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A reappraisal of epeirogenic flexure axes in southern Africa

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Abstract — Major drainage divides in southern Africa are interpreted to reflect lines of epeirogenic flexuring of the sub-continent associated with the formation of co-related basins. The Great Escarpment, which separates coastal and inland drainage systems, marks the locus of the Escarpment axis. It was initiated by Early Cretaceous rift flank uplift associated with the break-up Gondwana. Geophysical studies suggest that subsequent erosion, coupled with sedimentation on the continental shelf, would have resulted in progressive inland migration of this flexure. The divide between the Orange–Vaal River system and the Limpopo and Molopo–Nossib–Auob drainage basins is designated the Etosha–Griqualand–Transvaal (EGT) axis. Upper Cretaceous flexuring along this axis disrupted old drainage lines, and initiated deposition of the Kalahari formation. The end-Cretaceous Ovamboland–Kalahari–Zimbabwe (OKZ) axis forms the watershed between the Zambezi and Limpopo Rivers in Zimbabwe, and separates the latter river system from fossil endoreic drainage lines in the Kalahari, which originally emptied into the Makgadigadi Pans system. In the south of Botswana, this axis is defined by the Kalahari Schwelle, which separates the fossil Kalahari drainages from the Molopo–Nossib River system. Processes responsible for initiating the EGT and OKZ flexures are poorly understood. However, the inferred ages of both these two axes and the Escarpment axis correspond with episodes of alkaline volcanism in southern Africa. This argues for a link between continental flexuring and volcanic activity. Major Pliocene uplift occurred along a line intermediate between the Great Escarpment and the present coastline in the east of the country (the Ciskei–Swaziland axis). More subdued Plio–Pleistocene flexuring along a southwest–northeast axis (designated the Bushmanland–Harts axis) traversing the interior of South Africa was responsible for the formation of major pans ('floors') in Bushmanland and the Orange Free State. There are a number of subordinate lines of uplift (the Khomas, Otavi, and Zoutpansberg axes) which are parallel to the Bushmanland–Harts axis. They are presumably related to the same stress field, and thus probably of similar age. These latter axes are all sub-parallel to active faults in northern Botswana which are interpreted to reflect southwestwards migration of the east African rift system, following lines of structural weakness. Sequential uplift along the axes which have been identified provides a framework for interpreting the evolution of drainages and erosion surfaces on the sub-continent.

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Introduction

The geomorphological processes responsible for landscape evolution in southern Africa have been the focus of a lengthy and ongoing debate. A particularly controversial issue is whether or not discrete erosion surfaces of different ages occur on the sub-continent, and if so, how they can be correlated and dated (Partridge and Maud, 1987). An associated problem is the formulation of tectonic models to account for the initiation and evolution of successive erosion cycles. These questions are, in turn, central to an understanding of the development of drainage systems on the sub-continent (*e.g.* Dingle and Hendy, 1984; Cox, 1989).

In a remarkable paper, with important implications for understanding the geomorphological evolution of southern Africa, Du Toit (1933) argued that the major river divides within the interior of the sub-continent are controlled by axes of epeirogenic flexuring. These were designated the Griqualand–Transvaal and Kalahari–Rhodesia (now Kalahari–Zimbabwe) axes respectively. Subordinate southwest–northeast lines of flexure were recognized in Namibia (the Otavi and Khomas axes) and in the north of South Africa (the Zoutpansberg axis) (Figure 1). Du Toit (1933) stressed that these lines of flexure were associated with the development of co-related basins or depressions, but that subsidence was not necessarily symmetrical on either side of the axes. In essence therefore, the axes could be regarded as major crustal swells or antiforms.

This model was extended by King (1963), who proposed that the divide between coastal rivers and drainages in the interior of the sub-continent is a line of flexure, which he termed the Escarpment axis (Figure 1). King (1963) recognized that the Kalahari formation (Figure 1) was deposited in a major basin related to epeirogenic crustal subsidence. The Okavango and Makarikari (now Makgadigadi) depressions shown in Figure 1, which were originally identified by Du Toit (1933), could be considered as subsidiary depressions related to the main Kalahari basin. The Karoo–Lesotho depression shown in Figure 1 follows the modification made by King (1963).

Meyer (1973) subsequently argued that the divide between the Harts and Vaal drainages is also a line of crustal flexure. This is designated the Harts axis in Figure 1.

The axes identified by Du Toit, King, and Meyer were inferred by these authors to be Plio–Pleistocene in age.

Partridge and Maud (1987) and Partridge (1998) postulate that minor (150 m) early Miocene uplift occurred along the Transvaal–Griqualand axis, while somewhat greater (250 m) Miocene uplift affected the hinterland of Natal and the Eastern Cape. They infer that these movements were followed by minor (100 m) Pliocene uplift along the Griqualand–Transvaal axis. This was accompanied by major (900 m) flexuring in the east of southern Africa along a line (designated the Ciskei–Swaziland axis) located between the Great Escarpment and the east coast (Figure 1). The locus of this axis is defined

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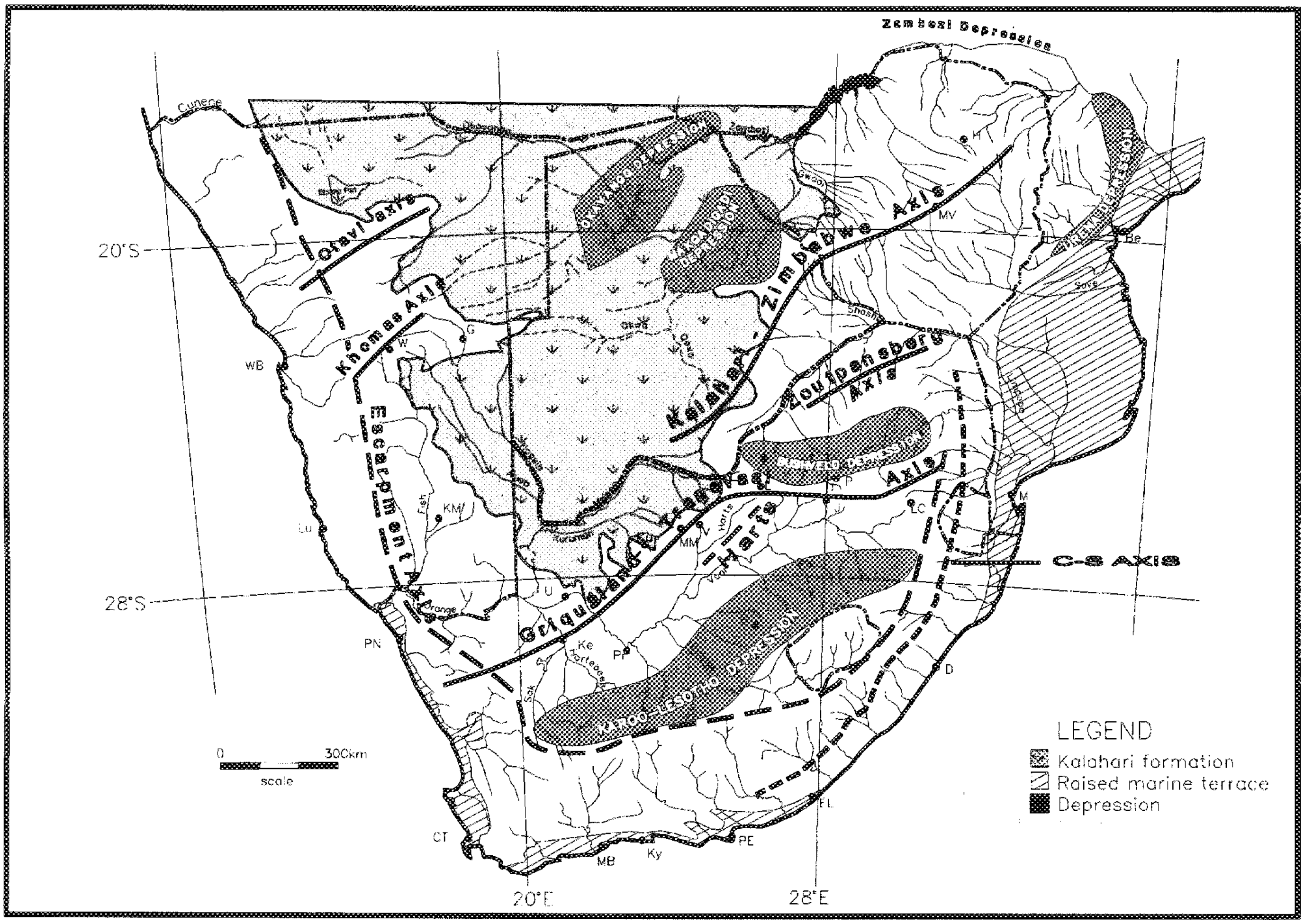

Figure 1 Main drainages in southern Africa, copied from the map in Du Toit (1933), with fossil drainage lines in the central Kalahari, Botswana (the Qoxo–Okwa system) added (fine dashed lines). Heavy solid lines are flexure axes identified by Du Toit (1933). Heavy dashed lines are the axes recognized by King (1963), Meyer (1973), and Partridge and Maud (1987) as discussed in the text. C–S = Ciskei–Swaziland axis. The Karoo–Lesotho depression is revised following King (1963). The remaining basins of depression are as recognized by Du Toit (1933). Note that Du Toit's Makgadigadi and Okavango depressions would now be regarded as subsidiary basins of the main Kalahari basin. CT = Cape Town; B = Bloemfontein; Be = Beira; D = Durban; EL = East London; G = Gobabis; H = Harare; J = Johannesburg; K = Kimberley; Ke = Kenhardt; KM = Keetmanshoop; Ku = Kuruman; Ky = Knysna; L = Lichtenberg; LC = Lake Chrissie; Lu = Luderitz; M = Maputo; MB = Mossel Bay; MM = Mahura Muthla alluvials; MV = Mvuma; P = Pretoria; PE = Port Elizabeth; PN = Port Nolloth; Pr = Prieska; U = Upington; V = Vryberg; W = Windhoek; WB = Walvis Bay; Z = Zeerust.

by convex-up inflections in the profiles of the coastal rivers (Partridge, 1998).

Lister (1987) has questioned the view that the central Zimbabwe watershed is a line of epeirogenic flexure, as proposed by Du Toit (1933), and suggests that it is a transient feature which has migrated progressively northward as a result of headward erosion by aggressive north-bank tributaries of the Limpopo. It is therefore necessary to establish whether the major river divides on the subcontinent are indeed related to crustal flexuring, or whether they merely reflect processes of drainage basin evolution.

Evidence for epeirogenic flexuring

Du Toit (1933) presented the following important evidence for crustal flexuring:

1. An alluvial gravel run (palaeo-drainage) at Lichtenburg, located on the crest of the Transvaal–Griqualand axis (Figure 1), contains distinctive red agates very similar to those found in the Bushveld Amygdaloid. This volcanic unit occurs at a lower altitude within the Bushveld basin to the northeast, arguing for crustal deformation (*i.e.* subsidence of the Bushveld basin) subsequent to deposition of the gravels.
2. A number of dry 'poorts', located immediately north of the Griqualand–Transvaal axis between Pretoria and Zeerust (Figure 1), were interpreted as wind gaps cut by major north–south rivers which must have originally crossed the river divide.
3. There is a marked steepening in the gradients of the Orange and Hartebeest Rivers where the Transvaal–Griqualand axis crosses these drainages (Figure 1). It was inferred that uplift across the Hartebeest and Sak was responsible for the ponding back of these rivers to form a series of major pans upstream of the axis.
4. Du Toit (1927; 1933) suggested that basining which produced the Makgadigadi Pans complex could be explained by flexuring along the Kalahari–Zimbabwe axis. He envis-

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aged that this axis beheaded a former link between the Okavango and the Limpopo Rivers.

The following are some of the more important recent lines of evidence for the formation of the major continental drainage divides by epeirogenic flexuring:

1. McCarthy (1983) has demonstrated that a major southeast-flowing river formerly joined the Orange some 30 km downstream from the confluence with the Vaal River. He inferred that this north-bank tributary, which he termed the Trans-Tswana River, was at least as big as the modern Orange. It must therefore have originated to the north of the modern watershed (*i.e.* north of the Griqualand–Transvaal axis). McCarthy (1983) proposed that the demise of this palaeo-tributary was related to tectonism along the Griqualand–Transvaal axis, and the associated development of the Kalahari basin.
2. Diamondiferous gravels are preserved astride the Griqualand–Transvaal axis in a northwest–southeast-oriented fossil drainage line at Mahura Muthla (Setswana for 'fat rabbit') (Wagner, 1914; Figure 1). The palaeo-channel attains widths up to 150 m, indicating that it is a relict of a large river which therefore must have originally also crossed the line of the modern drainage divide (Partridge, 1998). Diagnostic clasts in the Mahura Muthla gravels indicate that the headwaters of the palaeo-river were located to the northwest (Partridge, 1998). Disruption of the Mahura Mutha drainage is ascribed to flexuring along the Griqualand–Transvaal axis to form the Kalahari basin (Partridge, 1998).
3. During the tenure of their reconnaissance exploration licence RP1/87, Seltrust Botswana Explorations (Pty) Ltd. (Seltrust) identified a major southeast–northwest-oriented sub-Kalahari valley immediately to the west of the Kalahari–Zimbabwe axis (Davidson, 1988; Figures 2 and 3). Diamonds and picro-ilmenites were recovered from the surface Kalahari sands just to the west (downwind) of the valley axis (Figure 2). These kimberlitic heavy minerals were probably derived from gravels associated with the sub-Kalahari river (Davidson, 1988). The ilmenites all plot within the very distinctive chemical field defined by the Orapa kimberlite cluster (Figure 4). The area to the southeast of the sub-Kalahari drainage has been extensively prospected, but no kimberlites have been found with ilmenites matching the Orapa population. The closest

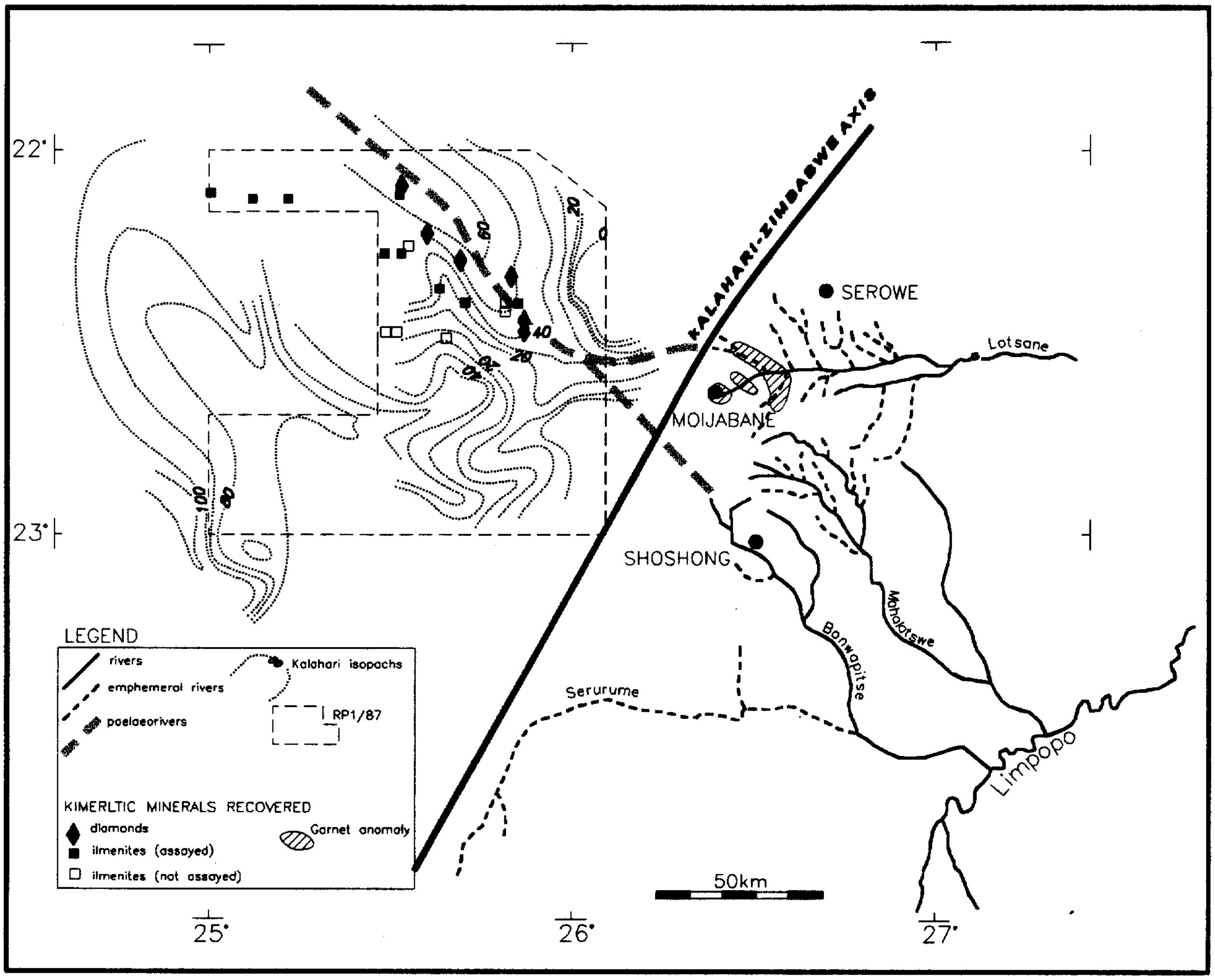

Figure 2 Location of kimberlitic heavy minerals recovered from Kalahari surface sands by Seltrust within RP1/87 in relation to a major sub-Kalahari valley, defined by the Kalahari isopachs. The broad dashed line shows the inferred abandoned line of the original link between the Okavango and Bonwapitse Rivers. This was subsequently beheaded by the Lotsane (Moore and Larkin, in prep.) The location of Figure 2 is shown in Figure 3.

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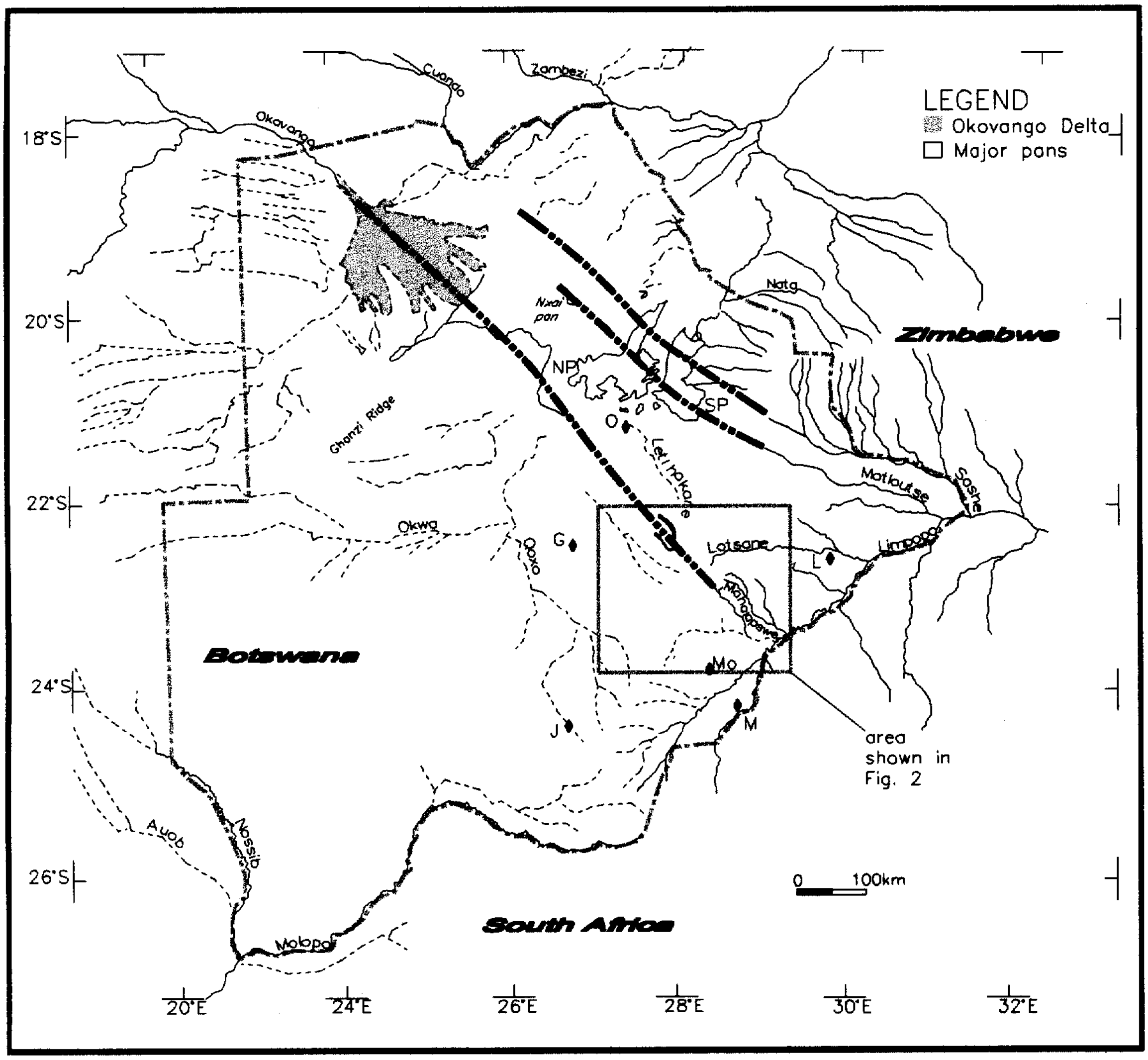

Figure 3 Reconstruction of palaeo-drainages in Botswana (bold dashed lines) Moore and Larkin (unpubl. data). The box shows the location of Figure 2. The heavy line within this box is the 60 m isopach from Figure 2. Diamonds denote kimberlite fields in eastern Botswana: J = Jwaneng; O = Orapa; G = Gope; Mo = Mosemane; M = Mochudi; L = Lerala. NP = Ntwetwe Pan; SP = Sowa Pan.

known kimberlites to the southeast of RP1/87 are those recently discovered near Mosemane (Figure 3) by the South African Minerals Corporation (SAMC) (company press release dated 02-11-98). Data for ilmenites from these kimberlites, kindly provided by SAMC, show that they are characterized by unusually high Mn concentrations (0.2 – 8.1% MnO; Average = 1.1% MnO; N = 144). In contrast, ilmenites recovered by Seltrust in RP1/87 (from soils above the sub-Kalahari valley) are Mn-poor (0.23 – 0.5% MnO; Average = 0.29% MnO; N = 6), and comparable to those from the Orapa kimberlites (0.17 – 0.45% MnO; Average = 0.28% MnO; N = 235). Thus, while the Kalahari isopachs (Figure 2) show that the sub-Kalahari valley slopes towards the northwest, the chemical fingerprint of the ilmenites from RP1/87 indicate derivation from the Orapa kimberlite field, which is located to the north. This requires that the drainage originally flowed to the southeast. It is inferred to be an abandoned course of the Okavango, which is the only major river located to the northwest (Figure 3). Flexuring along the Kalahari–Zimbabwe axis (or subsidence of the Kalahari basin) would account for the reversal of the direction of flow of this palaeo-river, and severance the link with the Limpopo, as originally mooted by Du Toit (1927; 1933).

4. Meyer (1973) provides detailed evidence for uplift along the watershed between the Vaal and Harts Rivers (the Harts axis). He argues that crustal flexuring along such an axis could account for the differing character and gradients of tributaries on either side of these two drainages. It would also explain the development of a major pan field to the southeast of the Vaal River, and river capture which modified the former Vaal and Harts drainage lines.
5. Flexuring along the Escarpment axis is generally ascribed to rift flank uplift associated with the disruption of Gondwanaland (*e.g.* Partridge and Maud, 1987). Gilchrist and Summerfield (1991) have developed a theoretical geophysical model to show that the marginal flexure will be maintained, but will probably migrate inland with time.
6. Evidence for uplift along the Ciskei–Swaziland axis is detailed in a very recent publication (Partridge, 1998).

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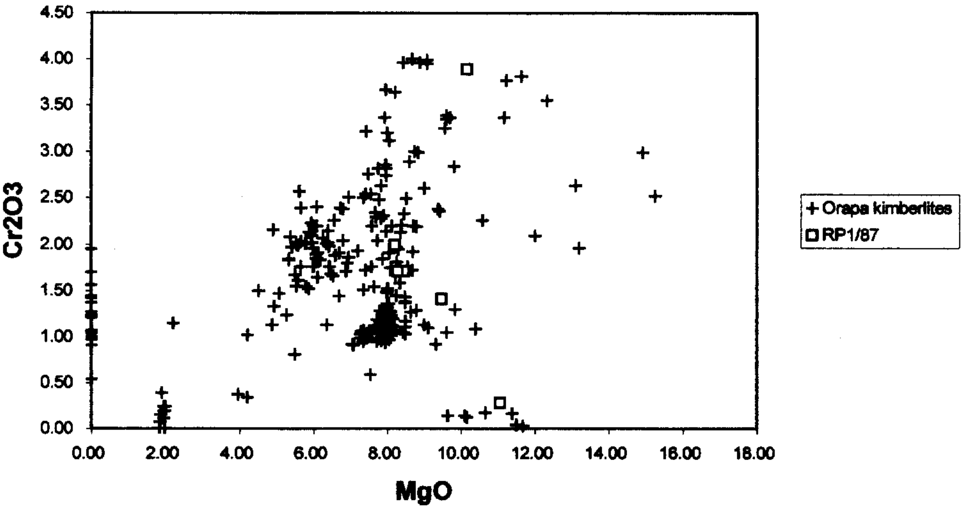

Figure 4 Ilmenites from the Orapa kimberlite and RP1/87 (data from Shee, 1978; Tollo, 1982 and Moore, unpublished data). Orapa Ilmenites with low Cr_2O_3 ($\ll$0.5%) and between 9 – 12% MgO are from ilmenite eclogites recovered from the AK1 pipe that are described by Tollo (1982). Note that one ilmenite from a soil sample in RP1/87 falls within this sub-population.

Collectively, the evidence discussed above provides compelling support for the view that the major drainage divides in southern Africa were initiated by crustal flexuring. Simple expansion of drainage basins by processes of headward erosion does not readily account for many of the abandoned river courses associated with these divides. Examples are the relict Mahura Muthla and Trans Tswana drainages and the dry poorts (wind gaps) associated with the Griqualand–Transvaal axis. The same applies to the inferred reversal of the sub-Kalahari valley identified to the west of the Kalahari–Zimbabwe axis in RP1/87 (Figures 2 and 3). The formation of pan fields is also difficult to explain in terms of simple headward erosion processes.

However, it must be stressed that crustal flexuring along the axes defined by the major watersheds involved the development of co-related basins of subsidence (*e.g.* the Bushveld and Kalahari basins) as originally envisaged by Du Toit (1933) and King (1963). As it is generally difficult or impossible to establish the absolute vertical movements involved in such crustal deformation, this paper focuses primarily on identifying and dating the major flexure axes, that is, the lines of *relative* uplift.

Configuration of flexure axes

Evidence for the configuration of the axes identified by the earlier authors, which is reviewed below, indicates that it is necessary to revise the loci of some of the lines of flexure inferred by Du Toit (1933) and Meyer (1973).

Escarpment axis

The Escarpment axis (King, 1963) forms the raised rim of the subcontinent which separates coastal and inland drainage systems. It is inferred to have been initiated by rift flank uplift of the continent associated with the disruption of Gondwanaland (Partridge and Maud, 1987; Partridge, 1998). King (1963) argued that erosion subsequent to uplift would have resulted in the coastal divide migrating inland, and that the original line of flexure may therefore have been located closer to the continental margin. This view is supported by a theoretical isostatic model developed by Gilchrist and Summerfield (1991). It predicts that headward erosion of coastal drainages,

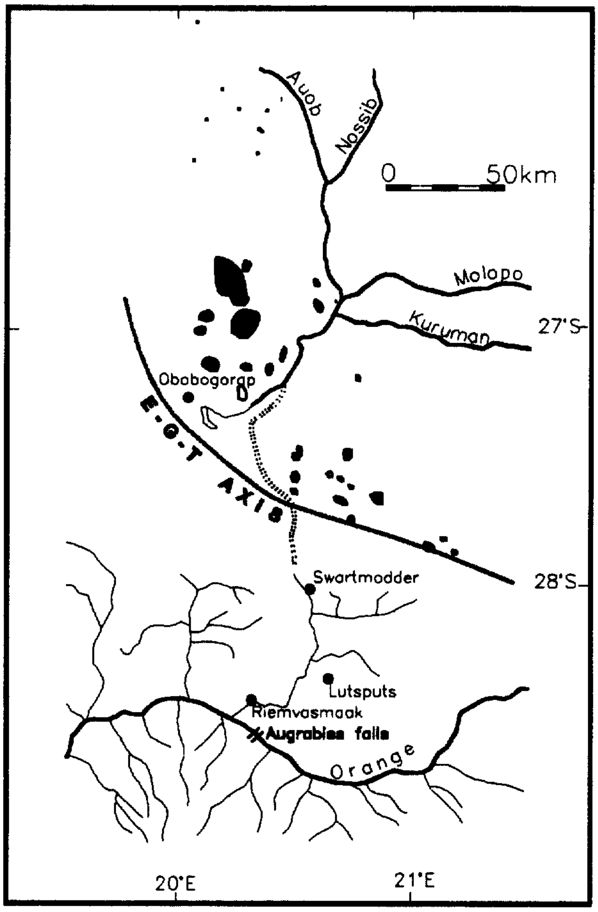

Figure 5 Detail showing the abandoned line of the Molopo River (parallel stippled line), taken from 1:1 000 000 Geological Map of the Republic of South Africa and the Kingdoms of Lesotho and Swaziland, South African Geological Survey, 1970. Shaded areas are pans.

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coupled with sedimentation on the continental shelf, would perpetuate the marginal flexure, and that this would migrate progressively further inland with time. However, Partridge (1998) argues that there is little firm evidence for inland migration of an isostatically triggered flexural bulge. The original locus of the Escarpment axis therefore remains controversial.

Griqualand–Transvaal axis

The Griqualand–Transvaal axis separates the Vaal–Orange drainage basin from the Limpopo and Molopo River systems. Du Toit (1933) envisaged that the axis crossed the Orange River near Boegoeberg, and continued to the west–southwest into Bushmanland (Figure 1). However, evidence from the lower reaches of the Molopo and environs argues for a revision of the configuration of this axis.

The Molopo–Nossib–Auob system was formerly a north-bank tributary of the Orange River (Dingle and Hendy, 1984; Partridge and Maud, 1987). An abandoned drainage line marks the former link between the two rivers, which joined some 15 km below the Augrabies Falls (Figure 5). The distribution of active and ephemeral drainage lines associated with the Molopo–Nossib–Auob and Orange–Vaal River systems is shown in Figure 6, compiled from 1:1 000 000 ICAO aeronautical charts. Major pans are also shown in this figure as they have been interpreted as relics of disrupted drainages (Du Toit, 1933; Meyer, 1973; Marshall and Harmse, 1992).

The headwaters of the Nossib and Auob flood during most rainy seasons, but the flow stops abruptly at the foot of the Auas highlands. In the lower sections of these rivers, water is confined to a series of pans in the river beds after rains. The furthest point reached by the Molopo floodwaters in living memory was Phephanelaagte in 1893, but flow typically only extends to Makopong in good rainy seasons (Figure 6; Wellington, 1955). The Kuruman River flooded in 1894, when it reached the Molopo, but the flow terminated in a small pan at Obobogorap (Figures 5 and 6; Wellington, 1955).

The longitudinal profiles of the Orange and Molopo above their confluence is illustrated in Figure 7 (data from 1:50 000 topographical maps). The Augrabies Falls represent a major nickpoint on the Orange River. Above the falls, the profile of this river is concave-up, with a relatively shallow gradient (1:670). Below the falls, gradients are high, but flatten some

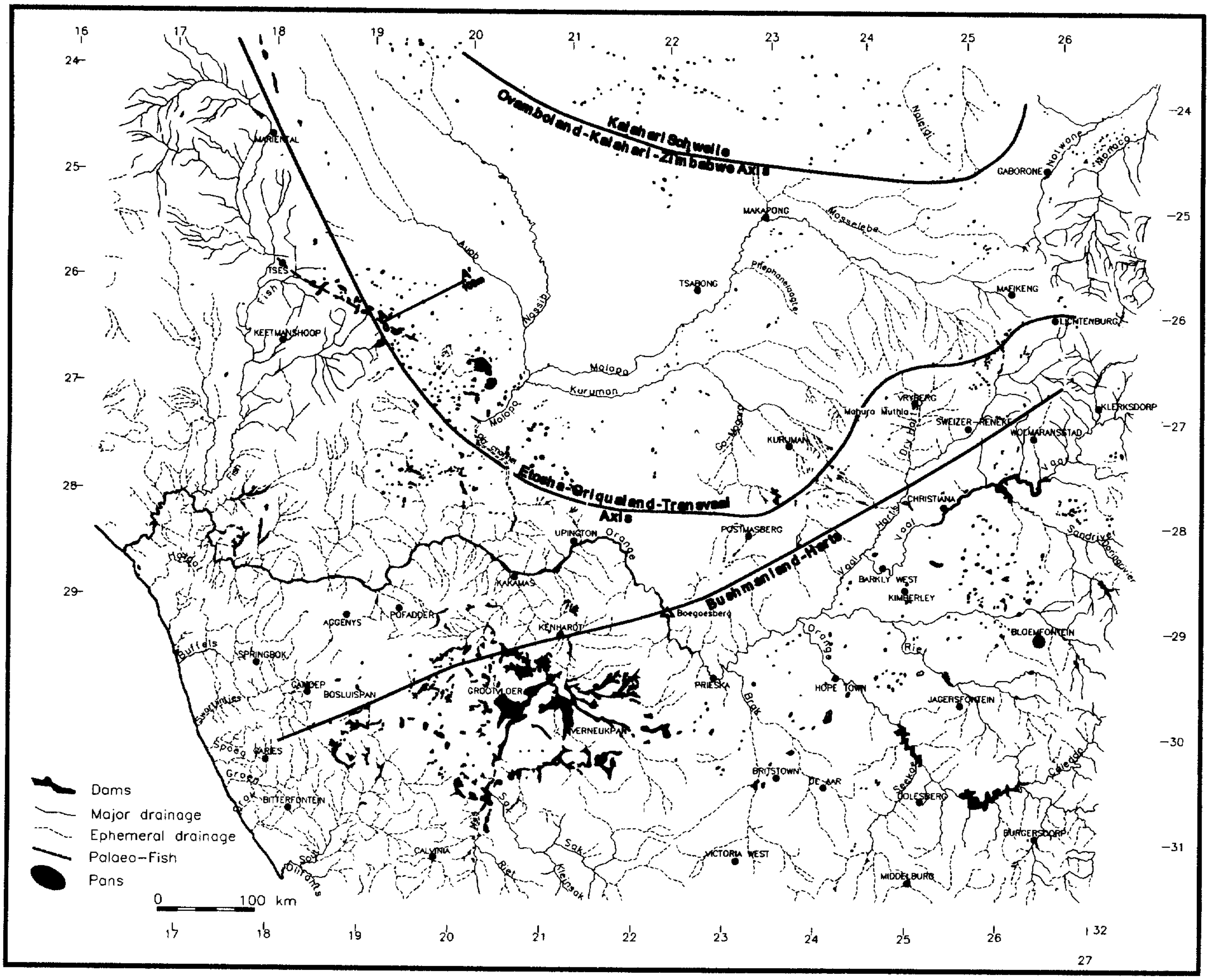

Figure 6 Active and ephemeral drainage and pans associated with the Limpopo–Marico, Vaal–Orange–Fish, and Molopo–Kuruman–Nossib–Auob drainage basins, compiled from 1:1 000 000 ICAO aeronautical maps.

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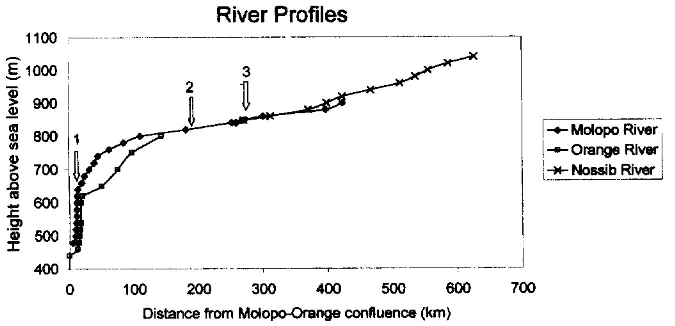

Figure 7 Longitudinal profiles of the Orange, Molopo, and Nossib Rivers. 1 = Riemvasmaak; 2 = Obobogorap; 3 = Molopo–Nossib confluence. (See Figure 5 for locations).

10 km before the confluence with the Molopo. The lower 13 km stretch of the Molopo, as far as Riemvasmaak, has a steep gradient, comparable to the section of the Orange River immediately below the Falls, and a distinct concave-up profile. Rapids characterize this stretch of the river, and tributaries form hanging valleys where they join the Molopo. Above Riemvasmaak, the profile changes to convex-up, and the gradient decreases rapidly. Where the Molopo terminates in a small pan (Abiquas Pan) in the vicinity of Obobogorup (Figure 5), the gradient is exceptionally shallow (1:3500). It increases slightly to 1:2400 above the confluence with the Kuruman River.

Mature rivers typically have concave-up profiles, with steep headwaters, and a progressive decrease in gradient in their lower reaches. However, Du Toit (1933) and Partridge (1998) point out that convex-up profiles are characteristic of drainages which cross a crustal upwarp. The profile of the Molopo above Riemvasmaak therefore argues that a crustal flexure may have crossed the abandoned channel which originally linked this river to the Orange River. This would have caused a decrease or reversal in the gradient of the lower reaches of the Molopo and the Nossib–Auob, which could explain the present-day flow regimes of these rivers, as well as the severance of the original link to the Orange. It is noted that Du Toit (1933) and Bootman (1997) have suggested that decreasing flow in the Molopo was the result of the capture of aquifers in Transvaal dolomites in the original headwaters of the river by drainages flowing northwards into the Bushveld basin. Bootsman (1997) notes that climatic deterioration also influenced the Molopo flow regime. These models are not in conflict with the inference that crustal warping beheaded the former link between the Molopo and Orange Rivers. Decreasing flow in the Molopo related to headwater capture and cli-

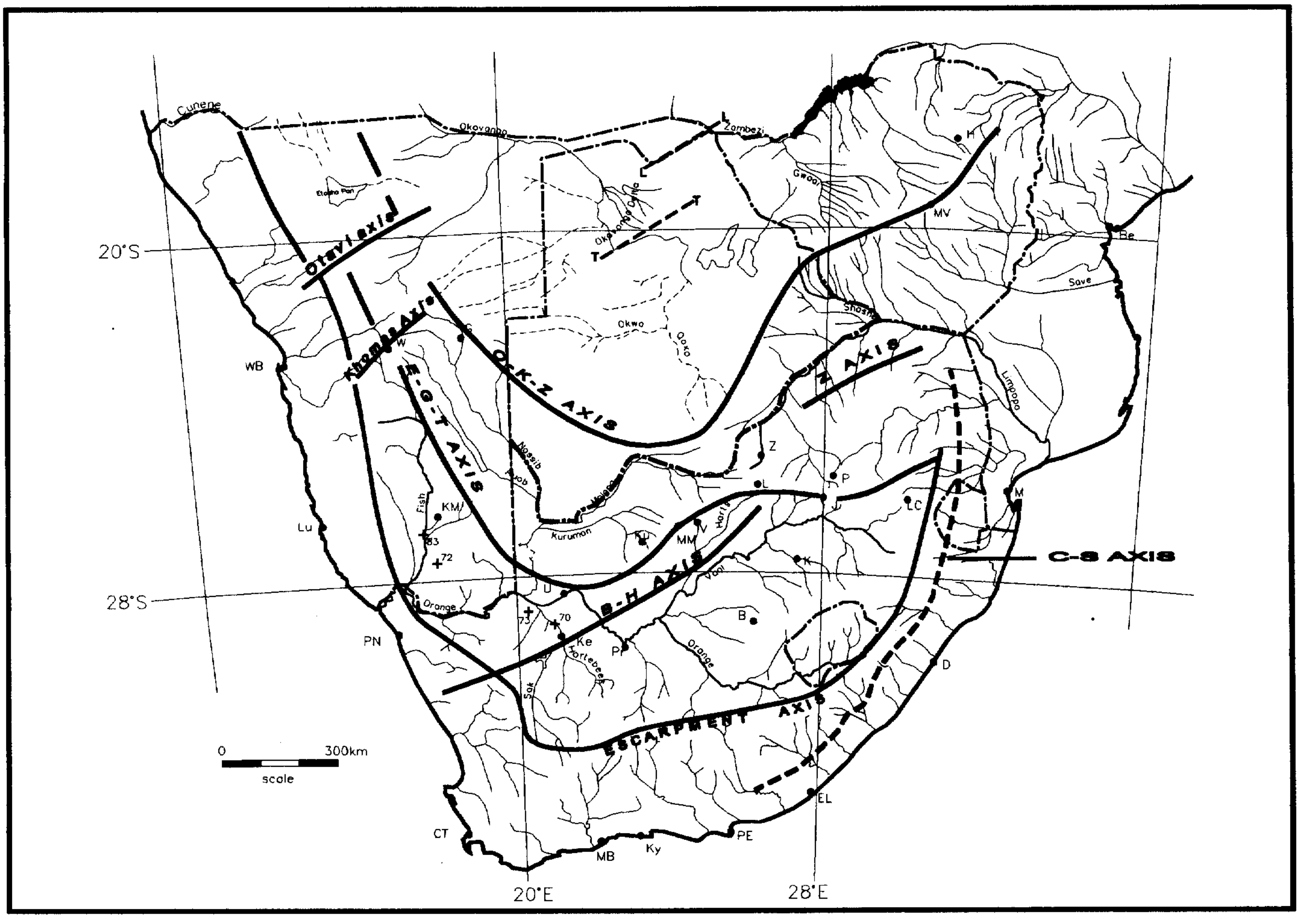

Figure 8 Revised epeirogenic flexure axes (this study). B–H = Bushmanland–Harts axis; C–S = Ciskei–Swaziland axis; E–G–T = Etosha–Griqualand–Transvaal axis; O–K–Z = Ovamboland–Kalahari–Zimbabwe axis; Z = Zoutpansberg axis; T–T = Thamalakane fault; L–L = Linyanti fault; + 73: Location of apatite fission-track sample with age in Ma. Town abbreviations as in Figure 1.

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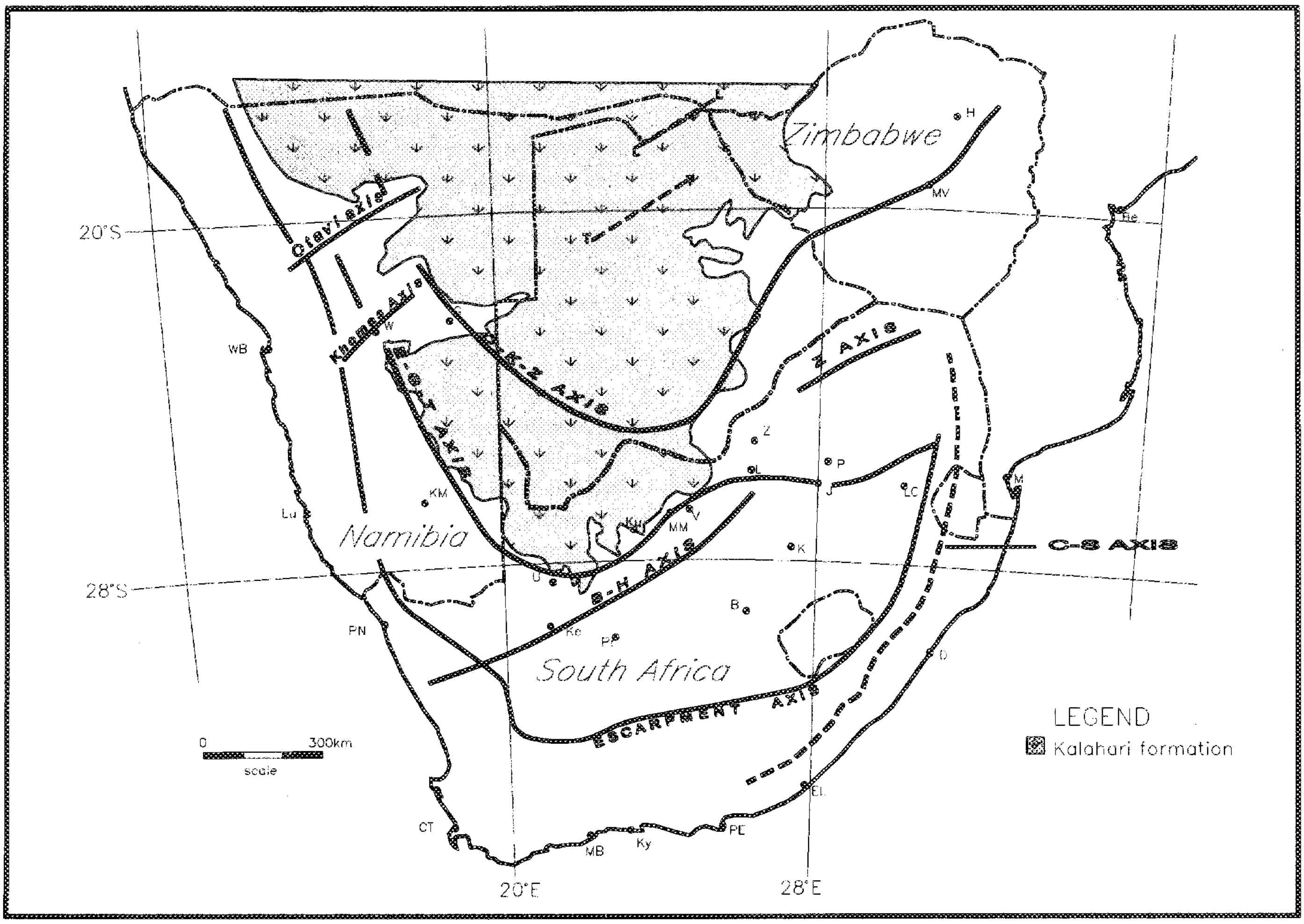

Figure 9 Location of eperiogenic flexure axes (as revised in this study) in relation to the main basin of the Kalahari formation. B–H axis = Bushmanland–Harts axis; C–S axis = Ciskei–Swaziland axis; E–G–T axis = Etosha–Griqualand–Transvaal axis; O–K–Z axis = Ovamboland–Kalahari–Zimbabwe axis; Z axis = Zoutpansberg axis; T–T = Thamalakane fault; L–L = Linyanti Fault. Town abbreviations as for Figure 1.

matic deterioration could account for the failure of this river to incise across the line of flexure.

The steep gradient of the Molopo below Riemvasmaak (Figures 5 and 7) argues for rejuvenation of the drainage. It is suggested that this was initiated once headward erosion of the Augrabies Falls had advanced upstream of the Molopo–Orange confluence at some stage following the inferred crustal flexuring. This would account for the similarity of the profiles of the lower Molopo and the section of the Orange downstream of the falls.

There is a broad northwest–southeast-trending swathe of pans (locally referred to as the 'Mierveld') between the Molopo–Auob and Orange Rivers (Figures 5 and 6). Many of the pans are located at the termination of short dismembered fossil drainage lines. Wellington (1955) has suggested that the headwaters of the Fish River were formerly linked to the Molopo–Auob along a course which is now marked by the Mierveld pans (Figure 6). A marked deflection of the course of the modern Fish River just west of Tses (Figure 6) was interpreted to be the elbow of capture of the headwaters of the river by the lower Fish. It is suggested that these features could be explained by crustal flexuring across the original line of this river. This would have resulted in low and possibly reversed gradients, and the formation of pans by processes such as those discussed by Marshall and Harmse (1992). In contrast, rivers on the coastal side of the flexure would have been rejuvenated. It is suggested that this was responsible for initiating headward erosion by the lower Fish, which ultimately beheaded the original drainage line (in the vicinity of Tses), to capture the present-day headwaters of the river.

The model proposed by Wellington (1955) for the origin of the Mierveld pans is closely analogous to that put forward by Meyer (1973) to account for pans developed to the west of the Dry Harts and east of the Vaal River. A corollary to these models is that pans and dismembered drainage lines provides important *a priori* evidence for the possible disruption of a former drainage system by crustal flexuring.

The location of the axis of flexure which is inferred to have crossed the former Molopo and Fish drainages is shown in Figures 5, 6 and 8. It coincides closely with the western margin of the Kalahari basin (Namibian Geological Survey 1:250 000 Geological Series 2618 Keetmanshoop) (See Figure 9). The Kalahari thickens from 0 – 100 m over a distance of approximately 75 km along line A–A' to the northeast of the axis (Figure 6). As surface topography is essentially flat-lying along this line, increasing Kalahari thickness reflects a dip in the basin floor to the northeast. This could be explained in terms of either uplift along the flexure axis, or subsidence

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of the Kalahari basin floor northeast of the axis. If the model for the disruption of the Fish River is accepted, this axis could therefore be envisaged as defining a broad crustal swell.

The flexure, which is inferred to have beheaded the former Molopo–Orange link and upper Fish, forms part of the watershed between the Orange–Fish and Molopo–Nossib–Auob drainage systems. An eastward continuation of this watershed, just to the north of Postmasberg, separates the northward-draining Ga-mogara tributary of the Kuruman River from a number of dismembered southwesterly oriented ephemeral drainage lines which terminate in a pan field (Figure 6). Pans are developed at the southern extremity of some of the Ga-mogara tributaries. The configuration of the most western of these tributaries suggests that they may have originally flowed to the south, but were captured by the Ga-mogara. The presence of pans and evidence for river capture in the headwaters of the Ga-mogara argues that the watershed in this area is also a line of flexure. An eastward continuation of this watershed would link with the Griqualand–Transvaal axis, which forms the eastern watershed between the Orange–Vaal and Molopo drainage systems.

It is noted that the disrupted drainage lines discussed above are not readily explained by simple headward expansion of drainage basins. The same applies to the convex-up profile of the Molopo and severance of the original link between this river and the Orange. Rather, the evidence presented argues that the watershed between the Vaal–Orange–Fish and Limpopo and Molopo–Nossib–Auob drainage systems represents a continuous, essentially crescentric line of flexure (Figures 6 and 8). It is proposed that this be designated the Etosha–Griqualand–Transvaal (E–G–T) axis to distinguish it from the original line of flexure recognized by Du Toit (1933). Lake Crissie and associated pans are located near the eastern extremity of the axis (Figure 8). It is suggested that they are relics of a fossil drainage system which was also disrupted by crustal warping along this flexure.

Kalahari–Zimbabwe axis

The Kalahari–Zimbabwe axis forms the central watershed between the Zambezi and Limpopo drainage basins in Zimbabwe. It curves to the south–southwest in Botswana, where it separates the Limpopo basin from from a fossil endoreic drainage system (the Qoxo–Okwa) which formerly emptied into the Makgadigadi basin (Figure 1).

The Molopo River is separated from the fossil central Kalahari drainage system by a low east–southeast to west–northwest oriented rise, referred to as the Kalahari Schwelle (Passarge, 1904; Figure 6). This watershed is continuous with the Kalahari–Zimbabwe axis recognized by Du Toit (1933). A northwest extension of the Schwelle separates the Qoxo–Okwa from the Nossib–Auob drainages. To the north of the Schwelle there is a marked concentration of pans (Figure 6). Many of these define distinct lineaments, suggesting that they are relics of a disrupted drainage system. This in turn argues that the Schwelle represents a line of crustal flexure, which is an extension of the Kalahari–Zimbabwe axis. It is proposed that this crescentric line of uplift be designated the Ovamboland–Kalahari–Zimbabwe (O–K–Z) axis (Figure 8).

The Escarpment, Etosha–Griqualand–Transvaal, and Ovamboland–Kalahari–Zimbabwe axes therefore define approximately concentric lines of crustal flexure that are broadly parallel to the margin of the sub-continent (Figure 8).

Bushmanland–Harts axis

Du Toit (1933) originally proposed that the Griqualand–Transvaal axis continued in a southwesterly direction, across Bushmanland towards the Atlantic Coast, crossing the Orange and Hartebees Rivers at points where there was a sharp downstream increase of the gradients of these rivers. He suggested that uplift along this axis could account for raised Plio–Pleistocene terraces along the Atlantic coast, and also the formation of major pans on the Hartebees River and tributaries (Figure 1). However, a number of lines of evidence indicate that it is necessary to modify the configuration of the flexure which traverses Bushmanland.

An east–northeast projection of the line of the axis across the Orange River passes immediately to the south of a dismembered ephemeral drainage line (Figure 6). The geometry of this abandoned channel indicates that it was probably once a north-bank tributary of the Orange. Immediately to the northeast of this inferred relict tributary are four ephemeral drainage lines with headwaters near Postmasberg, which terminate in a group of pans. Their orientation indicates that they are also beheaded former north-bank Orange tributaries.

Crustal warping along an east–northeast continuation of the axis which traverses Bushmanland could account for the disruption of these drainage lines. A further extension of this axis to the east–northeast would link up with the flexure forming the watershed between the Vaal and the Harts Rivers which was identified by Meyer (1973) (Figures 1, 6 and 8). It is suggested that this represents a single line of uplift, which it is proposed be designated the 'Bushmanland–Harts' axis. There is no clear evidence for the continuation of this flexure across the Etosha–Griqualand–Transvaal axis. Therefore, it may have terminated close to the latter axis, or merged with it, as proposed by Meyer (1973).

In summary, the major continental river divides in southern Africa define three essentially crescentric lines of flexure (the Escarpment, Etosha–Griqualand–Transvaal, and Ovamboland–Kalahari–Zimbabwe axes) which are roughly parallel to the coastline. The west–southwest to east–northeast-trending Bushmanland–Harts axis is essentially perpendicular to the Atlantic continental margin. It forms the divide between the Vaal and Harts Rivers, and has been responsible for the disruption of the Hartbees and a number of other Orange River tributaries. Three subordinate axes (the Khomas, Otavi, and Zoutpansberg axes) are sub-parallel to the Bushmanland–Harts axis.

The Etosha–Griqualand–Transvaal axis crosses the Johannesburg granite dome, which was a buoyant crustal feature in Archaean times (Truswell, 1977). Immediately to the west of Johannesburg, it coincides closely with the axis of a major anticline in the Transvaal Supergroup (1:1 000 000, Geological Map of South Africa and the Kingdoms of Lesotho and Swaziland, 1970 edition, Geol. Surv. S. Afr.). Similarly, in southeastern Botswana, the Ovamboland–Kalahari–Zimbabwe axis swings to the west along an east-west-oriented lobe of the Gaborone Granite exposed in the core of a Waterberg anticline (Geological Map of Botswana, 1984 edition, Geol. Surv. Botswana). It also broadly coincides with a major topo-

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graphical high (the Cargonian highlands) which separated major Dwyka depositional basins to the north and south (Visser, 1987). De Wit (1993; 1996) suggests that the Bushmanland–Harts axis is controlled by pre-Karoo structural elements. This evidence indicates that the loci of the flexure axes were in part influenced by earlier structural features on the sub-continent, which experienced repeated rejuvenation associated with basin development.

Dating of flexure axes

Relative ages

It is possible to infer *relative* ages for the major flexure axes in southern Africa on the basis of their relationship to the distribution of the Kalahari formation (Figure 9).

Initial uplift along the Escarpment axis has been ascribed to late Jurassic – Early Cretaceous rifting which initiated the disruption of Gondwana (Partridge and Maud, 1987). These authors propose that this initiated polycyclic erosion which produced a surface of advanced planation across the sub-continent (the African Surface). They conclude that the Kalahari formation was deposited on this erosion surface in the interior of southern Africa, and must therefore post-date initial flexuring along the Escarpment axis.

The Etosha–Griqualand–Transvaal axis closely follows the southern margin of the Kalahari formation (Figure 9). This flexure crossed, and is inferred to have beheaded, a number of major south-flowing drainages including the Trans Tswana (McCarthy, 1983), Mahura Muthla (Partridge, 1998), and the Molopo. The Kalahari is unusually thick in the vicinity of the Molopo River in southern Botswana (Gould *et al.*, 1987). Drilling carried out by Falconbridge in this area intersected thick basal Kalahari gravels (Blaine, 1984). It is postulated that the gravels represent an aggrading fluvial sequence associated with subsidence of the Kalahari basin along the Etosha–Transvaal–Griqualand hinge, which crossed the line of the palaeo-Molopo. The lower-most Kalahari units in south-eastern Namibia are fluvial (Mabbutt, 1955), consistent with this interpretation. A probable source of the clasts in the basal Kalahari gravels would be the underlying Dwyka diamictites (Mike de Wit, pers. comm., 1999). The disruption of other major south-flowing rivers (such as the Trans Tswana and Mahura Muthla) would also be expected to have contributed to fluvial sedimentation in the Kalahari basin.

Uplift along the Etosha–Griqualand–Transvaal axis is thus inferred to have initiated deposition of the Kalahari formation. This axis would therefore post-date the Escarpment axis, which initiated planation of the surface on which the Kalahari was deposited (Partridge and Maud, 1987).

Du Toit (1954) notes that in eastern Botswana, the Kalahari terminates in an abrupt erosional scarp, and infers that the formation must therefore have originally extended further to the east. Similarly, Meyer (1986) suggests that the Kalahari beds in the western Transvaal originally extended further to the east. In eastern Botswana, the margin of the Kalahari is closely associated with the Ovamboland–Kalahari–Zimbabwe axis (Figure 9). Uplift along this axis would have rejuvenated drainages such as the Limpopo and tributaries, initiating erosion of the coastal side of the flexure, which would thus form the local boundary to the Kalahari formation. This in turn requires that the Ovamboland–Kalahari–Zimbabwe axis post-dated the onset of Kalahari sedimentation, and must therefore be younger than the Etosha–Griqualand–Transvaal axis (which initiated Kalahari sedimentation).

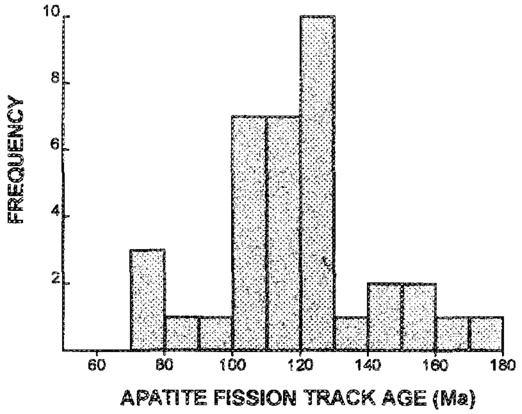

Figure 10 Histogram of apatite fission-track ages (Ma) for samples from transects across the west coast Escarpment, South Africa (Brown *et al.*, 1990). Note the major early Cretaceous and subordinate late Cretaceous (70 – 90 Ma) peaks. Positions of samples giving the younger ages are shown in Figure 8. They are all located at the inland extreme of the sampling transects, within the drainage basin of the Orange River and tributaries.

The Otavi axis is associated with a major embayment in the western margin of the Kalahari formation. A less pronounced embayment is associated with the Khomas axis (Figure 9). It is suggested that these features reflect erosion of the Kalahari margin following uplift along these axes. Both embayments extend across the line of the Ovamboland–Kalahari–Zimbabwe axis, indicating that uplift along the Otavi and Khomas axes and ensuing erosion post-date the former flexure.

Absolute ages

Escarpment axis

Brown *et al.* (1990) report apatite fission-track ages for samples taken on transects which cross the western escarpment of South Africa. A histogram of these ages is shown in Figure 10. The majority fall within the range 100 – 130 Ma, which Brown *et al.* (1990) interpret in terms of an early Cretaceous phase of accelerated erosion along the western margin of southern Africa. They note that these fission-track ages correlate with high sedimentation rates recorded in boreholes to the south of the Orange River on the southern African west coast, consistent with this interpretation.

The major population of apatite fission-track ages span the time of the opening of the Atlantic. Initiation of the early Cretaceous episode of erosion therefore could be explained in terms of marginal flexuring of the sub-continent associated with rifting. This is consistent with a lower Cretaceous age for *initiation* of the Escarpment axis as proposed by Partridge and Maud (1987; Partridge, 1998). It is noted that a theoretical geophysical model developed by Gilchrist and Summerfield (1991) predicts that this axis would remain active following rifting, and would migrate inland with time. Partridge (1998), however, considers that there is little evidence to support inland migration of the flexural bulge.

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Etosha–Griqualand–Transvaal axis

Fluvial gravels, which are relics of an abandoned northwest–southeast-oriented drainage, are preserved at Mahura Muthla, astride the Griqualand–Transvaal axis on the Ghaap Plateau (Figure 1; Wagner, 1914). The palaeo-channel attains widths of 150 m, indicating that the Mahura Muthla was originally a large river which must have flowed across the line of the axis. A silicified fragment of the fossil angiosperm, *Proteroatherospermoxylon rennei* was recovered from the Mahura Muthla gravels (Partridge, 1998). This range of this species is not well defined, but it is known from the Upper Cretaceous of Egypt, as well as from the Mzamba Formation of the Transkei coast, which is estimated to be of Santonian–Campanian age. This points to an upper Cretaceous age for the Mahura Muthla gravels (Partridge, 1998), and sets a maximum age limit for uplift. It is difficult to establish a firm minimum age of uplift, but Partridge (1998) suggests that it predated a period of early Palaeocene silicification which was probably responsible for fossilization of the logs recovered from the Mahura Muthla gravels. Deposition of the gravels suggests that the river was aggrading rather than eroding, possibly in response to uplift across its course. It is therefore suggested that the Etosha–Griqualand–Transvaal axis is closely comparable in age to the gravels.

In addition to the major early Cretaceous apatite fission-track age peak discussed by Brown *et al.* (1990), there are also subordinate populations of late Jurassic and late-Cretaceous ages (Figure 10). Sample sites yielding the younger ages (shown in Figure 8) are all located at the inland extremes of the sampling transects, within the drainage basin of the Orange River and its tributaries. Mike de Wit (pers comm., 1999) suggests that these younger ages may reflect thermal resetting of the crust related to the emplacement of Late Cretaceous olivine melilitite and kimberlite pipes in Namaqualand and Bushmanland. However, the sites where these younger ages were recorded fall outside the field of these volcanic pipes. Also, wall rocks marginal to the pipes typically do not show evidence of any significant thermal metamorphism (Moore, 1979). An alternative explanation for the younger ages documented by Brown *et al.* (1990) is that they reflect a period of accelerated erosion in the Orange River basin. This is supported by the large increase in sediment from the Orange River system during the Upper Cretaceous (Dingle and Hendy, 1984; Dingle and Robson, 1992), and high Campanian–Maastrichtian (Upper Cretaceous) sedimentation rates recorded in the Kudu 9A-1 borehole, located to the northwest of the present Orange River mouth (Rust and Summerfield, 1990). Flexuring across the E–G–T axis could have provided the trigger for this younger episode of accelerated erosion, as this would have resulted in the rejuvenated Vaal–Orange system. This would imply a late Cretaceous age for the E–G–T axis.

Miller (1993) suggests that the lowermost Kalahari formation in Namibia correlates with the basal Kalahari units in the Democratic Republic of Congo, which are inferred to be of Upper Cretaceous age (Cahen and Lepersonne, 1952). This is also consistent with an Upper Cretaceous age for the Etosha–Griqualand–Transvaal axis, as this line of flexure is inferred to have initiated Kalahari sedimentation in southern Africa.

Ovamboland–Kalahari–Zimbabwe axis

In an earlier section, it is argued that a major sub-Kalahari valley, located to the west of the O–K–Z axis in Botswana (Figures 2 and 3), is a relict channel of the Okavango. It was inferred that this valley originally linked the Okavango to the Limpopo, but was abandoned following flexuring along the axis. Ilmenites recovered from surface Kalahari sands overlying this palaeo-valley fall within the distinctive field for ilmenites from the Orapa kimberlites (Figure 4). The valley therefore drained these kimberlites prior to severance of the link with the Limpopo. The Orapa pipe has been dated at 87 – 93 Ma (Allsopp *et al.*, 1989). This sets an upper age limit for uplift along the Ovamboland–Kalahari–Zimbabwe axis.

Apatite fission-track dating indicates that a period of rapid erosion affected a widespread area in Africa at the end-Cretaceous – Palaeocene (Foster and Gleadow, 1992). This episode of erosion is also recorded in the Limpopo Valley in southwestern Zimbabwe (Belton *et al.*, 1998), pointing to rejuvenation of the Limpopo drainage system at this time. It is suggested that this could be explained by end-Cretaceous to early Tertiary uplift along the Kalahari–Zimbabwe axis. Further work (for example dating of basal sediments in the Makgadigadi Pan) is needed to confirm the inferred age inferred of this axis.

Ciskei–Swaziland axis

Partridge (1998) infers a Pliocene age for uplift along this axis. This would account for early Pliocene deposits located at an elevation of 400 m on the seaward side of the line of flexure.

Bushmanland–Harts axis

The age of the Bushmanland–Harts axis is constrained by fossil evidence from the Sak River, a major tributary of the Hartbees (Figure 7). Both rivers are ephemeral drainage with very low gradients. Consequently, floodwaters spread over the surrounding plains above any rock bar in theses rivers, forming large pans, which are locally referred to as 'floors' (Wellington, 1955).

High-level gravels preserved above the modern course of the Sak are interpreted as relics of an earlier major river of very different character (De Wit and Bamford, 1993). At one locality, these older, high-level gravels are preserved in a bedrock channel which is interpreted to reflect erosion under fluvial conditions. Associated fossil wood fragments can be assigned to Dipterocarpacaea, Fagacaea, Myrtacaea, Oleacaea and Rutacaea (Bamford and De Wit, 1993). These indicate a Miocene age, and a tropical to sub-tropical climate. Lower-level, and thus younger gravels are interpreted as a braided stream facies, deposited by a major river with flows between 90 – 120 cm/sec (De Wit and Bamford, 1993). They are inferred to have been laid down during Plio–Pleistocene pluvial episodes on the basis of a fossil wood specimen which can be assigned to the Polygalacaea (Bamford and De Wit, 1993). The character of the Sak River thus evolved from active Miocene erosion to Plio–Pleistocene aggrading in a braided stream system and ultimately senility, with the formation of the present-day pans ('floors') in an environment characterized by extremely low gradients.

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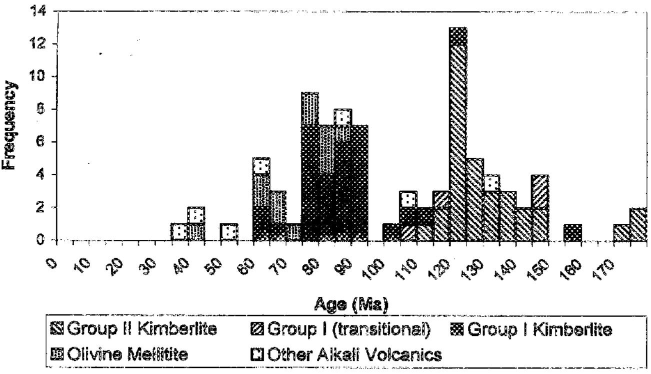

Figure 11 Histogram of ages of post-Gondwanaland kimberlites, olivine melilitites, and other alkaline volcanic pipes. Major peaks in alkaline volcanic activity occur in the lower Cretaceous, late Cretaceous, and early Tertiary. Sources of data: Allsopp and Barrett, 1975; Allsopp and Hargraves, 1985; Allsopp and Kramers, 1977; Allsopp and Roddick, 1984; Allsopp *et al.*, 1989; Anglo American Research Laboratories, Geology Dept. (1998); Brown, 1985; Davies *et al.*, 1991; Dingle and Gentle, 1972; Duncan *et al.*, 1978; Fitch and Miller, 1983; Green, 1985; Kramers *et al.*, 1983; Kramers and Smith, 1983; Kröner, 1973; McIntyre and Dawson, 1976; Moore and Verwoerd, 1988; Phillips *et al.*, 1998a; Phillips *et al.*, 1998b; Phillips *et al.*, (in prep); Raber, 1978; Reid *et al.*, 1990; Smith *et al.*, 1985; Smith *et al.*, 1994; Spriggs, 1988.

De Wit (1993) and De Wit and Bamford (1993) ascribe the evolution of the Sak River from active incision to its present-day senile character to the progressive climatic deterioration recorded by the fossil evidence (*i.e.* the change from humid Miocene to the present-day arid conditions). However, there is an alternative (but not necessarily incompatible) interpretation for the senile character of the modern river. The increase in gradient of the lower section of the Hartbees (Du Toit, 1933) is consistent with disruption of the drainage by crustal flexuring along the Bushmanland–Harts axis. It is suggested that the change to an aggrading character, represented by the Plio–Pleistocene braided river gravel facies, reflects a decrease in gradient of the river above the axis. This would imply a Plio–Pleistocene age for flexuring along the Bushmanland–Harts axis. Deteriorating climatic conditions would account for the failure of the Bushmanland drainages to incise across the line of flexure.

The Zoutpansberg, Otavi, and Khomas axes are oriented southwest–northeast, and thus roughly parallel to the Bushmanland–Harts axis. This suggests that they may be related to the same tectonic stresses, and hence of comparable age. Major faults in Botswana (the Thamalakane and Linyanti, Figure 9) have a similar orientation. Earthquake activity along these faults indicates that they are still active (Reeves, 1972). This suggests that the tectonic stresses which initiated the Plio–Pleistocene flexuring may still be active.

It is noted that the inferred timing of flexuring along the major axes recognized in southern Africa is consistent with the relative ages inferred on the basis of their relationship to the Kalahari formation. The conclusion that the Etosha–Griqualand–Transvaal and Bushmanland–Harts axes represent different lines of uplift is supported by the evidence that they were initiated at different times.

Tectonic framework for continental flexuring

There appears to be general consensus that the Escarpment axis was *initiated* by rift flank uplift associated with the disruption of Gondwana (*e.g.* Partridge and Maud, 1987; Partridge, 1998). King (1963) and Partridge (1998) suggest that rifting could also provide a mechanism to explain the north-east–southwest Plio–Pleistocene flexure axes. It has previously been noted that major active faults in northern Botswana (*e.g.* the Thamalakane and Linyanti faults, Figure 9) are parallel to these younger flexure axes, suggesting a link to a common tectonic process. Reeves (1972) proposes that faulting and seismic activity in northern Botswana reflects the southwestward propogation of the East African Rift system, following lines of structural weakness such as the Ghanzi–Chobe mobile belt. It is therefore suggested that the Plio–Pleistocene axes of flexure represent the initial expression of the extension of the rifting towards the Atlantic coast, and parallel to the east coast along the Ciskei–Swaziland axis.

The tectonic processes responsible for uparching along the Etosha–Griqualand–Transvaal and Ovamboland–Kalahari–Zimbabwe axes remain poorly understood. However, there is evidence which suggests a possible link with alkaline volcanism on the sub-continent.

A number of authors have suggested that southern Africa experienced episodic alkaline volcanic activity during the period immediately prior to, and following the disruption of Gondwana (*e.g.* Moore, 1976; Bailey, 1993). Figure 11 summarizes age data for kimberlite, olivine melilitite, and other alkaline volcanic pipes in southern Africa. This histogram excludes single-zircon U–Pb ages, which are frequently older than emplacement ages inferred from other dating methods, and appear to reflect a variety of mantle events which preceded pipe emplacement (LeCheminant *et al.*, 1998; Konzett *et al.*, 1998).

The age data presented in Figure 11 define three major peaks in alkaline volcanic activity — early Cretaceous, late Cretaceous, and early Tertiary. Miocene and Oligocene ages may either reflect younger volcanic events, or be outliers of the early Tertiary volcanic episode. The ages of the three major peaks in volcanic activity broadly match the inferred ages of the Escarpment, EGT, and OKZ axes respectively, suggesting a link to a common underlying geological mechanism.

The origin of kimberlites and other alkaline pipes in southern Africa remains controversial. Deep-originating mantle plumes have been proposed as a trigger for volcanic activity (*e.g.* Hartnady and Le Roux, 1985; Hatton, 1998), and may therefore also have initiated episodic crustal flexuring. Nevertheless, Smith *et al.* (1994) note that age and isotopic relationships of kimberlites in the Prieska area are not readily explained in terms of simple plume models. These authors tentatively suggest that volcanism may have been triggered by stress relief melting associated with changes in the pole of plate rotation. Similarly, Phillips *et al.* (1998b) propose that Group II kimberlites were emplaced following deep-seated extensional rifting associated with a change in the regional stress field related to continental break-up along the east coast of southern Africa. This raises the possibility that continental flexuring was also a response to changes in the regional stress

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field associated with continental break-up and changes in the pole of plate rotation.

Resolution of the origin of continental flexuring and intraplate alkaline volcanism is clearly fundamental to refining our understanding of plate tectonic processes.

Drainage evolution and the development of cyclic erosion surfaces

Key issues concerning the influence of crustal flexuring on the evolution of drainages and erosion surfaces in southern Africa are as follows:

The revised ages of the flexure axes proposed in this study offer a framework for establishing the timing of major river captures and the evolution of drainage systems on the subcontinent. Thus, Thomas and Shaw (1991) envisage that marginal warping of the continent associated with continental break-up of Gondwana initiated an endoreic drainage system which only recently broke through the girdle of high ground which forms the coastal escarpment. The Okwa–Qoxo and Okavango Rivers are considered to be relics of this endoreic drainage system. An alternative view, based on the reconstruction of the major southern African flexure axes, is that the Okwa–Qoxo is a consequent drainage system, *initiated* by early Tertiary flexuring along the Kalahari–Zimbabwe axis. This axis rose across the line of the Okavango, and would be responsible for severing the former link with the Limpopo, as originally envisaged by Du Toit (1933).

Gilchrist and Summerfield (1991) argue that rejuvenation of the escarpment axis could not provide a mechanism for initiating successive erosion surfaces — as originally proposed by King (1955). However, sequential uplift along concentric axes located progressively further inland would be expected to initiate successive rejuvenation of drainages on the coastal side of each flexure. This could in principle provide the trigger for a successive cycles of erosion, which might be reflected by surfaces of different ages.

Lister (1987) interprets the senile landscape which straddles the Zambezi–Limpopo watershed (*i.e.* the OKZ axis) in Zimbabwe to be a relict of the African erosion surface. This surface has been incised to the north and south by the younger Post-African I cycle of erosion. Uplift along the OKZ axis would provide a mechanism for initiating the Post-African I cycle of erosion in Zimbabwe, leaving relics on the African Surface on the axis crest. If the inferred early Tertiary age for the OKZ axis is correct, this would imply *initiation* of the Post-African I cycle of erosion much earlier than the Miocene age suggested by Partridge and Maud (1987).

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