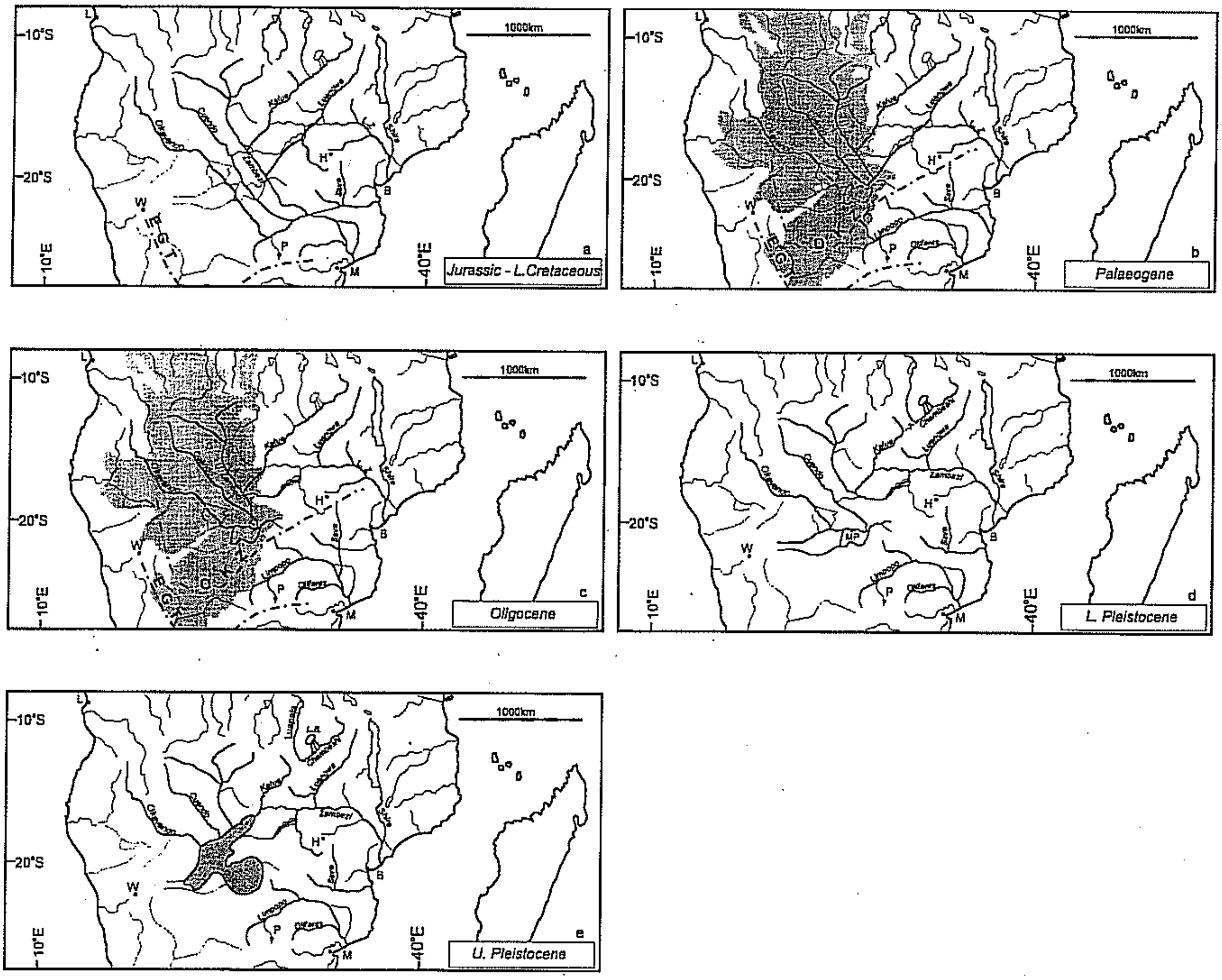


Figure 14. Successive stages in drainage evolution in south-central Africa.

Figure 14a. 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 Chambeshi (see Figure 1) formed the Kafue headwaters. The Shire – Lower Zambezi and Save formed a separate drainage systems. L.Z. = Lower Zambezi. City abbreviations as for Figure 1.

Figure 14b. Grey tone shows distribution of the Kalahari sediments. Other ornamentation and abbreviations as for Figure 14a. End-Cretaceous to early Tertiary crustal flexuring along the Okavango-Kalahari-Zimbabwe (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 a major endoreic system, which drained into the Kalahari basin, and contributed to deposition of the Kalahari Group sediments. Lower Palaeogene isopachs on the Mozambique margin (Figure 13c) indicate southward displacement of the mouth of the Shire - Limpopo.

Figure 14c. Ornamentation and abbreviations as for Figures. 14a and b. Headward erosion of the Lower Zambezi, initiated by crustal flexuring along the OKZ axis, resulted in 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.

Figure 14d. Ornamentation and abbreviations as for Figures. 14a and b. Continued headward erosion of the Lower Zambezi, led successively to capture of the Mana Pools basin and the Gwembe trough (location of Lake Kariba). 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. Plio-Pleistocene flexuring along an extension of the Ciskei-Swaziland Axis, just inland of the coastal margin (Partridge, 1998), initiated headward erosion of the lower Shave, and capture of the modern headwaters, originally a north-bank tributary of the Limpopo.

Figure 14e. Grey tone shows lake Palaeo-Makgadigadi. Other ornamentation and abbreviations as for Figure 14a. Displacement along the major North-east 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-Makgadigadi, which filled to around the 945m level. Diversion of the headwaters of these rivers is reflected by a break in erosion of the 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 Makgadigadi Pans complex within the past 50 000 years, suggest that the link between the Zambezi and Makgadigadi has been breached and re-established on a number of occasions.

by vegetation or tectonic disturbance. Thereafter, the surrounding organic material desiccates, eventually ignites, and is ultimately destroyed. This leaves a raised sandy bar marking the abandoned channel course.

Evidence supporting an analogous explanation for the origin of the Sowa spits comes from the area to the southeast of the pan. Thomas and Shaw (1991) have identified a windgap, indicative of an abandoned drainage line, in the vicinity of Mea Pan (Figure 8). Between this pan and the upper reaches of the Motloutse, there are tenuous relict drainage lines associated with a belt of small pans. The latter, by analogy with similar features elsewhere in southern Africa (Mayer,1973; Marshall and Harmse, 1992; Moore, 1999), are interpreted to be relics of an abandoned drainage which crossed the present drainage divide. It is inferred that this linked the upper Motloutse with the relict spit in the southeastern corner of Sowa Pan.

The three Sowa spits increase in size, and become better defined from south to north. This is interpreted to reflect an age progression, with the southernmost spit being the oldest, and most degraded by wave action and currents in the pan. This evidence argues that the abandoned drainage, which originally traversed Sowa Pan, was displaced progressively northward. Isopachs of pan sediments in the north of Sowa (Figure 8) are interpreted to reflect a major delta, formed by a substantial river which debouched into the Pan from the northwest. This delta is inferred to post-date the three spits, as it reflects damming of the river by Sowa Pan. The photofeature (Figure 9), interpreted as an abandoned delta by Mallinck *et al.*, (1981) marks a further position of the drainage which initially crossed, and was ultimately dammed by Sowa Pan.

A major drainage, the Cuando, is located to the northwest of Sowa Pan. The upper reaches of the river follow a straight northwest-southeast course, but it swings abruptly to the northeast along the Linyanti Fault at the Botswana border (Figures 2 and 10). This change in direction is typical of a major capture elbow, and suggests that the Cuando originally maintained the southeast course of the headwaters into Botswana, crossing Sowa Pan.

The Mea Pan windgap, relict drainage lines and belt of pans between the southernmost (inferred oldest) spit and the Motloutse argue that the latter river was originally linked to the Cuando (Figure 4). Severance of this link could account for the underfit of the modern Motloutse with the deeply incised valley in the lower reaches of this river.

A southeastwards projection of the line of the northernmost spit intersects one of the major Shashe tributaries (Figure 4), which is thus inferred to have beheaded the former Cuando – Motloutse link. The extremely broad (>1 000m) channel of the Shashe just above the confluence with the Limpopo is difficult to explain in terms of the modern ephemeral flow of the river. While this may reflect a climatic regime with higher precipitation, it is also consistent with originally more extensive headwaters, *i.e.* a link with the Cuando. The delta identified in the north of Sowa Pan is interpreted to represent a later stage in the evolution of the Cuando, after severance of the link with the Limpopo tributaries by uplift along the OKZ axis. This evidence points to a progressive northward displacement the course of the Cuando, analogous to that inferred for the evolution of the lower Okavango.

Luangwa

The abrupt change in course of the Luangwa just above the confluence with the Zambezi has been interpreted as a capture elbow by Thomas and Shaw (1991). These authors envisage that the palaeo-Luangwa continued to the southwest across the mid-Zambezi basin (Gwembe trough), which is the site of modern Lake Kariba. The deep sub-Kalahari valley crossing the Botswana-Zimbabwe border (Figure 9) straddles the line of the palaeo-Luangwa proposed by Thomas and Shaw, and is therefore inferred to have been incised by this old drainage.

Upper Zambezi

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 (Figure 12). 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 100km as far as the confluence with the Gwaai River (Figure 2). Wellington 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 capture, 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 zigzag gorges immediately below the falls reflects structural control by two major joint sets (Wellington, 1955).

Gravels deposited by the Zambezi before and during regression of the falls are preserved at heights of 110 to >250 m above the modern riverbed. They contain artefacts, which can be ascribed to the Magosian and earlier industries of the Middle Stone Age (Derricourt, 1976). Despite the uncertainty in dating of the Stone Age artifacts, 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 suggests that incision of the lower stretch of the gorge (between the Gwaai confluence and the Chimamba rapids) commenced within the Lower Pleistocene at least 1.25 x 10^6 years BP and was eroded over a period of between 540 000 and 790 000 years 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 years BP.

Kafue

The younger alluvium associated with the modern Okavango delta overlies a broad northeast-southwest trending belt of older alluvium, deposited in a fault-bound trough, that blankets the northeastern corner of Botswana (Figure 10). This alluvium extends across the Zambezi into Zambia, and possibly as far as the floodplain where the Kafue swings abruptly from a southerly to an easterly course (Figure 2) (Mallink *et al.*, 1981). The abrupt change in course of the Kafue is typical of a capture elbow, and Thomas and Shaw (1991, Figure 2.8) 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 945m shoreline of the Makgadigadi (Grove, 1969).

A new model for post-Gondwana drainage evolution in south-central Africa

The evidence for earlier drainage configurations, coupled with the offshore sedimentary information, provide a framework for developing a model for drainage evolution in south-central Africa subsequent to the break-up of Gondwana.

Jurassic – lower Cretaceous drainage reconstruction (Figure 14a)

The reconstruction of the palaeo-drainages in southern Africa following the opening of the Indian Ocean in the late Jurassic is presented in Figure 14a. The lower Zambezi displays a geomorphic unity, which distinguishes this section of the river from the middle and upper reaches (Wellington, 1955). A palaeo-drainage reconstruction advanced by Thomas and Shaw (1991) envisages that the lower Zambezi, with the Shire as a major north bank tributary, formed part of the early drainage system, initiated after the break-up of Gondwana. Palaeo-current directions in the Dande Sandstone Formation (Shoko, 1998) require that the lower Zambezi headwaters were located to the east of 32°E. This early drainage system is inferred to be the source of sediment supplied to the graben located in the north of the Mozambique plain during the Jurassic to lower Cretaceous (Figure 13a).

Thomas and Shaw (1991) envisage that the Kafue and Luangwa were originally major north bank tributaries of the upper Zambezi. They interpreted the sharp inflections in the courses of these two major rivers (Figure 2) as later capture elbows. The modern Chambeshi (Figure 1) flows to the southwest, towards the Kafue prior to swinging abruptly to the north, becoming the Luapala, a tributary of the Congo River. The occurrence of common fish species in the Kafue and Zaire system requires an earlier link between these drainages. The abrupt change in course of the Chambeshi is therefore interpreted to represent a capture elbow, implying that this river originally formed the Kafue headwaters, as shown in Figure 14a.

The deep sub-Kalahari valley straddling the Botswana-Zimbabwe border (Figure 9), located on a southwesterly extension of the upper Luangwa, is inferred to mark the original continuation of the line of this river. The Luangwa was therefore a former left-bank tributary of the upper Zambezi, in line with the reconstruction of Thomas and Shaw (1991). These authors proposed that the upper Zambezi, with the Kafue and Luangwa as major left bank tributaries, originally flowed into the Limpopo via the modern Shashe River. This provides an explanation for the width (in excess of 1km) of the latter river just above the present-day confluence with the Limpopo. It also accounts for the occurrence of common fish species in the Limpopo and Zambezi river systems (Skelton, 1994). Evidence for the former positions of major drainage lines in Botswana argues for a southeastwards continuation of the courses of the Okavango and Cuando to also link with the Limpopo, as shown in Figure 14a.

Palaeo-current directions in the Malongo Formation in southeast Zimbabwe and northeast South Africa indicate sources of sediment to the north and northwest during the mid-late Cretaceous (Botha and de Wit, 1996). The Save and Limpopo provide logical sources for these sediments, indicating that the two rivers entered the Mozambique plain in essentially the same position as they do at the present time. During the Jurassic-lower Cretaceous, major sedimentary basins developed in the vicinity of the modern mouths of these two rivers (Figure 13a). This evidence argues that both date to the initial disruption of Gondwana. The high sedimentation rates at this time probably reflect a period of accelerated erosion following continental break-up, comparable to that documented in the west of South Africa (Brown *et al.*, 1990).

Du Toit (1910) drew attention to the dominant northwest-southeast and northeast-southwest drainage lines which characterise the river systems of southern Africa. The main Limpopo tributaries define a similar fabric, pointing to a structural control, which has been active since the disruption of Gondwana. Note that the main river courses are unlikely to have been as linear as illustrated in Figure 14a. However, there is insufficient evidence to define their configuration in greater detail.

Upper Cretaceous

The east coast sedimentary record shows that the Zambezi, Save and Limpopo remained important sources of sediment during the upper Cretaceous. There is therefore no evidence during this period for any major change in configuration of the drainage system initiated after the disruption of Gondwana.

Palaeocene drainage reconstruction

The pattern of sedimentation on the Mozambique coastal plain changed markedly during the early Palaeogene (Palaeocene and Eocene), when the focus of sedimentation moved away from the area around the modern Save (Figure 14b). A major depocentre developed to the north of this river between Beira and the modern Zambezi mouth and a subsidiary basin to the south of the Save. This points to a southward displacement of the lower reaches of the latter river. The early Palaeogene marine sequence is relatively thin in the Natal Valley to the south of the Mozambique coastal plain (Figure 13c). This indicates that the Limpopo ceased to be a major supply of sediment to the Natal Valley during the lower Tertiary.

Du Toit (1933) demonstrated that the watershed between the Zambezi and Limpopo reflects a line of crustal flexure, which he termed the Kalahari-Zimbabwe Axis. This continues into eastern Botswana where it forms the divide between the Limpopo and fossil endoreic Kalahari drainages. The locus of this axis has recently been extended by Moore (1999) and renamed the Okavango-Kalahari-Zimbabwe (OKZ) Axis. Moore inferred a late Cretaceous to early Tertiary age for relative uplift along this line of flexure. It crossed the Jurassic to Cretaceous courses of the upper Zambezi, Cuando and Okavango (Figures 14a; b), and is therefore inferred to have been responsible for severing the original links between these rivers and the Limpopo. This initiated a major endoreic drainage system comprising the Okavango, Cuando, Upper Zambezi, Kafue and Luangwa (Figure 14b). The accompanying decrease in river gradients inland of the axis resulted in a senile river system, and deposition of the sedimentary load as part of the Kalahari sequence. The marked decrease in sediment supply to the Natal Valley via the Limpopo in the lower Tertiary (Figure 13c) is consistent with this interpretation. Evidence from southeastern Botswana and Sowa Pan indicates that the river piracy was not a single stage process, but involved successive river captures and progressive northward displacement of the Okavango and Cuando rivers before the final severance of their links to the Limpopo.

Relative uplift along the OKZ axis provides a possible mechanism for southward displacement of the Save depocentre (Figure 13c). A further likely consequence was the rejuvenation of rivers on the coastal side of the axis, leading to headward erosion of the Save and lower Zambezi. It is suggested that the Save may, as a result, have captured the upper Limpopo (Figure 14b). While there is no clear geomorphic evidence for such piracy, it is consistent with the development of the significant sedimentary basin to the south of the modern Save mouth.

Oligocene drainage reconstruction

The Zambezi remained an important source of sediment during the Oligocene, supplying the major depo-centre between the modern mouth and Beira. Extensive coeval evaporites formed in the area around the modern Save mouth, indicating that there was not any significant source of terrigenous material in this area. The subsidiary basin, which developed to the south of the Save during the early Palaeogene, was displaced further to the south, with maximum sedimentation in the area of the modern Limpopo mouth (Figure 13d). It is proposed that these sedimentation patterns can be explained by continued southward displacement of the Limpopo-Save mouth (Figure 14c). Headward erosion of the lower Zambezi, initiated in the Palaeogene, eventually beheaded the upper Luangwa, resulting in a significant expansion of the drainage basin. The timing of this capture cannot be accurately dated. However, it is noted that the Oligocene sequence associated with the Zambezi depocentre (Figure 13c) is thicker than that for the combined Palaeocene-Eocene (Figure 13b), pointing to an increase in sediment supply. An early Oligocene age of ~ 38 Ma is therefore proposed for capture of the Luangwa by the Lower Zambezi (Figure 14c). Nevertheless, it is noted that decreasing sediment supply may also reflect climatic changes (de Wit and Bamford, 1993).

Miocene to lower Pleistocene drainage reconstruction

A likely consequence of the capture of the Luangwa by the Lower Zambezi was a phase of accelerated headward erosion in the lower reaches of the river (Figure 14d). This offers an explanation for the incision of the Cabora Bassa gorge (by analogy with the inferred development of the Batoka Gorge). Subsequent inland extension of the headwaters of the lower Zambezi led first to capture of the middle Zambezi via the Kariba Gorge, and then to beheading of the Upper Zambezi by the Mid-Zambezi via the Batoka gorge, as envisaged by Wellington (1955). The resultant drainage configuration is shown in Figure 14(d).

Beheading of the Upper Zambezi has been dated as lower Pleistocene (1.25 to 2 Ma) (Derricourt, 1976). If a late Eocene age (38 Ma) is valid for the capture of the Luangwa, this implies headward erosion of some 550 km over a period of ~36 Ma, or an average rate of 0.016 m/year. This is almost an order of magnitude lower than the erosion rates of 0.09 – 0.13 m/year calculated by Derricourt (1976) for the incision of the Batoka Gorge. The reason for this discrepancy is not clear, but is likely to reflect the interplay of a number of the following factors:

Differences between base levels and flow regimes of the upper and lower section of the river at each point of capture.

Inaccuracies in dating the capture of the Luangwa and Upper Zambezi.

Different rates of erosion associated with different lithologies with differing structural fabrics.

Changes in climate, and thus in river flow during the evolution of the Zambezi.

It is not clear which of these factors played the dominant role in determining differences in erosion rates in the higher and lower reaches of the Mid-Zambezi. However, there is a fall of almost 400 m from the crest of the Victoria Falls (900 m) to the bed of the Zambezi at the end of the Batoka gorge (about 500 m). This provides an estimate of the lowering of the erosion base level of the upper Zambezi following capture by the Mid Zambezi. The Chicoa trough, which forms the lowermost basin of the Mid-Zambezi, is at an altitude of 400 m. Below the Cabora Bassa gorge, (inferred to have been incised following capture of the Mid-Zambezi by the Lower Zambezi), the river bed is at an altitude of approximately 200 m. This implies a lowering of Mid-Zambezi base-level by only some 200 m following capture by the lower section of the river. The large decrease in base level of the upper Zambezi may therefore have been an important factor in controlling the rate of erosion of the Batoka Gorge.

Upper Pleistocene drainage reconstruction

The northeast-southwest trending belt of "older alluvium" in north-eastern Botswana (Figure 10) has been ascribed to deflection of the Upper Zambezi and Kafue into northern Botswana by major southwest-northeast trending faults such as the Linyanti and Chobe (Figure 14e). This provided the volume of water required to sustain the maximum extent of the Makgadigadi lake, marked by the 945m shoreline (Grove, 1969, Cooke, 1980). The resultant interruption of flow to the lower reaches of the Zambezi, in turn accounts for the break in erosion of the Batoka Gorge prior to ~315 000 to 460 000 years BP recognised by Derricourt (1976). A late Pleistocene age is then implied for the older alluvium, consistent with the evidence that the faults bounding these sediments truncate Quaternary dunes (Mallink *et al.*, 1981).

All of the Makgadigadi shoreline features show a wide range in ages, extending to >52 000 years BP (the upper limit of ^{14}C dating) (Figure 11). These data are most readily interpreted in terms of periodic desiccation and filling of the Makgadigadi as the link between the upper and mid-Zambezi was severed and re-established. This can in turn be explained in terms of tectonism in the area of low relief that characterises northeastern Botswana. It is envisaged that the Zambezi was diverted to the southwest as a consequence of uplift along the Chobe and Linyanti Faults, which cross the line of the river (Figure 10). The fault scarp was subsequently breached as a result of sediment build up and erosion to restore the link between the upper and lower Zambezi. Oscillations in the level of Lake Palaeo-Makgadigadi are inferred to reflect the interplay between tectonism, sedimentation and erosion, extending at least over the period that carbon dating is reliable. The evidence for a recent history of major oscillations of the Makgadigadi shoreline suggests that a permanent link Zambezi is still in the process of being re-established.

The belt of alluvium illustrated in Figure 10 extends northeastwards into the Machili basin in Zambia and probably extends to the Kafue (Thomas and Shaw, 1991) indicating that the latter river was an important source of these sediments. The inferred late Pleistocene age for the alluvium requires a very recent link between the Upper Zambezi and Kafue and therefore of the recent capture of the headwaters of the latter by the Mid-Zambezi. Immediately downstream of the Kafue capture elbow (Figure 2), the river flows through the swamps of the Kafue Flats. It is suggested that such swampy terrain forms during the incipient stages of river capture in areas of low relief. The Kafue gorge, immediately above the confluence with the Zambezi, is ascribed to the lowering of the erosional base level of the Kafue following capture by the mid-Zambezi. There is a major area of swampy terrain between the Upper Kafue and the Lunsemfwa, a left bank tributary of the lower Luangwa (Figure 2). It is suggested that this reflects the initiation of a new phase of river capture. Similarly, the marshy ground of the Mulonga-Matebele plain in Zambia, which links the upper Kwando and upper Zambezi (Figure 2), probably heralds further headward advance of the predatory Zambezi river.

Displacement along the Linyanti Fault across the line of the Cuando explains the deflection of this river to the northeast to link with the Zambezi via the Linyanti swamps. The evidence that faulting in the north of Botswana has displaced Quaternary dunes suggests that this capture was relatively recent. The deltaic photofeature recognised by Mallinck *et al.*, (1981) to the northeast of Sowa Pan (Figure 9) was probably related to the 945 m level of the Makgadigadi Pan. This also points to a relatively recent link between the pan and the Cuando. Recent displacement along the Thamalakane fault can similarly account for disruption of the Okavango, and initiatiation of the modern inland deltaic system. Wellington (1955, Figure 89) envisages that this endoreic river will ultimately be captured by the Zambezi to re-establish a link to the Indian Ocean.

The Mozambique coastal plain is covered by a thin veneer of Pleistocene sediments which are related to abandoned channels of a major deltaic system. The orientation of these channels suggests that they are relics of the Limpopo River. Partridge (1998) has shown that major Plio-Pleistocene flexuring occurred along the Ciskei-Swaziland Axis, located just inland of the present-day Indian coastline. This accounts for raised Tertiary marine sediments in Mozambique and the east of South Africa. It is suggested that this uplift lowered gradients of the Limpopo and upper Save, leading to the development of the coastal deltaic system. It also rejuve-

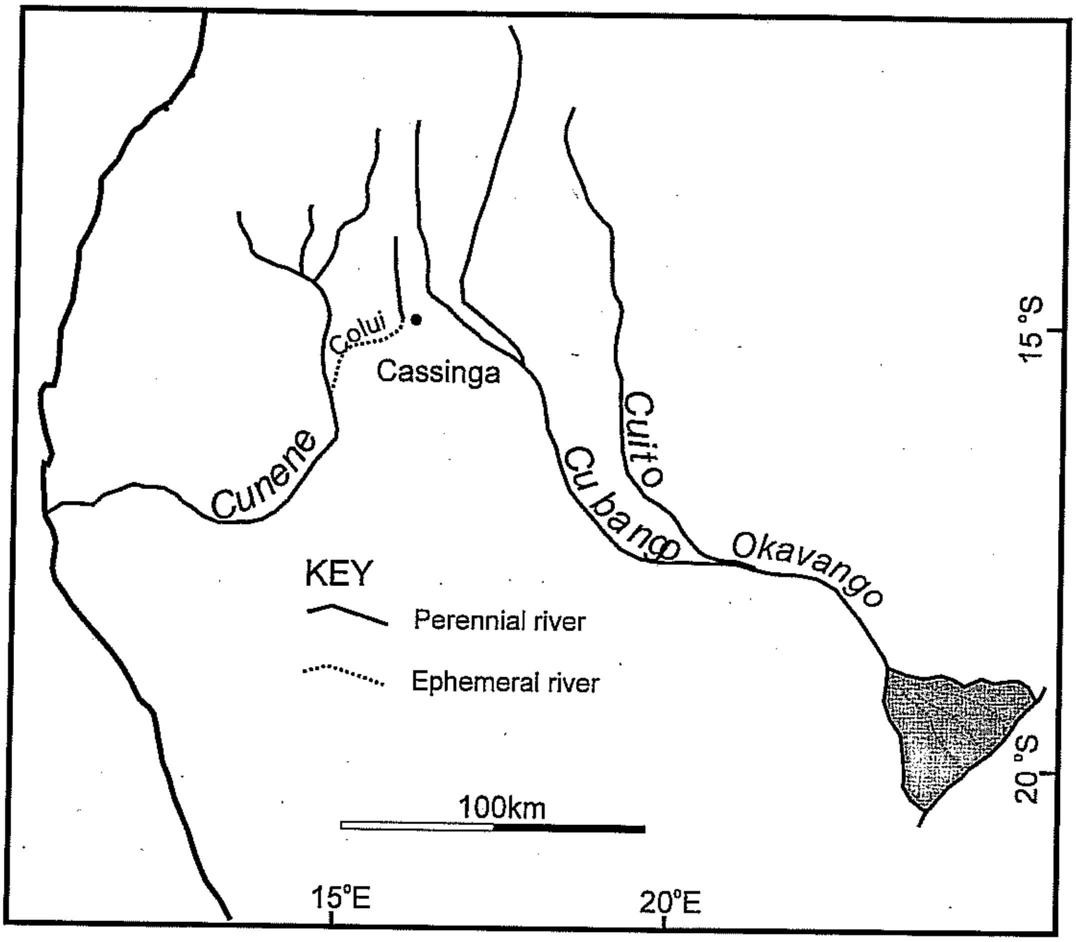


Figure 15. Headwaters of the Cunene and Okavango-Cubango. Solid lines are perennial drainages; dashed lines denote ephemeral drainage (the Colui).

nated the Lower Save River, initiating headward erosion and ultimately in the capture of the modern headwaters from the Limpopo (Figure 14d and e).

Dispersion patterns of fish and plant species

The broad model for river evolution, which has been presented, can be refined to explain details in the dispersion of fish fauna in southern Africa. Two examples emphasise the importance of relatively minor headwater captures in facilitating fish migration between major river systems.

The high Similarity Index between fish populations in the Okvango and the Cunene points to a former link between the two rivers. Figure 15 illustrates the upper reaches of these two major drainages. The Colui, which forms the eastern headwaters of the Cunene, is an ephemeral drainage. The headwaters of the Cubango (the western head stream of the Okavango) flow due south until just north of the town of Cassinga (Figure 15) where the course veers to the southeast. It is suggested that the upper Cubango originally formed the headwaters of the Colui, and that the change in course reflects capture by the lower Cubango. This accounts for the ephemeral flow in the modern Colui, and the migration of fish species between the Cunene and Okavango.

Capture of the Chambeshi by the Luapala, discussed previously, provides an explanation for the occurrence of common fish species in the Congo river system and the mid-lower Zambezi (Skelton, 1994). Lake Bengweulu, and a fringing area of marshy terrain linked to the Chambeshi (Figure 14e) were probably formed by the processes responsible for the capture of this river by the Luapala. If areas of marshy terrain are transient topographic features related to river piracy, as inferred previously, this would imply relatively recent capture of the Chambeshi by the Luapala. Detailed studies of genetic differences between fish species common to this river and the Kafue may provide a more rigorous constraint on the timing of the river capture.

Moore (1988) suggested that paired populations of plant species on the Limpopo and Zambezi argued for a recent link between these two major rivers. This is not supported by the reconstruction presented in this work. However, it has been argued that the Zambezi was deflected into northern Botswana on a number of occasions during the Quaternary to fill the Makgadigadi Pan system. This allowed the migration of Zambezi riverine plant species into this major inland lake. The headwaters of major Limpopo tributaries such as the Shashe and Motoutse are only some 100 km to the east of the pan, separated by a low watershed (Figure 4).

Seed dispersal over this short distance by animal and bird migration provides a mechanism for the exchange of plant species between the Limpopo and Zambezi.

Discussion

Thomas and Shaw (1991) envisage that marginal flexuring of southern Africa associated with disruption of Gondwana initiated a major endoreic drainage system, which has only recently broken through the coastal girdle of high ground. This contrasts with the model presented here, which requires an initial exoreic drainage system. The latter is supported by the development of major depositional basins on the Indian Ocean margin that date to the earliest period of continental break-up (Figure 13a). Opening of the Atlantic was also associated with the early development of major depocentres on the western continental margin (Dingle *et al.* 1983). Terrigenous sediment was supplied to the latter sedimentary basins by the Orange River (Dingle and Hendy, 1984) and also the Trans Karoo River (de Wit, 1999), which both drained the interior of southern Africa.

The drainage model presented in this work envisages that the Limpopo provided a conduit linking the major inland drainages to the Indian Ocean immediately following disruption of Gondwana. This river enters the Mozambique coastal plain along an inferred failed arm of a triple junction, exploited by a major westnorthwest trending late Karoo dyke swarm (Reeves, 1978). This is consistent with the model advanced by Cox (1989) for the initiation of drainage systems immediately following continental break-up. An endoreic river system formed as a response to end-Cretaceous epeirogenic flexing of the sub-continent. Sequential river captures have re-established a link between most of these rivers and the coast. Wellington (1955) envisages that the Zambezi is in the process of capturing the Okavango, the last of the major rivers, which originally formed the inland drainage system. This indicates that endoreic rivers are transitory features during drainage evolution.

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