Landscape evolution in Zimbabwe from the Permian to present, with implications for kimberlite prospecting

A.E. Moore
Department of Geology, Rhodes University, Grahamstown.
Somabula Explorations (Pvt.) Limited, Box CH399, Chisipite, Harare, Zimbabwe.
e-mail: andy.moore@info.bw

F.P.D. (Woody) Cotterill
AEON - Africa Earth Observatory Network and Department of Geological Sciences,
University of Cape Town, Rondebosch 7701, South Africa.
e-mail: fenton.cotterill@uct.ac.za

T. Broderick
19 Jenkinson Road, Chisipite, Harare, Zimbabwe
e-mail: makari@zol.co.zw

D. Plowes
49 Arcadia Road, Tigers Kloof, Mutare, Zimbabwe.
e-mail: plowes@mweb.co.zw

ABSTRACT

Evidence is presented to model drainage evolution across Zimbabwe since the Permian. This provides the framework to understand the marked difference in character of the rivers to the north and south of the modern central Zimbabwe watershed, which separates the Zambezi and Limpopo drainage basins. North-flowing tributaries of the Zambezi rising off this river divide have low gradients and senile characteristics. The northwest orientation of the upper sections of many of these rivers is unusual for tributaries of a major east-flowing drainage, but is in accord with the west-orientated fluvial system that deposited the Triassic sediments of the Karoo Supergroup in the Cabora Bassa basin of the Zambezi Valley. The modern drainage system to the north of the central Zimbabwe watershed is thus largely controlled by a surface that has existed since pre-Karoo times. Headwaters of the Zambezi tributaries were originally located well to the south of the modern divide, with high ground extending to the present-day Chimanimani and Nyanga mountainland in eastern Zimbabwe. This drainage system persisted until the late Triassic, when rifting, linked to the early disruption of Gondwana, initiated the formation of the modern Save and Zambezi river systems. The central Zimbabwe watershed represents a late Palaeogene (~43 to 33 Ma) asymmetric epeirogenic flexure, part of the Ovamboland-Kalahari-Zimbabwe Axis, which beheaded the headwaters of the early Zambezi tributaries. The resultant steeper gradients to the south of the watershed initiated the modern youthful south-flowing drainage system. A further disruption to the Zambezi drainage system occurred during Plio-Pleistocene arid episodes, when major dunes developed across dry river systems such as the Shangani, in the northwest of the country. Renewed flow in these rivers during subsequent wetter pluvial episodes resulted in them exploiting the inter-dune streets to develop new courses. Some, like the Shangani, incised their courses through the Kalahari sand cover to become superimposed drainages.

The landscape of much of Zimbabwe reflects the imprint of two major cycles of erosion (African and post-African) since the disruption of Gondwana. The African erosion cycle commenced with the disruption of Gondwana, while the ensuing post-African cycle of erosion was initiated by the late Palaeogene uplift along the line of the modern central watershed. This rejuvenated the river network, leading to removal of the carapace of deeply weathered saprolite that developed under the humid mid-Cretaceous climate of the earlier African cycle. The post-African surface is thus an etch surface, with the characteristic plain and inselberg topography marking the weathering base of the African erosion event. A very subordinate Plio-Pleistocene cycle is reflected by terraces immediately marginal to the major river systems. The confinement of the Save and Zambezi drainages to graben structures resulted in their evolution largely independently of the two major erosion cycles that moulded the landscape of the rest of the country.

The palaeo-drainage reconstruction has important implications for the dispersion of diamonds and associated pathfinder minerals from primary kimberlite sources. The Sese-Murowa kimberlites are inferred to be the primary source of hitherto unexplained alluvial diamonds in basal gravels of the Somabula Karoo outlier, located on the central Zimbabwe watershed, some 120 km to the northwest. The drainage evolution model also provides a framework to infer likely distal kimberlite sources for a number of major unexplained kimberlitic pathfinder mineral anomalies associated with the southern margin of the Kalahari Formation.

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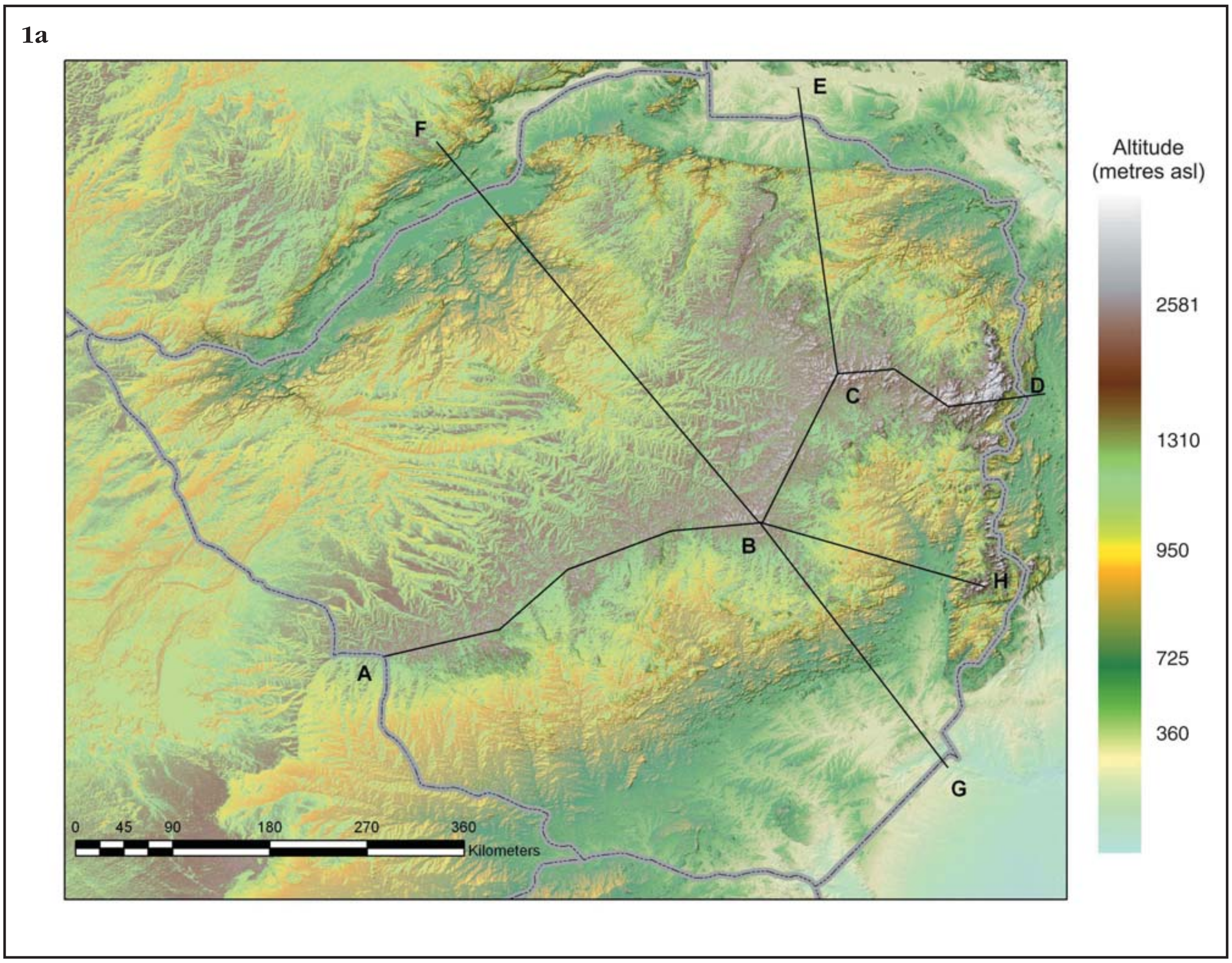

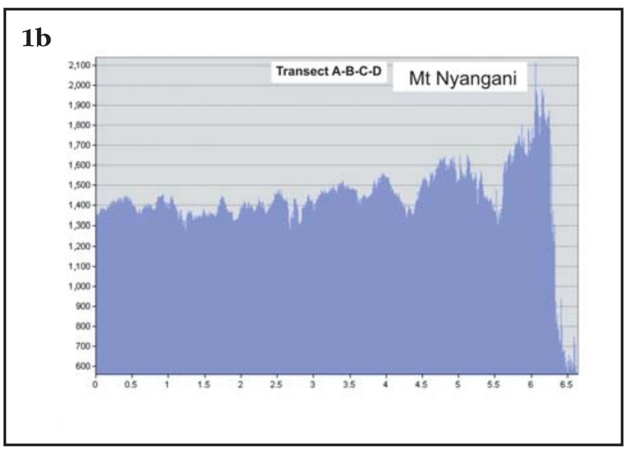

Figure 1. (**a**) SRTM3 digital elevation model for Zimbabwe. Lines show the locations of elevation profiles illustrated in Figures 1b-1f. (**b**) Elevation profile along the Central Zimbabwe Watershed (A-B-C-D) (**c**) Elevation profile (C-E) from Harare north to the Zambezi Valley, crossing the escarpment formed by the Mavuradonha Mountains. (**d**) Elevation profile (B-F) from the Central Zimbabwe Watershed, in the vicinity of Felixburg, northeastward to the Kariba Dam on the Zambezi River. (**e**) Elevation profile B-H, crossing the rift-bound Save River, towards the Chimanimani Mountains. (**f**) Elevation profile B-G from the vicinity of Felixburg towards the exit of the Save River from Zimbabwe, which is the lowest point in the country. NZLB: Northern Marginal Zone of Limpopo Belt; CZLB: Central Zone of Limpopo Belt.

Introduction

Some two thirds of Zimbabwe is underlain by the granite-greenstone complex that forms the Archaean Zimbabwe Craton. This tectonic setting is similar to that of large areas of neighbouring South Africa to the south, and Botswana to the west, both of which are underlain by extensive areas of the Archaean Kaapvaal Craton. However, from a geomorphological perspective, the Zimbabwe Craton stands apart in lacking the extensive late Archaean to mid-Proterozoic platform sedimentary sequences that cap large tracts of the Kaapvaal Craton. Palaeozoic-Mesozoic sediments of the Karoo Supergroup and the younger Kalahari Formation also cover a much more limited area in Zimbabwe than is the case to the south and west. This ameliorates the problem of differentiating between surfaces related to major erosion cycles, and structural benches caused by horizontal or near-horizontal sedimentary cover sequences. Consequently, it is possible to unravel the geomorphological evolution of Zimbabwe in considerable detail over a period of time stretching back to at least the Permian. This in turn makes Zimbabwe an important field laboratory for interpreting the processes

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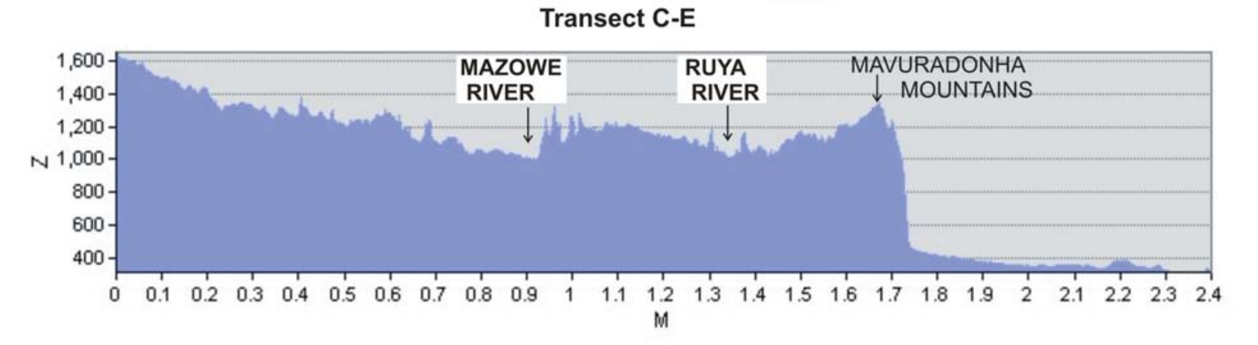
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RUYA RIVER
MAVURADONHA MOUNTAINS
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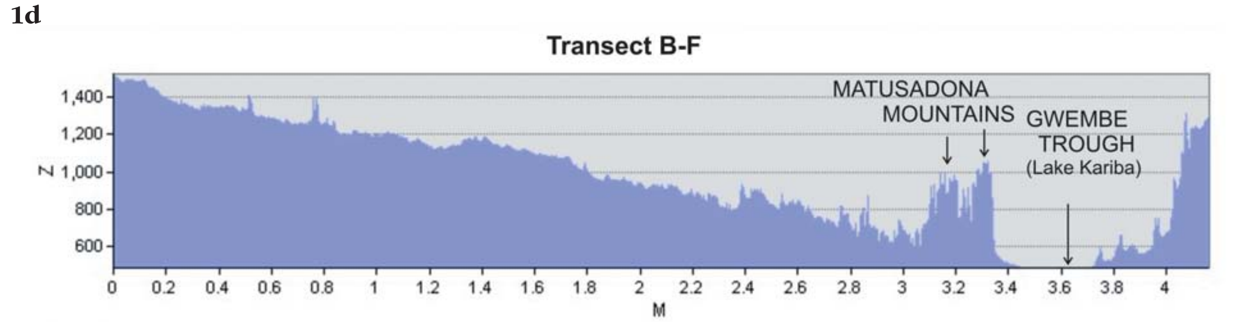
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MATUSADONA MOUNTAINS
GWEMBE TROUGH
(Lake Kariba)
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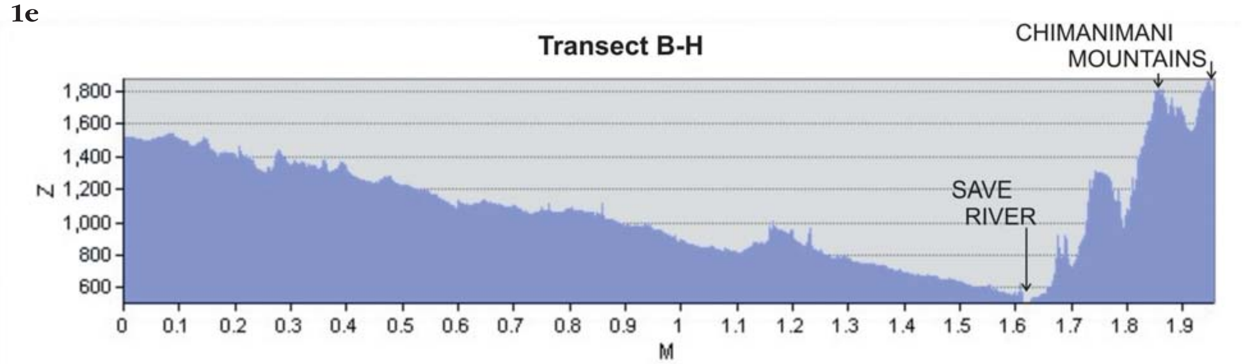
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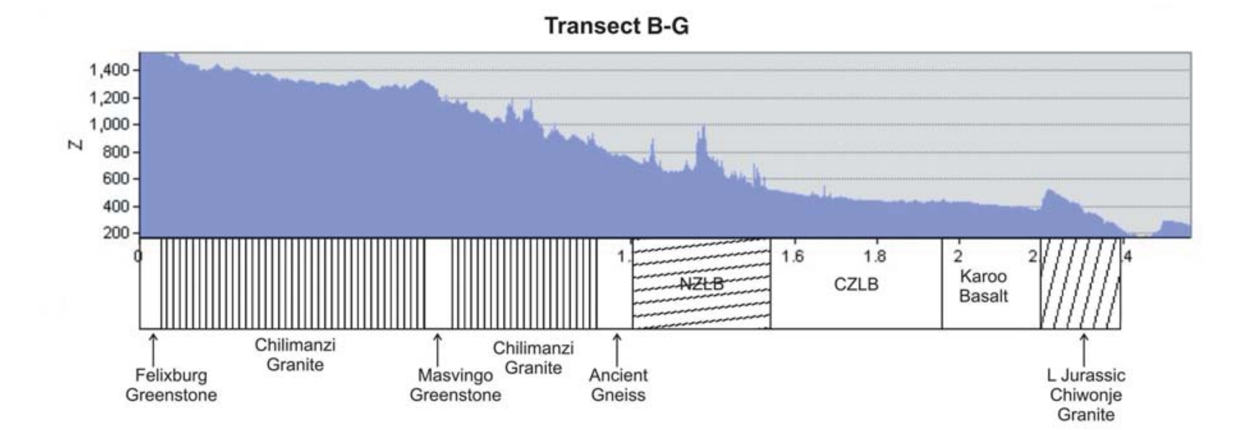
Transect B-G
Z
NZLB
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Karoo Basalt
Felixburg Greenstone
Chilimanzi Granite
Masvingo Greenstone
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Ancient Gneiss
L Jurassic Chiwonje Granite

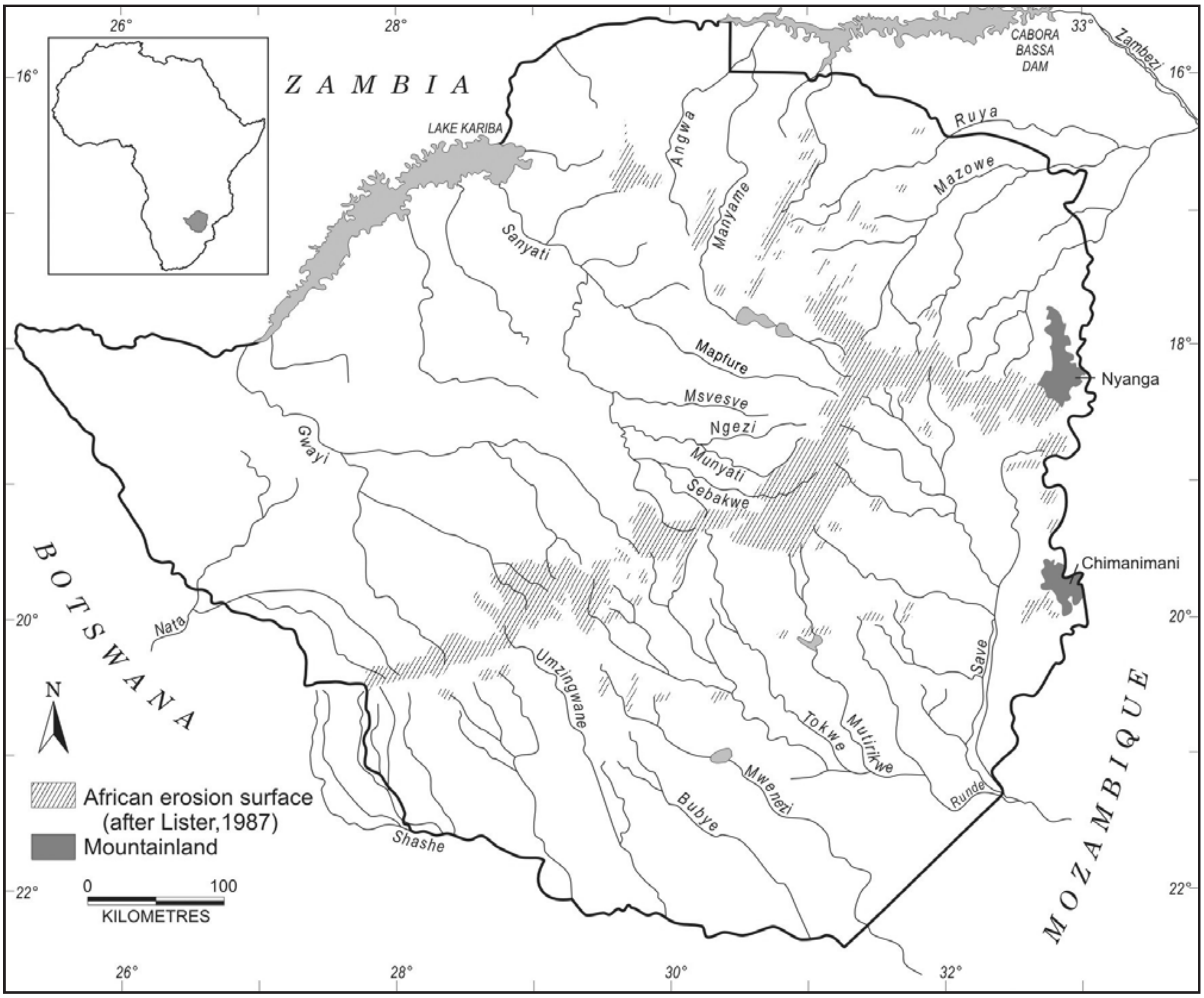

Figure 2. Major drainages in Zimbabwa

which controlled the geomorphic evolution of the entire sub-continent.

The present study reviews drainage evolution in Zimbabwe from the Permian to the present, and explores the implications for broader processes of landscape evolution. The resultant narrative provides a framework for understanding the dispersal of diamonds and associated pathfinder minerals from their primary kimberlite sources.

Modern topography and drainage of Zimbabwe

The modern topography of Zimbabwe is illustrated in the SRTM3 digital elevation model (DEM) presented in Figure 1a. The lines shown on the figure mark the positions of elevation transects shown in Figures 1b to f. The modern drainage network is illustrated in Figure 2.

Zimbabwe is bisected by a broad, southwest – northeast oriented topographic high, which forms the watershed between the Zambezi drainage basin to the north, and the Limpopo and Save drainages to the south (Figure 2). This major river divide is characterised by a senile surface of low undulating relief, which is reflected by remarkably long, flat horizons (Figure 3a) (du Toit, 1933; Lister, 1987). Elevations on this watershed (Figure 1b) increase progressively to nearly 2600m at the summit of Nyangani – the highest point in the country (Figure 3b). The Chimanimani mountains (Figure 3c), which straddle the Zimbabwe-Mozambique border some 200 km to the south of Nyangani, rise to over 2400 m. The Great Dyke, a major linear layered mafic/ultramafic igneous complex, with a north-northeast strike, traverses much of central Zimbabwe (Figure 4). This intrusion is planed to the same level as the senile landscape of the central watershed, but to the north and south of the divide, stands proud of the surrounding granite-greenstone terrain as a linear topographic high (Figures 3d and 3e).

There is a marked difference in character of the river systems to the north and south of the central Zimbabwe watershed. The country immediately to the north of this major river divide is characterised by a mature drainage network, with meandering rivers with low gradients of the order of 1:700 flowing in broad shallow valleys (Lister, 1987). Northwards from Harare (Figure 1c), the surface is characterised by an initial gentle decrease in altitude, with a distinct notch marking the incision by the east-flowing Mazowe River. Thereafter, elevation increases to the mountainland of the Mavuradonha Mountains, which form the prominent Zambezi Escarpment. This range stands some 600 m above the Zambezi Valley, which is a low relief plain with altitudes generally less than 500 m (Figure 3f). To the northwest of the watershed, the land shows a relatively even fall in elevation from over 1500 m in the vicinity of Felixburg to below 700 m in the vicinity of Lake Kariba (Figure 1d). The mountainland overlooking Lake Kariba on this traverse is the upfaulted Matusadonha range.

Many of the major tributaries of the modern Zambezi that rise off the central Zimbabwe watershed have an overall northwest orientation (Figure 2). However, the uppermost reaches of a number of these drainages – for example the headwaters of the Munyati, Sebakwe and Ngezi rivers – flow to the southwest (Figure 2). The two major orientations shown by the modern Zambezi tributary system (southeast to northwest and northeast to southwest) are thus broadly away from the Chimanimani and Nyanga highlands respectively. The Mazowe River, which flows to the northeast to link with the lower Zambezi is an exception to these generalisations. A further exception is provided by west-flowing tributaries of the Gwayi River (Figures 2 and 5) that traverse sandy sediments of the Kalahari cover, parallel to the alignment of a major fossil dune system (Thomas and Shaw, 1991). Optical luminescence dating indicates a late Pleistocene age for these relict dunes, but they are probably of considerably greater vintage (McFarlane and Eckardt, 2007), plausibly linked to a Plio-Pleistocene arid episode.

The rivers to the south of the watershed have an overall southeasterly orientation, to link with either the east-flowing Limpopo, which forms the southern border of Zimbabwe, or the south-flowing Save River. The latter (Figure 3g), located within a half-graben structure (Swift, 1962), forms a barrier between the Chimanimani mountainland and the northwest-flowing modern Zambezi tributaries (Figure 2). The lowest point in the country, below 250 m, is in the extreme southeast, where the Save River enters Mozambique at Mahenye.

In comparison to the senile upper reaches of the Zambezi tributaries, the drainage system to the south of the central Zimbabwe watershed is more youthful in character. The south-draining rivers having significantly steeper gradients (~1:170) compared to those of the Zambezi tributaries (Lister, 1987), as well as more deeply incised, rectilinear courses. Figures 1(e) and 1(f) illustrate two surface elevation profiles to the southeast of the watershed. The former exhibits a relatively even gradient until encountering the Save River, from which it rises steeply to the Chimanimani mountain range. The second profile (Figure 1(f)), is marked by several prominent breaks in slope, which correspond with major geological boundaries. Examples are the northern margin of the Masvingo-Bikita Greenstone Belt, the boundary between the northern and central zones of the Limpopo Belt and the northern edge of the Late Jurassic Chiwonje granite pluton in the extreme southeast of the country.

Pre-Karoo and Karoo topography and drainage

Several lines of evidence form the basis for reconstructing the pre-Karoo and Karoo topography and drainage systems. These include the modern distribution of Karoo sediments, and their outcrop patterns, isopach data, and evidence provided from diamond exploration programmes in Zimbabwe.

The main Karoo depocentre in Zimbabwe is the mid-Zambezi basin in the north-west of the country (Stagman, 1978) (Figure 6). A second major depocentre, the Cabora Bassa basin, occurs in the rift-bound Zambezi Valley in the extreme north of the country (Oesterlen and Millsteed, 1994) (Figure 6). Two further Karoo sub-basins occur in the south of the country. The westernmost of these, known as the Tuli basin, is elongated in a direction just north of east, while the second – the Save-Runde Basin – is elongated roughly southwest to northeast. An isolated linear Karoo outcrop is preserved astride the central Zimbabwe watershed in the Somabula district, while a second outlier straddles the watershed around the village of Featherstone (Figure 6).

The lower Karoo sequence in the mid-Zambezi basin commences with Permo-Carboniferous glacial rocks and overlying coal measures, followed by generally fine-grained sediments. The latter are overlain by dominantly coarse clastic Triassic sediments of the upper Karoo sequence, capped by ~180 Ma basalt lavas. At the basin margins, the lower and upper Karoo are separated by an erosional unconformity, well marked by a transgressive conglomerate, the Escarpment Grit. Glacial striations on basement rocks, and erratics recovered to the south of Lake Kariba, and east of the mid-Zambezi basin, show consistent glacial movement to the west (Figure 7) (Stagman, 1978; Ait-Kaci Ahmed, in press).

The Cabora Bassa Basin contains up to 10 000 m of Karoo sediments, deposited within the Zambezi half-graben. They commence with a discontinuous Permian basal glacial facies which merges into carbonaceous shales that are separated by a major lower Triassic unconformity from an overlying thick, predominantly fluviatile Mid-Late Triassic sequence (Broderick, 1990; Oesterlen and Millsteed, 1994). Palaeo-current studies of the fluviatile sediments of the mid-Triassic Angwa Sandstone Formation (Oesterlen and Millsteed, 1994; Shoko, 1998) indicate dominantly westerly transport directions. This broadly matches the westerly movement of the earlier Permian glaciers immediately to the south of Lake Kariba. In the overlying late Triassic Pebbly Arkose Formation, there is a change in sediment transport direction to the northwest and north.

Compared to other Karoo sequences in southern Africa, the Cabora Bassa succession is unusual in that


3a
3b
3c

Figure 3. (**a**) Senile surface of the central watershed near Gweru. (**b**) Nyangani Mountain in the Zimbabwe eastern highlands. Lister (1987) interpreted the mountain summit to be a relict of the Gondwana surface, and ascribed the gently undulating plain traversed by the Matinderere River in the foreground to the post-Gondwana erosion cycle. (**c**) Chimanimani Mountains, Zimbabwe eastern highlands. (**d**) Post- African surface with inselbergs and Great Dyke standing proud, northeast of Harare. (**e**) Deeply incised internal structure of the Great Dyke reflecting strong lithological control. Note spoil associated with artisanal adits into chromite seams, right foreground.


3f


3g


3h

Figure 3. continued (**f**) Keg and Hilux on the low relief plain of the Zambezi Valley near Mana Pools with rifted escarpment in the background. (**g**) Save River Valley at Birchenough Bridge. Note prominent alluvial deposits. (**h**) Bornhardts of the post-African Surface, near Masvingo. (**i**) Typical African Surface weathering profile with deeply kaolinized saprolite capped by ferricrete, 10 km east of Gweru on the Bulawayo-Harare road. Photo curtesy of John Moore. (**j**) Rounded alluvial diamonds from Chiadzwe, Save Valley with black coating, indicative of radioactive damage, followed by metamorphism.

the sediments are rarely capped by late Triassic flood basalts. Instead, continuous sedimentation, dominated by red beds, continued during the Jurassic and extended into the early Cretaceous (Oesterlen and Millsteed, 1994). These post-Karoo sediments are represented by the Jurassic Chenje and Ntumbe Beds of Broderick (1990), which were subsequently grouped together as the Dande Sandstone Formation by Oesterlen and Millsteed (1994). The latter also encompasses the Upper Jurassic-Cretaceous Kadzi Beds (Broderick, 1990) to the east. These post-Karoo sediments are interpreted to reflect deposition by coalescing alluvial fans, sourced from the Zambezi Valley scarp to the south (Broderick, 1990). Palaeo-current directions in the Dande Sandstone (Oesterlen and Millsteed, 1994) are consistent with this interpretation. Broderick (1990) noted that deposition by alluvial fans rising off the escarpment has continued to the present time. These observations, coupled with the evidence for more northerly transport directions in the Upper Triassic Pebbly Arkose Formation, discussed above, indicate that the Zambezi Valley fault scarp was initiated by at least the late Triassic, and remains active today. Low intensity seismic activity in the Cabora Bassa basin (Scholz *et al*., 1976) is consistent with the latter observation.

The linear, southeast-northwest orientated Somabula Karoo outlier, preserved on the central Zimbabwe watershed to the southwest of Gweru (Figures 6 and 8),

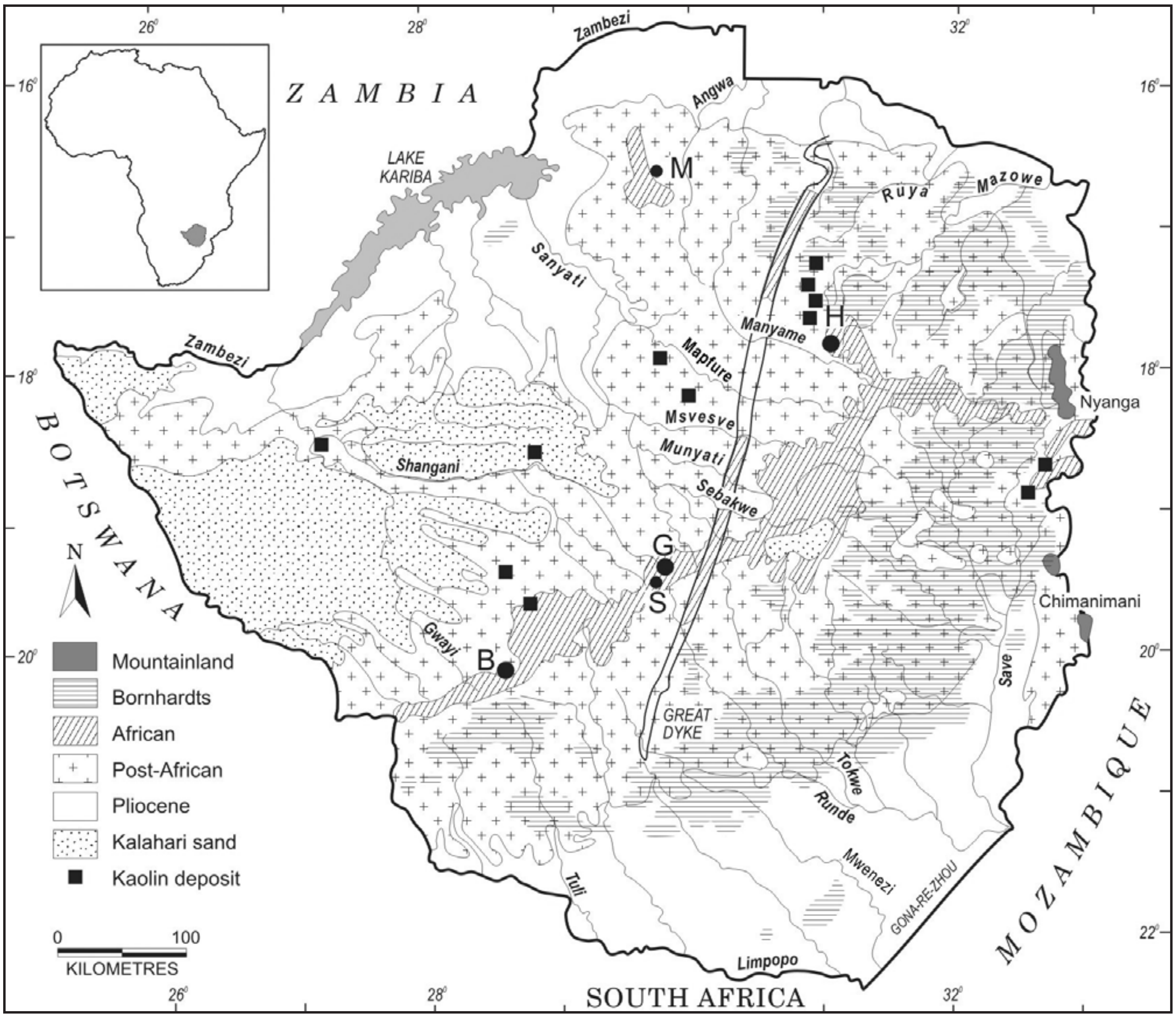

Figure 4. Erosion surfaces of Zimbabwe, adapted from Lister (1987). Distribution of bornhardts is from Whitlow (1980). Squares show most important kaolin deposits in Zimbabwe. As discussed in the text, the African erosion surface recognised by Lister on the central Zimbabwe watershed is reinterpreted in this study to largely represent an exhumed pre-Karoo surface, while the Pliocene surface in southern Zimbabwe is considered to be an extension of the post-African Surface. B = Bulawayo, G = Gweru, H = Harare, S = Somabula, M = Mwami.

has a discontinuous basal diamond-bearing conglomerate overlain by Upper Karoo sediments. Moore and Moore (2006) interpreted the basal conglomerate to represent a lag deposit formed by fluvial winnowing of former Permian tillites during an erosional episode which preceded deposition of the Somabula upper Karoo sequence. This event was correlated with the unconformity separating the lower and upper Karoo sequences in the mid-Zambezi basin. The upper Karoo sediments that overlie the basal diamond-bearing conglomerate at Somabula have been interpreted to represent a braided river system, that exploited the former Permian glacial valley. Palaeo-current and isopach evidence indicate that the flow of the upper Karoo Somabula river system was to the northwest (Bührman, 1997; Moore and Moore, 2006).

It was recognised at an early stage that the clast assemblage and heavy mineral suite in the Somabula gravels offered a potential "fingerprint" of the provenance area, and thus evidence for the location of the primary kimberlite source of the associated diamonds. Zealley (1918) noted that while the clasts in the Somabula gravels are dominated by vein quartz and quartzites of likely proximal provenance, they also include a variety of exotic lithologies. He noted that the latter can be matched with rock varieties in the vicinity of Shurugwi, located some 50 km to the southeast of the Somabula gravels, and thus south of the modern watershed (Figure 8). This evidence point to northwesterly glacial flow to deposit the basal Somabula sediments, as shown in Figure 7.

The Somabula heavy mineral suite is dominated by staurolite (~98%), with subordinate kyanite and garnet. A wide variety of associated minerals, including beryl, chrysoberyl, corundum, topaz, tourmaline, zircon, chromite, gold and PGM alloys have also been reported

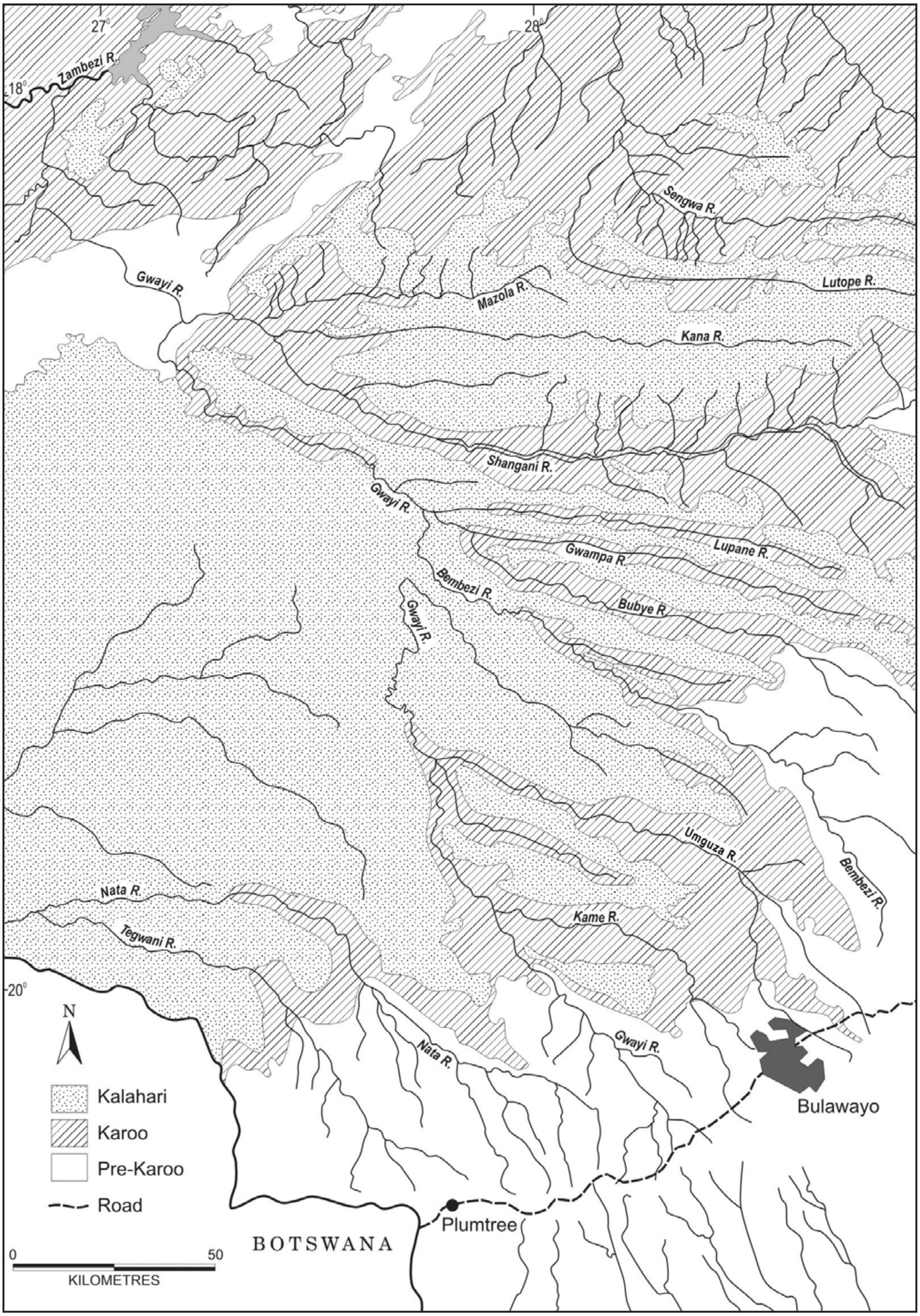

Figure 5. Drainages and the distribution of the Karoo Supergroup in western Zimbabwe.

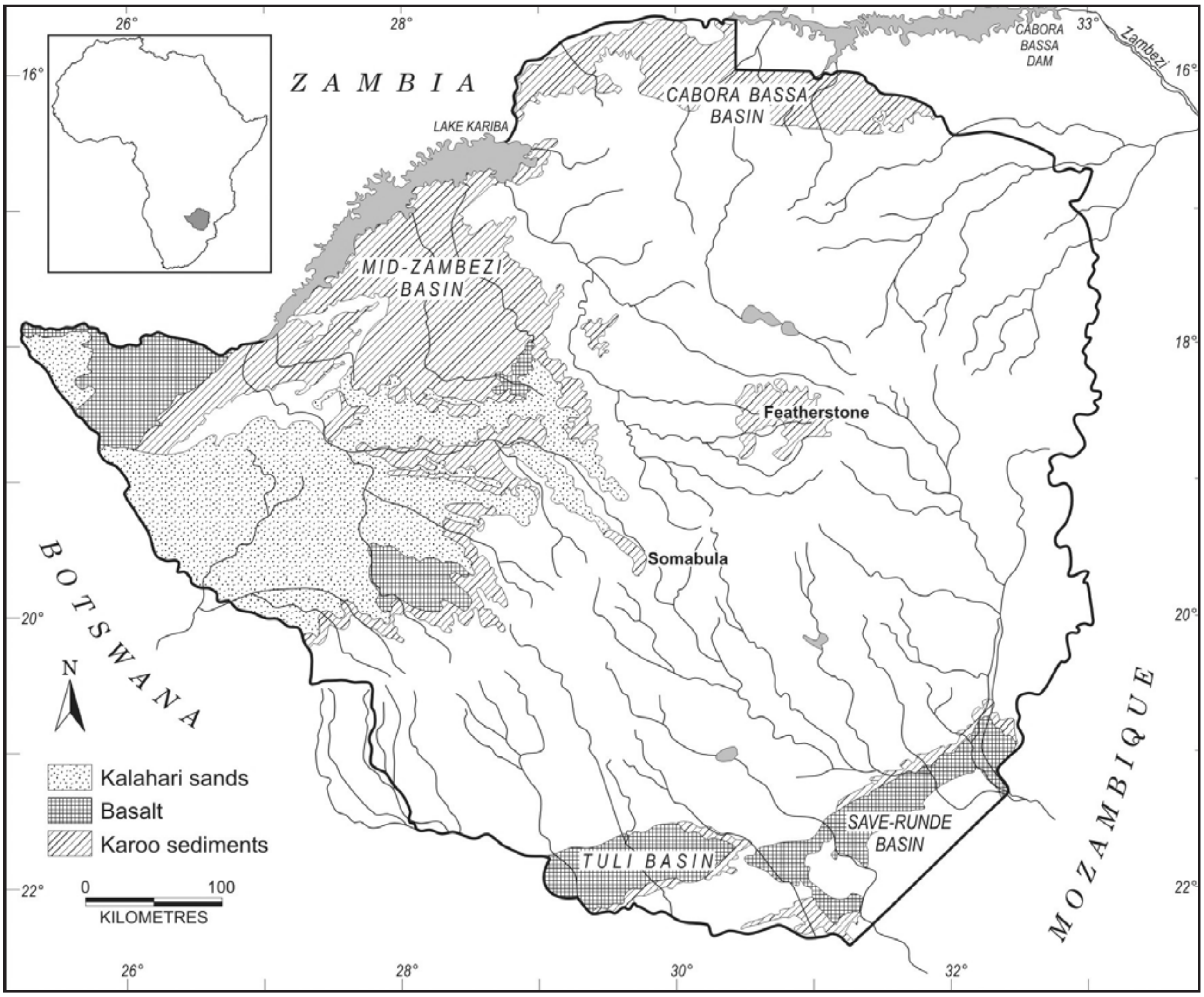

Figure 6. Distribution of Karoo sediments in Zimbabwe

(Macgregor, 1921; Phaup, 1958). Staurolite is also the dominant heavy mineral phase in the basal Featherstone gravels (Butterfield, 1965), suggesting the same provenance area as the Somabula Karoo deposit.

A second Karoo outlier on the central Zimbabwe watershed is located in the Featherstone Area, some 50 km to the south of Harare (Figure 6). Discontinuous basal conglomerates, similar in lithology to the basal diamond-bearing unit at Somabula, have been reported from the east of the Featherstone outlier (Butterfield, 1965). They are overlain by Upper Karoo sediments, correlated with the Pebbly Arkose Formation, followed by Karoo-age basalts (Worst, 1962; Anderson, 1978).

Spence (2000) described two linear trains of kimberlitic heavy minerals preserved on the central Zimbabwe watershed at Daisyfield and Mambo, some 25 to 30 km to the southwest of the Somabula outlier (Figures 8 and 9). Both trains have a southeast-northwest orientation, roughly parallel to the Somabula outcrop. The bedrock in both cases is Archaean basement granite. The anomalous concentration of kimberlitic pathfinder minerals defined by loam sampling at Daisyfield is confined to an area approximately 250 m in width, and 2.5 km in length which bifurcates to the northwest (Figure 9) and is open at both ends. Ilmenite dominates the kimberlitic heavy mineral assemblage, with some samples yielding several thousand grains, but there is a steep drop in numbers towards the margins of the anomaly. Garnets are typically present in markedly lower numbers (generally <10 per sample), with some 20% of these described as G10 varieties (*i.e.* Cr-rich and Ca-poor, matching compositions of inclusions in diamonds) (Spence, 2000).

The ilmenites often have perovskite reaction rinds while kelyphytic rims are preserved on the garnets. Both minerals are described as being dominantly sub-angular, although those at the margins of the linear heavy mineral train show somewhat better rounding. Scattered sub-angular blocky quartzite or vein quartz clasts, with percussion rings on the surface, occur within the main heavy mineral anomaly. An unidentified fragment of fossilised wood was also recovered, and angular silcrete fragments closely similar to those found at the base of Karoo in the Charter Area of the Featherstone outlier (Anderson, 1978). Detailed prospecting over the

Daisyfield heavy mineral anomaly, including magnetic and EM surveys, and drilling and pitting, has failed to identify a local kimberlite source for the unabraded kimberlitic minerals (Spence, 2000).

Mike de Wit (personal communication, 2008) suggests that the linear Mambo and Daiseyfield kimberlitic mineral anomalies could reflect the occurrence of local thin kimberlite stringers. However, if present, such stringers have never been conclusively identified, and it would be expected that the associated halo would become progressively more diffuse away from the source. In contrast, mineral counts drop off sharply at the anomaly margins (Spence, 2000). Moore and Moore (2006) interpreted these two linear kimberlite pathfinder anomalies as the winnowed relics of former Permian glaciers, that exploited shallow pre-Karoo valleys, closely analogous to Somabula. The sharp decrease in heavy mineral counts documented at the margins of both anomalies is consistent with a glacial origin, while rounding of grains at the anomaly margins can be explained by abrasion in melt-water streams along the sides of the glacier. The bifurcation of the Daiseyfield anomaly to the northwest was interpreted to reflect splitting of the glacier around a low topographic high, indicating transport to the northwest, as illustrated in Figure 7.

Pre and Early-Karoo Drainages

Amm (1940) analysed isopachs of the Karoo sediments of the mid-Zambezi basin to the north of Bulawayo, and demonstrated that the pre-Karoo surface was inclined to the northwest, broadly parallel to the modern surface to the north of the central Zimbabwe watershed. Amm concluded that headwaters of

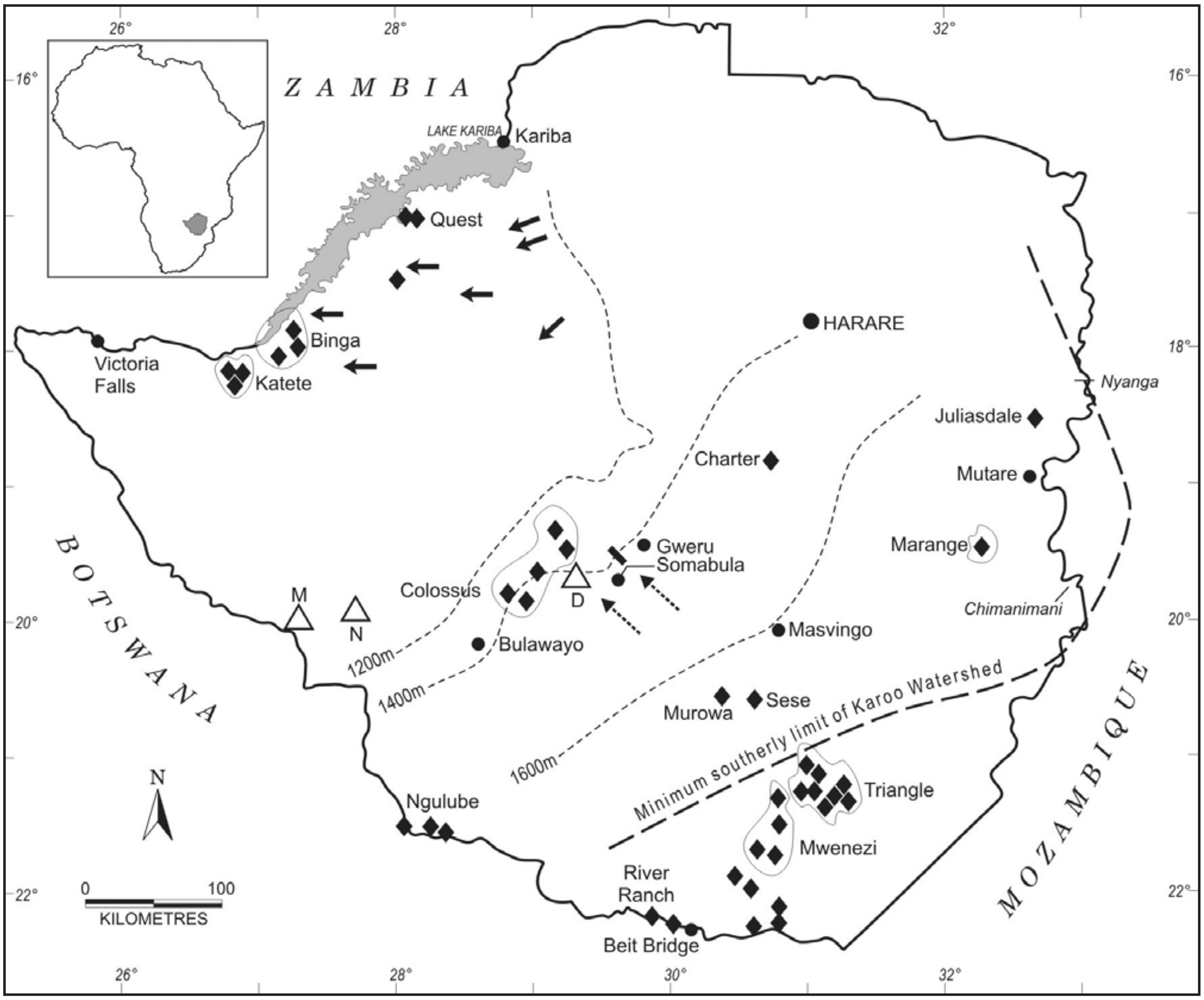

Figure 7. Distribution of known kimberlites (solid diamonds) in Zimbabwe. Triangles: Major unexplained kimberlitic heavy mineral anomalies; D = Daisyfield; M = Maitengwe; N = Nanda. Dotted lines represent contours on the pre-Karoo floor, with heights in metres above present day sea level (from Lister, 1987). The modern watershed is close to the 1400 m pre-Karoo contour. Lister envisaged a pre-Karoo watershed in the vicinity of her 1600 m contour for this surface, some 80 km south of the modern watershed. Heavy dashed line represents the probable minimum southward location of the pre-Karoo watershed, inferred in this study. As discussed in the text, this watershed may have been located to the south of the Mwenezi cluster. Solid arrows: Permian ice movement directions, from Lister (1987) and Ait-Kaci Ahmed (in press). Dashed arrows: Permian ice movements inferred in this study.

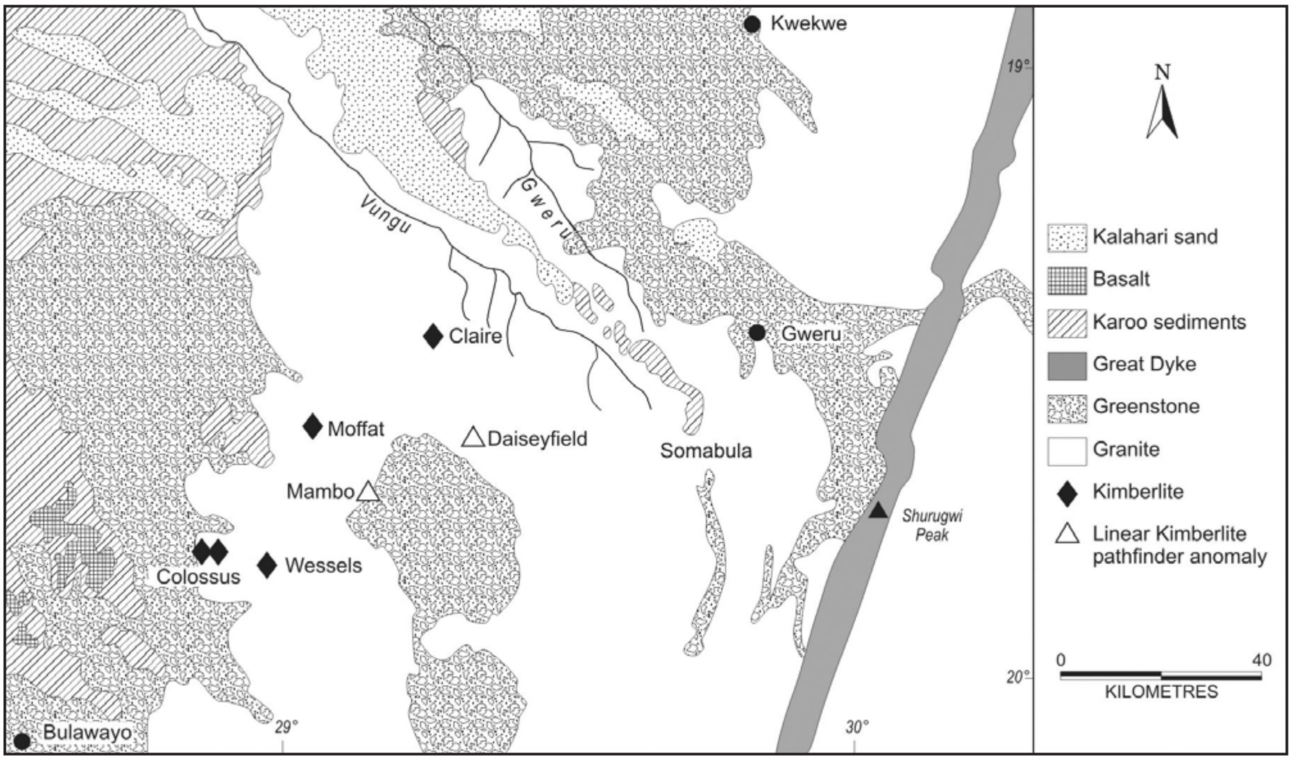

Figure 8. Detail of the geological setting of the Somabula Karoo outlier.

northwest-orientated Zambezi tributaries flowing across the granite-greenstone basement to the south of the mid-Zambezi Karoo basin (Figure 5) represent exhumed pre-Karoo drainage lines. Northwest of Bulawayo, the southern margin of the Mid-Zambezi Karoo basin, is characterised by a number of elongate outcrops of Karoo sediments with a general southeast-northwest orientation (Figure 5). Drilling of one of these Karoo "fingers" by Reunion Mining (Ian Plews, personal communication, 2000) showed that the sediments fill former pre-Karoo valleys, oriented broadly down the slope of the pre-Karoo surface recognised by Amm (1940).

Butterfield (1965) and Anderson (1978) interpreted the headwaters of major Zambezi tributaries flowing over the granitic basement to the south of the Featherstone outlier (for example the Munyati River, Figure 2) to represent part of an exhumed pre- or early-Karoo drainage system. Several lines of evidence constrain the vintage of these major rivers, and underwrite our reconstruction of the antecedent Karoo drainage system. These are summarised in turn.

The Munyati and Ngezi rivers have both incised courses through the resistant jaspilites of the Mwanesi Greenstone Belt to form very dramatic deep U-shaped poorts (ravines), resembling glacial valleys (Figure 10). These breaches are completely discordant to the outcrop of the Mwanesi metasediment, and do not appear to be exploiting faults or other major lines of structural weakness (Worst, 1962). The Ngezi and Munyati drainages have also cut dramatic poorts across the Great Dyke, located immediately to the west of the Mwanesi Greenstone Belt (Figure 10). Further to the north, the Musvesve and Manyame have also cut courses almost at right angles to the strike of the Dyke, as has the Sebakwe to the south. Of these, only the Sebakwe breach, which exploits a major fault (1: 1 000 000 Geological Map of Zimbabwe, 1977), appears to be structurally controlled. This river has also incised a dramatic valley (Sebakwe Poort) across Shamvaian conglomerates of the Kwekwe greenstone (Figure10).

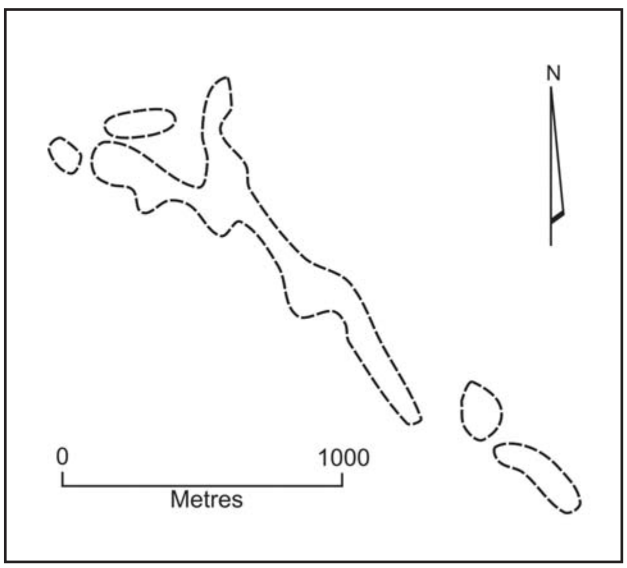

Figure 9. Geometry of the Daisyfield kimberlitic ilmenite-garnet anomaly as defined by grid loam sampling. Heavy mineral counts drop off sharply across the margins of the anomaly. Note the bifurcation of the anomaly to the northwest. The anomaly is open to both the northwest and southeast.

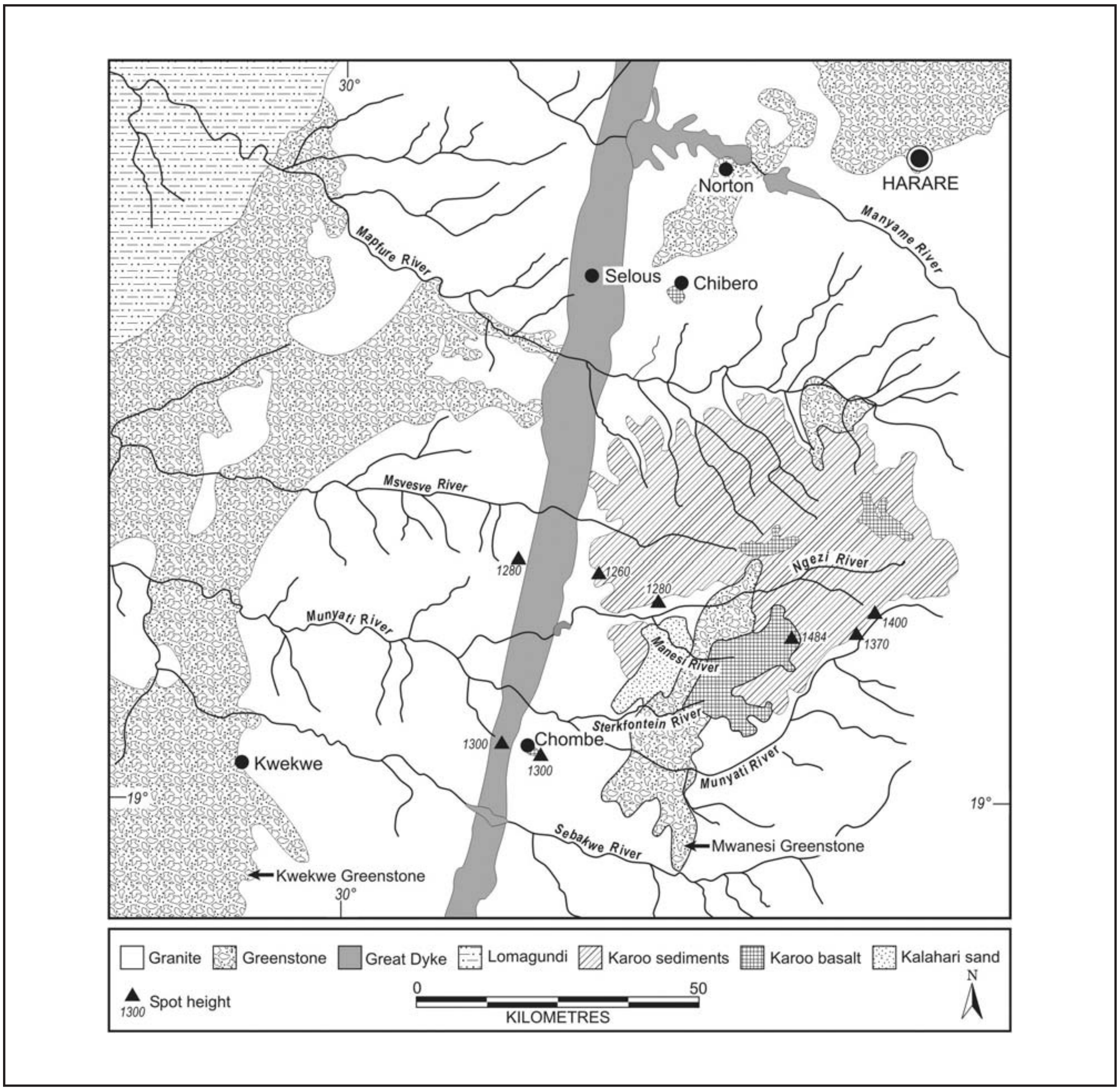

Figure 10. Relationships between modern rivers, Karoo sediments and lavas and the Mwanesi Greenstone Belt and Great Dyke.

Two alternative possibilities could account for river incision across the resistant jaspilites of the Mwanezi Greenstone and mafic/ultramafic lithologies of the Great Dyke. One is that the rivers were initiated on a very subdued surface, when the resistant lithologies did not offer significant topographic barriers. Alternatively, the rivers may have been superimposed from younger cover sequences that originally buried both the Mwanesi Greenstone and Great Dyke. This would be comparable to the discordance of the Vaal River to the concentric resistant sedimentary units surrounding the Vredefort Dome, interpreted by King (1963) to reflect superimposition of this river course from an original Karoo cover. Several observations are pertinent to evaluating these alternatives.

The highest elevation of the Featherstone basalt is at Featherstone Koppie (1484 m) (Figure 10), which is of comparable elevation to much of the banded ironstone ridges of the Mwanesi Greenstone. A former basalt cap to the greenstone belt is therefore plausible. Given the major unconformities separating the lower and upper Karoo formations in the mid-Zambezi basin and at Somabula, comparable erosional episodes would therefore be anticipated in the Featherstone area. This, coupled with the evidence in the Featherstone outlier for erosion of the upper Karoo sediments prior to being covered by the basalt cap (Worst, 1962), raises the possibility that the Mwanesi Greenstone was originally covered by Karoo sediments.

Immediately to the west of the Featherstone Karoo outlier, the bevel marking the crest of the Dyke across the gabbronorite, and marked by the websterite/bronzitite (P1) break in slope, is between 1280 to 1320 m. The base of the Featherstone basalt cover is at

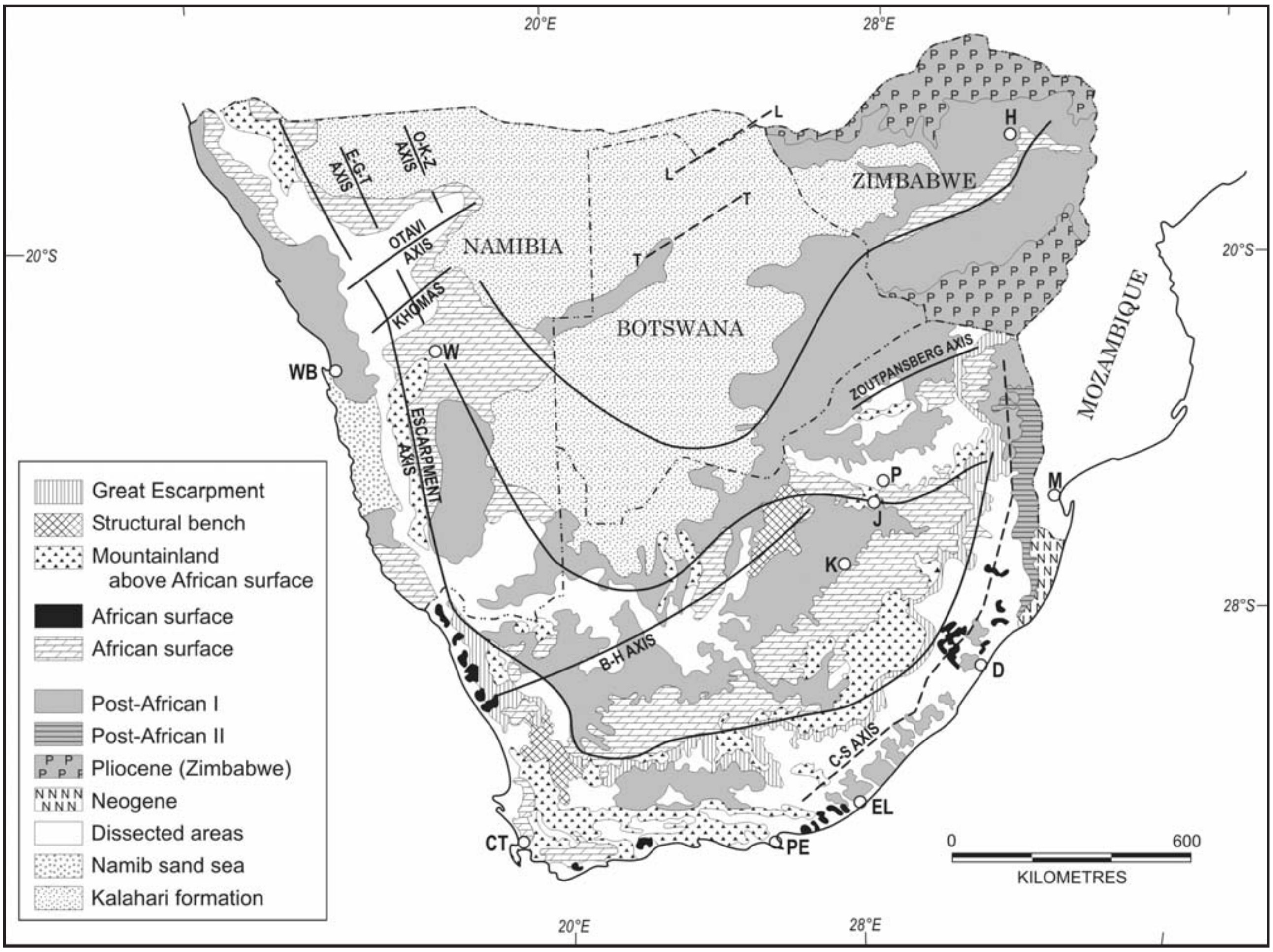

Figure 11. Flexure Axes in southern Africa, from du Toit, 1933, as modified by Moore (1999) in relation to the major erosion surfaces recognised in Zimbabwe by Lister (1987) and elsewhere in southern Africa by Partridge and Maud (1987; 2000). E-G-T = Etosha-Griqualand-Transvaal Axis; O-K-Z = Ovamboland-Kalahari-Zimbabwe Axis; B-H = Bushmanland Harts Axis; C-S = Ciskei-Swaziland Axis (after Partridge and Maud, 1987). L-L = Linyanti Fault; T-T = Thamalakane Fault; CT = Cape Town; D = Durban; EL = East London; H= Harare; J = Johannesburg; K = Kimberley M=Maputo; P = Pretoria; WB = Walvis Bay, W = Windhoek.

approximately 1432 m, and thus at a higher elevation than the crest of the Dyke, indicating that the lavas originally capped the intrusion. In the west of the Featherstone outlier, the base of the upper Karoo sediments is at an elevation of 1260 m, and thus 20-60 m below the level of the Dyke crest. The Dyke therefore stood proud of the surrounding granite terrain when these Upper Karoo sediments were deposited. Nevertheless, in view of the evidence for a major period of erosion separating the lower and upper Karoo, the difference in elevation between the Dyke crest and the base of the Featherstone upper Karoo sediments may simply reflect selective erosion of country rock granites during the earlier erosional episodes. It is thus possible that Lower Karoo sediments originally also covered the Dyke. In this case, the Munyati and Ngezi Rivers could in principle have been superimposed on the Great Dyke from either a basalt or Karoo sedimentary capping.

However, two minor streams, the Manesi and Sterkfontein, which rise on the Karoo rocks between the Ngezi and Munyati (Figure 10), are not readily explained by superimposition. Both have also cut dramatic U-shaped valleys across the jaspilites of the greenstone belt, but appear to be gross underfits to these respective breaches. Thus, the headwaters of the Manesi (a tributary of the Ngezi), cover an area to the east of the Mwanesi greenstone of only 45-50 km^2, while headwaters of the Sterkfontein, a Munyati tributary, are even more restricted. It seems inconceivable that the U-shaped valleys across the jaspilites could have been superimposed from a Karoo cover from streams with such restricted catchments. A more plausible explanation is that the Manesi and Sterkfontein are exhuming earlier drainage lines. The rounded skyline of the jaspilite ridges is strongly suggestive of glacial sculpturing, while the U-shaped profiles of the defiles of all of the rivers traversing the Mwanezi Greenstone jaspilites are strongly reminiscent of glacially carved valleys, suggesting that they were originally incised during the Permian glaciation. A glacial origin for the defiles traversing the Mwanesi jaspilites would in turn favour a similar origin for those incised across the Great Dyke by the same rivers. Detailed follow-up fieldwork is required in this area to identify possible striated pavements or other evidence for glacial activity.

At Chibero, some 20 km to the south of the village of Norton on the central watershed (Figure 10), the base of a small Karoo basalt outlier is at about 1330 m asl. This is closely similar in elevation to the planation across the Dyke in the vicinity of the village of Selous, immediately to the west. To the south, as far as the Musvesve River, the Dyke merges with the surrounding granite surface. It is therefore unlikely that this portion of the Great Dyke presented a pre-basalt topographic barrier to glacial flow. Collectively, the evidence discussed indicates that the major modern rivers crossing the Great Dyke established their courses in early or likely pre-Karoo times.

Provenance of Somabula diamonds and associated heavy mineral suite

An early conundrum in identifying the provenance of the Somabula diamonds was the origin of the staurolite and kyanite that dominate the associated heavy mineral assemblage, as neither phase was not known to occur to the southeast, the apparent source of many of the associated clasts, or, indeed, anywhere else in the country. When staurolite and kyanite were discovered in late Proterozoic rocks of the Mwami mica field, some 300 km to the north of Somabula (Figure 4), it was proposed that the heavy mineral suite in the basal gravels was derived from this area (Macgregor, 1921; Master, 1995). However, this interpretation conflicts with evidence for a north-sloping pre-Karoo surface (Amm, 1940; Lister, 1987), and the lower elevation of Mwami (~1200 m) relative to Somabula (~1350 m). Also, exotic clast lithologies in the Somabula gravels and palaeo-current indicators both point to a southerly provenance area.

The upper reaches of major exhumed Karoo drainages such as the Ngezi, Munyati and Sebakwe flow away from the Nyanga and Chimanimani highlands in eastern Zimbabwe (Figures 2 and 4). Stocklmayer (1980) recorded staurolite-bearing schists in the Nyanga area, while spectacular kyanite schists occur in the Chimanimani range. These two areas of mountainland therefore provide a plausible source for the staurolite and kyanite that dominate the heavy mineral suite of the basal Somabula gravels. A corollary is that mountainland in eastern Zimbabwe has persisted from pre-Karoo times to the present.

The modern rivers that cross the Great Dyke all flow well to the north of Somabula (Figure 4), making them unlikely candidates as the conduits to supply the staurolite and kyanite that dominate the heavy mineral suite in the basal gravels. This suggests that the linear Somabula Karoo outlier formed part of a drainage line that extended to the south of the modern watershed, While further work is required to pinpoint this inferred channel, it is noted that transport directions were not static during the Permian glaciation, but showed systematic changes in orientation (Moore and Moore, 2004). The exhumed drainages such as the Munyati and Sebakwe, with dominant northwesterly and subordinate southwesterly orientations, probably reflect a late Permian snapshot of the glacial system. It is feasible that during the early stages of the glaciation, there was a dominant southwesterly-flowing glacial system, rising from headwaters in the Nyanga area, fed by tributaries rising off the Chimanimani highlands to the southeast, which supplied staurolite and kyanite to Somabula.

In summary, during lower and upper Karoo times, a northwesterly oriented drainage system, which supplied sediment to the mid-Zambezi basin (Figure 6), rose from headwaters that extended in an arc from the Zimbabwe eastern highlands to the southwest of the country (Figure 7). While the southern limit of the pre-Karoo watershed is not well established, Visser (1987) identified a major east-west oriented Permian glacial valley (the Tshipise Valley), immediately to the south of the modern Limpopo, which forms the southern border of Zimbabwe (Figure 4). The watershed must therefore have been located somewhere to the north of the Tshipise Valley. The position of the pre-Karoo divide is further discussed in relation to evidence provided by recent diamond exploration programmes in Zimbabwe.

Today, the Zimbabwe eastern highlands are isolated from the modern northwest oriented drainage system by the Mazowe and Save rivers, while the Zambezi is a major east-flowing river. It is therefore necessary to investigate the processes responsible for modifying the Karoo drainage network to form the modern drainage system, and also the timing of major drainage reorganisations.

Evolution of the post-Karoo drainage system

Impact of Gondwana rifting

The modern Save flows within a half-graben structure (Swift, 1962), located between the Chimanimani mountainland and the northwest-flowing modern Zambezi tributaries (Figure 2 and 3g). The Save River basin thus represents a barrier that prevents dispersion of staurolite and kyanite derived from the Nyanga and Chimanimani mountainland into modern exhumed pre-Karoo drainages such as the Munyati and Sebakwe. Initiation of the Save River system must therefore post-date the Permian (early-Karoo) glacial network. Three major alkaline ring complexes within the Save drainage basin (Shawa, Dorowa and Chishanya) are all dated at ~205 Ma (late-Karoo) (Bristow, 1984). They are typical of volcanism associated with major grabens, suggesting that the rifting which initiated the Save half graben could be of comparable age, and thus related to the early stages of Gondwana break-up (Moore and Blenkinsop, 2002). Accordingly, initiation of the Save River is ascribed to this late Gondwana-age rifting. This was a key event because it marked the first major reorganisation of the long-lived northwesterly pre-Karoo and Karoo drainage network into the mid-Zambezi Karoo basin.

Lowered baselevels following the disruption of Gondwana initiated headward erosion of the rift-bound Lower Zambezi. An important event in the headward advance of the main channel of the lower Zambezi was the capture of the Luangwa, a former southwest flowing tributary of the (west-oriented) Karoo drainage system. This capture, inferred to be of Oligocene age (Moore and Larkin, 2001) would have led to a significant expansion of the Lower Zambezi drainage basin. A further consequence was a marked lowering of the Luangwa erosional base level, thus enhancing headward erosion of the Lower Zambezi. This led initially to the capture and reversal of flow direction of the mid-Zambezi, and subsequently the capture of the Upper Zambezi in the late Pliocene or early Pleistocene. This in turn initiated rapid incision of the Batoka Gorge, and headward advance of the Victoria Falls (Moore and Larkin, 2001; Moore *et al.*, 2007).

Flexure of Kalahari-Zimbabwe Axis

Maufe (1927, 1935) and du Toit (1933) presented evidence to show that the central Zimbabwe watershed reflects the locus of a major axis of epeirogenic flexure, which du Toit (1933) designated the Kalahari-Rhodesia (now Kalahari-Zimbabwe) Axis. Moore (1999) demonstrated that this flexure formed part of a more extensive arcuate uplift (the Ovamboland-Kalahari-Zimbabwe (OKZ) Axis). Moore *et al.* (2009) infer a late Palaeogene age for uplift along the OKZ Axis to explain a marked Oligocene increase in sediment flux in the Zambezi Delta off the Mocambique coast, recognised by Walford *et al.* (2005), and ascribed by these authors to epeirogenic continental uplift. Support for this interpretation is provided by apatite fission track (AFT) evidence for late Palaeogene (43-33 Ma) erosion events in the Limpopo and Zambezi valleys (Belton, 2006, and further corresponds to a major depositional event in the Limpopo delta (Burke and Gunnell, 2008). We suggest that this erosion and the ensuing increase in sediment flux in the Zambezi and Limpopo deltas. reflects drainage rejuvenation triggered by uplift along the OKZ Axis. It is noted that this uplift event was coeval with an episode of alkaline volcanism in southern Africa (Moore *et al.*, 2008)

Crustal warping along the Kalahari-Zimbabwe Axis would have beheaded the headwaters of the northwest-flowing Zambezi tributary system that had been in existence since pre-Karoo times. To the south of the axis, drainage directions would have been reversed. Moore and Larkin (2001) suggest that the uplift also intitiated headward erosion of the Lower Zambezi, and ultimately the capture of the Luangwa, as discussed earlier. The flexure would have also caused headward expansion of the Mazowe River (a south bank tributary of the Lower Zambezi) into northeast Zimbabwe, resulting in the isolation of the Nyanga highlands from the original Karoo drainage network (Figure 4).

The low gradients and senile character of the modern river system to the north of the Kalahari-Zimbabwe axis, and their orientation broadly parallel to the pre-Karoo and Karoo drainage lines indicate that the associated early surfaces were not markedly modified by the flexuring. However, the present day northwest-oriented Zambezi tributaries do not always simply exploit pre-Karoo drainage lines. Thus the modern river courses in the Bulawayo area (Figure 5) are marginal to the linear Karoo "fingers", which mark the position of pre-Karoo and Karoo drainage channels, and therefore reflect an inverted topography. Similarly, the Karoo drainage line reflected by the linear Somabula Karoo outlier forms relatively elevated ground separating parallel modern bounding rivers (the Vungu and Gweru, Figure 8).

The more youthful characteristics of the drainages south of the Kalahari-Zimbabwe Axis, with their steeper gradients and often rectilinear courses, points to rejuvenation by the Kalahari-Zimbabwe flexure. Their southeast orientation may reflect exploitation of reversed former northwest-draining channels. However, as their flow directions are in accord with the major south-draining Save and east-draining Limpopo river systems, this possibility is difficult to test.

Influence of Plio-Pleistocene climatic changes

The east-draining tributaries of the Gwayi River reflect a further stage in river evolution in Zimbabwe. Their courses are parallel to a major degraded dune system, which probably formed across dessicated former drainage lines, such as the lower reaches of the northwest-flowing Shangani, during a Plio-Pleistocene arid episode. During subsequent wetter pluvial periods, renewed flow in these rivers exploited the interdune streets. In some cases, as with the lower Shangani, they incised their courses through the Kalahari sand cover to flow across the Karoo sediments as superimposed drainage lines (Thomas and Shaw, 1991).

Evolution of cyclic erosion surfaces in Zimbabwe

Lister (1987) suggested that the Zimbabwe topography reflected a succession of erosion cycles, that could be broadly matched with those previously recognised in South Africa (*e.g.* King, 1963). The principle erosion surfaces which she recognised are shown in Figure 4.

Lister correlated the summits of mountainland in the eastern highlands, such as Nyangani in the Nyanga area and the Chimanimani summits (Figures 3b, 3c and 4), with the Gondwana surface recognised by King (1976) in the Drakensberg-Lesotho highlands. A fringing post-Gondwana surface, also of limited extent, was recognised at a lower level (Figure 3b). The senile surface of the central Zimbabwe watershed (Figure 3a and 4) was interpreted to represent the equivalent of the widespread African surface (Lister, 1987).

The more broken country to the south and north of the watershed, frequently with granite bornhardts (inselbergs) standing proud of the surrounding plains (Figure 3h), was correlated with the post-African surface. Lister (1987) recognised broad younger surfaces of

Plio-Pleistocene age in the low-lying Zambezi and Limpopo valleys (Figure 4). Numerous small post-African outliers (not shown in Figure 4) were identified in the latter area.

The Great Dyke, which traverses virtually the whole of Zimbabwe with a north-north-east strike, forms a prominent ridge rising above Lister's post-African surface (Figure 3d), but merges with the senile surface of the central watershed around Selous. Lister (1987) interpreted much of the crest of this linear intrusion, standing proud of her post-African surface, to be a relic of the African surface.

The evidence for drainage evolution across Zimbabwe since the Permian provides a framework to refine and modify key aspects of Lister's model for landscape evolution in Zimbabwe.

Survival of Gondwana erosion surfaces?

The question of whether Gondwana-age erosion surfaces are preserved in southern Africa has been the subject of a long-standing debate. King (1976) interpreted a high level bevel in the northeast of the Drakensberg mountainland to be a Gondwana erosion relic. However, this interpretation is complicated by the presence of prominent scarps formed by massive, essentially flat-lying, Karoo lava flows, which raise the problem of distinguishing erosion surfaces from lithological bevels. Moreover, several subsequent studies (*e.g.* Partridge and Maud, 1987; Fleming *et al.*, 1999) indicated that the Drakensberg mountainland has been lowered by several hundred metres since continental break-up, arguing against the preservation of Gondwana-age erosion surfaces. A further complication is that accordant summits may not necessarily reflect a relict erosion surface (Gilchrist *et al.*, 1994).

Analogous concerns must apply to the Gondwana surface recognised in Zimbabwe by Lister (1987). In the Nyanga area of the eastern highlands of Zimbabwe, Nyangani Mountain is armoured by a thick dolerite sill, which again raises the issue of distinguishing between erosional surfaces and lithological bevels. In addition, the Nyanga and Chimanimani mountainlands are separated by over 100 km, exacerbating the problem of correlating relic erosion surfaces on the basis of accordant summits.

African and post-African erosion cycles

There are also problems in linking the senile landscape of the central Zimbabwe watershed to the African erosion cycle as it is most unlikely that the linear garnet-ilmenite kimberlite pathfinder anomalies found at Daisyfield and Mambo, astride the central watershed, would have survived the associated deep weathering. While much of the granitic bedrock straddling the watershed is characterised by some degree of weathering and breakdown of feldspars, the deep kaolinized weathering profiles with silcrete and ferricrete carapaces that characterise the African cycle of erosion elsewhere (Partridge and Maud, 1987) are not common. Rather, the principal kaolin deposits in Zimbabwe occur away from the watershed, mainly on the post-African Surface of Lister (1987) (Figure 4) (Mugumbate *et al.*, 2001). A rare example of a typical African weathering cycle profile, preserved on the watershed some 10 km east of Gweru on the Bulawayo-Harare road, is illustrated in Figure 3i. Silcretes also occur to the north of Bulawayo (Mike de Wit, Personal Communication, 2008) suggesting that the African Surface was originally more widespread in Zimbabwe. However, the very rare relics of this surface on the central watershed suggest that in this area, the characteristic duricrust carapace has been largely stripped by erosion.

Moore and Moore (2006) presented several lines of evidence for a former thin veneer of Karoo rocks covering the central drainage divide. As discussed earlier, the Daisyfield and Mambo pathfinder anomalies are interpreted to represent heavy mineral lags formed by winnowing of Karoo sediments that previously filled shallow valleys, analogous to the Somabula Karoo outlier. To account for the preservation of the Daisyfield and Mambo kimberlitic pathfinder mineral anomalies, it is suggested that during the African erosion cycle, the Karoo sedimentary veneer persisted over a significant portion of the ground that forms the modern central Zimbabwe watershed. This would have shielded the kimberlitic minerals in the basal glacial Karoo units from the deep African Cycle chemical weathering. Subsequent removal of the Karoo cover would have concentrated the heavy minerals as lags marking the lines of the original Karoo valleys. This interpretation implies that the senile landscape of the central Zimbabwe watershed is largely an exhumed pre-Karoo surface, with only limited preservation of profiles formed under the African weathering cycle.

Much of Lister's post-African surface is characterised by the presence of numerous granite bornhardts (Whitlow, 1980) (Figure 3h). Any model for the evolution of this surface must address the origin of these dramatic topographic features. King (1963) has drawn attention to the close accordance of the summits of granite bornhardts in the Rusape area of the eastern highlands, and speculated that they were relics of a former erosion surface. However, Twidale (1987; 2002) suggested that bornhardts are exhumed landforms that developed within an uneven deep weathering profile, with depth of weathering being a function of jointing. Twidale's view that bornhardts represent areas of lower joint density relative to the fringing plains is supported by a study of bornhardt topography across the Matobo granite batholith southwest of Bulawayo (Pye *et al.*, 1984 and confirmed recently by Römer, (2007). We ascribe the deep uneven weathering base to the African erosion cycle, and suggest that stripping of this carapace was initiated by the late Palaeogene uplift along the OKZ Axis that forms the central Zimbabwe watershed. The Post-African surface to the north and south of the watershed, with characteristic bornhardt topography, is thus an etch surface comparable to those envisaged by Twidale (1987; 2002). Clay deposits fringing the senile central watershed are presumably relics of the original deep-weathered carapace formed during the African cycle of erosion.

Uplift along the watershed, and the ensuing drainage rejuvenation would also have initiated stripping of the soft Karoo sediment capping to exhume the pre-Karoo surface. Based on this reconstruction, it becomes a matter of semantics whether this senile watershed surface is ascribed to the post-African erosion cycle, or is considered to be primarily an exhumed pre-Karoo surface.

The horizontal, flat crest of the Dyke, viewed from a distance (Figure 3d) belies a marked internal topography that closely reflects internal lithological variations (Figure 3e). Duricrust and clay weathering profiles that are typical of the African Surface elsewhere in southern Africa are also absent from the Dyke crest. Both observations make it unlikely that the African Surface is preserved anywhere on the Dyke crest. Ultrabasic rocks are more susceptible to weathering than granites under tropical conditions. However, the depth to which alteration penetrates is typically far more restricted (McFarlane, 1989). Following erosion of the African Surface weathering carapace, the Great Dyke would therefore have been left standing proud of the surrounding granite terrain, including the bornhardts, as part of the Post-African etch surface.

Plio-Pleistocene erosion surfaces

Lister (1987) envisaged that the post-African erosion surface was incised by a younger Pliocene erosion cycle, resulting in the development of a broad Pliocene erosion surface fringing both the Zambezi and Limpopo rivers (Figure 4). However, the plain of low relief fringing much of the Zambezi in the north of the country is of tectonic origin, and bounded by a major fault scarp that was probably initiated by at least the upper Triassic. In the southeast of the country, the boundary between the Pliocene and post-African surfaces recognised by Lister is not marked by a clear step, but rather shows an even, gradational contact (Figure 1e). Along the profile shown in Figure 1f, the breaks in slope correspond closely with lithological boundaries, making it most unlikely that they delimit erosion surfaces of differing ages.

Lister (1987) recognised a number of post-African Surface relics, characterised by the presence of bornhardts, within her Pliocene Surface in southern Zimbabwe. The most extensive areas of bornhardt topography in this area (Figure 4) correspond with the late Jurassic Mateke Hills granite and Marungudzi alkali ring complex which intrude the metamorphic terrain of the Central Zone of the Limpopo Mobile Belt. This suggests that the presence of bornhardts in the mobile belt is primarily linked to lithological factors. This evidence, coupled with the topographical profiles shown in Figures 1e and 1f, argues that the low relief plain that characterises the Limpopo Belt is an extension of the post-African Surface rather than a younger erosional planation. This is consistent with conclusions reached by Partridge and Maud (1987, 2000) who ascribed contiguous ground in South Africa and Botswana to the post-African erosion cycle (Figure 11).

Further support for this interpretation is provided by a study of Cretaceous sediments of the Gona-re-Zhou Plateau (Figure 4) in the extreme southeast of the country (Botha and de Wit, 1996). These are a sequence of sediments interrupted by periods of non-deposition, during which palaeosols developed. They form a plateau that stands approximately 170 m above the incised courses of lower Save tributaries such as the Runde (Figure 4). Although the plateau is ascribed to the Pliocene erosion surface (Lister, 1987), it is capped by a thick silcrete, which Botha and de Wit (1996) interpret to represent a relict of the African erosion surface. These authors suggest that a 35 m bench above the Runde River may reflect Plio-Pleistocene erosion processes, implying a very restricted surface of this age.

Summary of the erosional history of Zimbabwe

The discussion presented above indicates that much of Zimbabwe experienced two major post-Gondwana erosion cycles (African and post-African), and a very subordinate Plio-Pleistocene cycle. Although the modern Zambezi was initiated at the time of the disruption of Gondwana, evolution of this river largely entailed headward erosion (Moore and Larkin, 2001) within the bounding rift system. An exception to this generalisation is provided by the headwards incision of the Mazowe River (a major south bank tributary of the lower Zambezi) into northeast Zimbabwe. Headward erosion of the rift-bound Save has also not left a profound imprint on the evolution of land surfaces over much of the rest of the country. Within the Save Valley, sediment supplied by tributaries draining the mountainland to the east has resulted in the accumulation of extensive alluvial fan deposits – a process which continues to the present time (Figure 3g).

Thus, the Save and Zambezi erosion cycles initiated at Gondwana breakup continued to the present day, essentially independently of the development of the African and post-African surfaces over much of the remainder of the country. This conclusion – that erosion cycles of different ages and duration have operated essentially independently - differs from the classic model for landscape evolution proposed by King (1963), which envisages that earlier surfaces become senile once uplift triggers a new erosion cycle. A further difference is that *in Zimbabwe,* the African and Post-African surfaces are not separated by erosional scarps (See profiles in Figure 1). Scarp retreat is therefore not envisaged as a major factor in the evolution of post-Gondwana erosion landsurfaces.

Implications for cyclical landscape evolution in southern Africa

Gilchrist and Summerfield (1991, 1994) have strongly criticised the view that the southern African landscape reflects the imprint of multiple post-Gondwana erosion cycles (as envisaged by King, 1963; Lister, 1987; Partridge and Maud, 1987). The principle objection raised was that the model proposed by King (1955) to explain the initiation of successive erosion cycles was geophysically untenable. King envisaged that the crust behaved rigidly, and would only experience flexural uplift once erosion, controlled by scarp retreat, had cut a coastal plain with a threshold width of ~500 km. This was postulated to cause episodic uplift, leading to a series of stepped erosion surfaces separated by scarps. Conversely Gilchrist and Summerfield (1991; 1994) argued that geophysical modelling requires that the incision of a coastal plain would result in continuous rather than episodic isostatic uplift.

Nevertheless, there is compelling field evidence for post-Gondwana erosion surfaces of different ages in southern Africa (King, 1963; Lister, 1987; Partridge and Maud, 1987; Marker and McFarlane, 1997). The present study also strongly supports a multi-cycle erosion history for the evolution of the Zimbabwe landscape. It is therefore necessary to consider mechanisms responsible for triggering new erosional episodes. Moore (1999) noted that the major watersheds in southern Africa define three roughly concentric lines that are broadly parallel to the coastline. He suggested that these three river divides represent axes of flexure, which were designated inland from the coast as, the Escarpment, Etosha-Griqualand-Transvaal (EGT) and Ovamboland-Kalahari-Zimbabwe (OKZ) axes respectively (Figure 11). Essentially, this extends the models proposed by Maufe (1927 and 1935), du Toit (1933) and King (1963) to account for the major southern African river divides. Moore (1999) inferred that the flexures were of different ages, with the Escarpment Axis initiated in the early Cretaceous by the disruption of Gondwana, and the EGT Axis in the mid-Cretaceous. In the present study, we argue for late Palaeogene age for the OKZ Axis. Moore *et al.* (2009) demonstrate that the ages of these three flexures correlate with major reorganisations in spreading regimes along the Atlantic and Indian ridges surrounding southern Africa, which suggests that they are related to plate tectonic processes. These authors noted that the ages inferred for the initiation of the three concentric axes broadly correspond with episodes of major unconformities in the southern African offshore sequence, interpreted to reflect tectonic instability (McMillan, 2002) and episodes of alkaline volcanism across the sub-continent (Moore *et al.*, 2008).

Uplift along the Escarpment Axis at the time of break-up of Gondwana would have initiated the erosion that cut the coastal plane, resulting in an inland migrating isostatic flexure (Gilchrist and Summerfield, 1991; 1994). This rising marginal flexure also exerted a strong control on erosion by the inland drainage system – in other words, on an inland cycle of erosion coeval with the initial incision of the coastal plain (ie. the African erosion cycle). Ongoing uplift along this Axis has taken place to the present day, possibly with a significant rejuvenation event at ~100 Ma. when the Falkland Plateau separated from the Agulhas Bank (Moore *et al.*, 2008)

Partridge and Maud (1987) have noted that the African erosion surface is multi-cyclic. Mid-Cretaceous uplift along the EGT Axis provides a mechanism for rejuvenation of this cycle of erosion. In Zimbabwe, the African erosion cycle was ultimately terminated by the late Neogene uplift along the OKZ Axis. So it becomes necessary to re-evaluate the ages of erosion surfaces recognised elsewhere in southern African (Partridge and Maud, 1987) in terms of their spatial relationship to the three arcuate axes identified in southern Africa by Moore (1999) (Figure 9).

In the Congo basin, major planations recognised within the sedimentary sequence have been dated as early Cretaceous, late Cretaceous and mid-Tertiary (Cahen and Lepersonne, 1952; Giresse, 2005). Their ages are broadly coeval or slightly younger than those of the three flexures recognised in southern Africa by Moore (1999). This points to broadly contemporaneous episodes of uplift with ensuing erosion cycles across large areas of the continent, consistent with the observations made by Cahen and Lepersonne (1952) and King (1963).

In addition to the three arcuate axes identified by Moore (1999) there are a number of Plio-Pleistocene lines of flexure that played an important role in the geomorphic evolution of the sub-continent. Examples are the Otavi and Khomas Axes (du Toit, 1933), the Bushmanland-Harts Axis (Moore, 1999) and the Ciskei-Transkei Axis (Partridge and Maud, 1987) (Figure 11). Uplift along the Otavi Axis was responsible for erosion of a major embayment in the African surface and outcrop of the Kalahari Formation. Uplift along the Ciskei-Swaziland Axis resulted in deep incision of river courses to the east of this axis, to dissect the coastal post-African surface (Figure 11).

Zimbabwe kimberlites and unexplained pathfinder anomalies

One of the long-standing conundrums in Zimbabwe diamond prospecting has been the primary kimberlite source of the Somabula diamonds. The drainage model, presented above, provides a framework to identify possible candidates. The locations of known kimberlite fields in Zimbabwe are shown in Figure 7 (data from Mafara, 2001). The pipes immediately to the south of Lake Kariba intrude Karoo sediments, while the Colossus and River Ranch kimbelites have early Palaeozoic ages (Allsopp *et al.*, 1989; Kramers and Smith, 1983). Field evidence (*e.g.* cross-cutting dolerite dykes, Williams and Robey, 1999) suggest that most of the kimberlites to the south of the modern watershed are of pre-Karoo age.

The Murowa-Sese kimberlites are located directly up the Karoo palaeo-slope from the Somabula deposit (Figure 7). They are diamond-bearing, with Murowa being mined by Rio Tinto Zimbabwe, and thus represent plausible sources for the diamonds in the Somabula basal gravels. Kimberlites in the Murowa-Sese cluster could potentially also be the source of G10 garnets recovered in the Daisyfield and Mambo pathfinder anomalies. However, as these kimberlites are reputedly ilmenite poor, the source of the ilmenites in these two anomalies remains unexplained, and thus a potential exploration target. It follows that if the Somabula diamonds were glacially derived from the Murowa-Sese kimberlites, the pre-Karoo watershed must have been located to the south of Lister's 1600m contour, as shown in Figure 7.

Prospecting carried out by Reunion Mining in the late 1990's identified a major garnet anomaly associated with the margin of the Kalahari Formation in the Nanda area (Figure 7). A small number of Mn-rich kimberlitic ilmenites were recovered from the fine (<425 μm) sample fractions (Philip Dewhurst, personal communication, 1997). However, very detailed follow-up work failed to identify a local kimberlite source. As a significant proportion (~10%) of the Nanda garnets are G10 varieties, the primary kimberlite source represents an important exploration target. Potential candidates would be pipes in the Mwanezi cluster, which are located to the southeast of Nanda. This possibility is supported by the occurrence of both G10 garnets and Mn-rich ilmenites in the Mwanezi-1 kimberlite (Williams and Robey, 1999). Detailed chemical fingerprinting of the Nanda ilmenites would be required to test this possibility. Such a link would require that the pre-Karoo watershed was further to the southeast than shown in Figure 7.

A further garnet-dominated kimberlitic mineral anomaly, containing ~20% G10 garnet varieties, was identified in the vicinity of Maitengwe (Figure 7) by Cratonic Resources (Spence, 1999). The high proportion of associated G10 garnets makes the source of this anomaly an important prospecting target, but detailed prospecting in the Maitengwe area failed to identify a local kimberlite source. The drainage evolution model developed in the present study suggests that this source could be located to the southeast of the Maitengwe kimberlitic mineral anomaly.

Recently, alluvial diamonds have been discovered in the Save Valley at Chiadzwe, just to the south of the Marange kimberlites (Figure 7) (Roberts, 2006). Details of the geological setting are sketchy, but this appears to be a second-cycle alluvial deposit, with the diamonds reworked from local basal conglomerate of the Umkondo Group, which has been dated at approximately 1106 to 1112 Ma (Hanson *et al.*, 2004). Artisanal miners working the deposit have produced a significant proportion of relatively large stones, many in excess of 10 mm in diameter (approximately 3 to 5ct, Figure 3j). The majority of stones are reported to be of poor quality, but a subordinate number are of exceptional quality (Peter Lowenstein, personal communication, 2006). The diamonds characteristically have a black coating, indicative of radioactive damage followed by metamorphic heating, and have characteristic nitrogen and infra red signatures (Roberts, 2006). A singular characteristic of the Marange alluvial diamonds is the high proportion of rounded and fractured stones that have the appearance of having been mechanically abraded (Figure 3j). This contrasts with the sharp crystal faces that characterise a major proportion of the diamonds recovered from other southern African alluvial deposits (*e.g.* de Wit, 2004).

The primary source of the Marange alluvial stones is an enigma, but is inferred to be located to the west (Roberts, 2006). This is broadly consistent with Umkondo palaeo-current directions (Button, 1977; 1978), which indicates a southwesterly to southerly provenance area for the sediments. The ~1 Ga age for the host Umkondo Group sediments requires the existence of kimberlites older than any in Zimbabwe for which reliable dates are available, and an important exploration target.

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