Of diamonds, dinosaurs and diastrophism: 150 million years of landscape evolution in southern Africa

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The state of knowledge on the tectonic and geomorphological evolution of southern Africa during the post-Gondwana period is reviewed in the context of Alex du Toit's fundamental contributions to these fields of geology. Basic to an understanding of post-rifting events are, firstly, the high elevation which much of Africa possessed prior to rifting; secondly, the erosion of one to three kilometres from its surface during the Cretaceous; and thirdly, the role of Neogene uplift in re-establishing high elevations, particularly within the eastern half of the subcontinent. This history is traced through the massive denudation of the early Cretaceous, which was followed by the establishment of a dense, integrated drainage net on a well-planed land surface from the Santonian onwards. The configuration of the Upper Cretaceous river system is fundamental to a comprehension of the present distribution of alluvial diamonds and of gems transported into the sea via these conduits. Equally significant for an appreciation of the present macro-geomorphology of southern Africa is the continent-wide planation surface — known as the African Surface — generated by the multi-phase cycle of Cretaceous erosion. This surface forms a readily identifiable datum across the high plains because of the widespread preservation of deep weathering and massive cappings of laterite and silcrete on remnants which have survived later dissection. The African silcretes reflect a world-wide shift to greater aridity at the beginning of the Palaeocene. The evidence for large-scale Neogene uplift, particularly within the eastern half of the subcontinent, is now beyond question and argues for the late development of at least the southern part of the African Superswell. The largest movements post-date the Miocene and have contributed both to the anomalous elevations of the eastern hinterland and to the strong east–west climatic gradient across southern Africa. Controversies surrounding the mechanisms underlying these recent movements appear to have been resolved in favour of buoyancy forces originating from a massive low-density anomaly in the Earth's mantle below East and southern Africa.

Die kennisvlak aangaande die tektoniese en geomorfologiese evolusie van suidelike Afrika gedurende die na-Gondwana-tydperk word in heroorweging geneem binne die konteks van Alex du Toit se fundamentele bydraes tot hierdie afdelings van geologie. Essensiëel m.b.t. 'n begrip van gebeure wat op slenkvorming gevolg het, is eerstens die hoë elevasie van Afrika voor slenkvorming; tweedens, die erodering van een tot drie kilometer van die oppervlak tydens die Kryttydperk; en derdens, die rol van Neogene opheffing wat weer hoë elevasies tot gevolg gehad het, veral binne die oostelike helfte van die subkontinent. Hierdie geskiedenis word nagegaan soos dit tydens die massiewe denudasie van die Vroeë Kryt, wat gevolg is deur die ontstaan van 'n digte ge-integreerde dreineringsnet op 'n goed geplaneerde landoppervlakte vanaf die Santonium, verloop het. Die konfigurasie van die Bo-Krytse rivierstelsel is fundamenteel tot die begrip van die huidige verspreiding van alluviale diamante en van edelstene wat na die see weggevoer word d.m.v. hierdie kanale. Van net soveel belang vir die verstaan van die huidige makrogeomorfologie van suidelike Afrika, is die kontinentwye planasieoppervlak van Afrika wat tot stand gebring is deur die multifasige siklus van Kryterosie. Hierdie oppervlak vorm 'n geredelik identifiseerbare gegewe reg oor die hoë vlaktes a.g.v. die wydverspreide bewaring van diep vewering en massiewe deklae van lateriet en silkreet op oorblyfsels wat latere insnyding oorleef het. Die Afrikasilkrete reflekteer 'n wêreldwye verandering na groter ariditeit aan die begin van die Paleoseen. Die bewyse vir grootskaalse Neogene opheffing, spesifiek binne die oostelike helfte van die subkontinent, is nou bo alle twyfel en dui op die laat ontwikkeling van ten minste die suidelike gedeelte van die Afrika Superswel. Die meeste beweging was na die Mioseen en het bygedra tot beide die anomale elevasies van die oostelike hinterland en tot die sterk oos–wes klimaatsgradiënt dwarsoor suidelike Afrika. Strydvrae aangaande die meganismes van hierdie onlangse bewegings skyn opgelos te wees ten gunste van kragte van dryfvermoë, wat ontstaan het a.g.v. 'n massiewe laedigtheidsanomalie in die aarde se mantel onder Oos- en suidelike Afrika.

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Introduction

Within the great legacy left to geology by Alexander Logie du Toit were a number of seminal papers dealing with aspects of geomorphology. In particular, Du Toit was concerned with the evolution of major drainage systems, such as those of the Orange and Vaal rivers, and with the recent tectonic movements which he believed had left an important imprint on the face of southern Africa. The influence of his views on these matters was underlined by repeated references to them made both by John Wellington (1955 and others) and Lester King (1967 and others), whose treatises on the geomorphology of southern Africa have remained standard works of reference for many years.

Du Toit's extensive writings, culminating in the third edition of *The Geology of South Africa*, which appeared in 1954, six years after his death, make it clear that he regarded good field observation as the most powerful tool of the geologist. His own perspicacity in describing field relationships, the meticulous detail with which he recorded his observations, and the insight evident in their interpretation, have ensured that even his earlier papers remain widely read. I am a loyal disciple of Du Toit in my belief that observation remains the cornerstone of our science. Geology should be based primarily on observable facts, and models — so much the present fad in almost every branch of science — are, in my view, useful in geology only insofar as they can satisfactorily replicate or explain such observations, or predict from them.

In 1987 a paper appeared in the *South African Journal of Geology* entitled 'Geomorphic evolution of southern Africa since the Mesozoic' (Partridge & Maud, 1987). Prepared with the collaboration of my friend and colleague of long standing, Rodney Maud, this review sought to chronicle landmarks in the development of the southern African subcontinent since the break-up of Gondwanaland, an event which was documented by Du Toit with insight ahead of his time in *Our Wandering Continents* (1937). In the ten years which have elapsed since our first attempt at a 'modern' synthesis, much new evidence has come to hand: chronological control, although in some respects still relatively crude, has improved considerably, constraints on the distribution and amplitudes of tectonic movements are more precise, and the mechanisms underlying such movements are better understood. We also have a sounder appreciation of how global climates have changed since the Cretaceous and are able to identify both regional and global climatic influences, which have caused southern African deserts to wax and wane during the latter part of this period. And we have, also, the magisterial monograph compiled by Kevin Burke, the previous Du Toit lecturer, on the African Plate (Burke, 1996). I shall make more than passing reference to Burke's challenging ideas during the course of this lecture.

How well has our 1987 review stood the test of time? I would venture to suggest, fairly well. But a better story can now be told, a story which has, as its backdrop, a panoply of high plains, forbidding escarpments, inhospitable dune fields, and rugged mountain massifs unique on this planet. And what a drama was played out against this slowly changing set! The tropical lushness of the Cretaceous, which saw dinosaurs roaming the length and breadth of the subcontinent as kilometres were swept from its surface by powerful rivers into the surrounding oceans, ended abruptly as comet impacts and massive volcanism brought to an end, forever, the halcyon days of the Mesozoic. At times throughout this long First Act, and particularly towards its culmination, explosive eruptions threw up clusters of volcanic cones; the diamonds which were carried to the surface in these kimberlites were distributed through the network of Cretaceous rivers, some ultimately finding their way to the oceans. As climates dried and cooled during the Cainozoic and ocean circulations became established in relation to newly formed Antarctic landmass, so the first blankets of desert sand began to move inland from the west coast. The process of desertification was aided by the rise of the eastern parts of the country in two upheavals, the second mightier than the first. As the Tertiary drew to a close, changes in the mosaic of environments became ever more profound. Woodlands opened up and grasslands spread over the high plains; new antelope species, adapted to open habitats, replaced earlier bush-loving lineages, and man's earliest ancestors took their first faltering steps across the veld.

This history is unique to Africa, and is inextricably linked to the turbulent geological and climatic events which brought to a climax a wellnigh continuous record of crustal evolution rooted deep within the Archaean, 3.8 billion years ago.

Gondwanaland and its rifting

Let us begin our story during the last days of Gondwanaland, when the southern hemisphere was dominated by a single huge landmass. Two factors of fundamental importance are the central position which Africa occupied in the Gondwanaland mosaic, and the vast extent of the cover of sedimentary and volcanic rocks belonging to the Karoo Supergroup and its

Figure 1 Reconstruction of Gondwanaland by Alex du Toit (1937), showing present extent of Gondwana (Karoo) strata (black) and their likely former extent (shaded).

equivalents, over both Africa and its neighbours. Both are clearly illustrated in Du Toit's 1937 reconstruction of Gondwanaland (Figure 1), which subsequent studies of ocean-floor magnetic anomalies have proved to be essentially correct. By the mid-Jurassic, it is probable that much of southern Africa south of 15°S was covered by Karoo strata — perhaps excluding the southern part of the Cape Fold mountains, from which rocks of the Dwyka, Ecca, and lower Beaufort groups were stripped by erosion as the area was uplifted from early Triassic times. Despite the continuity of this cover, earlier structural elements were not entirely obliterated: the existence of separate Karoo and Botswana basins, with subsidiary depositories along their northern and eastern margins, reflects the influence of the basin-and-swell structure which has characterized much of the continent since the end of the most recent of the Pan-African orogenic events, some 560 Ma ago. Johan Visser has drawn attention to the importance of the axis separating the Karoo and Botswana basins as a divide between ice sheets in Dwyka times, which he has named the Cargonian Highlands (Visser, 1987). This feature was not entirely overtopped by ice during the Permo–Carboniferous, although its flanks were ultimately overlapped, except in a few small areas, by later Karoo sediments; its structural significance was re-established in Cretaceous and later in Neogene times, leading to the formation of the Kalahari and Bushveld basins. It was, in fact, Du Toit who, in his classic paper of 1933 on 'Crustal movement as a factor in the geographical evolution of South Africa', drew attention to the most recent phase of reactivation of what he called the Griqualand–Transvaal axis, which is a northeastward extension of the Cargonian Highlands.

This highlights a point of fundamental importance: the inter-basin swells, which, as Kevin Burke (1996) has pointed out, are unique to the African continent, were repeatedly rejuvenated and uplifted during the Phanerozoic in relation to the thick and mechanically strong intervening cratons; in the northern part of the continent this uplift has been associated with major rift faulting and volcanism. What is now clear is that these events have persisted into the recent geological past and are, in fact, continuing today. In this respect I differ from Burke's view that major tectonic activity within the African plate effectively ceased some 30 million years ago. I suggest the the evidence now at our disposal points to a rather different conclusion.

The rifts along which Africa separated from South America in the west, and India and Antarctica to the east were almost certainly associated with pre-existing Pan-African welts. As faulting began to rough out the future continental margin, so the volcanism which brought the cycle of Karoo deposition to an end began to shift from foci near the centre of the continent into the marginal zones. Recent evidence (Hargraves *et al.*, 1997) indicates that the Drakensberg and Lebombo basalts are of much the same age — around 183 Ma; monoclinal warping in the Lebombo zone began shortly thereafter, reflecting early activity along the eastern rift zone, but along the coast of Namibia widespread fissure volcanism occurred later, with the extrusion of the 130 Ma Etendeka basalt along the incipient Atlantic margin. As in the case of the much younger rift system of East Africa, uplift of the rift flanks preceded separation; the remains of these elevated rift shoulders are preserved in the cordon of high ground which is especially evident inland of the Great Escarpment in Lesotho and the Eastern Cape (De Swardt & Bennet, 1974). On the evidence of the morphology of kimberlite pipes, comparatively small thicknesses of material have been eroded from these high areas, at least since the early Cretaceous (Hawthorne, 1975). There is little firm evidence, either from onshore or offshore deposits, to suggest that similar elevated areas in the hinterland of the Atlantic coast were the result of the inward migration of an isostatically triggered flexural bulge, which remained active as recently as the Eocene, as has been claimed by Gilchrist & Summerfield (1990; 1994).

Along the southeastern coast, the Falklands Plateau was detached from the Mocambique Ridge along a right-lateral transcurrent fault. The initiation of movement along this Agulhas–Falkland Fracture Zone was accompanied by a shift in sedimentary depocentres from continental cratonic areas to the actively developing marginal zone (Dingle *et al.*, 1983). Here, localized horst and graben development favoured rapid taphrogenic sedimentation, which was associated locally with extrusive volcanism (e.g. the Suurberg volcanics of the northern Algoa Basin). Notable among these early deposits is the upper Jurassic Enon Conglomerate, which accumulated as a series of bajada deposits in fault-bounded intermontane basins adjoining the southern coast.

The precise dating of final separation of Africa, South America, and Antarctica remains unresolved, but most authorities now place the initiation of drift between 129 and 121 Ma (Fouche *et al.*, 1992). The end of this interval coincided with a major period of kimberlite emplacement between 120 and 118 Ma, which reflects extensional melting related to the break-up phase (Smith *et al.*, 1994). The Falkland Plateau probably cleared the Agulhas Bank around 100 Ma ago (Dingle *et al.*, 1983). Along the west and east coasts, continental separation appears to have occurred as a clean break with minimal shearing movements.

By late Aptian and early Albian times (*c.* 110 Ma) basining movements along the coastal margins had virtually ceased, and widespread epeirogenic sedimentation over the subsiding continental shelf began to bury the earlier graben infillings. The upper Cretaceous marine sequences of the continental shelf and the Cretaceous–Palaeocene Mzinene and St. Lucia Formations of the Natal–Kwazulu coastal plain are typical of this phase.

All of the evidence which I have presented points to one conclusion: that at the time of rifting, the margin of southern Africa possessed substantial relief. How high the subcontinent actually stood is indicated by several lines of evidence: firstly, rates of terrigenous sedimentation on the continental shelf during the immediate post-rifting period (early Cretaceous) exceeded, by an order of magnitude, those which characterized the Cainozoic (Dingle *et al.*, 1983; Martin, 1987). Only in some areas, such as the Orange Basin, were there departures from this general trend (Rust & Summerfield, 1990), which are probably a result of the enlargement of onshore catchments through piracy as the drainage net evolved. Secondly, fission-track analyses of apatite crystals (Brown, 1991; Brown *et al.*, 1994), although often difficult to interpret because of uncertainties relative to regional geothermal history, indicate that, by the mid Cretaceous, between one

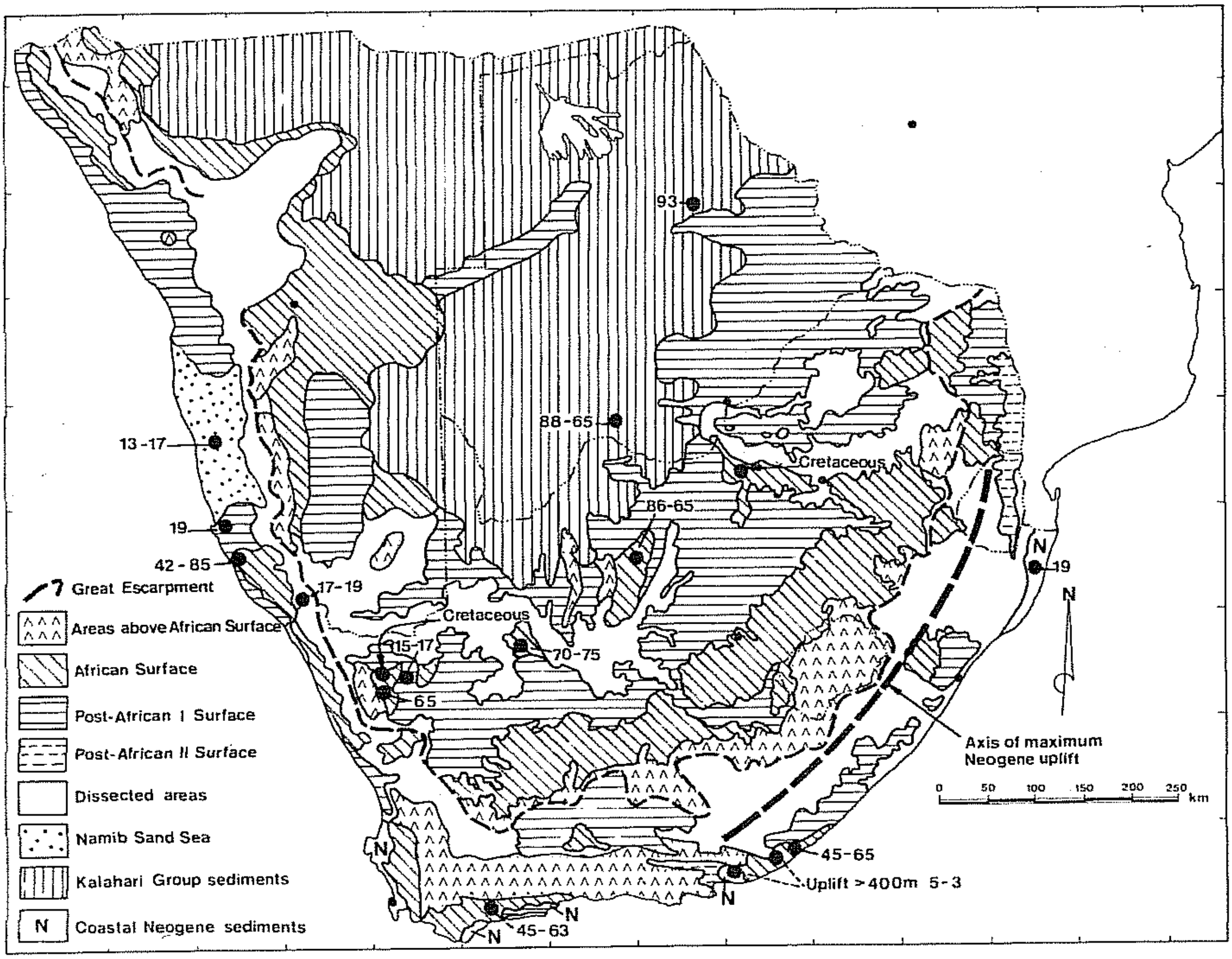

Figure 2 Simplified map showing the distribution of land surfaces in southern Africa. Heavy dots show localities at which constraints on the age of the surfaces are available (range in Ma).

and three kilometres had been removed from the post-rifting surface of the subcontinent, with relatively little subsequent denudation. In the process, a great deal of the Karoo cover was stripped from all but the main Karoo Basin. The bracketing of the bulk of onshore erosion and concomitant offshore sedimentation within the Cretaceous is independently confirmed by the preservation of the crater facies of kimberlitic diatremes in a number of localities extending from Bushmanland to the Kalahari Basin, which have ages ranging from about 90 to 60 Ma (Figure 2). This indicates beyond any doubt that, over considerable areas of the continental interior, little additional landscape lowering has taken place during the Cainozoic; indeed, the main interval of erosion was over by the beginning of the Upper Cretaceous.

Such a massive shedding of Cretaceous erosional detritus to the oceans would not have been possible without the existence of a high-standing landmass. Rodney Maud and I suggested in 1987 that pre-rifting elevations probably ranged from about 2400 m in Lesotho to 1500 m in the western interior; subsequent estimates for the latter area do not contradict these conclusions (e.g. Brown *et al.*, 1990; Rust & Summerfield, 1990). These high elevations were due, in part, to uplift along the rift shoulders and were responsible for the existence, from the time of continental separation, of a substantial marginal escarpment. This precursor of today's Great Escarpment, which forms a great horseshoe rampart between 50 and 200 km inland of the coast (Figure 2), was driven back with vigour by early Cretaceous erosion. In part, the result of the high energy potential provided by the elevated margin, and in part a response to the humid tropical climates of the Cretaceous, this prolonged interval of erosion dumped two to four kilometres of sediment on large areas of the continental shelf, with up to twice those thicknesses preserved in some basins off the south coast (Dingle *et al.*, 1983). Rates of sedimentation were not uniform throughout this period, and a hiatus shortly after the beginning of the Upper Cretaceous may be associated with an interval of extensional tectonics, with a concomitant marine regression; an important period of kimberlite emplacement around 86 Ma was almost certainly linked to these movements (Smith *et al.*, 1994). While this and other Cretaceous events were of undoubted importance, they had little influence on the course of the cycle of denudation set in train by continental separation and the break-up of Gondwanaland.

African Surface

The legacy of this great cycle of erosion was profound. The marginal escarpment, which defined much of the southern African coast, receded rapidly and, on the evidence of studies of basalt pebble sizes in east coast rivers and in marine Cretaceous deposits (Matthews, 1978), had reached a position within about 20 km of today's Great Escarpment by the end of the Cretaceous. Erosion to the new oceanic base level cut a gently sloping bench across the coastal hinterland as the escarpment receded. Kevin Burke (1996) doubts whether this coastal pediment is of great antiquity, but the weight of evidence is conclusive (Figure 2). In the Eastern Cape, Upper Cretaceous marine deposits relating to the Campanian–Maastrichtian transgression are preserved in a hollow on this surface at Need's Camp Lower Quarry (Lock, 1973; Siesser & Miles, 1979). A short distance away at the Upper Quarry, later marine strata record a subsequent Eocene transgression. Similar Eocene deposits near the mouth of the Great Fish River contain rolled silcrete pebbles (Siesser & Miles, 1979; Maud *et al.*, 1987), which, as will be demonstrated later, were derived from the erosion of an extensive duricrust capping which formed on this land surface at the beginning of the Cainozoic. In the southern Cape, near Swellendam, this silcrete caps an alnoite pipe, which is part of a cluster dated to around 63 Ma (Moore, 1979); and in the Spehrgebied of southern Namibia, Cretaceous marine strata of Santonian age are present on the local equivalent of the same surface (J.D. Ward, pers. comm., 1997).

What is clear too, is that, throughout this major interval of Cretaceous erosion, land surfaces on either side of the receding escarpment were formed under the influence of two separate base levels of erosion. In the coastal hinterland, sea-level constituted the ultimate control, but inland of the Great Escarpment, the base level for erosion was provided by major river systems such as the Orange and Limpopo at their point of egress from the interior plateau through the Great Escarpment. This created the unusual situation that land surfaces of essentially the same age were cut at different levels above and below the escarpment line. As in the case of its coastal equivalent, available evidence points unambiguously to the fact that the interior plateau surface had been formed by the Upper Cretaceous. The net result of this situation was the creation of two vast erosional bevels, above and below the Great Escarpment. These enormous pediplains were grouped together as the African erosion surface by Lester King in a number of seminal papers (King, 1944; 1947; 1949; 1951; Fair & King, 1954; King & King, 1959), and I believe it is appropriate to maintain this nomenclature. Above the African Surface, a number of mountain massifs were preserved (Figure 2), including the ranges of the Cape Fold Mountains (Figure 3), the Namaqualand Highlands, the mountains of the Eastern Cape and Lesotho, and the ranges inland of the Namibian escarpment. Evidence from the morphology of kimberlite pipes adduced by Hawthorne (1975) indicates that, even on the highest of these remnants in Lesotho, some 300 m of material has been eroded subsequent to the emplacement of these pipes around 90 Ma ago, indicating that all vestiges of the original Gondwana surface were removed by Cretaceous erosion.

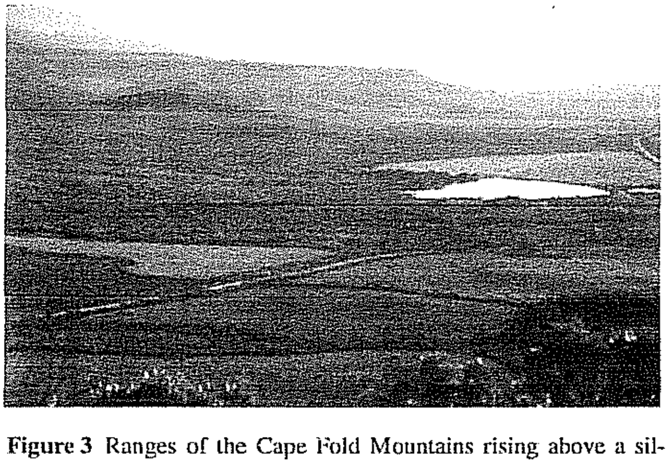

Figure 3 Ranges of the Cape Fold Mountains rising above a silcrete-capped shoulder of the Cretaceous African Surface. Langeberg Mountains, east of Barrydale (Photo: T.C. Partridge).

In common with most continental areas, southern Africa appears to have enjoyed warm, humid climates during most of the Cretaceous. The Upper Cretaceous, in particular, seems to have been characterized by an extensive tree cover on the basis of the abundance of logs and plant material preserved in the marine sequences; a large, fine terrigenous component in these sediments argues for high rainfall and deep weathering (Dingle *et al.*, 1983). These conclusions are supported by evidence from the crater fills of kimberlite pipes in Botswana and the Northern Cape, with their richly fossiliferous paludal sediments (Scholtz, 1985; Smith, 1986; Rayner *et al.*, in press). There are suggestions, however, that by the end of the Cretaceous a degree of desiccation had occurred, resulting in the establishment of somewhat drier forest and shrubland communities than had characterized earlier periods. On the basis of recent work by De Wit *et al.* (1992), the remains of the dinosaur *Kangnasaurus coetzeei*, found east of Springbok in the early years of this century, were trapped in such crater sediments. In the intervening areas of the subcontinent, erosion has almost entirely removed all but a few remnants of terrestrial deposits of Cretaceous age. An exception is the Kalahari Basin of Botswana and the Northern Cape, in which up to 500 m of sediment has accumulated in places; as will be indicated presently, the lower units of this sequence, comprising the Kalahari Group, are in all probability of Cretaceous age, although no diagnostic fossils have yet been forthcoming.

Cretaceous drainage net

It may be expected that a warm and wet Cretaceous would have left some legacy, however fragmentarily preserved, of a well integrated drainage net and deep weathering of susceptible rocks beneath the African Surface; this is, indeed, the case. Over large tracts in the North-West Province, extending into the Northern Cape, the remains of an ancient drainage system are preserved as a series of sinuous gravel lags, following the highest points of the topography. In many cases these remnants provide the last remaining evidence of the former presence of the African Surface; they have, in fact, acted as a protection from subsequent erosion, in the process creating an unusual inversion of topography whereby intact or slightly lowered remains of the original channel deposits now appear in the landscape as ridges. The gravels of the Lichten-

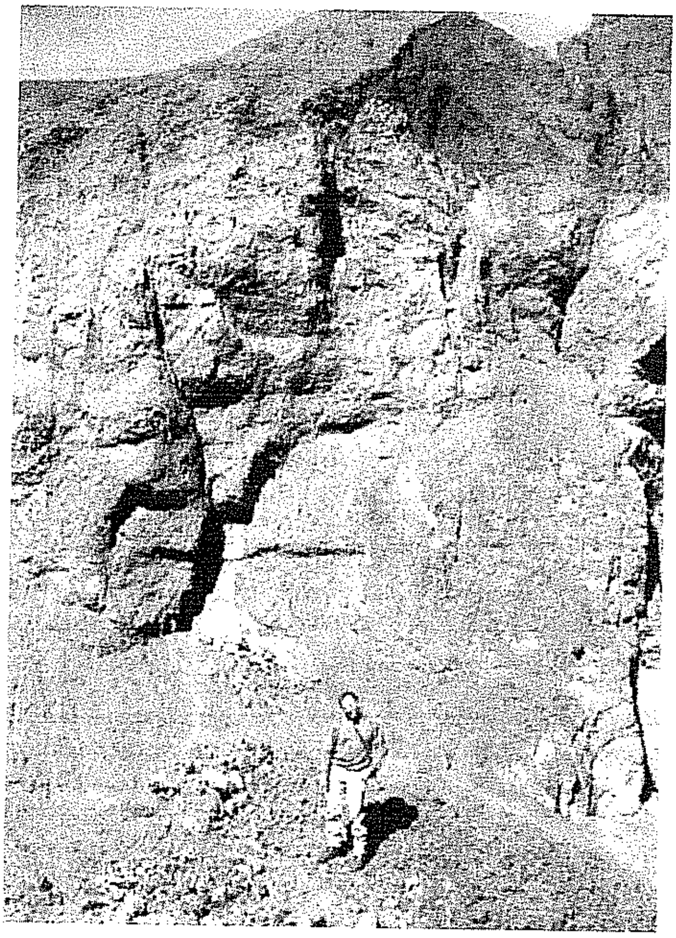

Figure 4 Mature laterite profile in fluvial sediments of Cretaceous age. Near Ventersdorp, North-West Province. (Photo: T.C. Partridge).

burg area were, in fact, the subject of a typically comprehensive and insightful survey by Du Toit, published posthumously in 1951. A Cretaceous (more specifically, Upper Cretaceous) age has been established for these African fluvial gravels at two places: at Mahura Muhtla on the Ghaap Plateau and at Grasfontein in the Lichtenburg area. At Grasfontein, a deep, fine-grained pot-hole filling associated with these gravels has yielded pollen of Cretaceous age (on the basis of studies by Anton Scholtz — R.M.H. Smith, pers. comm., 1988). Pot-hole infillings in analogous settings show evidence of pervasive laterization which bears testimony to the humid, tropical climate which prevailed at the time (Figure 4).

Mahura Muhtla has provided similar information, but with more important implications because of its location on the crest of the southern watershed of the Kalahari Basin. Here, a number of channel segments totalling 4.5 km in length, and with an average width of about 150 m, are preserved. In places the channel is cut up to 10 m into the dolomite bedrock, which is polished and pot-holed. The channel is sinuous in plan, comprising 2.5 meanders, and its preservation must be ascribed largely to its location in a watershed area which has been subject to minimal lowering since the accumulation of the deposits. A considerable proportion of the channel fill is well exposed in depth through past diamond digging activities (Figure 5) which took place mainly between 1900 and
1914 (Wagner, 1914). The fills consist of calcified, fine
vium (chiefly silt) containing alternating layers of fine
bles (mainly orange agates) and cobble conglomerate
particular interest is the presence of silicified wood, often
served as fairly large logs segmented by joints, some of w
lie on the bedrock surface parallel to the axis of the char
A study of a number of specimens of this wood by
Zavada of the University of Southwestern Louisiana
shown most to be of gymnosperm affinities without diag
tic value from a chronological point of view. One was, h
ever, of angiosperm type, and can be placed in the spe
Protoatherospermoxylon renniei, which is known from
Upper Cretaceous of Egypt (Krausel, 1939) and from
Mzamba Formation of the Transkei coast (Klinger
Kennedy, 1980). A best estimate of the ages of the
deposits at the latter is Santonian–Campanian (86 – 65 M

Sedimentary structures within the channel fills have, un
tunately, been obliterated by the calcification process, mal
it impossible to establish the flow direction by this me
Diagnostic clasts include lithologies derived from within
dolomite, a short distance to the south, and orange aga
whose nearest occurrence is in Ongeluk Lava of the Gric
land West Supergroup, buried beneath Kalahari Group s
ments some distance to the northwest. The latter evide
firmly defines the original flow direction as from nort
south, *implying* that this river system was active *before*
formation of the Kalahari Basin. The reason why I h
devoted special attention to this locality is that it provides,
the first time, evidence that basining (or, perhaps, uplift al
the Cargonian Highlands/Griqualand–Transvaal axis, wh
forms the southern margin of the basin) post-dates about
Ma. As the southern margin of the basin became defined,
drainage was interrupted and reversed, at least temporar
leading to the entrainment of local lithologies from the sou
Estimating a minimum age for the activity of this drainag
more difficult, but I venture to suggest that it must have p
ceded a major period of silicification which, as will be sho
presently, dates to the early Palaeocene and was probal
responsible for fossilization of the Mahura Muhtla logs.

The evolution of the late Cretaceous drainage net is of c
siderable importance from the point of view of the distril
tion of diamondiferous alluvial gravels within southern Afr

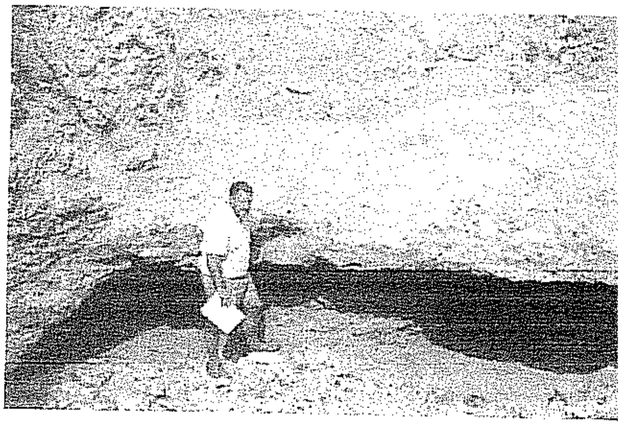

Figure 5 Diamond diggings in Cretaceous fluvial gravels p
served on the southern watershed of the Kalahari Basin at Mahu
Mutlha, Northern Cape. (Photo: L.M. Partridge).

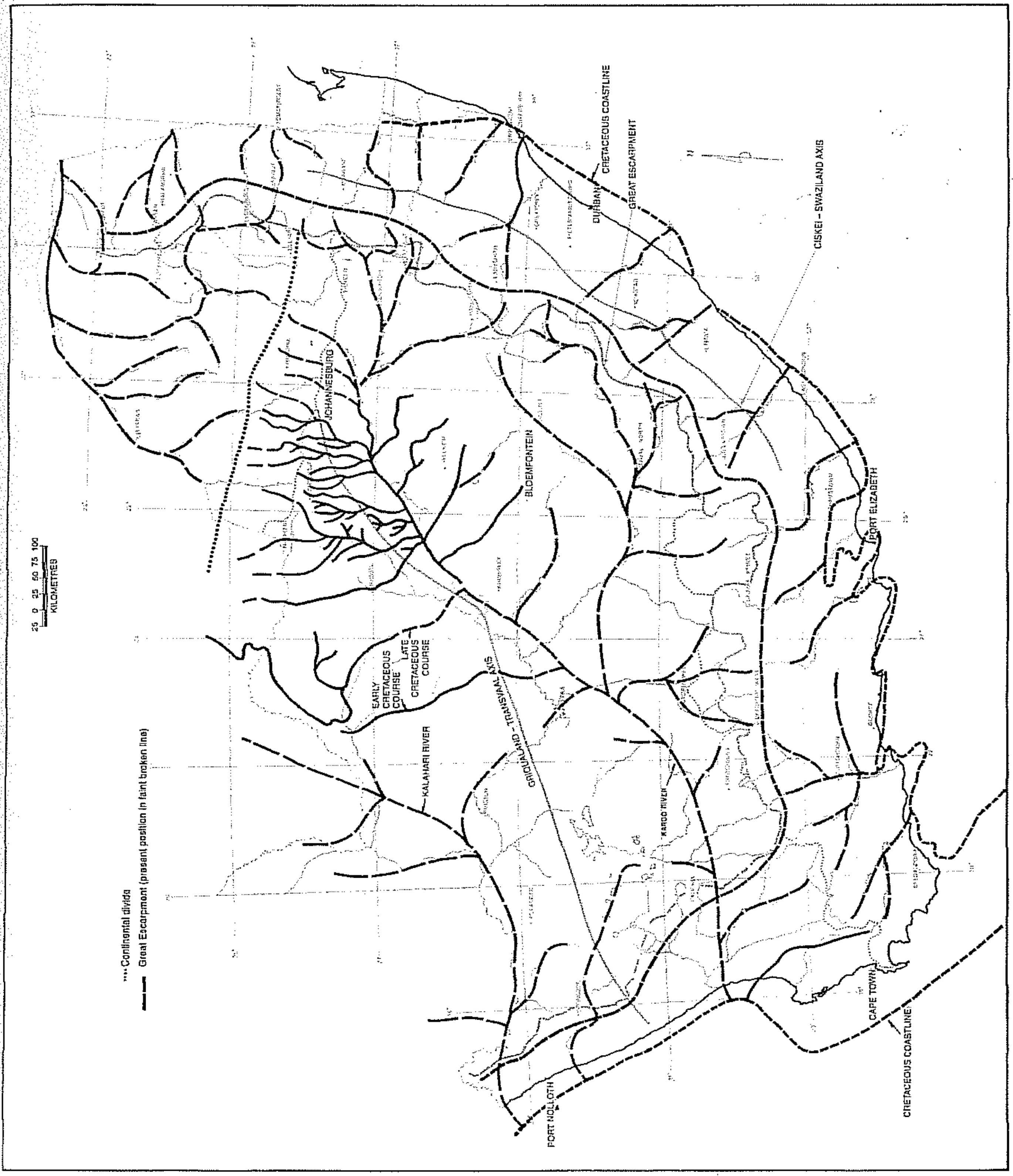

Figure 6 Map of South Africa showing reconstructed Upper Cretaceous drainage net, with present river system shown in faint lines.

and the transportation of diamonds from kimberlites on the Kaapvaal Craton to the sea. The evidence presented previously indicates that, by about halfway through the Upper Cretaceous, the African Surface had attained an advanced state of planation and geomorphic stability which permitted the establishment of a well-integrated drainage net (Figure 6). The major kimberlite eruption event at *c*. 86 Ma occurred around the same time, and a previous important event between 120 and 118 Ma predated the achievement of this stable state by no more than about 30 Ma. The late Cretaceous rivers were therefore able to tap the richly diamondiferous crater facies of the kimberlite volcanoes or erode the enriched upper zones of the underlying pipes and fissures. Like the Lichtenburg gravels, the so-called Rooikoppies gravels of the Wolmaransstad–

Schweizer Reneke area are, in fact, remnants of this drainage net (Marshall, 1990). The existence of other axial rivers, of which the original deposits have been destroyed by erosion, can be inferred from the reworking of diamonds into more recent drainages such as the Bamboespruit and Harts rivers, the catchments of which lie in areas where diamondiferous kimberlites are unknown and probably absent. Tania Marshall has identified one such palaeo-river, which she named the Kimberley River, as having drained the panveld of the northern Orange Free State (Marshall, 1988); this may well have formed a segment of the Karoo River, postulated by Mike De Wit as an early conduit to the Atlantic Ocean for diamonds eroded from pipes in the Boshoff and Kimberley areas (De Wit, 1993). Although no gravel remnants of the Karoo River have been identified to the west of Kimberley, De Wit believes that its abandoned channel deposits were the source of diamonds preserved in the now defunct channels of the Geelvloer Valley/Commissioners Valley/Koa Valley system, which drained the western half of the Northern Cape during the Tertiary. The Karoo river is inferred to have exited to the sea near the present mouth of the Olifants River, which would account for the major Cretaceous component and size of the submarine delta of that system (Dingle & Hendey, 1984); the present mouth of the Orange River apparently became active only in Coniacian times. The subsequent distribution of diamonds along the Atlantic coast by currents, and their redeposition in a series of eustatically controlled marine terraces, was a consequence of major economic importance for ern Africa.

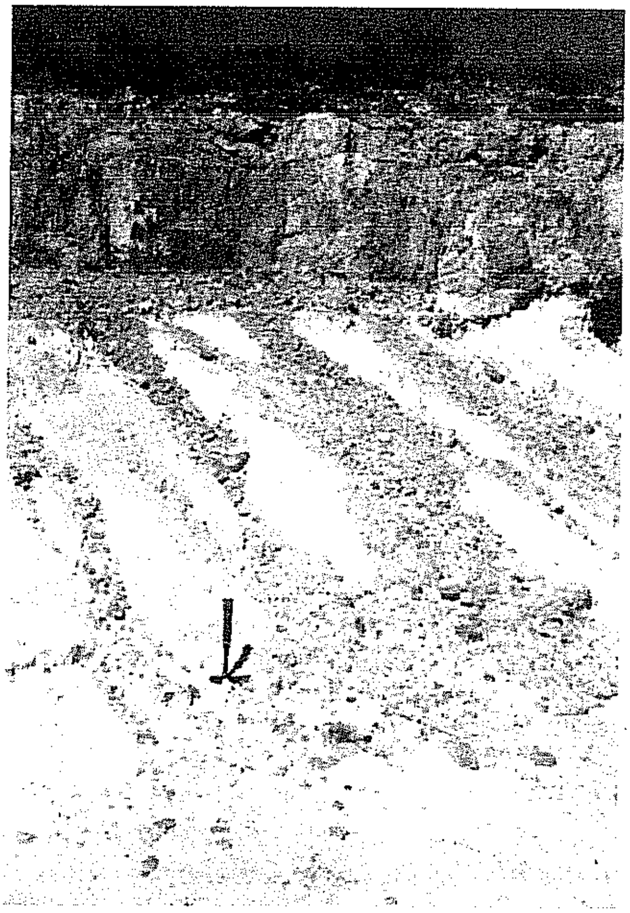

Figure 7 Silcrete duricrust overlying deeply kaolinized Dwyka tillite. Grahamstown, Eastern Cape. (Photo: T.C. Partridge).

Figure 8 Relict columnar structure preserved in silcrete. So of Uniondale, Eastern Cape. (Photo: T.C. Partridge).

A more northerly river, referred to as the Kalahari R De Wit (1993), is postulated to have drained areas now pied by the southern part of the Kalahari Basin. Di sources north of the present continental divide, whic formed in the Neogene by subsidence of the Bushveld and uplift along the Griqualand–Transvaal axis as D (1933) has pointed out, are likely to have been tapped b the Kalahari and Kimberley rivers.

These remnants of Upper Cretaceous river systems importance for an understanding of the subsequent ev of drainages in southern Africa, since they were evi more extensive and better integrated than their Cai counterparts. Although partly the result of uplift and ba during the early Miocene, which initiated the Post-Af cycle of erosion; this reorganization was also a function aridification of climates during the Cainozoic. Hence, periods of fluvial activity, represented either in defun tems such as that of the Koa, or high terraces of existing such as the Orange, Vaal, Limpopo, and Sundays, c bracketed within discrete time intervals within the Te during which wetter conditions prevailed (De Wit, 199 tingh, 1996; Partridge *et al.*, in press).

Cainozoic aridification and tectonic events o Neogene

I have dwelt at length on southern Africa during the ceous because the events of that period are, I believe, c for a proper understanding of the subsequent tectonic an sional history of the subcontinent. Of equal signifi however, were the events which ushered in the Cain The end of the Cretaceous saw southern Africa transec a great planation surface — the African Surface — cut levels above and below the Great Escarpment and inter here and there by high-standing mountain massifs (Fig These pediplains were evidently covered by forest or land, and the warm, mesic Cretaceous climates had give to deep weathering and kaolinization beneath their undulating surface. Although rarely preserved in unpro situations, such deep weathering profiles can be obs today at various localities on remnants of the African Su

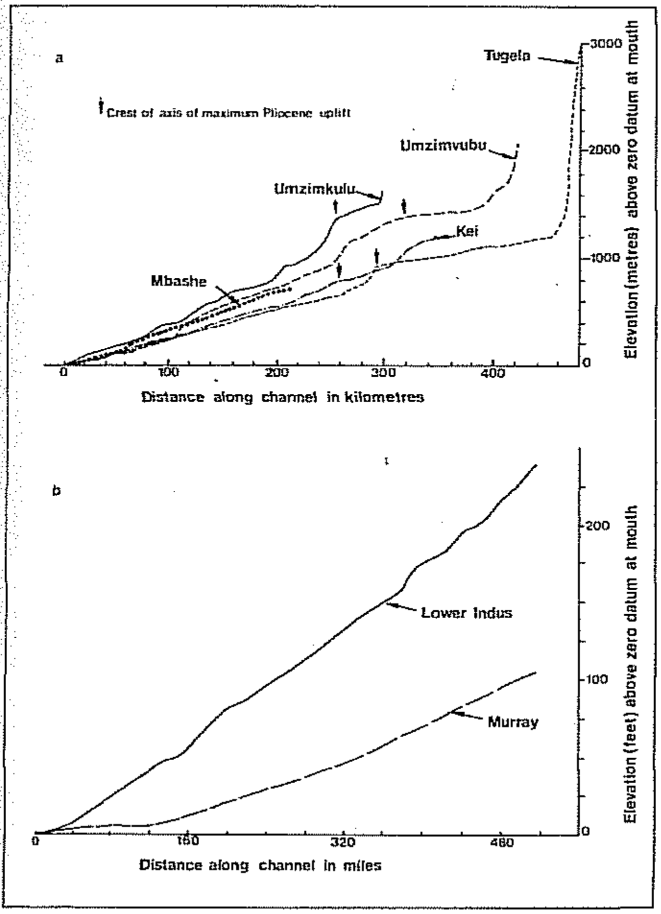

Figure 9 a) Long profiles of major rivers that cross the southeastern coastal hinterland of southern Africa. b) Typical river long profiles in areas unaffected by recent uplift (after Leopold *et al.*, 1964).

where regolith development may attain up to 50 m. In the eastern part of the subcontinent, such as the interior of Kwazulu–Natal and the highveld of Mpumalanga, thick laterites cap these deeply leached profiles (Figure 4), such as are forming today in tropical Brazil through relative enrichment of iron and aluminium oxides. By contrast, in the south and west and parts of the lower Limpopo valley, cappings of a very different type are preserved. These silcrete duricrusts (Figure 7) are extraordinary widespread. Their importance lies not only in the manner in which they have preserved remnants of the African Surface because of their resistance to erosion, but in the evidence which they provide of major climatic change at the end of the Cretaceous.[1]

Many authors have postulated a genetic link between the deep weathering profiles and silcrete formation, such as can be demonstrated in the development of laterites. The conditions surrounding the generation of silcrete, in multiple layered sequences or in massive cappings up to 20 m thick are, however, more ambiguous (Partridge & Maud, 1989). Because both silica and titanium (the latter often significantly enriched in silcretes associated with deep weathering profiles) are fairly soluble at low pH, most authorities believe that the formation of these mature silcretes is compatible with the humid conditions and leached, acidic soils which characterized the latter part of the Cretaceous. Silica is, however, also readily soluble at high pH. We have argued previously that, although advanced weathering and uptake of silica into solution would undoubtedly have been favoured by the torrid Cretaceous climates, there is abundant evidence, on a global scale, for cooling and desiccation at the end of that period (e.g. Frakes, 1979), which were evidently associated with an increase in soil pH. This would have led, inevitably, to silica precipitation. In support of this mechanism we point to the well-developed relict columnar or prismatic structure preserved in many silcretes (Figure 8) which is indicative of a sodic soil environment. Such sodic soils are characteristic of arid, rather than humid, areas and are absent in the contemporary wet tropics; their presence therefore confirms the onset of major desiccation after the cessation of enhanced Cretaceous weathering. Of special significance is the conclusion reached by Judith Gassaway of the US Geological Survey, based on an analysis of silcretes on four continents (some, such as those of the Laramide Basin, in chronologically well-constrained stratigraphic settings), that this major period of silcrete formation dates to the earliest Palaeocene (Gassaway, 1988; 1990). This finding is entirely compatible with the evidence which Rodney Maud and I have assembled from the southern and eastern Cape. A major change in atmospheric chemistry at, or immediately after, the end of the Cretaceous is implied (Partridge & Maud, 1989). The considerable thickness and multi-cyclic character of many such silcretes demands that their formation occurred over at least hundreds of thousands, and probably millions of years. Such an extended period of genesis is incompatible with the aftermath of a cometary impact, whose atmospheric effects, although catastrophic at the time, can be shown by studies of dissipation and fallout of volcanic ejecta, to be unlikely to persist for more than 5 to 10 years. I do not question the fact that such an impact was responsible for mass extinctions at the end of the Cretaceous, but I reject it as an instigator of long-term climatic change. The real cause can almost certainly be found in the prolonged Deccan volcanism of India, which began at this time and which released enormous volumes of dust and gases over a significant period. Of local or even regional importance

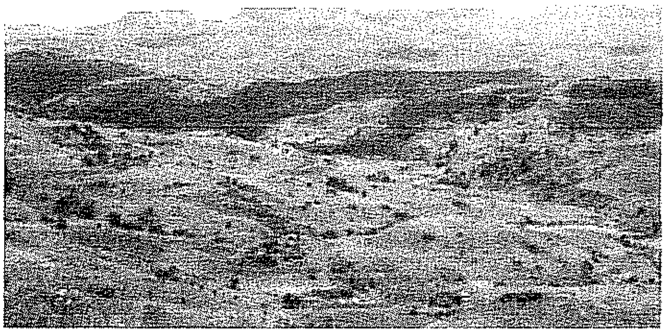

Figure 10 Pliocene dissection of Valley of a Thousand Hills, Kwazulu–Natal, with laterite-capped remnants of the African Surface on the skyline. (Photo: R.R. Maud).

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[1] It should be pointed out that later silcretes are preserved in several areas; these are, however, not associated with deep weathering, and usually occur in the vicinity of saline playas and channels of the western interior.

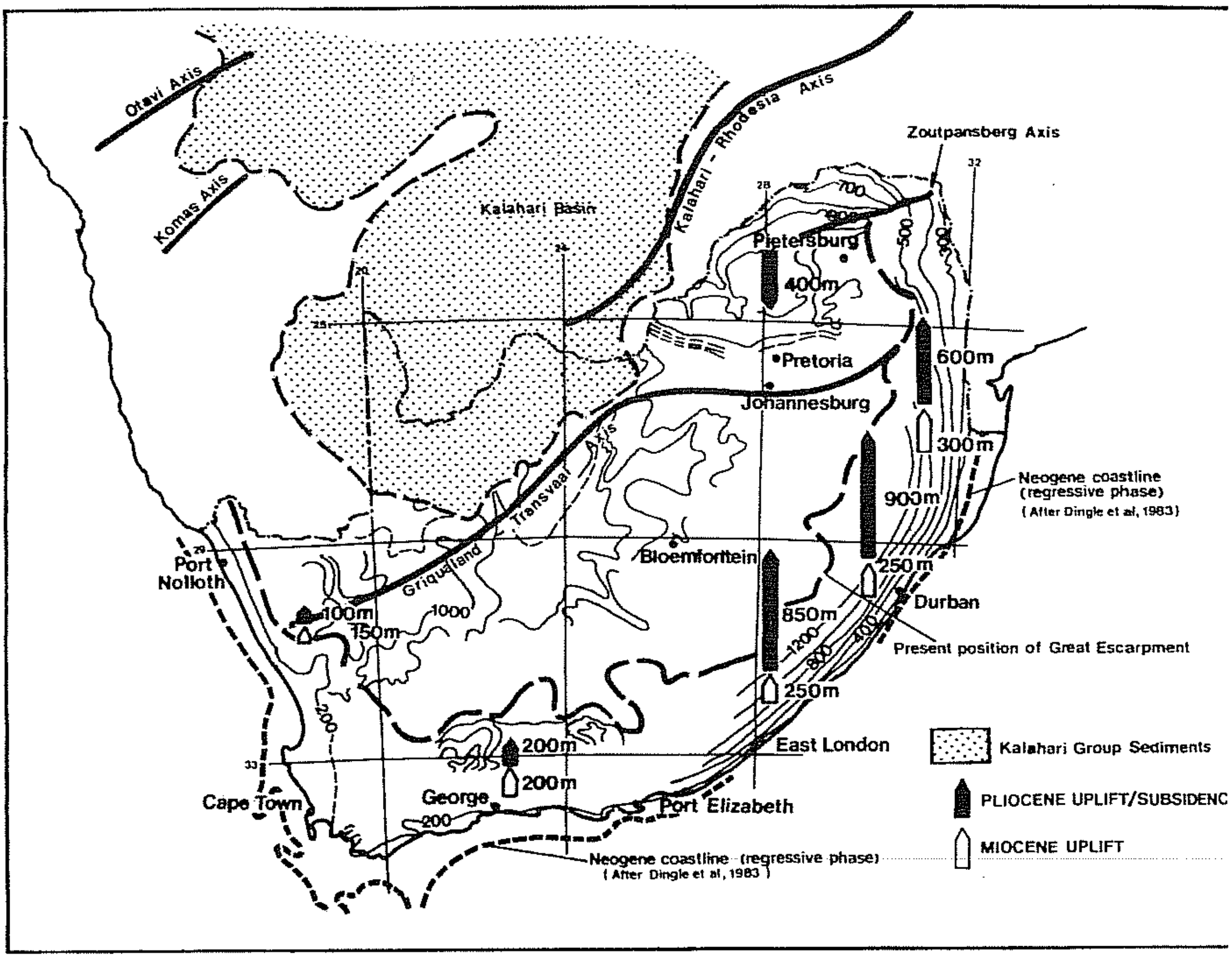

Figure 11 Generalized contours on the Post-African I (Miocene) erosion surface. Open arrows indicate the amplitude of early Mioce uplift; solid arrows show Pliocene uplift or subsidence. The present position of the Great Escarpment is shown by the broken line (after P tridge & Maud, 1987). Interior axes of uplift are after A.L. du Toit (1933).

was the eruption, at almost the same time, of more than 270 melilitite volcanoes in the south and west of southern Africa; the distribution, composition and age of which have been the subject of a major study by Moore (1979).

These events saw the final demise of the dinosaurs and the emergence, across the globe, of floral and faunal communities adapted to the new climatic regime which ushered in the Cainozoic era. With the exception of more mesic intervals during the early Miocene and the Pliocene, the Cainozoic saw a general decline in fluvial activity (De Wit, 1993; Partridge, 1997); these changes are not compatible with the continued occurrence of deep weathering and, *contra* Burke (1996), such occurrences are almost certainly referable to the Cretaceous. Comparatively little is known of the early part of the Cainozoic because onshore Palaeogene deposits are rare in southern Africa and restricted largely to the coastal areas. The Eocene Bathurst Formation of the southeastern coast (Maud *et al.*, 1987), and its equivalents along the Namibian coast at Buntfeldschuh and Bogenfels (Ward & Corbett, 1990), rest upon remnants of the African Surface and help to place an upper limit on the duration of this landscape cycle. No terrestrial deposits which can be ascribed with certainty to the Oligocene are known, although deposition was almost certai occurring in the Kalahari Basin through that interval. M marine successions on the continental shelf contain Eocene/Oligocene unconformity, but early and middle C gocene sediments have been encountered in several boreho around the entire length of the southern African coast, and McMillan & Rogers (in press) point out, there are no grou for inferring a major sea-level fall at that time. The dearth Oligocene strata may be attributed, rather, to non-deposit or destruction due to subsequent uplift and erosion.

Early Miocene epeirogenesis: initiation of the Afric Superswell and the Post-African I cycle

The earliest Cainozoic event for which widespread evide exists is a modest epeirogenic uplift which can be plac with reasonable confidence, in the early Miocene. Bu (1996) favours an earlier onset of uplift, at around 30 Ma, the basis of dates for the beginning of greatly intensi intraplate volcanism in the northern part of Africa. As he pointed out, this contrasts with restricted evidence of volc and tectonic activity during the earlier part of the Cainoz In southern Africa, where volcanism has been absent betw the Eocene and present, age constraints based on radiometric methods cannot be imposed and we must rely more heavily on geomorphic and palaeontological indicators. The best evidence for early Miocene uplift in southern Africa comes from the western part of the subcontinent, where incision of no more than 100 – 200 m below remnants of the African Surface reflects rejuvenation of the by now sluggish drainages of the early Cainozoic. This downcutting produced a rolling surface studded with koppies which, in conformity with the proposal of King & King (1959), we have called the Post-African I Surface. Associated fluvial deposits in the Koa Valley, the lower Orange River, and in the coastal hinterland of Namibia contain terrestrial faunas which date to between 19 and 17 Ma (Corvinus & Hendey, 1978; De Wit, 1993; Pickford *et al.*, 1995; 1996). In the hinterland of Kwazulu–Natal, larger uplift, totalling around 250 m, is indicated by the greater separation of remnants of the African and Post-African I Surfaces, but chronological control is restricted to evidence of a modest increase in terrestrial sedimentary inputs to the continental shelf during the Burdigalian and Langhian (19 – 16 Ma) (Dingle *et al.*, 1983). Although tectonic uplift was the proximal cause of the increased fluvial activity, the faunal evidence indicates that, at least in the western hinterland of southern Africa, conditions were sufficiently humid to support woodland environments where, today, conditions are at best semi-desert (Hendey, 1978; Pickford *et al.*, 1995; 1996). During this and succeeding phases of incision through the Cainozoic, drainage patterns became increasingly controlled by the pre-Karoo topography exposed by Cretaceous stripping. Studies by De Wit (1993) and Pickford *et al.* (1996) have indicated, however, that by the Serravallian conditions had become markedly drier, and only major river systems

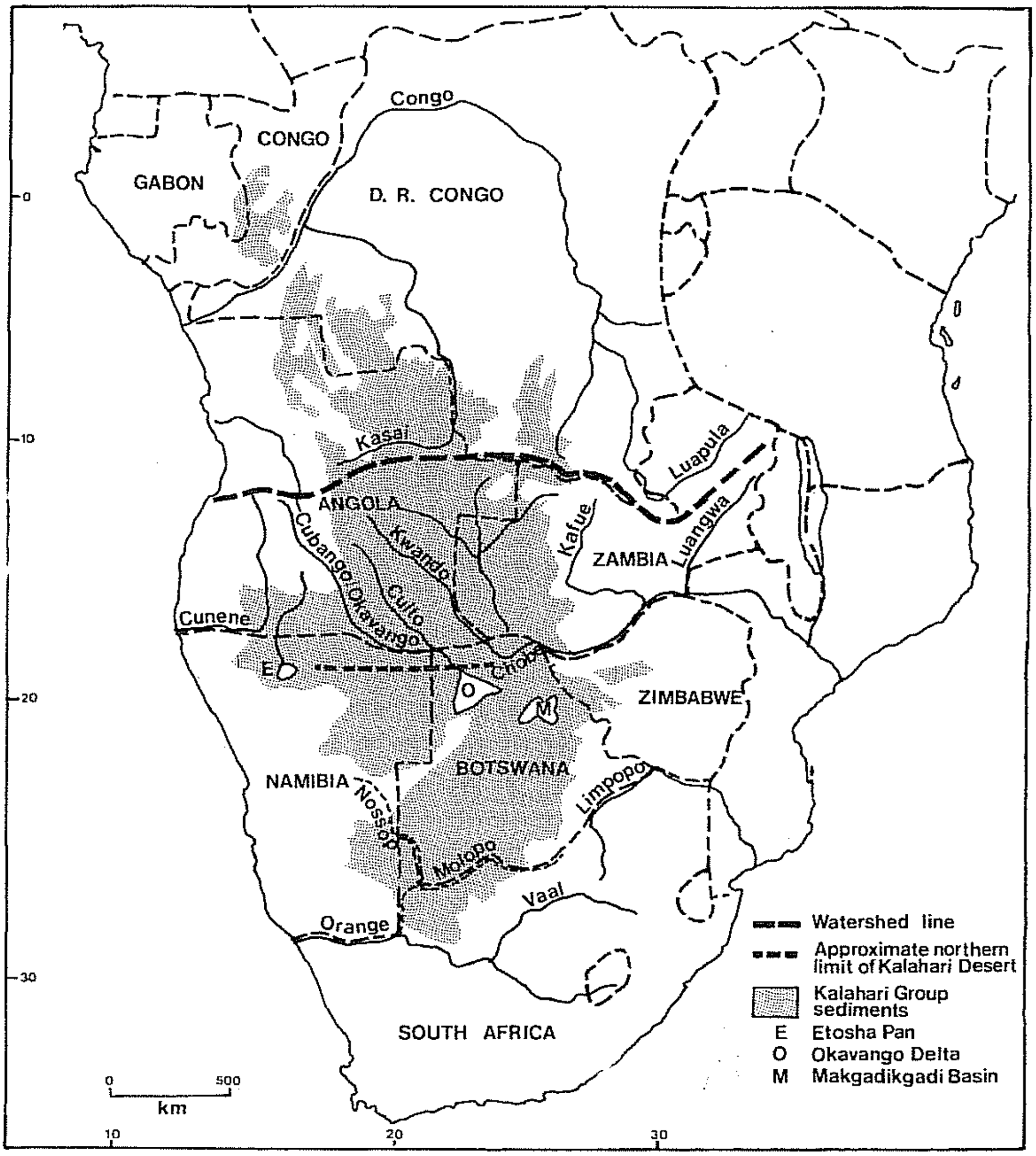

Figure 12 The Mega-Kalahari Desert (shaded area), in which an almost continuous cover of previously active, windblown sand is present (after Thomas & Shaw, 1991).

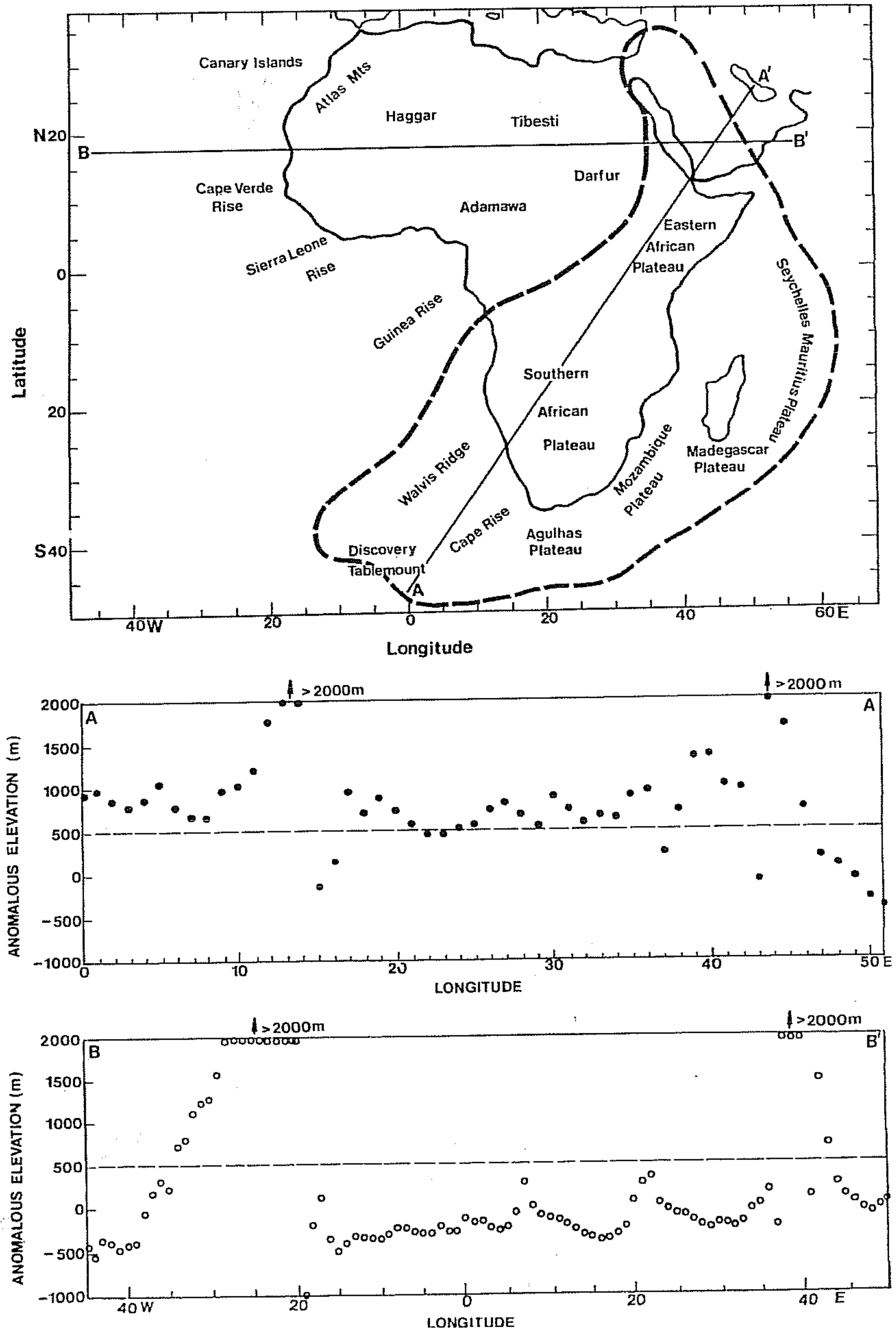

Figure 13 The African Superswell (upper diagram, outlined by bold dashed line). A–A and B–B (lower two diagrams) are cross sections along the two transects (after Nyblade & Robinson, 1994).

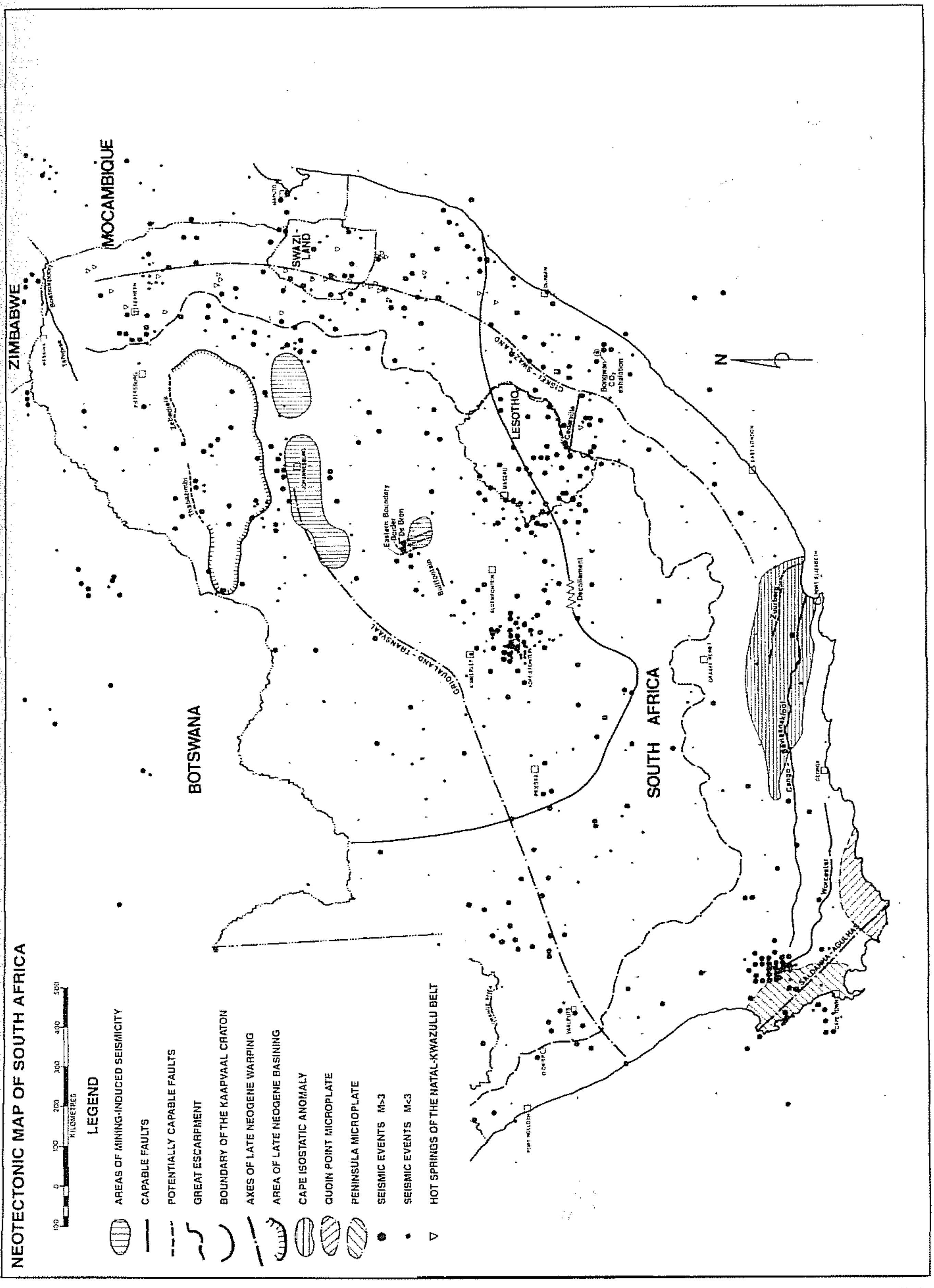

Figure 14 Neotectonic map of southern Africa. Locations of all historical seismic events were provided by the South African Council for Geoscience.

such the Orange maintained their flow. This drying out was associated with the initiation of cold upwelling within the Benguela current system, which followed the establishment of the East Antarctic ice sheet around 14 Ma. One of its important consequences was the formation, for the first time, of the Namib Sand Sea, which has apparently persisted since that time.

Pliocene uplift: responses and mechanisms

The absence of major onshore incision accompanied by terrigenous sedimentation on the continental shelf, argue strongly against the occurrence of large-scale tectonism and uplift within the middle Cainozoic. The more dramatic events which elevated the eastern part of the subcontinent (and much of the eastern hinterland of Africa up to the Red Sea) to their present elevations occurred considerably later. Evidence for this late uplift comes from a variety of sources, and its general timing and amplitude are no longer a matter of doubt. Maximum uplift in southern Africa occurred along an axis located some 80 km inland of the southeast coast stretching from Port Elizabeth to Swaziland. Evidence for the extent of this deformation is provided by the long profiles of major rivers of the southeast coast, which are convex upward (Figure 9), clearly and consistently reflecting the influence of recent uplift and warping in an area where similarly pervasive structural and lithological controls are absent. In the area between Paterson and Bathurst, to the east of Port Elizabeth, marine deposits recognized by McMillan & Rogers (in press) as of undoubted early Pliocene age have been raised to elevations of up to 400 m above present sea-level along the seaward flank of the axis, some 15 km from the coast. In the same area, remnants of the African Surface, which are locally overlapped by transgressive marine deposits of late Cretaceous and Eocene age, have been upwarped to inclinations of up to 40 m per kilometre (Maud *et al.*, 1987), which contrasts strongly with gradients of less than 3 m per kilometre in areas unaffected by tectonics. These surface remnants are clearly identifiable and can be readily correlated, not only through their summit accordances, but because of the presence on them of relict duricrust cappings associated with deep weathering profiles. They can be traced through successive topographic sections into the northern areas of Kwazulu–Natal (Partridge & Maud, 1987). Since maximum Pliocene sea-levels are now known to have been about 35 m, on the basis of global correlations by the PRISM Project of the US Geological Survey (Dowsett & PRISM Project Members, 1994), all of these data combine to indicate total uplifts of no less than 700 – 900 m along the crest of the axis of warping. Offshore responses, which indicate a major increase in sedimentation to near Cretaceous rates above a well-defined seismic acoustic reflector, combine with micropalaeontological evidence in indicating that these movements have occurred within the last 5 Ma (Martin, 1987).

In the western part of the subcontinent, the effects of this uplift were less strongly felt and were, once again, reflected largely in an increase in fluvial activity through the westward steepening of river gradients; by contrast, major gorge cutting and dissection occurred in the southeastern coastal hinterland (e.g. the carving of the 500-m-deep Valley of a Thousand Hills) (Figure 10). An important consequence was the amplification of relief along the Great Escarpment through downcutting in the headwater reaches of most rivers. More or less simultaneous subsidence within the Bushveld Basin and reactivation along the Griqualand–Transvaal Axis, documented by Du Toit (1933), were important concomitant events within the continental interior. These Neogene tectonic events are summarized cartographically in Figure 11. In areas of more susceptible lithology inland of the coast, these movements led to replaning of the landscape to produce an undulating Post-African II Surface, but elsewhere the response was overwhelming in dissection and increase of local relief.

The important impacts of these events on regional climates and on plant and animal communities merit some discussion. Uplift of 1000 m is equivalent, in its effects on surface temperatures, to the cooling experienced during an Ice Age in higher latitudes. Its close coincidence in time with the global interval of Pliocene cooling and aridification which occurred between 2.8 and 2.6 Ma would have significantly amplified its overall effects. Among the landscape responses was the creation, for the first time, of the Kalahari Desert which stretches from the Northern Cape to the equator (Figure 12) and whose dunes, now stabilized by vegetation, were reactivated repeatedly during the Pleistocene. I have argued previously, together with Peter deMenocal and Bernard Wood (Partridge *et al.*, 1995), that these events in combination can go far towards explaining the aridification of eastern Africa, the expansion of grasslands, and the accompanying major turnover in antelope and other faunas which occurred in this area during the latter part of the Pliocene. The emergence of our earliest ancestors, the australopithecines, in the eastern hinterland of Africa at that time may have owed much to the massive changes wrought by a combination of tectonic and climatic influences during this critical period.

What are the likely mechanisms of an uplift which was, by any geological standards, very large and very late, and was apparently unrelated to major faulting or volcanism? The answer must be sought in a variety of geological and geophysical evidence. The elevated areas of eastern and southern Africa form part of a globally important positive relief anomaly which Nyblade & Robinson (1994) have called the African Superswell (Figure 13). Extending into the surrounding oceans to the edge of the African Plate, this anomalous area is almost an order of magnitude larger than the Tibetan Plateau; defined in relation to global mean-continental and ocean-floor elevations, its mean amplitude exceeds 500 m and, within large parts of the eastern hinterland of Africa, including southern Africa, the anomaly is greater than 1000 m. A major focus of discussion over the last decade has been the mechanism of uplift where such elevated areas are flanked by passive continental margins. One school of thought holds that thermal mechanisms are limited to the margins of newly developing rifts and that their effects are reduced with time owing to subsequent sediment loading; more areally extensive uplifts post-dating continental rifting are considered to be isostatically induced. Proposed causes of these regional movements include a response to differential unloading, as a result of the recession of escarpments (Gilchrist & Summerfield, 1990; 1994), heating of the lithosphere (as is indicated, for example, by high heat-flow measurements in the Kaapvaal Craton of southern Africa — Nyblade *et al.*, 1990), or lithos-

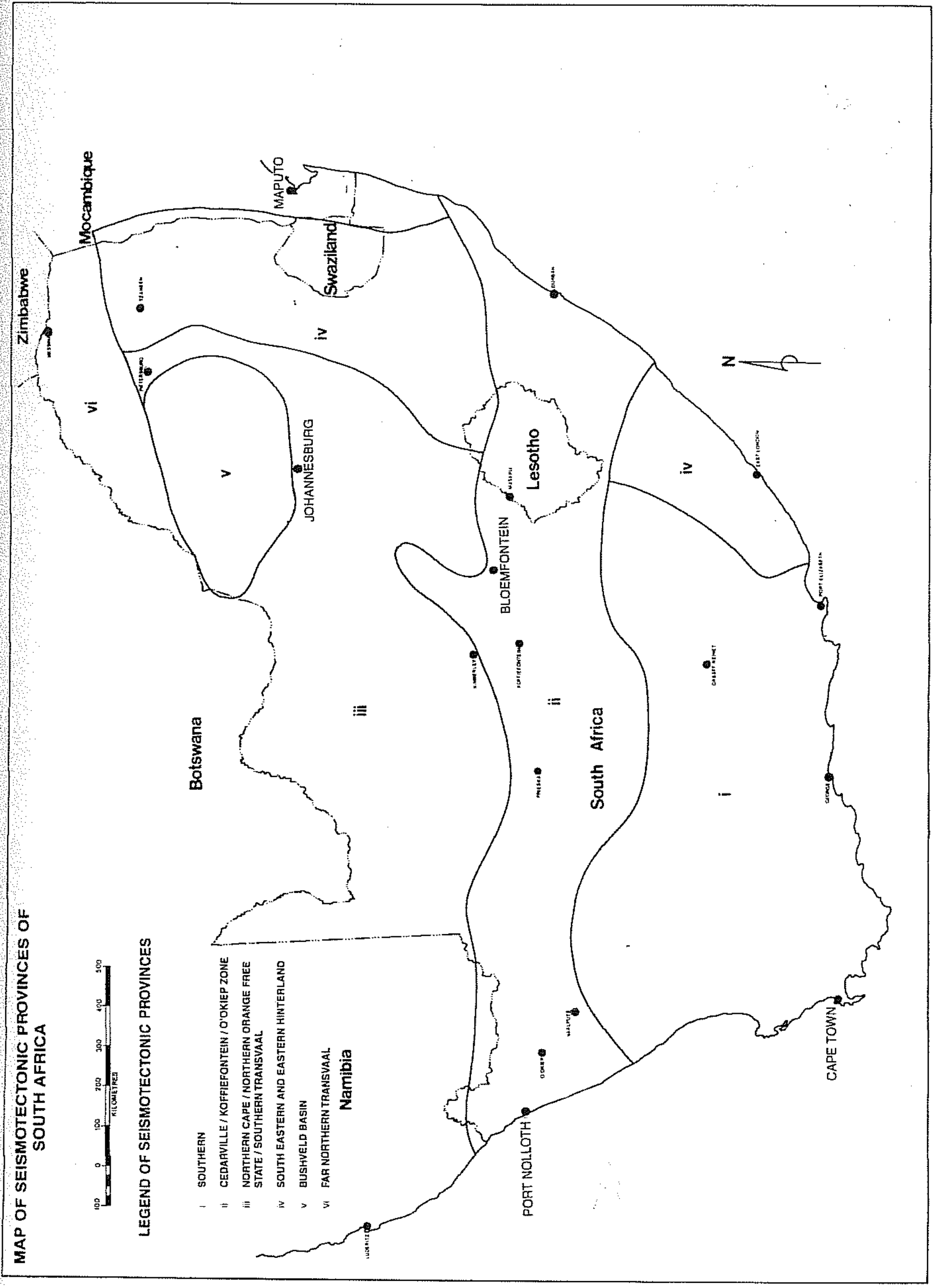

Figure 15 Southern African seismotectonic provinces, based on the data of Figure 14.

pheric thinning, inferred from studies of the regional gravity field and recent volcanism (e.g. beneath the East African Plateau — Ebinger *et al.*, 1989). Although some or all of these mechanisms are undoubtedly in operation, none can satisfactorily explain the geographical extent of the African Superswell or its uplift history, which, on the basis of the evidence from southern Africa, extends through most of the Neogene.

In a recent paper, Lithgow-Bertelloni & Silver (1998) reexamine the problem in the context of dynamic topography, driven by buoyancy forces resulting from lateral density heterogeneities within the Earth's mantle. In their analysis, buoyancy is produced either by cold, subducting slabs (passive upwelling) or by large, active plumes generated in the basal thermal boundary layer. Both alternatives were modelled by them for Africa. The subducting slab model does not satisfactorily replicate the residual topography of the superswell, as defined by Nyblade & Robinson (1994). However, a model of dynamic topography originating from a primary thermal source [manifested in the density field below 325 km depth, which has been reconstructed from the results of seismic tomographic analyses carried out by Su *et al.* (1994) and Grand *et al.* (1997)] reproduces the residual topography well, both in terms of aerial extent and amplitude. It should be noted that these tomographic images have consistently shown that the largest S-wave anomaly within the Earth's mantle is located beneath the eastern and southern parts of Africa (the 'African Super-plume').

The analyses of Lithgow-Bertelloni & Silver (1998) confirm that the unusually high topography of both regions originates from the measured thermal profile within the underlying mantle and is independent of isostatic influences, such as lithospheric thinning or unloading due to large-scale scarp recession. The ability of the new model to provide a good simulation of existing elevated topography from the present configuration of the mantle anomaly gives strong support to the notion that much of the uplift has been comparatively recent, as is indicated by the geological evidence. Thus, despite massive denudation during the Cretaceous, most of southern Africa has re-attained a high elevation in the Neogene as a result of buoyancy forces arising from thermal anomalies deep within the mantle.

In a 1995 paper, Chris Hartnady and I noted that the deformational style in southern Africa possibly reflects the continuing southward development of the African Superswell, which may, in turn, be related to the southward propagation of the East African Rift System (Hartnady & Partridge, 1995). In support of this contention, mention must be made of the results of unpublished neotectonic studies carried out during early 1996. Figure 14 shows the distribution of historic earthquake epicentres and their relationship to, in particular, the axis of Neogene uplift (along which, not coincidentally, the majority of southern Africa's thermal springs are located). From such raw data it is possible to define a series of seismotectonic provinces in southern Africa (Figure 15); on this map particular attention is drawn to Province ii (the Durban–Port Nolloth zone) and Province iv (the Port Elizabeth–Swaziland zone of Neogene upwarping), and v (the Bushveld Basin). It is possible, indeed highly probable, as Hartnady has suggested in a number of papers (Hartnady, 1985; 1990; Hartnady *et al.*, 1992), that the broad zones of intraplate seismicity delineated by the first two of these represent areas of incipient southward extension of the East African Rift system. The coincidence of the provinces in the eastern part of the subcontinent with areas of Neogene uplift (and subsidence, in the case of the Bushveld Basin) in fact indicates, that far from being events of the geological past, these movements may be continuing today, or even accelerating.

Afterword

I have attempted, in this brief review, to demonstrate that, not only is Africa unique among the wandering continents in its recent geological and geomorphic evolution, but that the tectonic events which have given rise to its high plains are far from over. I would like to conclude by quoting from a paper written by Alex du Toit in 1910 entitled 'The evolution of the river system of Griqualand West'. The significance of this bench-mark study has become fully apparent to me only after a very recent re-reading. I quote: '.... as a result of denudation an extensive peneplain was produced at the 6,000-foot level in the Stormberg area at a period when the continent stood at a much lower level than now; from this peneplain there rose to a height of from 2,000 to 5,000 feet — possibly higher — such portions of the volcanic masses of the Drakensberg and Basutoland as had escaped erosion by the head waters of the Orange River ... in the area under consideration the oldest recognizable peneplain is that whose lowest altitude stands now somewhere about 4,000 feet ..... the probability is considerable that the same forces operated over the whole area in question and that the planation in Griqualand West was synchronous with that in the Stormberg..... the cutting of the Kaap–Stormberg peneplain can be ascribed to the close of the Cretaceous epoch, while the entrenchment of the river valleys and the present surface features may have been produced entirely within Tertiary and post-Tertiary times. Through a renewal of river activity brought about by this (late) elevation of the continent, aided by such tilting as may have occurred, the peneplain was gradually dissected into its present condition.' Almost 90 years later I could not have penned a better summary. It is sobering to realize that the results of years of recent fieldwork and research were anticipated by a pioneer geologist working with minimal field aids and without access to the wealth of data from sister disciplines which we now take so much for granted. Alex du Toit was, indeed, a man ahead of his time.

Acknowledgements

It is appropriate on this occasion to pay tribute to those mentors and colleagues who have aroused and fed my passion for African landscapes and, in so doing, have contributed in no small way to the synthesis presented here. My father, Cooper Partridge, fostered an early interest in geology and landforms that was extended, during my years of study, by two outstanding South African earth scientists, Tony Brink and Dennis Fair. More recently, the keen mind and ready wit of Rodney Maud have enlivened many a field trip into remote corners of Gondwanaland and have helped to resolve some thorny problems of landscape evolution.

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