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THE KAROO IGNEOUS PROVINCE: AN INTRODUCTION

by

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ABSTRACT

The Karoo rocks are amongst the earliest manifestations of igneous activity accompanying the break-up of Gondwanaland during the early Mesozoic. Remnants of the once extensive lava sequence and the associated dolerite sills are found throughout southern Africa south of latitude 15°S, the present outcrop being *ca.* 140,000 km^2. The main peak of volcanic activity is dated at about 190 m.y. and is probably coincident with the earliest stages of the opening of the Indian Ocean by the separation of Antarctica from southern Africa. A conspicuous later peak of activity occurred at about 120 m.y. (Lower Cretaceous) at the time of the opening of the South Atlantic, the rocks of this age being mainly developed in SWA/Namibia. Over most of southern Africa Karoo tectonics are extensional in nature and are strongly controlled by existing basement structure. Events leading up to the volcanism began with the establishment of a sedimentary trough in the southern part of the continent during the Ordovician. The trough received the sedimentary accumulations of the Cape and Karoo Supergroups (the Karoo basin) with, during the Karoo period, a thinner sequence of shallow marine and continental sediments stretching far to the north. The tectonism of the Cape Fold Belt was initiated relatively early in the Karoo period. The succeeding volcanic rocks can be broadly subdivided into those of the central parts of the continent (e.g. the Karoo basin dolerites, the lava sequences of Lesotho and neighbouring areas of the Cape Province) which are overwhelmingly basaltic in nature with the exception of some more dacitic types at the base locally. These sequences extend into the Transvaal (Springbok Flats), Namibia (Mariental) and Botswana but the major outcrops in Namibia consist of the mixed basaltic-acid (latite and quartz-latite) succession of the Etendeka of Lower Cretaceous age. In the east a monoclinal lava sequence is found stretching from northern Mozambique to Natal, and probably marks the boundary between normal continental crust and thinned continental crust bordering the Indian Ocean. The rocks of this zone are varied, consisting of picrite basalt, nephelinites, basalts, tholeiitic andesites, and great thicknesses of rhyolites in the southern part of the structure termed the Lebombo Monocline. An alkalic series including phonolites overlies the Karoo rocks in the Zambezi valley. Large plutonic complexes are developed principally in Namibia (e.g. Erongo, Brandberg, Okonjeje) and the Nuanetsi–Sabi area of south-east Zimbabwe (e.g. Northern Ring, Mateke, Dembe-Divula, Marangudzi). Syenitic plutons of Cretaceous age are present in southern Malaŵi (Chilwa Series). Carbonatites are present both here and in south-east Zimbabwe, where they are of early Karoo age (*ca.* 200 m.y.). Extensive geochemical studies demonstrate the strongly bimodal (acid-basic) nature of the Karoo sequences, especially along the margins of southern Africa. The Karoo province provides excellent material for testing a number of rival hypotheses of magma generation. These are (a) the role of crustal contamination versus an enriched lithospheric source for the generation of continental basalts, and (b) the origin of silicic volcanics. Are these fractionation products of associated basalts or are they generated by partial melting in the crust or mantle?

CONTENTS

I. INTRODUCTION

During the period extending from the late Triassic, through the Jurassic and into early Cretaceous, the fragmenting Gondwanaland supercontinent was subjected to an igneous event of huge proportions. Evidence for this magmatic activity is now found in scattered outliers of volcanic sequences and an underlying intrusive sub-volcanic complex in nearly all of the southern continents. The vast areal extent of dykes and sheets of intrusive dolerites and gabbros and their derivatives, and less abundant granites, granophyres and undersaturated alkaline rocks, including carbonatites, mostly in the form of ring complexes, demonstrates that the lava sequences are small erosional remnants of a once much thicker and presumably more extensive volcanic blanket.

Karoo igneous rocks in southern Africa and similar rocks in Antarctica and Tasmania date from the early Mesozoic and are the earliest manifestations of Gondwanaland flood basalt activity. This event was followed by the Paraná (Serra Geral) basalts of South America in the early Cretaceous and the coeval Etendeka suite in SWA/Namibia (hereafter referred to simply as Namibia). In the early Tertiary the Deccan traps were erupted in India and in the later Tertiary the Ethiopian and Yemen traps appeared in north-east Africa and Arabia. Though not associated with Gondwanaland, similar provinces also developed in the northern hemisphere at a variety of times, the Siberian traps in the early Mesozoic, the North Atlantic province in the early Tertiary and the Columbia River province in the late Tertiary.

In southern Africa the Mesozoic igneous activity is broadly referred to as the Karoo volcanic event as it followed, without any major hiatus, the extensive and prolonged sedimentation of the Karoo Supergroup. Major outcrops of Karoo volcanics are now preserved in areas where different tectonic regimes prevailed during their eruption. These are the thick monoclinally warped lavas of the Lebombo–Nuanetsi–Sabi lineament; the horizontally bedded intracratonic sequences of Lesotho, Botswana and central Namibia; and the Etendeka sequence of the Atlantic seaboard in north-western Namibia (Fig. 1).

These sequences, with their undoubted relationship to the rifting and fragmentation of Gondwanaland, resulted in the Karoo igneous rocks being selected for detailed investigation under the sponsorship of the South African National Geodynamics Programme. The theme of the research project is the petrology and geochemistry of Karoo volcanics in relation to geodynamic processes. This volume presents the results and interpretations of the Karoo volcanic project and, we hope, provides a little more insight into one of the more significant events in our Earth's history. It is hoped that this contribution will serve as a useful introduction to the reader in gaining an insight into the Karoo Igneous Province as a whole, particularly the overall geology, stratigraphic relationships and details of the distribution of the various Karoo igneous rocks.

II. DISTRIBUTION AND AGE

Igneous rocks emplaced during the Karoo volcanic event occur scattered throughout the southern subcontinent of Africa. The area presently underlain by the exposed but eroded remnants of the volcanic rocks amounts to at least 140,000 km^2, with the outcrops occurring within an area extending from the coastal regions of the south-eastern Cape Province (33°12′S) northwards through Lesotho, Botswana, southern Namibia, Zimbabwe and Zambia. To the west, Cretaceous lavas form extensive outcrops in the Etendeka region and extend to the Namibian seaboard as well as further to the north and south. To the east, early Jurassic and younger basalts and rhyolites are continuously exposed for close on 1100 km where they are involved in the easterly dipping monoclinal Lebombo–Sabi flexure, while further north the exposures of the lower Zambezi valley include Jurassic basalts and younger rhyolites as well as the Cretaceous alkaline lavas of the Lupata Series. Karoo igneous rocks have also recently been identified as far north as latitude 15°S on the Mozambique coast near António Enes.

The area of sub-outcrop is in turn far greater than that of sub-aerial exposure. Extensive sub-outcrops have long been assumed to be present beneath the Cainozoic deposits of the Kalahari Basin, the available evidence having prompted Poldervaart (1952) to suggest the existence of a Karoo basin extending from Keetmanshoop in south-eastern Namibia to Palapye in eastern Botswana, and northwards to the Victoria Falls. He considered that the basalts at the top of the succession here constituted "the largest single area of Karoo basalt of the African continent". Subsequent accumulation of borehole and aeromagnetic data has shown Poldervaart's estimate to be excessive (Green, 1966; Reeves, 1979), since the sub-outcrop within the basin is not continuous, but nevertheless the Central Kalahari outcrops and sub-outcrops of basalt alone have an estimated area greater than 150,000 km^2, roughly six times the size of the Lesotho–northern Cape remnant. In Zambia, likewise, there is evidence of further sub-outcrops beneath Kalahari sands and alluvium, and Drysdall and Weller (1966) suggest that the greater part of the extensive Barotseland basin of western Zambia may be underlain by Karoo sediments and volcanics. These sub-outcrops would appear to extend south-westwards via Caprivi into north-eastern Namibia. Furthermore, the monoclinal flexure of the Lebombo carries Karoo basalts and rhyolites beneath Cretaceous–Tertiary sediments to the east, and there is good evidence from geophysical and borehole data (Darracott and Kleywegt, 1974) for believing that the sub-outcrop of volcanics extends at least as far as the present coast south of Maputo (Lourenço Marques). Further north, the huge area incorporating the Mozambique "bulge" between 20° and 26°S is, according to the interpretation of Flores (1970), at least in part underlain by Karoo and Cretaceous volcanics (the latter possibly equivalent to a southward extension from the Lupata area). This view is reinforced by the fact that volcanics have been intersected in deep wells near the Mozambique coast between latitudes 22° and 25°S, at depths of 1800–3300 m (Flores, 1970, 1973), more than 300 km east of the Lebombo outcrops.

Covering a profoundly greater area of outcrop than the lavas is the sub-volcanic complex of dykes, sills and central ring intrusions. Examples of these are found in an area stretching from Angola, through Zambia, into Malaŵi and Mozambique and southwards to a latitude of about 33°S. The ring complexes consist of suites of highly differentiated tholeiitic and alkaline rock types, including carbonatites, and are frequently located in linear belts as in Damaraland in Namibia (Martin *et al.*, 1960), Nuanetsi in south-eastern Zimbabwe (Cox *et al.*, 1965) and in Angola (Rodriques, 1970). These complexes are often interpreted as sites of central volcanic activity but they probably did not contribute significantly to the main Karoo flood lava pile.

Intrusive sills and transgressive sheets are usually located within horizontal Karoo sedimentary strata where they may attain thicknesses of several hundred metres and exhibit marked differentiation effects. Within the main Karoo sedimentary basin sill intrusions are particularly well developed in terms of both thickness and number in strata of the Beaufort Group. In the lower Karoo horizons sills are common but are thinner. Above the Beaufort Group dykes become more prominent. Generally dykes are unrelated to the sills and have a non-uniform distribution both within Karoo strata and in the underlying pre-Karoo rocks. In several areas they are concentrated in prominent swarms, for example the Rooi Rand dykes of the southern

Lebombo, the Gap-dyke swarm in Transkei, and the swarms in Damaraland (Namibia), northern Botswana (Reeves, 1978a), Nuanetsi, along the lower Zambezi, and in southern Malaŵi (Vail, 1970). In some instances these swarms are identified as being the principal feeding channels to the overlying lavas but in several areas, e.g. Lesotho, lavas appear to have been erupted from more diffuse zones of narrow dykes.

Thus the widespread nature of the sub-volcanic complex implies a much greater original extent of the lavas before erosion. Similar conclusions are suggested by the occurrence of abundant basalt xenoliths within some younger diatremes exposed in areas now several hundreds of kilometres distant from present-day remnants. Heterolithic kimberlite breccias of this type occur, for example, at Postmasburg and Prieska in the northern Cape (Du Toit, 1954) and Kolonkwanen (26°39.4′S, 21°59.6′E) on the northern Cape–Botswana border (J.B. Hawthorne, pers. comm.) where diatremes contain up to 70% lava fragments. These occurrences are of particular significance, being suggestive of an original continuation, far to the south and west, of the Kalahari and Lesotho lava fields. In central Zimbabwe, present-day outcrops of Karoo lavas amount to no more than minor outliers at Featherstone south of Harare (Salisbury — 18°45′S, 30°45′E), but some evidence for believing that the greater part of Zimbabwe was once covered by volcanics has been presented by Worst (1962). It is therefore reasonable to accept that even the considerable thickness (1370 m) of basaltic lavas building the escarpment east of the Lesotho plateau is but a remnant of a once thicker pile. The original thickness of this remnant overlying the stable craton remains unknown, but it is unlikely to have approached the estimated 6000–10,000 m attained within the Lebombo region where volcanism was contemporaneous with monoclinal flexing and crustal depression along the eastern edge of the craton (Saggerson and Logan, 1970) or rifting (Flores, 1970; Burke and Dewey, 1973).

A very large number of radiometric age determinations have been carried out on Karoo rocks and are discussed in a later chapter. In summary, the main phase of basaltic volcanism in the Lesotho–Cape Province area appears to have started at about 190 m.y. (Fitch and Miller, 1971) with minor eruptions which may be slightly older. In the same area dolerite ages obtained by these authors and by McDougall (1963) suggest that basaltic magma continued to be emplaced until about 150 m.y. Fitch and Miller (1971) suggest that volcanism in the Province was episodic, but it is felt that the available data are too few to offer unequivocal support to this proposal.

In north-western Namibia age relations are complex and not so far fully resolved. Some igneous activity of the same age as that of the Lesotho area evidently occurred, giving dates of 180–190 m.y. (e.g. dolerites and gabbro at Okonjeje, mica from the Spitzkop granite) but much of the activity appears to be somewhat younger. Ages seem to group round values of *ca.* 134 m.y. (dolerites, Paresis complex rhyolites, Messum complex) and round 121 m.y. (Etendeka lavas, some dolerites).

In the southern Lebombo region the main phase of volcanism appears to be a little later than that of the Lesotho area, at about 185 m.y. although some younger ages are also reported. In the north, at Nuanetsi, volcanism probably started at 200 m.y. and continued to at least 173 m.y. In the Zambezi valley Karoo lavas have yielded ages of *ca.* 166 m.y. and the overlying Lupata Series ages as young as 106 m.y. On the north Mozambique coast ages of *ca.* 160–180 m.y. have been obtained from the main outcrop, with two dates in the range 120–130 m.y. from the extreme north (near Mozambique Island). The intrusions of the Chilwa Alkaline Province in Malaŵi (Woolley and Garson, 1970) yield ages ranging from 105 to 136 m.y.

In summary, it seems likely that the great majority of Karoo igneous rocks date from the earliest part of the Jurassic period, accepting the Lower Jurassic as ranging from 192 m.y.–171 m.y. (Van Hinte, 1976). Relatively minor igneous activity may have persisted through the Middle Jurassic and to a lesser extent the Upper Jurassic. A conspicuous peak of activity is then recorded in the Lower Cretaceous in Namibia, the Zambezi Valley, Malaŵi, and possibly also in north Mozambique (accepting the base of the Cretaceous as 135 m.y., Van Hinte, 1976).

III. TECTONIC SETTING

Because of a probable connection between Karoo volcanism and the break-up of the Gondwanaland supercontinent a brief review of continental drift and of marine geological features adjacent to southern Africa may be of interest. The principle events are summarized below.

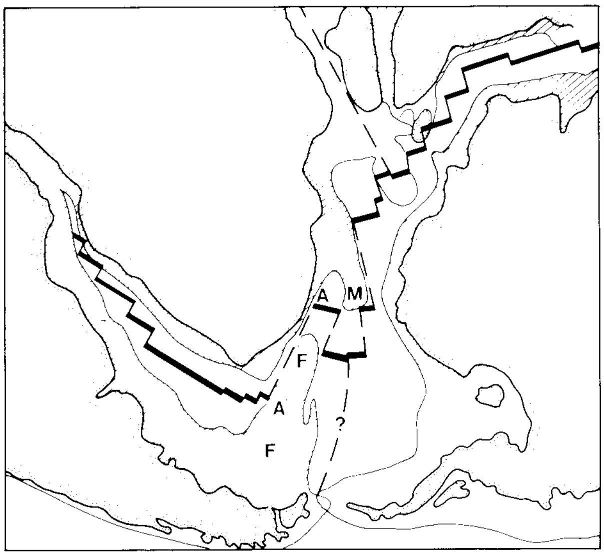

Figure 2
The break-up of Gondwanaland at the time of anomaly M-1 (115 m.y.) after Norton and Sclater (1979). Heavy lines — spreading axes; broken lines — transform faults; diagonal shading — areas assumed to consist of continental crust, thinned in part; stipple — existing continental coast lines; continuous light lines — existing continental shelf edges; A-A Agulhas fracture zone; F — Falkland plateau; M — Mozambique ridge.

The fragmentation of the supercontinent (see Fig. 2) was initiated by the separation of East Gondwanaland (Madagascar, India, Antarctica, Australia) from West Gondwanaland (Africa, South America). Kent (1974) reports tectonic activity in East Africa in the late Carboniferous which may represent the earliest stages of this process. Extensional tectonics in the Zambezi and Limpopo regions during the Ecca (Permian) are similarly proposed by Cox (1970). Kent *et al.* (1971) and Kent (1974) note a Permian marine transgression in East Africa and Madagascar and the establishment of open marine conditions in the early Jurassic.

Movements during this early period of separation appear to have been accomplished by spreading at short east–west ridge segments and motion on long north–south transform faults, though the record is fragmentary. The oldest indentifiable sea floor spreading magnetic anomalies are found in the Mozambique Basin (Ségoufin, 1978) and extend from M-0 to M-22, the latter dated at *ca.* 145–150 m.y. The anomalies run approximately east–west with M-22 lying at latitude 22°S immediately west of Bassas da India (see Fig. 3) and M-0 lying directly to the south at latitude 27°30′S. Madagascar appears to have drifted from the north into its present position (Norton and Sclater, 1979) and the implied magnetic anomalies in the Somali basin have recently been discovered (Parson *et al.*, 1981). The existence of east–west anomalies in both the Mozambique and Somali basins does not support the alternative suggested position for Madagascar against the coast of Mozambique (e.g. Flores, 1970). Previous work suggested that the oldest identifiable sea floor spreading magnetic anomaly in the South Atlantic was M-12, dated at approximately 128 m.y. Many authors have accepted this as the time of opening of the South Atlantic (e.g. Larson and Ladd, 1973; Dingle and Scrutton, 1974; Rabinowitz and La Brecque, 1979) though dates as old as 160 m.y. have also been suggested (Emery *et al.*, 1975). More recently, Austin and Uchupi (1982) have concluded that the ocean crust off Cape Town is not older than magnetic anomaly M-9 (121–126 m.y.). The essential elements of movement in this second main stage of breakup include the opening of the South Atlantic by rifting and the development of the Agulhas fracture zone as a transform fault as the Falkland plateau moved to the south-west relative to South Africa. The extreme eastern end of the Falkland plateau, which is known to be underlain by continental basement (Barker *et al.*, 1976) appears to have fitted into the Natal valley (e.g. Scrutton, 1976).

Amongst the various bathymetric features near the coast of southern Africa, the Walvis Ridge (Goslin *et al.*, 1974; Goslin and Sibuet, 1975; Richardson *et al.*, 1982) appears to be a purely oceanic structure. The Agulhas Plateau (Scrutton, 1973; Emery *et al.*, 1975) has been similarly interpreted but now appears to include at least some continental material (Tucholke *et al.*, 1980). The Agulhas bank in contrast is an extension of the continental crust, abutting abruptly along the Agulhas fracture zone against oceanic crust (Du Plessis and Simpson, 1974). From the point of view of Karoo studies particular interest is attached to the Natal valley (Dingle *et al.*, 1978) and Mozambique ridge, because of their position adjacent to and offshore from the thick volcanic sequence of the Lebombo monocline. Seismic basement crops out in the Almirante Leite and Naude ridges within the Natal valley and on the Mozambique ridge itself (Dingle *et al.*, 1978). Basalt has been recovered from a drill hole (site 249) on the Mozambique ridge (Erlank and Reid, 1974) and basalts are also encountered in deep drill holes (4.5 km) beneath the sedimentary cover in eastern Mozambique near Maputo (Hazzard *et al.*, 1971). It seems likely, though it is far from proven by present data, that the basalts observed in these areas represent the upper part of an essentially continental sequence of crustal rocks which has been thinned by extension and block faulting (see section in Scrutton, 1976). Geophysical data are so far less than adequate to define the junction between continental and oceanic crust in this south-eastern part of the African coast. The occurrence of Precambrian basement rocks *east* of the Lebombo monocline at its southern end indicates that at least locally the Lebombo is not the continental margin and reinforces the impression that there may be a wide zone of thinned continental crust lying offshore. An analogy is found in the structure of the west Greenland coast in the vicinity of Svartenhuk peninsula and Ubekendt Island where a thick Tertiary basalt sequence dips off the basement into the Davies Straits but is faulted offshore against a second zone of basement rocks (Clarke and Pedersen, 1976). Thus, with present data it seems most plausible to regard the Lebombo monocline as marking an abrupt transition from normal to thinned and block-faulted continental crust, rather than as the true continental edge.

The sedimentary rocks of the Karoo were deposited over most of southern Africa upon a basement of much greater age, the disposition of which is shown in Fig. 3. The oldest basement units are the Archaean cratons of Zimbabwe and the Transvaal, which are separated by the Limpopo belt in which deformation was completed at about 2600 m.y. (Van Breemen and Dodson, 1972) and metamorphism by about 2000 m.y. The Angola craton in the north-west has been a

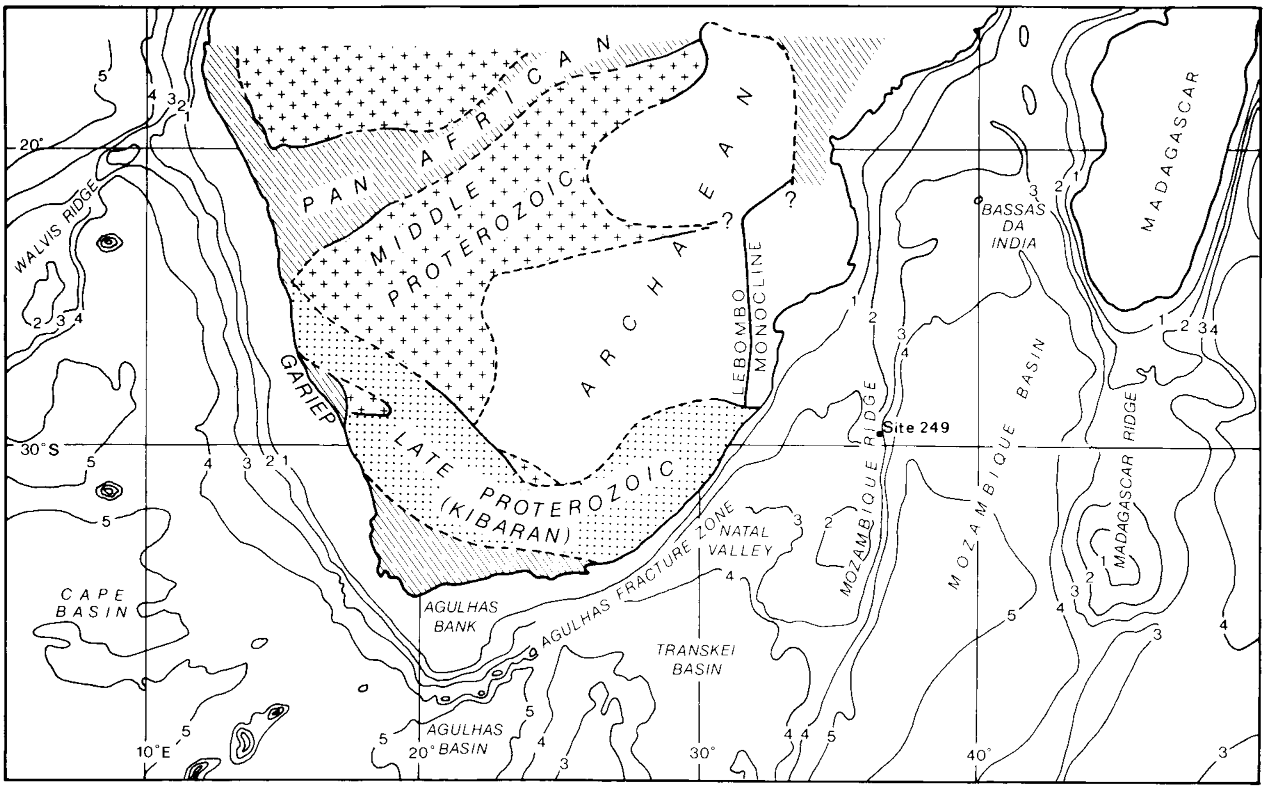

Figure 3

Basement geology of southern Africa (largely after Clifford, 1970, and Hartnady, C.J., pers. comm.) and bathymetric features in the surrounding oceans (after Scrutton *et al.*, 1975; Norton and Sclater, 1979). Tectonic boundaries: Solid lines, observed; dashed lines, inferred and geophysical.

stable area since approximately 1850 m.y. The Transvaal craton is bounded in the south and west by the Namaqua–Natal belt, a zone of tectogenesis metamorphosed at about 1000 m.y. (Nicolaysen and Burger, 1965). Rocks of a similar age are also found in the Upper Zambezi valley. Somewhat younger are the extensive areas of basement rocks which were metamorphosed during the Pan-African thermo-tectonic event of late Precambrian to early Palaeozoic age (700–400 m.y.). The main subdivisions within this group are the Mozambique belt in the east with its offshoot in the Zambezi valley (Zambezi belt), the Katangan belt in Zambia and the Damaran and Gariep belts in Namibia. Also broadly assignable to this episode are the relatively small inliers of the Malmesbury Group which form the basement to the Cape Supergroup in the extreme south.

Many of the metamorphic belts listed have undergone a complex tectonic evolution including periods of rejuvenated tectonic activity at a variety of times (e.g. Kröner, 1977). Minor rejuvenation of these apparently long-lived lines of crustal weakness has had considerable influence on the deposition of Karoo sediments and on the focusing of igneous activity.

The clearest examples of basement control are found in zones adjacent to the Rhodesian craton. To both north and south, zones of extensional tectonics concentrated in the Limpopo and Zambezi valleys coincided with the younger metamorphic belts and led to the development of troughs of Karoo sedimentation. Later, ring complexes and dyke swarms were emplaced along the centre line of the Limpopo belts, and sub-units within the belt exerted a detailed influence on the disposition of positive and negative areas of sedimentation and volcanic accumulation (Cox, 1970). Ring complexes were also intruded into the Damara belt in Namibia.

Further to the south the more extensive cover of Karoo sediments obscures the basement geology. However, it is at least possible that the main Karoo basin, a structure elongated in an east–west direction, owes its existence and location to similar extensional tectonics operating on a basement of Namaqualand–Natal belt gneisses, assumed to continue beneath the basin. In the east the Lebombo monocline is frequently plausibly assumed to be located along or near the southward extension of the western front of the Mozambique belt, though there is no direct evidence of this because of the thick cover of Karoo and younger rocks. Zones of Karoo extensional tectonics can be recognized by the occurrence of both normal faults and dyke swarms. In some areas these are coincident and clearly match the broad outlines of basement structure (e.g. Limpopo valley) but the particularly extensive west-north-west dyke swarm (Reeves, 1978a) which extends from south-east Zimbabwe across Botswana into Namibia (see Fig. 1) does not coincide with any known earlier structures. Clearly the idea that extension during the Karoo period operated upon a continental crust well endowed with ancient zones of inhomogeneity and weakness explains many but not all of the features of Karoo tectonics.

IV. PRE-VOLCANIC HISTORY

The onset of the main phase of Karoo volcanism was the culmination of a long period of marginal and intracratonic sedimentation which, in South Africa, lasted from the Ordovician through to the early Jurassic. The tectonic and sedimentary history of this period has been reviewed in two papers by Rust (1973, 1975) and these sources have been used extensively for the summary presented here. Where appropriate the results of more recent studies have been incorporated.

In South Africa, events leading up to the Karoo volcanism began with the establishment, in the Ordovician, of a deepening, latitudinal trough south of 21°S. This trough was characterized by marine and transitional environments and is sited on an eroded basement of Pan-African medium-grade metamorphic rocks and intrusive granites. For close on 200 m.y. it received from the north and north-west the supermature arenites, shales and siltstones which collectively attain a thickness in excess of 8000 m and constitute the Cape Supergroup. It has now been well established (Johnson, 1976; Stapleton, 1977; Dunlevey and Hiller, 1979) that a considerable hiatus separates these sediments from the overlying glaciogenic materials of the Dwyka Group, the lowestmost unit of the Karoo Supergroup. This hiatus appears not to have affected the continuing development of the trough as it is also the site of thick accumulations of sediments of the Dwyka Group (~1200 m) and the succeeding Ecca Group (~3000 m). However, strata from these groups overstep those of the Cape Supergroup to the north and lie directly on cratonic basement rocks of a wide variety of ages over much of southern Africa. Moreover, the supply of sediment to the southern Karoo basin changed from the north to the south, and non-marine environments replaced the marine environment in the southern trough during accumulation of middle and upper Ecca Group sediments.

Thus, during the lower Permian a complementary shallow-water shelf-type environment was established to the north of the deep southern trough. In all probability the shelf-type repository existed as several basins, not always interconnected, and grooved by glacially-eroded valleys. The thick piles of Dwyka tillite are located in these valleys throughout Namibia, northern Cape Province, Orange Free State, Transvaal and Natal, and the overlying Ecca strata frequently overstep the tillites to form the base to the Karoo sequence on the topographic highs. The Windhoek Highlands and Witwatersrand Arch probably existed as more positive structural elements and were subsidiary suppliers of detritus to the basins. Further north, the lower Karoo sediments collected in the fault-controlled Zambezian and Tuli–Soutpansberg troughs stretching in an arcuate configuration around the Rhodesian Craton which existed as a major positive structural feature until the late Triassic.

In the south, deposition of the Beaufort Group sediments from the middle of the Permian to the early Triassic proceeded conformably on those of the Ecca Group. Again the maximum thickness (>5000 m) is located along the site of the southern trough with progressive thinning to the north. The depositional basin was much more restricted and Beaufort sediments are therefore absent from Namibia, western Botswana, central and eastern Transvaal and the Soutpansberg basin. Correlatives of the lower Beaufort, the Madumabisa shales are, however, found in the Zambezian repositories in Zimbabwe and Zambia.

There is strong evidence that by the middle of the Permian a prominent orogenic mountain belt was established south and south-east of South Africa and that deformation of the deep southern trough was initiated. This mountain belt supplied molasse-type sedimentary material to the Karoo basin during the middle and late Triassic to form some of the coarse arenaceous units in the middle and upper parts of the Beaufort Group and the overlying Molteno Formation of the Stormberg Group. The Molteno Formation has a limited distribution within the main Karoo basin thickening from 28°S southwards in a wedge shape to reach in excess of 700 m along the southernmost outcrops north of 32°S.

The uppermost units of the Stormberg Group, the Elliot (Red Beds) and Clarens (Cave Sandstone) Formations, overlie the Molteno Formation and had a much wider distribution than the latter, overstepping it to the north to form a thin cover over most of the Transvaal and eastern Botswana. Only remnants of this veneer are preserved beneath volcanics in the Springbok Flats area, along the

Lebombo range and in the Soutpansberg trough. In Namibia correlatives of the Clarens Formation, the Etjo Sandstones, occur over considerable areas in the southern Kaokoveld and the Waterberg and Omatako Hills north of Okahandja. During deposition of the Upper Stormberg sediments the southern mountain belt was well established and upwarping of the basin margins had begun so that the provenance for much of the Clarens Formation was Beaufort sediments as well as granite-gneiss terranes. In the far north, strong faulting controlled sedimentation in the Zambezian repositories and initially correlatives of the lower Stormberg Group were confined to narrow troughs but upper Stormberg sediments overstep lower Karoo rocks and form thin but extensive deposits on the Rhodesian Craton.

The existence of a major orogenic belt immediately south of, and impinging on, the southernmost part of South Africa suggests that volcanic activity associated with this orogenic belt may have supplied material to the Karoo sedimentary pile in South Africa. There is growing evidence that there is indeed a significant component of distal volcanic material in the Karoo sediments. Lock *et al.* (1974) have reviewed some of the evidence, and additional information is provided by Elliott and Watts (1974), Lock and Johnson (1974), Martini (1974), Wilson (1974), Ho Tun (1979) and in the review of Le Roux *et al.* (1979). Volcanic materials described by these authors are located in Dwyka, Ecca, and lower Beaufort sediments and are generally believed to have sources beyond the Karoo basin. These volcanic products do not have the same significance as the bentonites described from the Elliot Formation by Botha and Theron (1967), the laumontite in Stormberg sediments discussed by Fuller (1970) and the thin basaltic flows and breccias found in the Elliot and Clarens Formations at Siberia (Robey, 1976) and Birds River (Eales and Booth, 1974) in the Dordrecht district (see Fig. 4) and at Tent Kop in the Maclear district (Du Toit, 1954). These occurrences are found stratigraphically within a hundred metres of the main pile of Karoo lavas and foreshadow the true beginning of major volcanic activity *within* the Karoo Basin.

V. THE REGIONS OF THE KAROO PROVINCE

A. Lesotho and North-eastern Cape Province

In the highlands of Lesotho and the north-eastern Cape (see Fig. 4) the remnants of the once extensive pile of basaltic flood lavas attains a maximum thickness of about 1400 m at Mont-aux-Sources (18°45′S, 28°50′E). Detailed work has been carried out during the present project on the lower part of the sequence, which follows, in general, conformably on the Clarens Formation, although locally there is a more complex relationship between the two. Intercalations of basalt and sandstone are common in the lower part of the volcanic succession in the Barkly East and Maclear areas, indicating that the earliest volcanic activity overlapped considerably with the deposition of the uppermost Karoo sediments. Prior to the onset of the main eruptive stage the sub-volcanic surface acquired considerable topographic relief of the order of 100 m or more. Local unconformities between the volcanic succession and the underlying sandstone abound and many of the volcanic units wedge out against prominent Clarens Sandstone arches (Du Toit, 1954, p. 301; Lock *et al.*, 1974).

The work of Lock *et al.* (1974) and Mitchell (1980) has shown that the early volcanic history of the area in the vicinity of Barkly East (30°57′S, 27°32′E) and Jamestown (31°07′S, 26°47′E) was complex. In these areas volcanic activity apparently commenced at discrete centres which built up lava shields and, through periods of explosive activity, deposited thick sequences of pyroclastic rocks over wide areas. The location of these centres can be identified by the large breccia-filled vents at Kelvin Grove, Broadford, Belmore and Glen Fillan in the Barkly East district (Du Toit, 1904), at Tulloch in the Elliot district, and at Modderfontein and Zwartfontein in the vicinity of Jamestown (Gevers, 1928).

Evidence for the existence of aqueous environments during the early stages of volcanic activity is plentiful. The presence of thin sandstone lenses interbedded with the lower volcanics demonstrates the existence of playa lakes. Some of the lenses are extensive, stretching for several kilometres, although they are seldom more than 10 m thick. One exception is the very extensive lens exposed in the

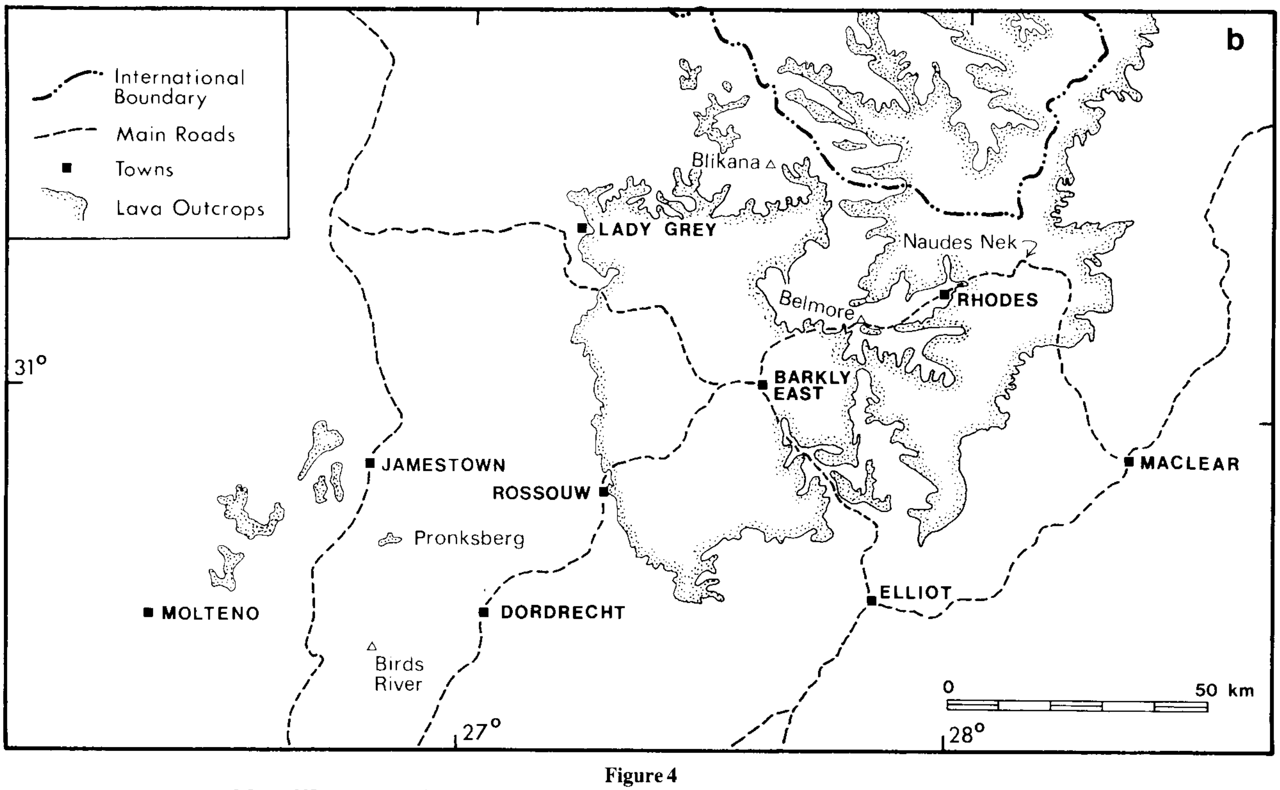

Figure 4
Map of Karoo volcanic outcrops and principal localities in the north-eastern Cape Province.

TABLE I
Average Analyses — Central Area of Karoo Province

	Lesotho Type	Moshesh's Ford Type	Kraai River Type	Omega Type	Vaalkop Type	Pronksberg High-K Type	Springbok Flats Type	Hangnest bulk Type	Pronksberg Dacite	Bellmore Andesite	Roodehoek Dacite	Chilled Dolerite (Lesotho type)
%												
SiO_2	51.50	52.47	54.17	50.93	52.94	53.66	51.10	53.88	65.40	63.24	66.35	51.76
TiO_2	0.95	1.03	0.87	0.93	1.12	1.01	1.32	1.09	0.78	0.79	0.78	1.00
Al_2O_3	15.69	15.98	15.23	15.83	15.50	16.23	14.45	15.83	17.13	15.84	16.01	15.23
Fe_2O_3	10.96	10.21	10.07	10.97	10.47	10.21	13.36	9.96	6.35	7.09	6.03	10.90
MnO	0.16	0.18	0.20	0.24	0.22	0.23	0.18	0.16	0.17	0.18	0.16	0.20
MgO	7.01	5.94	6.58	7.10	6.40	6.45	6.30	6.53	2.36	3.24	2.49	6.86
CaO	10.69	10.36	10.05	11.00	9.55	6.75	10.61	9.24	2.77	4.95	2.56	10.57
Na_2O	2.17	2.49	2.12	2.37	2.53	3.35	1.96	2.19	3.38	2.26	2.49	2.28
K_2O	0.70	1.13	0.56	0.50	1.04	1.90	0.53	0.89	1.44	2.25	2.95	0.56
P_2O_5	0.16	0.21	0.15	0.14	0.22	0.20	0.19	0.22	0.21	0.17	0.19	0.17
ppm												
Ba	177	264	173	153	276	649	235	310	761	571	650	213
Sr	192	309	214	217	279	524	185	201	323	295	256	208
Rb	12	20	21	10	27	38	7.5	28	146	104	123	13
Zr	94	146	118	80	117	139	117	150	203	203	227	97
Nb	4.9	16	4.8	3.1	7.1	16	3.7	4.6	13	11	11	6
Zn	86	83	83	77	90	87	94	88	97	84	87	87
Co	48	41	38	50	45	40	51	39	19	23	20	46
V	240	193	240	238	254	161	285	186	68	104	91	243
Ni	94	70	51	104	23	72	57	3.7	28	32	23	87
Cr	283	273	264	341	338	235	156	385	54	89	86	275
Cu	87	72	63	88	43	75	150	20	27	37	22	92
Y	24	26	28	25	29	26	31	26	31	31	31	26
N*	(49)	(19)	(24)	(13)	(11)	(7)	(5)	(10)	(12)	(8)	(7)	(22)

*N is number of analyses included in average for the major oxides. Averages for trace elements are for the same or fewer number of analyses. All analyses recalculated to 100 % volatile-free (Microfiche Card 2 attached to this volume).

Total Fe as Fe_2O_3.

Heuningneskloof west of Barkly East. This lens has a maximum thickness in excess of 130 m and extends for over 25 km (Swart, 1979). Other evidence for aqueous environments comes from the presence of pillow lava and lava-pod complexes in the lowermost lavas at several localities (McCarthy, 1970; Botha, 1971; Lock *et al.*, 1974). The main bulk of the lava succession comprises an uninterrupted sequence of basalt lava flows. Nearly all flows are of the pahoehoe type and are amygdaloidal. Thicknesses of individual flows vary from less than half a metre to more than 50 m.

Applying normal stratigraphic techniques, Lock *et al.* (1974) have subdivided the volcanic sequence in the Barkly East area into a number of lithostratigraphic units which can be mapped over wide areas. The succession in the Barkly East area commences with the basal Moshesh's Ford Formation comprising coarse-grained olivine-basalts (Drumbo and Donnybrook members) and various types of pyroclastic rocks. The Moshesh's Ford Formation is overlain by the Kraai River Formation, characterized by massive aphanitic basalts and widespread development of pillow-lava, lava tubes and lava-pod complexes. In the vicinity of the Kraai River Pass just west of Barkly East an unusual unit which may represent a ponded lava flow, the Omega Member, occurs at the base of the Kraai River Formation. All the volcanic rocks overlying the Kraai River Formation are grouped into the Lesotho Formation which, apart from the recognition of the distinctive Barkly Basalt member and the underlying Birkhall pyroclastic member near the base of the formation, is not subdivided. The Lesotho Formation thus comprises the vast bulk of basalt flows that build the Lesotho highlands. These stratigraphic subdivisions of the volcanic sequence apply only to the Barkly East region. Mapping by Mitchell (1980) indicates that stratigraphic subdivision of the volcanic outliers in the Jamestown district is also possible and that the succession is somewhat different although no formal stratigraphic names have been proposed for the volcanic sequence. Whether subdivision on similar lines is possible in the main outcrop area of basalts is not known.

The distinctive field and stratigraphic characteristics of the basalts persist into their petrographic and chemical characters, allowing recognition of a number of basalt magma types. These magma types have been named for the stratigraphic units within the volcanic sequence in which they occur and are the Lesotho, Moshesh's Ford, Kraai River, Pronksberg High-K, Vaalkop and Omega types. The Lesotho type is overwhelmingly dominant throughout the Central area and the other types are, in relation, trivial in volume.

Average compositions of the basalts of the different magma types are presented in Table I. All the basalts are unequivocally tholeiitic and have small amounts of olivine or quartz in their CIPW norms. It is also apparent from the averages that the different types are compositionally well characterized and readily distinguished by consideration of SiO_2 content, absolute and relative degrees of incompatible element enrichment, variations in Cr and Ni, REE patterns, and initial $^{87}Sr/^{86}Sr$ ratios. Basalts of the Lesotho type exhibit the widest compositional variability with strong evidence that the variation in some elements is related to height in the lava pile. Thus, within a 600 m section through the Lesotho Formation at Naude's Nek Pass (30°45′S, 28°05′E) basalts from the uppermost 100 m are richer in Fe, P, Zr and Ce and poorer in Mg, Cr and Ni than those at the base of the section (see Table II). Cox and Hornung (1966) demonstrated a similar change with regard to the Fe/Mg ratio in a 1500 m section of the Lesotho Formation basalts from the Letele Pass–Kao area of nothern Lesotho.

Trivial volumes of silicic lavas are associated with the lowest basalts at several places. These silicic lavas have compositions in the andesite–dacite range and are found at Belmore between Rhodes and Barkly East (Lock *et al.*, 1974), Moyene in southern Lesotho (Du Toit, 1904, p. 108), Pronksberg (Du Toit, 1911) and Roodehoek (Gevers, 1928) near Jamestown. At Roodehoek the occurrence takes the form of an intrusion into the Elliot Formation. These silicic lavas have been investigated by Rumble (1979) who showed that the Pronksberg dacite pre-dates basalts correlated with the Drumbo member of the Moshesh's Ford Formation whereas the Belmore andesites and dacites are younger than the Drumbo member. Average compositions of the dacitic rocks from Belmore, Pronksberg and Roodehoek are presented in Table I. The Belmore andesites show a greater compositional range than do the Pronksberg and Roodehoek types and averages of each show distinctive chemical features. Two important chemical features of the Karoo dacitic rocks are their corundum-normative character (up to 6 weight % *c* in some Pronksberg samples) and their high initial $^{87}Sr/^{86}Sr$ ratios (>0.7095).

TABLE II
Average of Samples from Top and Base of the Naude's Nek Section through the Lesotho Formation

	Base (N = 7)	Top (N = 6)
MgO %	7.49	6.47
Cr ppm	337	195
Ni ppm	99	73
Fe_2O_3 %	10.97	11.52
P_2O_5 %	0.16	0.18
Zr ppm	85	109
Ce ppm	24	29

Analyses recalculated to 100 % volatile free.
Total Fe as Fe_2O_3.

Thus in the north-east Cape, a feature of the overall development of the Karoo igneous event is that the earliest eruptions were characterized by diversity in style and composition of the erupted products. This later evolved into widespread and regular effusion of compositionally monotonous lavas which built the bulk of the volcanic pile.

The intrusive dolerites have been the subject of rather more thorough investigations than their volcanic counterparts. This arises out of the advanced differentiation effects these rocks exhibit in many intrusions (e.g. Maske, 1966; Eales and Robey, 1976), their reactivity towards host sediments (Mountain, 1960;

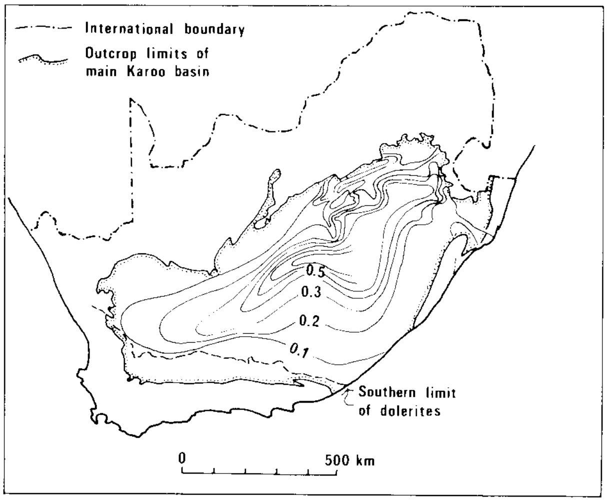

Figure 5
Contours of dolerite: sediment ratio in the main Karoo basin as determined from deep borehole data (after Winter and Venter, 1970).

Kenyon, 1976), the occurrence of marginally economic concentrations of Fe–Ni–Cu sulphides (Dowsett and Reid, 1967) and their importance in creating reservoirs and aquifers for groundwater. The wealth of published data available prior to 1949 has been reviewed by Walker and Poldervaart (1949) and some subsequent noteworthy contributions to the mineralogy, petrology and geochemistry of these rocks may be found in papers by Nockolds and Allen (1956), Erlank and Hofmeyr (1966, 1968), Eales (1974, 1979), Le Roex and Reid (1978), Eales and Snowden (1979) and Richardson (1979).

The complex of dykes, sills, "bell-jar intrusions" and irregular bodies has intruded the Karoo sedimentary strata with remarkable facility. As Winter and Venter (1970) have shown from deep borehole data, the greatest frequency of dolerite (highest dolerite–sediment ratio >0.5) is attained within a roughly ellipsoidal zone extending along a north-easterly axis from the eastern Orange Free State, through Lesotho and the southern Transvaal (see Fig. 5). These authors have also noted that dolerite sheets "seem to terminate at a critical distance of a few thousand feet below the basalts" and that dolerite intrusions are rare in the basement below the Karoo sedimentary cover. Thus it would appear that the basic magma feeding the extensive lavas and sills moved into the upper crust along narrow, localized zones. This inference is supported by the tendency for dykes to have a non-uniform distribution and instead to cluster into distinct zones or swarms (Vail, 1970).

The view that the sub-volcanic complex represents, in part, feeder channels for the overlying lavas is well substantiated in the Cape Province where the overwhelming majority of dolerites from a wide area are unequivocally identifiable, from major and trace element compositional data, with the basalts of the voluminous Lesotho formation (Table I). Hypabyssal representatives of the volumetrically smaller Moshesh's Ford and Kraai River lavas have also been identified. Consideration of the compositional data of the dolerites in relation to the petrographic subdivisions established by Walker and Poldervaart (1949) fails to establish any relationship between the two, except in the case of the orthopyroxene-bearing Hangnest type which Le Roex and Reid (1978) have shown is chemically distinctive with high SiO_2 (53.88 %) and Zr (150 ppm) and very low Ni (3.7 ppm) (data are averages for samples from the type locality). Robey (1976) has also established that there is no systematic variation in the chemical composition of dolerites with height of emplacement within the Karoo sedimentary succession.

A significant feature of many of the thick sills and plug-like bodies is their internal differentiation. The most common type of differentiation is produced by gravity settling or flow concentration of phenocrysts. Compositional variation is usually subtle and detectable only with precise chemical data for closely-spaced samples collected through the intrusion, e.g. the Hangnest and Blaauwkrans sills near Calvinia (31°27'S, 19°44'E) (Le Roex and Reid, 1978). Flow differentiation occasionally results in narrow schlieren within, or along, margins of sills highly enriched in cumulus phases, usually olivine (Eales and Marsh, 1979).

Alternatively, and less commonly, differentiation effects may be more pronounced with the development of thick piles of ultramafic and mafic cumulates displaying igneous lamination and cryptic layering. Examples of intrusions showing these features are found in Transkei and Natal, e.g. Insizwa, Ingeli, Tabankulu (Maske, 1966) and Elephant's Head (Poldervaart, 1944; Eales, 1979). At Birds River (31°25'S, 26°45'E) a succession of strongly fractionated liquids have been emplaced at high levels along a ring fracture. A seven-fold enrichment of incompatible elements (e.g. Zr, Nb, K, Ba, Y, etc.) within the igneous suite suggests that the complex is a unique example of pronounced fractionation of Karoo dolerite magma in the eastern Cape area (Eales and Robey, 1976).

B. The Algoa Basin

Volcanic rocks of the Suurberg Group (Rogers, 1905; Hill, 1972) crop out sporadically around the margins of the Cretaceous Algoa Basin north of Port Elizabeth (33°55'S, 25°35'E). The volcanic rocks are poorly exposed and apparently overlie the Cape and Lower Karoo Supergroup rocks with considerable discordance and are, in turn, overlain conformably by the succeeding Uitenhage Group whose lower fluviatile sediments are approximately late Jurassic and/or early Cretaceous. A single K/Ar whole-rock age determination on a basalt yielded an age of 162 ± 7 m.y. which correlates well with the volcanic activity of the Central area.

Hill (1972) described the igneous suite as comprising lavas with interbedded tuffs and intrusives. Chemical data presented by Hill (1972), and Marsh *et al.* (1979) demonstrate that the tuffs are rhyolitic and the lavas basaltic to intermediate (latitic) in composition. The basaltic rocks are unequivocally tholeiitic in character and are indistinguishable from basalts of the Lesotho Formation although Rogers (1905) reported analcite as a filling of vesicles in one of the samples he examined. In terms of lithology the Suurberg volcanic sequence shows affinities with the basalt-rhyolite and basalt-quartz latite suites of the Lebombo and Etendeka regions respectively.

C. Botswana

Poor exposures of basalt occur over an extensive area of eastern Botswana and extend westwards beneath the younger Kalahari Beds. Borehole and aeromagnetic data indicate that the Karoo basalts probably underlie an area in excess of 150,000 km^2 with maximum thickness exceeding

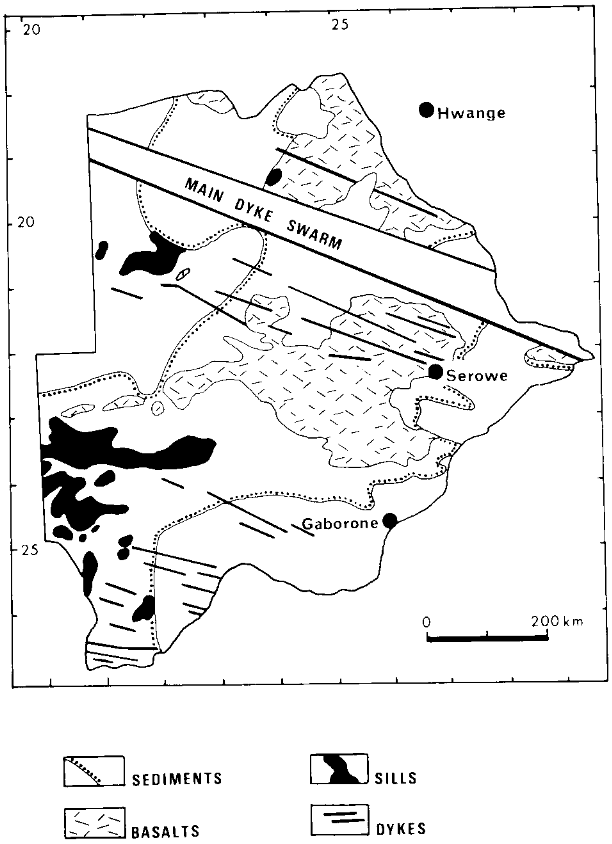

Figure 6
Surface geological and aeromagnetic data interpretation of Karoo geology of Botswana (after Jones, 1979).

400 m in eastern Botswana (Reeves, 1978b). The basalts appear to be confined to two main basins — a northern basin which is a continuation of the Karoo outcrops of the Hwange (Wankie) and Victoria Falls area of western Zimbabwe, and a central basin extending westwards from the outcrops in eastern Botswana. These two basins are separated by a *ca.* 1000 km long east-south-east-trending dyke swarm. In south-western Botswana extensive dolerite sheets occur in Karoo sediments (Fig. 6).

During the present study seven samples of basalt and dolerite, obtained from boreholes near Serowe (22°24'S, 26°44'E) have been analysed. Some of these samples exhibit the marked enrichment of incompatible elements characteristic of the basalts of the northern Lebombo–Nuanetsi–Tuli areas, but others are very similar to the Lesotho type of the Central area. Karoo igneous rocks in Botswana are clearly deserving of detailed study.

D. Springbok Flats

In the central Transvaal Karoo basalts underlie in excess of 5000 km^2 of the Springbok Flats (25°S, 28°30'E). Outcrops are extremely limited and only a few samples have been included for the purpose of regional comparison in this study. These indicate that the Springbok Flats basalts have strong compositional similarities to the Lesotho type magma of the Cape Province, especially differentiated dolerite compositions. A more detailed investigation of these basalts currently under way (Marsh, unpublished data) indicates that the basalts are in excess of 900 m thick in some places and the chemical characterization of the basalts is also confirmed. However, in a borehole in the north-eastern edge of the outcrop area a thin unit of plagioclase-phyric, low-MgO basalts exhibiting pronounced enrichment of incompatible elements, similar to that of low MgO basalts of the northern Lebombo–Nuanetsi area, occurs interbedded within the basalt sequence.

E. South-central Namibia

Near the town of Mariental (17°65'E, 24°37'S) in central Namibia basalts of the Kalkrand Formation underlie an area of 8000 km^2. The basalts have a maximum thickness of a little over 350 m and lie conformably on sedimentary rocks of the Ecca and Dwyka Groups (Heath, 1972). Compositionally the basalts are similar to the Lesotho magma type though there is a suggestion from the meagre age data that the Kalkrand basalts are slightly younger than the main bulk of the Lesotho Formation basalts in Lesotho (Gidskehaug *et al.*, 1975; Siedner and Mitchell, 1976). The Kalkrand basalts represent the northernmost extension of the Lesotho type magma with no indication in their chemistry of pronounced enrichment of incompatible elements characteristic of the basalts of the Etendeka, northern Botswana and Zimbabwe.

F. Northern Namibia

Igneous rocks broadly correlated with the Karoo suite and which were emplaced during the development and evolution of the South Atlantic Rift between Africa and South America, are found sporadically outcropping along the west coast of South Africa and Namibia (see Fig. 7). Remnants of a suite of hypabyssal intrusives and lava flows are best developed between latitudes 22°S and 18°S in the coastal region of Namibia. The hypabyssal suite comprises a linear belt of ring complexes and plutons of highly differentiated tholeiitic and alkaline rock types and carbonatites, and dykes of dolerite, lamprophyre and quartz porphyry. The last two are relatively uncommon and, in general, are confined to the vicinity of differentiated ring complexes. The most extensive outcrop of lavas is in the Etendeka region where they cover an area in excess of 15,000 km^2 and have a maximum known thickness of over 900 m at Tafelberg (14°10'E, 20°09'S) on the eastern edge of the outcrop area. Smaller areas of lavas occur further north towards the Kunene River and south of the Etendeka in the Gobobosebberge (14°10'E, 21°23'S) and north of Cape Cross (13°58'E, 21°46'S). Inland, volcanics are known from Erongo and as sub-outcrops below the Kalahari Group east of Grootfontein (18°10'E, 19°35'S) and in Caprivi.

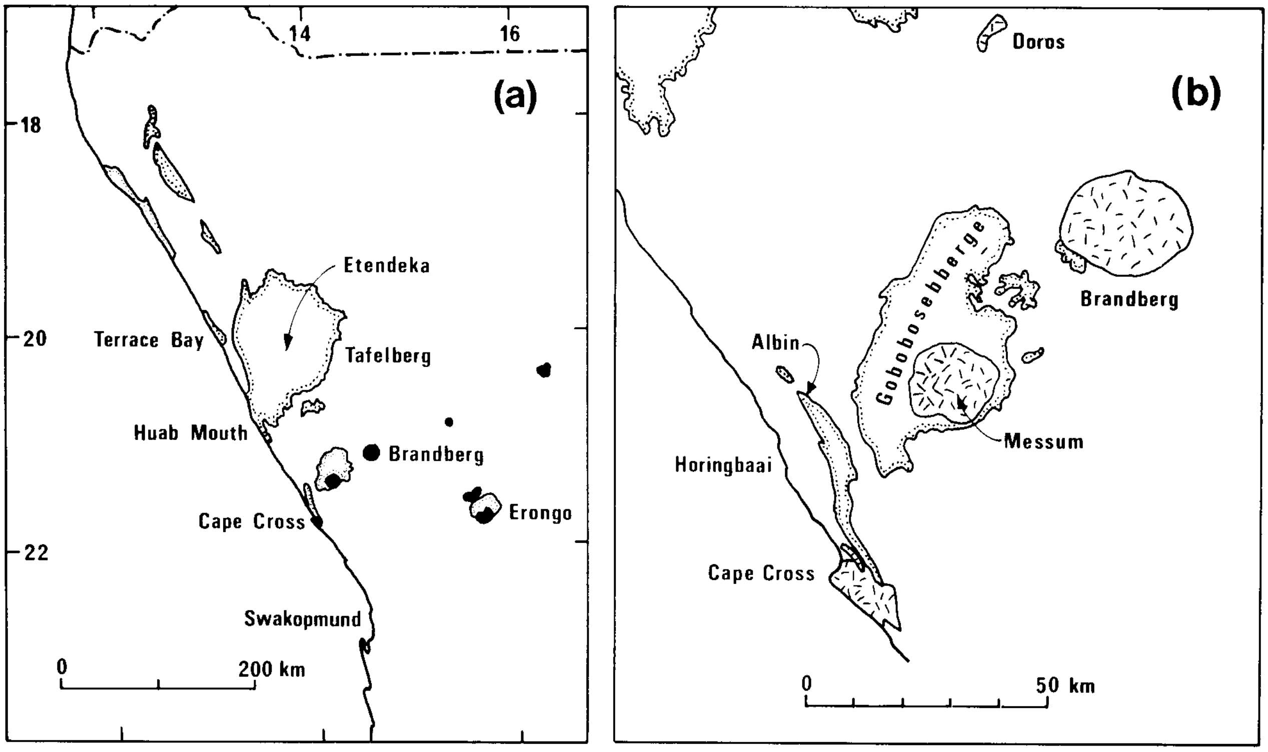

Figure 7

(a) Map of north-western Namibia showing principal localities and outcrops of Etendeka Formation lavas (speckled outline) and post-lava sub-volcanic ring complexes and plutons (black).

(b) A detailed map of the lava outcrops and sub-volcanic intrusions in the vicinity of Cape Cross.

TABLE III
Analyses of Etendeka Formation Lavas, Northern Namibia

	KLS-24 Least evolved basalt	KLS-42 Most evolved basalt	Average Latite	Average Quartz-latite	Average Dacite
%					
SiO_2	51.82	57.81	59.23	68.00	68.62
TiO_2	1.00	1.81	2.29	0.95	0.91
Al_2O_3	14.83	12.66	13.87	12.89	13.30
Fe_2O_3	11.82	13.94	11.21	6.61	6.14
MnO	0.18	0.20	0.13	0.10	0.10
MgO	6.78	2.30	1.70	1.26	1.25
CaO	10.50	6.07	4.23	2.74	3.54
Na_2O	2.11	2.26	2.48	2.69	3.28
K_2O	0.83	2.69	4.42	4.46	2.57
P_2O_5	0.12	0.26	0.44	0.29	0.28
ppm					
Rb	19	96	154	175	177
Ba	217	496	1100	627	634
Sr	216	188	215	131	194
Zr	114	238	457	279	292
Nb	7.5	16	26	22	25
Cr	73	9.4	16	10	7.5
V	264	372	62	53	50
Ni	63	5.1	6.1	4.5	1.8
Co	55	43	24	13	11
Zn	89	104	147	78	83
Cu	98	71	21	42	24
Y	24	39	57	37	37
La	14	33	73	47	48
Ce	32	73	149	93	100
Nd	19	39	74	46	47
N*	—	—	(4)	(19)	(3)

*N is the number of analyses used to calculate the averages of major oxides. Averages for trace elements are for the same or fewer number of analyses. All analyses recalculated to 100 % volatile free (Microfiche Card 2 attached to this volume). Total Fe as Fe_2O_3.

These latter occurrences presumably represent westward extensions of the Karoo volcanics in Botswana.

The present study has focused attention on the lavas of the Etendeka and the Cape Cross–Messum area (Fig. 7), where they are collectively grouped into the Etendeka Formation, and the regional swarm of dolerite dykes. The inland occurrences have not been included in this study. The sub-volcanic ring complexes are intimately associated with the volcanic rocks but each is a major study on its own. Most of the complexes have been investigated in some detail by previous workers and Martin *et al.* (1960) have reviewed these studies.

The lavas of the Etendeka Formation are essentially horizontal on the eastern edge of their outcrop areas but towards the coast they are extensively faulted and tilted with dips up to 20°E. The faults strike sub-parallel to the coastline and there is evidence of pre- and post-extrusion movement on the faults. In many places the lavas are comformably underlain by sediments of the Karoo Supergroup but the thickness of the sedimentary rocks is variable and the lavas frequently overstep on to Precambrian basement rocks. Within the volcanic sequence the lower lavas are also overstepped by lavas higher in the sequence in places. The existence of considerable relief at the onset of volcanism is implied by these relationships. The lava sequence over much of the Etendeka comprises basic to intermediate rocks interbedded with latites and quartz latites and dacites. The complete succession is not preserved and at Tafelberg the present relative thicknesses are: basic to intermediate lavas — 70 %; latite — 5 %; dacite and quartz latite — 25 %.

The basic to intermediate lavas are generally fine-grained and aphyric and have been designated the Tafelberg basalt type. They exhibit a continuum in chemical composition between rocks that classify as true basalts ($SiO_2 = 51.8$ %; MgO = 6.8 %) and those of more evolved character ($SiO_2 = 57.8$ %; MgO = 2.3 %) (see Table III). Despite the considerable compositional range displayed by these lavas there is no indication of serial variation with height in the sequence. In many places in the coastal region the Tafelberg-type basalts are underlain with some interbedding by plagioclase-phyric basalts, termed the Albin basalts, whose thickest development is in the eastern Gobobosebberge and the lava outcrops north of Cape Cross. Although these Albin basalts are texturally distinct from the Tafelberg type their chemical compositions are extremely similar.

The latites are slightly more SiO_2-rich and MgO-poor compared to the most evolved basalts but are clearly distinct in terms of petrography, mineralogy and trace element compositions. To date they are known only from the Tafelberg area but no attempt has been made to map out their areal extent. A distinct compositional gap separates the latites from the quartz latites and dacites. These silicic rocks exhibit a narrow range in the concentration of most elements except CaO, Fe_2O_3, Na_2O, K_2O, Sr and Rb. The basic, intermediate and silicic lavas of the Etendeka Formation differ petrographically, compositionally and isotopically from similar Karoo lava types of other areas in southern Africa.

A large number of sills and dykes intrude the volcanic sequences, the Karoo sedimentary strata and the Precambrian Basement rocks. Dykes in particular occur in a number of swarms one of which has been studied by Botha and Hodgson (1975). The work of Siedner and Mitchell (1976) suggests that these intrusives range in age from 120 to 185 m.y. This has hampered proper investigation of the relationship of the intrusives to the lavas, as unequivocal contemporaneity of lavas and intrusives can only be demonstrated in a few cases by dating or consideration of

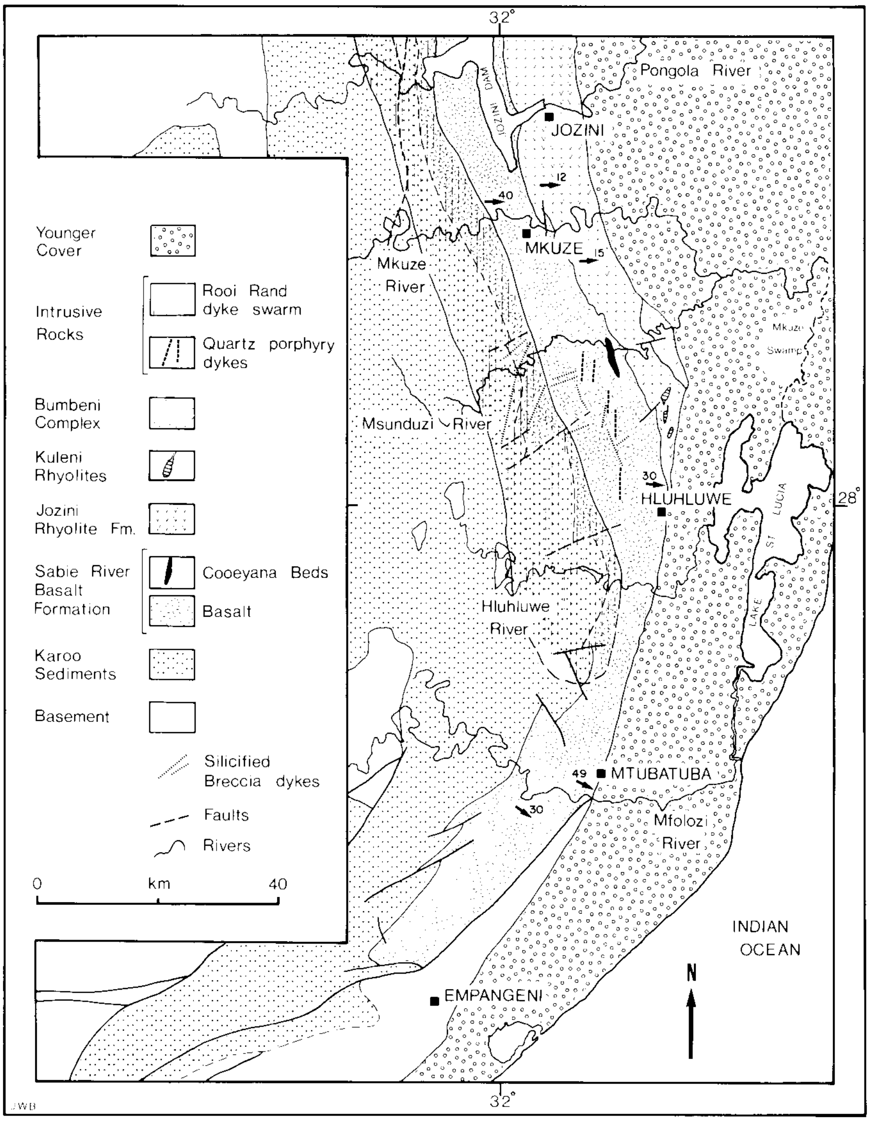

Figure 8

Geological map of the southern part of the Lebombo monocline (after Van Wyk, 1963; Stratten, 1965; Bristow, 1976; Armstrong, 1978). Compiled by J.W. Bristow.

field relationships. Amongst the dykes and sills three main geochemical groups can be recognized. The first two exhibit geochemical and isotopic features characteristic of the Tafelberg basalts of the Etendeka Formation and the Lesotho basalt magma type of the Central area respectively. The third type, designated the Horingbaai intrusives, are the most depleted (in terms of major and trace element concentrations and Sr- and Nd-isotopic compositions) of any Karoo basic rocks. The Horingbaai dolerites are best developed north of Cape Cross where they occur as narrow, fine-grained, aphyric dykes cutting the Albin-type lavas and underlying basement rocks. Feldspar-phyric dykes and sills also intrude the lowermost lavas in the coastal region. None has been analysed to date but they are presumably compositionally similar to the Albin type basalts which they resemble petrographically.

G. The Lebombo Monocline

The Lebombo monocline (Figs. 8, 9, 10, 11) is an almost straight north–south flexure running from Empangeni in Zululand to the Limpopo River on the border between South Africa and Zimbabwe. It is marked throughout most of its length by the Lebombo Mountains, a low range reaching approximately 600 m above sea level, which separates the coastal plain of Zululand and Mozambique on the east from the long valley forming the eastern Transvaal and Swaziland lowveld to the west. Major rivers flow from west to east and cut gorges through the Lebombo on their passage to the sea. The Lebombo range owes its existence to the excavation of soft sediments and weathered basaltic rocks from the lowveld area by subsequent streams, leaving the more resistant rhyolitic volcanics standing as a prominent ridge.

As indicated previously the Lebombo probably marks the sudden transition from normal continental crust to thinned crust, the latter possibly extending as far east as the Mozambique ridge (see Fig. 3). It may also be related to the junction between the Mozambique belt and the Archaean of the Kaapvaal craton. The Lebombo terminates in the south at the southern boundary between the craton and the 1000 m.y. old Namaqualand–Natal belt. At the termination the powerful Empangeni–Eteza fault brings up basement east of, that is on the downwarped side of, the monocline.

A typical traverse from west to east across the Lebombo starts on virtually flat-lying Karoo sediments resting unconformably on the basement and then crosses a broad plain of basaltic rocks, often deeply weathered. Structures are difficult to discern in this zone which means that thickness estimates for the basaltic sequence are difficult to obtain. This is partly a consequence of the unknown influence of strike faulting. At the sediment–basalt contact

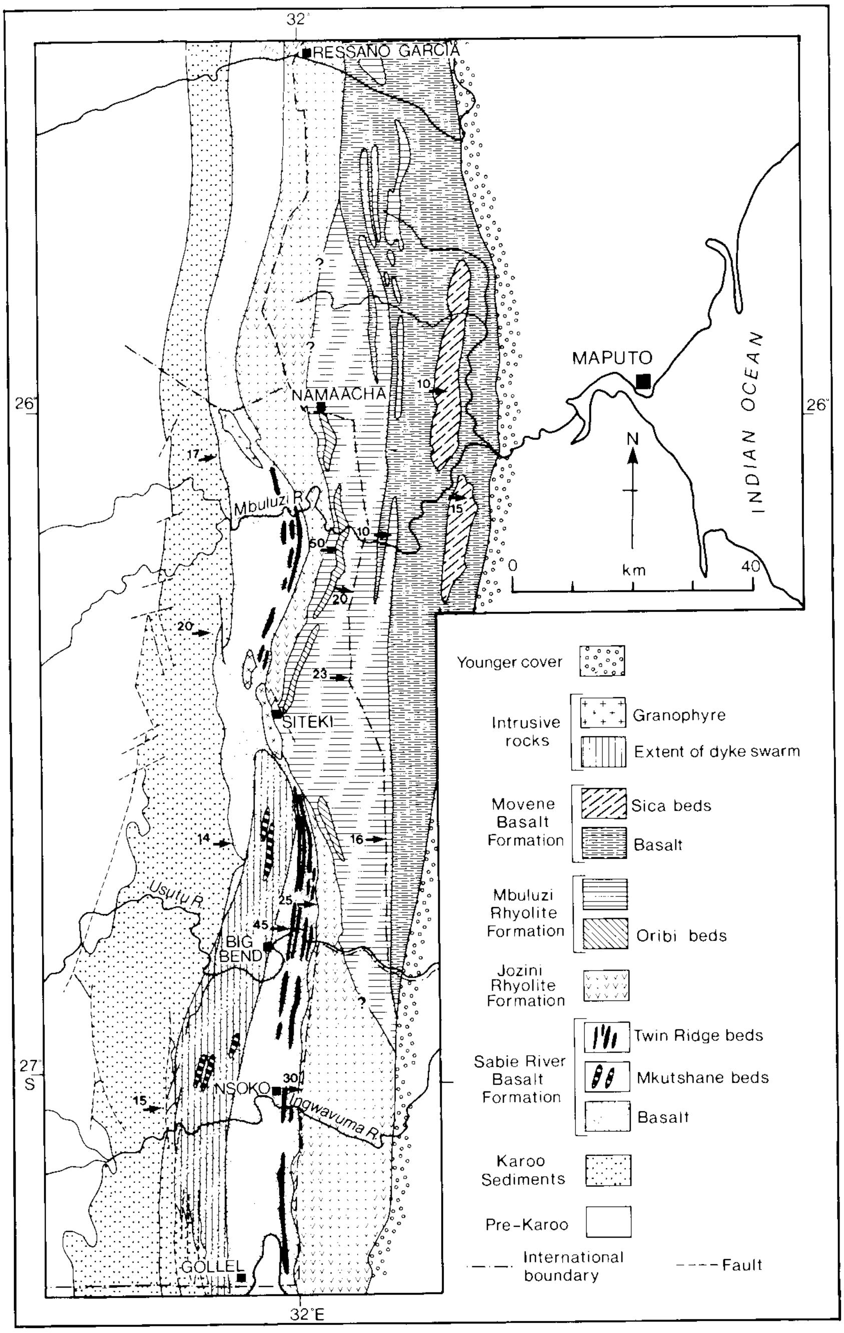

Figure 9
Geological map of the Lebombo monocline in Swaziland and adjacent areas of Mozambique (after Wachendorf, 1971; Cleverly, 1977; Betton, 1978; Geological Survey of South Africa).

many such faults have been mapped and mainly throw down to the west, off-setting the dip of the monocline. The effect is to make overestimation of the thickness of the basalts likely, though none of the mapped faults has a very substantial throw. A summary of thickness estimates from different areas is given in Table IV.

Passing eastwards, the dip of the volcanic rocks increases gradually to a maximum which is usually about 45° and occasionally as much as 65°. The zone of maximum dip lies within the basalt outcrop in northern Zululand (Bristow, 1976) but northwards rises through the succession until it coincides with the base of the overlying rhyolites in northern Swaziland (Cleverly, 1977). Elsewhere the zone has not been delineated.

The rhyolites are seen overlying the basalts everywhere except in the extreme south and extreme north of the Lebombo where they disappear beneath the cover of younger sediments. They reappear, however, (see later sections) in the Nuanetsi district north of the Limpopo and in the Lupata Gorge on the Zambezi. These localities together with the Etendeka region in Namibia are the only rhyolite (*sensu lato*) occurrences of any great volume of Karoo age in southern Africa. Their confinement to the marginal, monoclinal zones of the province can be no coincidence, and Betton (1978) has suggested that crustal thinning is a prerequisite for their formation.

The rhyolites form the main Lebombo range, the top of which is locally a well-preserved erosion level (King, 1951). The dip gradually diminishes eastwards to a value of 15° or less, at which point the rhyolites in most areas pass beneath the younger sediment cover. However, between latitudes 25°S and 27°S (see Fig. 9) an overlying series of basalts is encountered with, locally, in the area west of Maputo, an intercalation of further rhyolites forming the hills of the

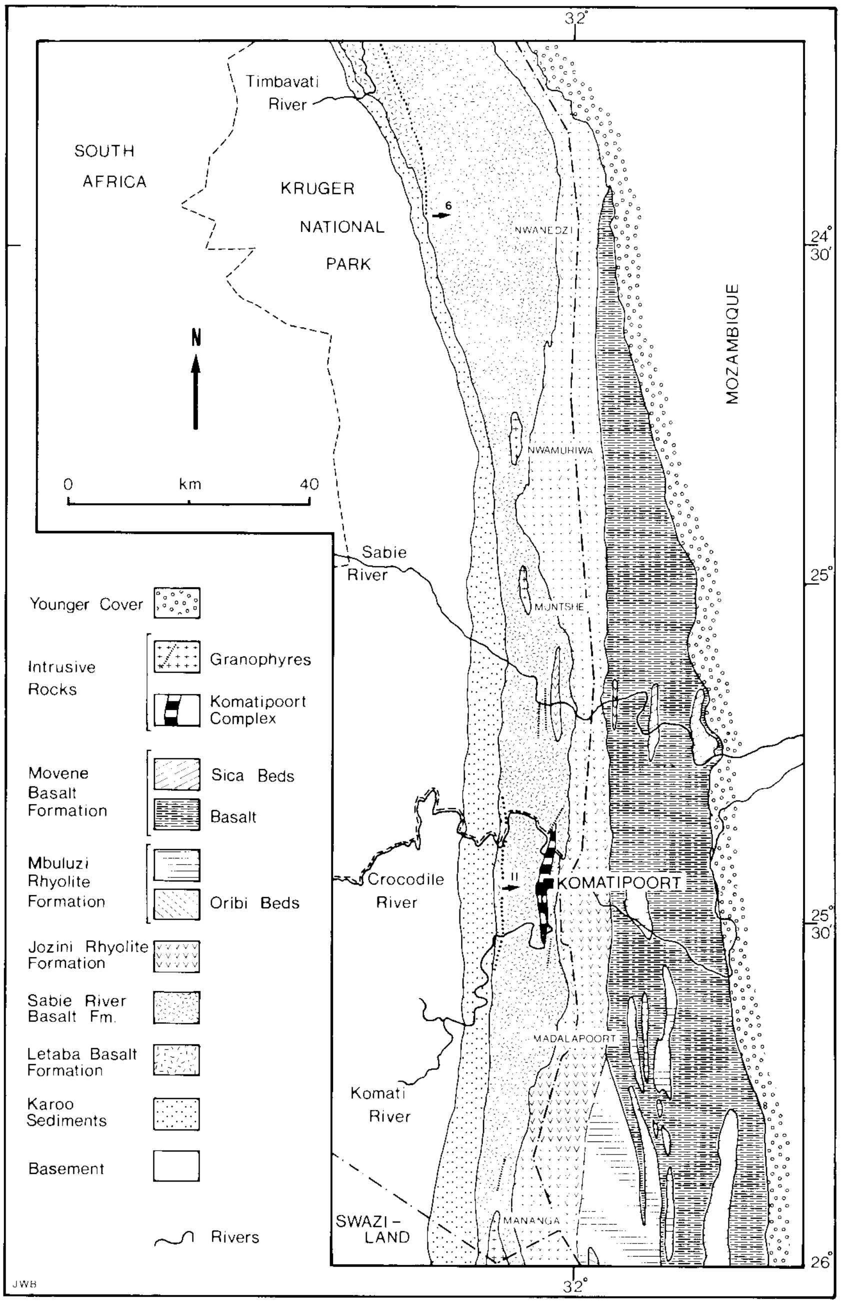

Figure 10
Geological map of the central part of the Lebombo monocline (after Van der Schijf, 1968; Logan, 1979; Bristow, 1982). Compiled by J.W. Bristow.

Little Lebombo (Pequenos Libombos). Some thickness estimates of rhyolitic volcanics are given in Table IV.

In addition to the lavas discussed above, basic dykes form an integral part of the Lebombo structure though these have only been mapped from the northern border of Swaziland southwards. Dykes reach their maximum development in northern Zululand where the intense Rooi Rand swarm (Bristow, 1976; Armstrong, 1978) forms a range of hills at the western edge of the basalt outcrop. The swarm reaches a maximum width of 20 km at its southern end but it is only about half this width in Swaziland, where it fades out quite abruptly in the vicinity of Siteki, though smaller numbers of dykes are present to the north. The length of the swarm is 200 km. The dykes are densely crowded together and in many localities screens of intervening country rocks are rare or absent. Within the area delimited as a dyke swarm (Fig. 8), at least in some sections, 40% of the material is estimated as being intrusive, though it is much less in Swaziland. The dykes characteristically hade to the west at angles of 65–70°, a feature Du Toit (1929) attributed to post-emplacement tilting of the swarm. It seems possible, however, that the hade is an original feature.

The stratigraphy of the Lebombo lavas has recently been revised by Cleverly and Bristow (1979). The Mashikiri Nephelinite Formation lies at the base of the sequence in the northern Lebombo (see Fig. 11) and consists of variable flows of nephelinite and related types. The main field characteristic is the presence of large stellate aggregates of prismatic clinopyroxene phenocrysts and, occasionally, nepheline phenocrysts. Overlying these rocks, and overstepping them southwards is the Letaba Basalt Formation in which most of the lavas carry abundant olivine phenocrysts. The rocks are mainly tholeiitic picrite basalts, and are highly distinctive geochemically because of great enrichment in K, P, Ti and a variety of trace elements including Rb, Ba and Sr compared with normal picrite basalts (see Table V). Included within the group are flows

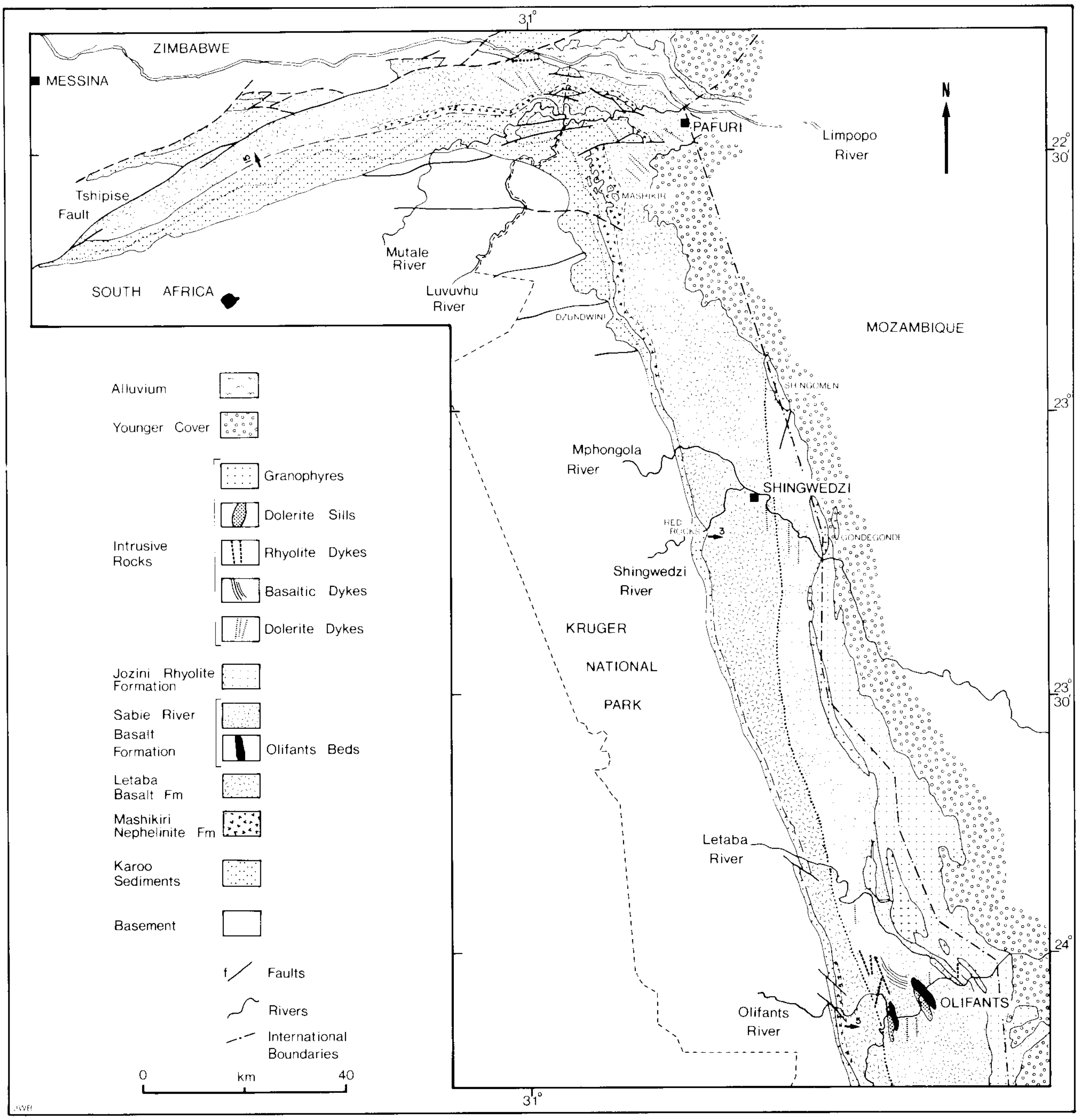

Figure 11

Geological map of the northern Lebombo (after Söhnge, 1945; Van Eeden *et al.*, 1951; Cox *et al.*, 1965; Van der Schijf, 1968; Fripp *et al.*, 1979; Bristow, 1982). Compiled by J.W. Bristow.

of absarokite and shoshonite. These are rare in the north but make up most of the sequence towards the southern end of the outcrop. Overlying the Letaba Basalt Formation the succeeding Sabie River Basalt Formation extends for the entire length of the Lebombo. Though somewhat variable in the details of their geochemistry the lavas of this formation are virtually all low-MgO basalts and tholeiitic andesites. Within the lower half of the formation a group of thin rhyolite flows in the central part of the Swaziland outcrop is known as the Mkutshane Beds. These rocks are quite distinct from the other Karoo rhyolites in terms of their trace elements and isotopes. Thin rhyolite flows termed the Twin Ridge Beds are interbedded with basalts at the top of the formation and traceable for most of the length of the Swaziland outcrop. They are not geochemically distinct from the overlying rhyolites.

The main rhyolite sequence is divided into two formations, the widespread Jozini Rhyolite Formation beneath and the locally developed Mbuluzi Rhyolite Formation above, the main distinction between the two being the presence of quartz phenocrysts in the Mbuluzi rhyolites. Within this latter formation particularly quartz-rich flows are distinguished as the Oribi Beds.

The individual flows of both formations have been mapped within Swaziland by Cleverly (1977) and Betton (1978), some 30 different units having been recognized. Flows are typically sheet-like, from 80 to 350 m thick, and traceable along strike for up to 50 km. Bristow and Cleverly (1979) show that they possess features typical of both ignimbrites and lavas, and suggest that the latter may have originated by post-eruptive remobilization of degassed ash-flow deposits.

Above the main rhyolite sequence the overlying basalts are referred to as the Movene Basalt Formation, a unit which is largely confined to Mozambique and has not been studied during the present project. However, descriptions

TABLE IV
Thickness Estimates of Volcanic Sequences, Lebombo and Nuanetsi

Area	Letaba Basalt Formation	Sabie River Basalt Formation	Rhyolite	Total	Reference
Swaziland–Maputo	—	5000 m	7500 m	12,500 m	Cleverly (1977)
Swaziland	—	3000 m	no estimate		Urie and Hunter (1963)
Southern Lebombo	—	4100 m (Empangeni) 6400–8900 m (Pongola River)	2000 m	6100–10,900 m	Bristow (1976)
Nuanetsi	1900 m	3000 m	1700 m	6600 m	Cox *et al.* (1965)

TABLE V
Average Analyses of Karoo Volcanic Rocks, Lebombo Monocline and Nuanetsi

	1	2	3	4	5	6	7	8	9	10
%										
SiO_2	52.57	49.49	70.68	51.67	49.97	44.86	49.49	52.41	52.00	71.57
TiO_2	1.51	2.14	0.50	3.12	3.07	2.87	2.70	2.77	2.04	0.44
Al_2O_3	14.78	13.68	12.65	13.13	8.22	11.45	8.82	13.65	13.36	12.89
Fe_2O_3	12.48	15.21	6.34	13.56	12.02	14.52	12.33	12.10	14.84	5.23
MnO	0.17	0.22	0.10	0.18	0.16	0.19	0.15	0.15	0.21	0.09
MgO	5.68	5.87	0.35	5.32	15.52	7.51	15.20	5.64	4.76	0.40
CaO	9.37	10.34	1.47	8.17	7.07	10.20	7.55	8.79	8.34	1.39
Na_2O	2.61	2.41	3.16	2.43	1.43	5.86	1.63	2.28	2.51	2.89
K_2O	0.69	0.42	4.61	1.95	2.10	1.60	1.70	1.72	1.51	5.03
P_2O_5	0.23	0.22	0.14	0.49	0.45	0.93	0.43	0.49	0.32	0.08
ppm										
Rb	18	11	130	42	55	49	34	33	42	157
Ba	283	128	1475	790	917	1365	794	692	579	1640
Sr	312	190	153	785	1000	1080	857	795	271	85
Zr	135	144	1085	339	402	166	308	332	177	763
Nb	5.5	7.5	84	19	19	96	19	24	18	102
Cr	153	125	7.5	81	804	93	941	192	41	13
V	260	351	6.2	261	204	311	191	228	262	5.4
Ni	86	67	3.8	80	827	70	761	95	36	4.5
Co	49	53	5.2	—	81	54	88	53	59	6.5
Zn	98	110	135	121	110	127	103	99	101	112
Cu	136	287	8.8	142	83	241	72	75	79	6.3
Y	30	36	129	38	28	23	25	33	33	83
N*	(48)	(38)	(49)	(10)	(19)	(8)	(48)	(27)	(8)	(19)

1. Average basalt, Sabie River Formation, southern Lebombo and Swaziland.
2. Average Rooi Rand dolerite, southern Lebombo and Swaziland.
3. Average Jozini rhyolite, southern Lebombo.
4. Average aphyric lava, Sabie River section (representing shoshonitic/absarokitic type).
5. Average picrite basalt, Letaba Basalt Formation, northern Lebombo.
6. Average nephelinite, northern Lebombo.
7. Average picrite basalt, Letaba Basalt Formation, Nuanetsi.
8. Average basalt, Sabie River Basalt Formation, Nuanetsi.
9. Average interbedded basalt, Nuanetsi Rhyolite Formation, Nuanetsi.
10. Average rhyolite, Nuanetsi

*N is the number of analyses used to calculate the averages of the major oxides. Averages for trace elements are for the same or fewer number of analyses. All analyses recalculated to 100 % volatile free (Microfiche Card 2 attached to this volume). Tocal Fe as Fe_2O_3.

by Assunçao *et al.* (1962) and Wachendorf (1971, 1973) indicate a thickness of approximately 2000 m and rock types which are similar to those of the Sabie River Basalt Formation. The analyses given by Assunçao *et al.* (1962), however, suggest that *ne*-normative varieties may be common. Within the formation the rhyolites of the Little Lebombo are termed the Sica Beds.

Occupying a similar stratigraphic position to the Movene Basalt Formation in the south Lebombo a variable group of rhyolitic lavas, ash-flow tuffs, with a basal unit of trachybasaltic and trachyandesitic lavas (the Mpilo Member) is referred to as the Bumbeni Complex (see Fig. 8). It reaches a total thickness of 225 m in the vicinity of the Msunduzi River.

Of the intrusive rocks of the Lebombo reference has already been made to the Rooi Rand dyke swarm. Several large granophyre intrusions are also present. These are probably essentially sill-like and are characteristically intruded close to the contact between the Sabie River Basalt Formation and the Jozini Rhyolite Formation. The largest bodies are at Siteki in Swaziland, Mananga on the northern border of Swaziland, and at Muntshe Ridge in the Kruger National Park. Additional intrusions include the Komatipoort Complex (Saggerson and Logan, 1970), an elongated layered gabbro exposed in and around Komatipoort, and small elongated syenite plutons intruding the central portion of the Bumbeni Complex (Van Wyk, 1963; Stratten, 1965; Bristow, 1976). Domes of intensely contorted rhyolite lava and dykes crop out south of the Msunduzi River (see Fig. 8) and are termed the Kuleni rhyolite.

H. Nuanetsi

The Nuanetsi igneous province lies in south-eastern Zimbabwe and forms the northern termination of the Lebombo monocline. At Nuanetsi the north–south-trending Lebombo structure swings to the north-east to form what has been termed the Mateke–Sabi Monocline. The huge, lava-filled, Nuanetsi syncline marks this change of strike and is cut by a number of large intrusive complexes

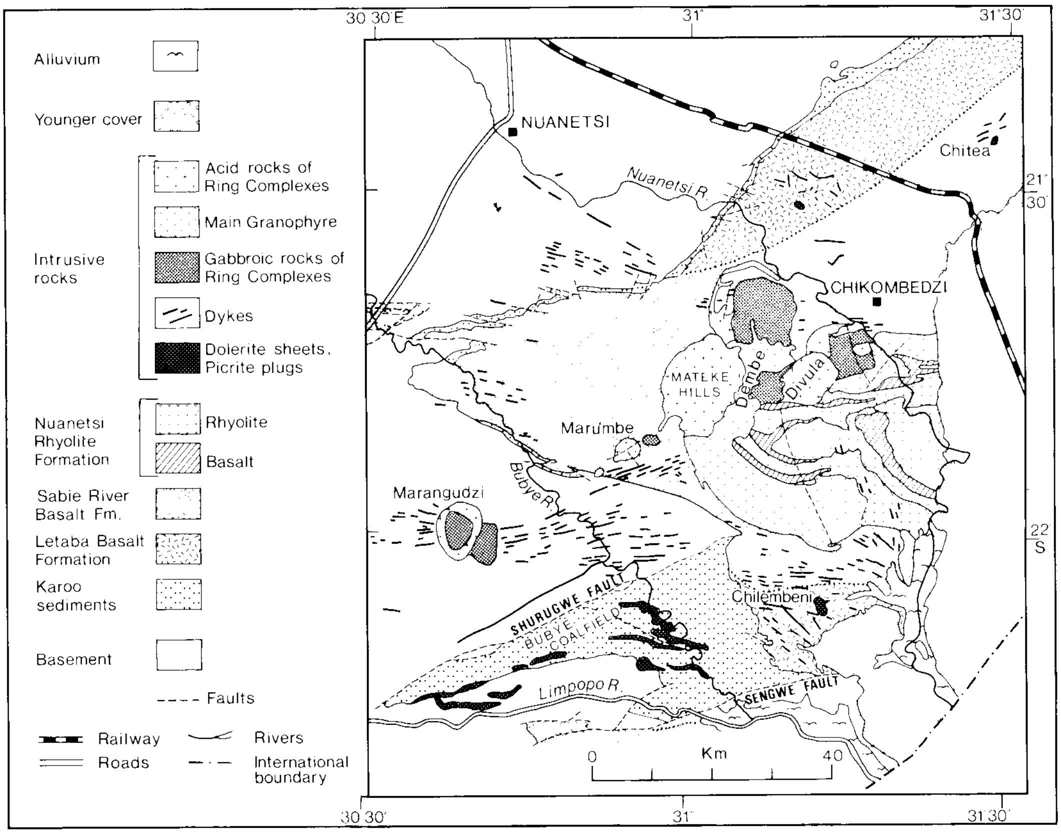

Figure 12
Generalized geological map of the Nuanetsi area, south-east Zimbabwe (after Cox *et al.*, 1965).

(see Fig. 12). The geology of the Nuanetsi district was investigated in outline by Lightfoot (1938) and Tyndale-Briscoe (1949), and described in some detail by Cox *et al.* (1965). Palaeomagnetic studies have been published by Gough *et al.* (1964) and Brock (1968), and an assessment of the tectonics by Cox (1970), and a variety of petrogenetic and age studies have also appeared (Manton, 1968, 1973; Cox and Jamieson, 1974; Foland and Henderson, 1976). In the present review the stratigraphic nomenclature of the volcanic rocks is brought into line with the usage advocated by Cleverly and Bristow (1979) for the Lebombo.

The Karoo rocks of Nuanetsi lie on a basement of Limpopo belt gneisses (see Mason, 1973) and thus contrast with the Lebombo volcanics which lie on Archaean basement. The response of the basement to extensional forces during the Karoo period (Cox, 1970) resulted in the formation of a depositional trough extending along the line of the Limpopo valley and into the southern part of the Nuanetsi area. Karoo sediments were deposited here (the Bubye Coalfield) to a thickness of approximately 600 m but they are much thinner and locally even absent in the area to the north. The rapid change of sedimentary thickness coincides with the Shurugwe Fault which was active as a monoclinal flexure during the period of sedimentation. The earliest volcanics were erupted onto a surface of the Clarens Formation, and barchan dunes are locally preserved beneath the lavas (Cox *et al.*, 1965, Fig. 33). The first lavas erupted were picrite basalts assignable to the Letaba Basalt Formation of the Lebombo Group. These are found on both limbs of the Nuanetsi syncline but are absent in the west. On the southern limb a maximum thickness of about 2000 m is present but this thins westwards very rapidly. The Letaba Basalt Formation is succeeded by the olivine-poor and olivine-free lavas of the Sabie River Basalt Formation. These reach a maximum thickness of approximately 5000 m in the eastern part of the Nuanetsi syncline and overstep the Letaba Basalt Formation to the west. A group of rhyolites with interbedded basalts completes the volcanic sequence and occupies the core of the syncline, reaching a thickness of about 1800 m at the eastern end. The correlation of this sequence with the rhyolite formations established in the Lebombo by Cleverly and Bristow (1979) is not clear. In its great thickness it is comparable with the Jozini Rhyolite or Mbuluzi Rhyolite Formations but the presence of abundant interbedded basalt invites lithological comparison with the Twin Ridge Beds within the Sabie River Basalt Formation of Swaziland. For present purposes the new stratigraphic name of Nuanetsi Rhyolite Formation is proposed for these rocks and the various subdivisions established (see Cox *et al.*, 1965, Table I) may be referred to as members within the formation.

Intrusive rocks are abundant within the volcanic succession. In terms of outcrop area the largest intrusion is a transgressive acid sill termed the Main Granophyre which lies approximately at the base of the Nuanetsi Rhyolite Formation. It dies out on the southern limb of the Nuanetsi syncline but is presumed to be continuous beneath the younger sediment cover with a similar body cropping out along the Mateke–Sabi monocline to the north-east (see Fig. 13). The sill thus appears to extend for at least 170 km. The main granophyre is cut by a number of intrusive complexes most of which lie on a north-east-trending line which coincides with the centre of the Limpopo belt. The dominant rock types are gabbros with later granites, granophyres and micro-granites. Nepheline syenites occur additionally in the most westerly complex, Marangudzi (Foland and Henderson, 1976). All the intrusions except the Main Granophyre show characteristic ring structures which are described in detail by Cox *et al.* (1965) though there are additional papers on specific complexes by Vail (1962, 1966, Dembe-Divula) Johnson (1964, Marumbe), Cox (1964, Masukwe) and Stillman (1970, Northern Ring). Minor intrusions, particularly dolerite dykes, are also abundant in the Nuanetsi area and may be divided into discrete swarms, although the early picrite dykes of the northern limb of the Nuanetsi syncline do not have any well

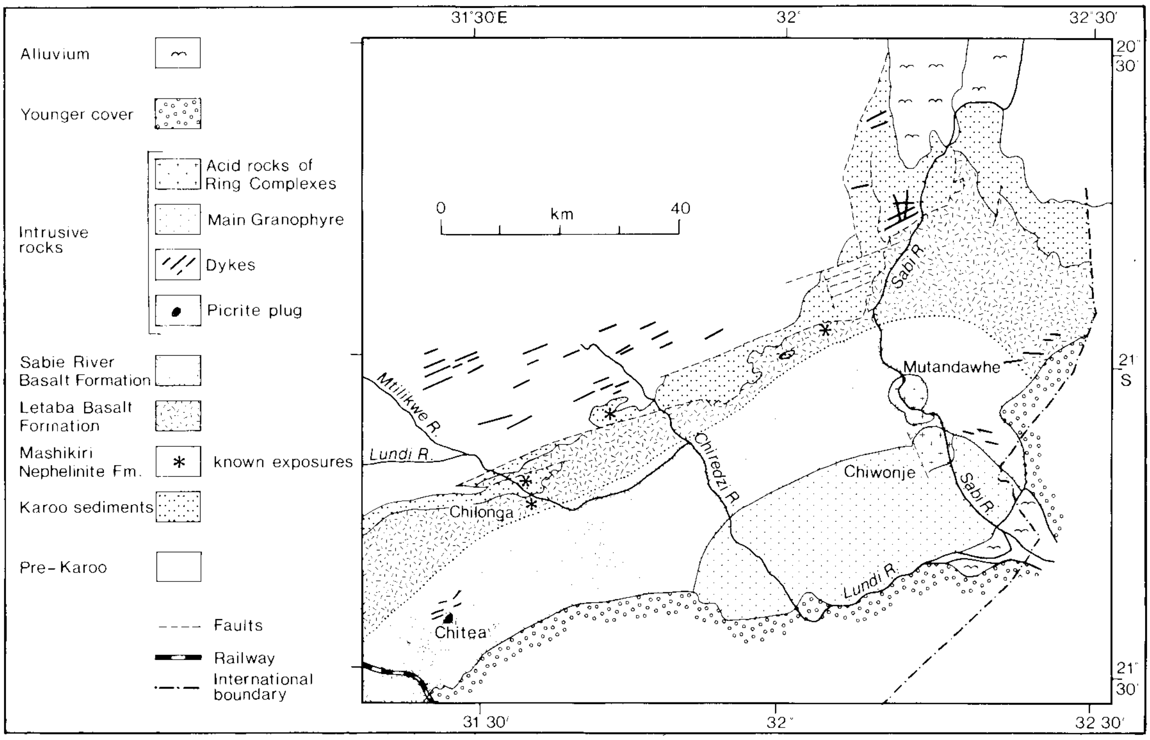

Figure 13

Geological map of the Sabi area, south-east Zimbabwe (after Swift *et al.*, 1953; Cox *et al.*, 1965).

defined trend. Dykes with the north-westerly trend (Duvi and Bubye swarms) may be traced for no less than 1000 km to the north-west (Reeves, 1978a, and see Fig. 1).

In petrological and geochemical character the Nuanetsi igneous rocks are similar to those of the northern part of the Lebombo already described (see Table V). The picritic lavas of the Letaba Basalt Formation include a similar variety of olivine-rich, glassy types some of which appear to have been erupted almost completely in the liquid state, even though they have MgO contents approaching 10%. Like those of the Lebombo some of these lavas have very high contents of K and related trace elements. Low pressure differentiates are formed by the fractionation of olivine and clinopyroxene from such liquids and form very rare shoshonitic lava flows or potassic syenogabbros in minor intrusions. However, some picrites showing substantially less enrichment in the incompatible elements are also present (e.g. the Bezi dyke, see Fig. 12 and Table V). The overlying Sabie River basalts are also enriched in K and related elements relative to Karoo basalts from other areas such as the southern Lebombo and Lesotho, though the effect is not so striking as in the underlying olivine-rich lavas. The basaltic members of the Nuanetsi Rhyolite Formation continue this trend towards diminution of K-content, and some analysed rocks are not obviously different from those of the southern Lebombo (see Table V). As in the Lebombo there is a striking silica gap separating the basic lavas from the rhyolites, a feature which is also notable in the gap between gabbroic and acid rocks within the intrusive complexes, though one or two hybrid intrusions have been recognized. The acid rocks of Nuanetsi show some geochemical differences when compared with acid rocks from the Lebombo but they are less obvious than the differences shown by the basic rocks.

I. The Sabi River Area of Zimbabwe

The rocks in this area (see Fig. 13) form a natural north-eastern extension of the Nuanetsi province and have been described by Swift *et al.* (1953) and Cox *et al.* (1965). The basalt and Karoo sediment outcrops are continuous between the Nuanetsi and Sabi areas, along the Mateke–Sabi monocline which shows gentle dips to the south-east. The Main Granophyre of Nuanetsi reappears in the Sabi district having been overstepped by younger sediments believed to be of Cretaceous age (Cox, 1963) in the intervening area. The Nuanetsi rhyolite Formation does not, however, crop out in the Sabi district. The Letaba Basalt and Sabie River Basalt Formations are still clearly identifiable in the Sabi district though the boundary between them has not been mapped in detail. However, the Sabi succession differs from that of Nuanetsi by the local appearance of nephelinites assignable to the Mashikiri Nephelinite Formation at the base of the sequence, most notably at Bendezi Hill on the Lundi River. Two acid ring complexes, Mutandawhe and Chiwonje, are found in the Sabi district (Wood, 1961), cutting the Sabie River basalts and the Main Granophyre respectively. Mutandawhe is notable for the relatively large amount of quartz-syenitic (nordmarkitic) rock types which are exposed, a feature which it shares with the Marumbe Complex in Nuanetsi. Base metals have been worked in the aureoles of the Sabi complexes at the P. & O. and Hippo mines.

J. Carbonatites of Eastern Zimbabwe

Three carbonatite complexes, Shawa, Dorowa and Chishanya, lie to the north of the Sabi district and, on the basis of an age determination of 209 m.y. (Nicolaysen *et al.*, 1962) on Shawa, must be considered to belong to the Karoo igneous activity. Shawa and Dorowa have been described by Johnson (1961, 1966) and Chishanya by Swift (1952). Johnson in Cox *et al.* (1965) drew attention to the similarity between the volatile-rich ijolitic magma he postulated as being parental at Shawa and the nephelinites at the base of the Karoo sequence in south-eastern Zimbabwe and the northern Lebombo. The involvement of CO_2-rich fluids in the initial stages of Karoo magmatism is discussed further in the light of more recent geochemical data on the Mashikiri nephelinites (Bristow, 1984).

K. The Tuli Syncline

The large area of basaltic rocks measuring 240 km by 50 km lies immediately west of the Nuanetsi syncline, from

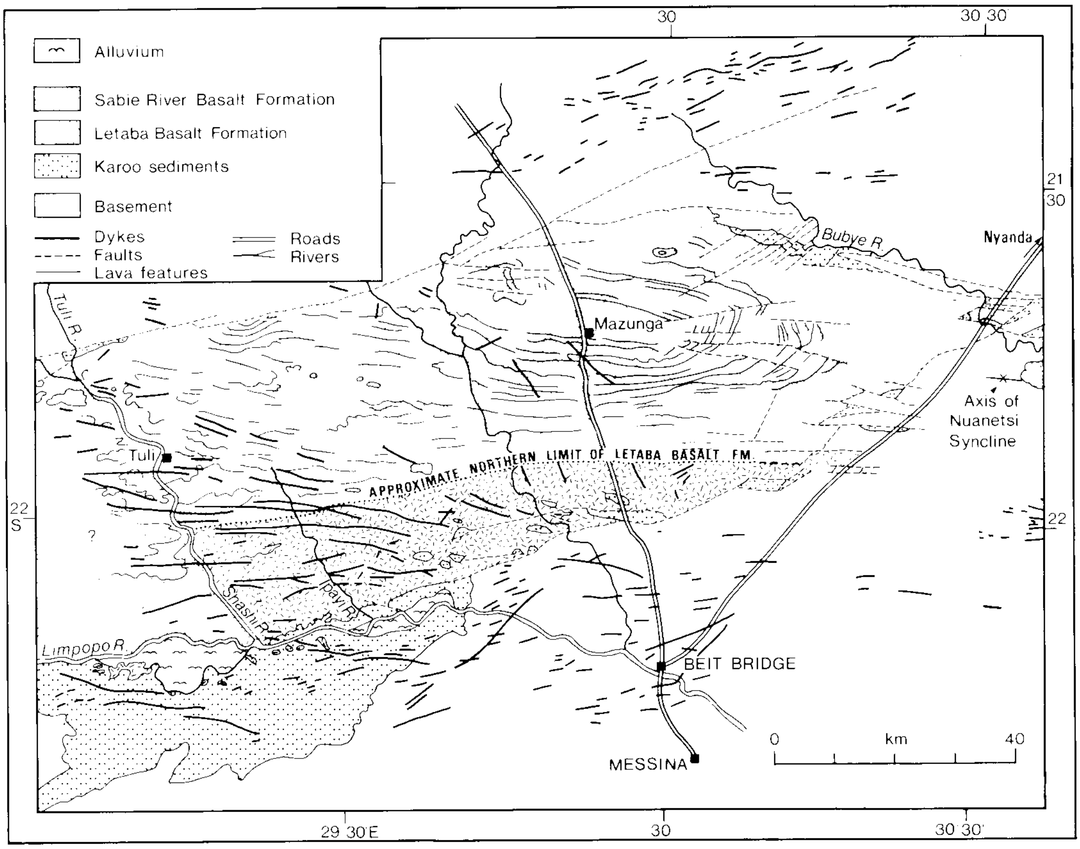

Figure 14
Geological map of the Tuli syncline, southern Zimbabwe (based on an unpublished map by J.R. Vail).

TABLE VI
Average Analyses of Karoo Lavas from Northern Localities

	1	2	3	4	5	6	7	8	9	10
SiO_2	49.4	49.6	50.0	53.19	51.50	50.38	54.77	52.51	58.38	72.26
TiO_2	2.08	3.08	2.94	2.83	3.18	0.85	0.43	0.71	0.70	0.50
Al_2O_3	14.71	8.38	14.82	11.68	13.14	14.54	20.30	14.54	14.60	11.91
Fe_2O_3	11.61	13.72	14.52	11.94	14.15	11.09	5.28	9.15	7.29	3.46
MnO	0.13	0.15	0.15	0.16	0.18	0.20	0.32	—	—	—
MgO	5.83	15.41	4.65	7.68	5.45	8.64	0.42	7.01	4.23	0.50
CaO	6.76	6.89	9.55	8.95	9.32	9.99	1.53	9.65	6.70	0.91
Na_2O	3.24	1.52	2.73	2.19	2.42	1.93	8.67	2.88	3.26	3.27
K_2O	3.88	1.68	1.00	1.63	1.06	0.69	6.27	0.93	2.35	5.23
P_2O_5	0.59	0.37	0.43	0.39	0.42	0.15	0.07	0.09	0.04	0.10
Number of analyses	(3)	(9)	(12)	(6)	(8)	(21)	(3)	(5)	(6)	(3)

1. Tuli Syncline — average of shoshonites and absarokite (Vail *et al.*, 1969).
2. Tuli Syncline — average Letaba Basalt Formation (Vail *et al.*, 1969).
3. Tuli Syncline — average Sabie River Basalt Formation (Vail *et al.*, 1969).
4. Featherstone — average basalt (Cox *et al.*, 1967).
5. Nyamandhlovu — average basalt (Cox *et. al.*, 1967).
6. Malaŵi — average dolerite dyke (Woolley *et al.*, 1979).
7. Lupata — average of phonolites and kenyte (Woolley and Garson, 1970).
8. Norther Mozambique coast — average basaltic type (Jaritz *et al.*, 1977, analyses 1329A, 1329B, 1334, 1349, 1350).
9. Northern Mozambique coast — average andesitic type (Jaritz *et al.*, 1977, analyses 290, 291, 292, 294, 298, 299).
10. Northern Mozambique coast — avergage rhyolite (Jaritz *et al.*, 1977, analyses 320, 323, 327A).

Measured concentrations reported, volatile contents not shown. Total Fe as Fe_2O_3.

which it is separated by a narrow strip of basement rocks near the Beit Bridge–Fort Victoria Road. A petrographic and geochemical account of a limited number of samples is given by Vail *et al.* (1969) though no detailed map is available apart from a previously unpublished photo-geological map made by J.R. Vail in 1966. A version of this is reproduced here (Fig. 14). The syncline is very asymmetrical but has a well-defined northern limb at its eastern end. Further west it is probable that the structure is essentially monoclinal, dipping gently to the north, the northern edge of the syncline being fault-bounded by movements rejuvenating the Tuli–Sabi shear belt, one of the most important structural elements of the Limpopo basement (Mason, 1973).

The thickness of the lava sequence in the syncline is not known though the early estimate of 1500 m at the synclinal axis by Cox *et al.* (1965) is almost certainly an overestimate. The outcrop pattern suggests near-horizontality over considerable areas and a borehole near Mazunga (Worst, 1962) penetrates only 400 m of lavas. The Tuli syncline is thus tectonically an extension of the western part of the Nuanetsi syncline, where, as previously mentioned, Karoo sediments and the lower part of the lava sequence are much reduced in thickness. Nevertheless a thin sequence of olivine-rich lavas which correlate with the Letaba Basalt Formation has been identified on the south side of the outcrop in north–south traverses along the Ipayi and Shashi rivers and along the road through Mazunga. This sequence is notable as the first in which shoshonitic lavas of Karoo age (see Table VI) were discovered (Vail *et al.*, 1969). It is overlain by basalts of the Sabie River Formation, which are virtually continuous in outcrop with those of the Nuanetsi syncline and form most of the surface outcrop of the Tuli structure. Towards the western end of the syncline a strong swarm of dolerite dykes with east-south-east trends appears, representing the eastern part of the extensive swarm described by Reeves (1978a) from Botswana. In the basement area to both north and south, however, dyke swarms show the east-north-east (Limpopo) trend.

L. The Limpopo Valley

The lavas of this area (e.g. the north side of the Soutpansberg) have not been investigated during the present project. It is known, however, from the work of Van Eeden *et al.* (1955) and Rogers (1925) that considerable thicknesses of olivine-rich lavas (Letaba Formation) are present with occasional underlying nephelinites (Mashikiri Nephelinite Formation). The extent to which these rock types persist westwards towards the Kalahari margin outcrops south of Serowe and Palapye is not known.

M. Featherstone, Central Zimbabwe

The Featherstone outlier is widely separated from other Karoo basalt outcrops and lies almost in the centre of the Rhodesian Craton. Worst (1962) noted the petrographic similarity between the lavas here and those from the Sabi district in south-east Zimbabwe, the comparison being with rocks now assigned to the Letaba Basalt Formation in the latter area. Olivine is a prominent phenocryst phase compared with basalts of Sabie River Basalt formation type and groundmass glass and quench structures are quite abundant. Analyses (see Table VI) show the rocks to be distinctly magnesian though not picritic (Cox *et al.*, 1967). Trace elements also indicate affinities with the lavas of south-east Zimbabwe. The source of the Featherstone lavas is mysterious since dolerite dykes seem to be represented only very sparsely in the vicinity. However, an actual origin in south-east Zimbabwe, the nearest basalt outcrops of which are 300 km distant, seems difficult to believe.

N. Western Zimbabwe

A small amount of information on the large outcrop in the Victoria Falls–Hwange (Wankie) area and round Nyamandhlovu 200 km to the south-east is available in the work of Cox *et al.* (1967). The rocks appear to be mainly olivine-free and have the low magnesium contents typical of the Sabie River basalt type. Virtually all the samples studied are slightly to moderately feldspar-phyric and slightly augite-phyric. As is the case with the Featherstone rocks, trace elements, as also the contents of K and P, show similarities to the lavas of south-east Zimbabwe and the northern Lebombo rather than to Swaziland, southern Lebombo or Lesotho.

O. Dyke Swarms of Southern Malaŵi and the Lower Zambezi

There are several occurrences of Karoo lavas in this general area (see Figs. 1 and 15) but apart from a little detailed work on the Lupata lavas (Coelho, 1959a; Woolley and Garson, 1970) they are not at all well known. However, a number of well-developed dyke swarms have been identified and have in one case, the Cholo swarm of Malaŵi (see vicinity of Blantyre on Fig. 15), been the subject of a detailed geochemical study (Woolley *et al.*, 1979).

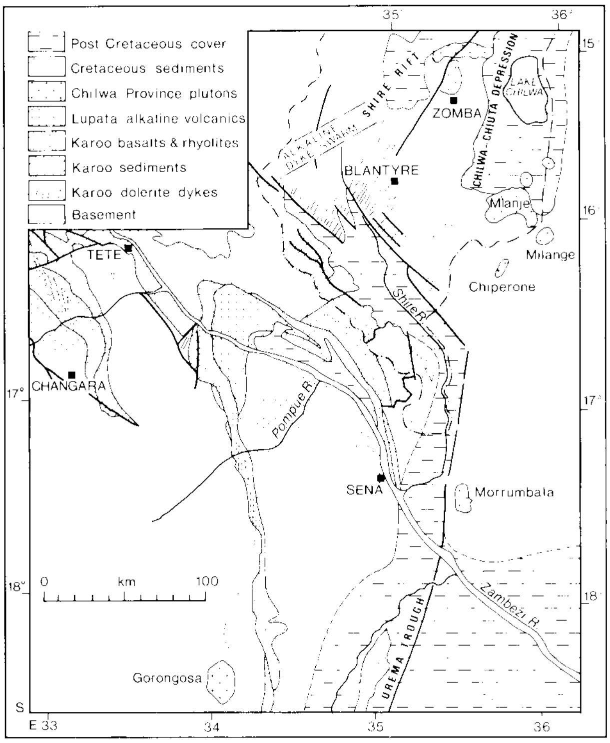

Figure 15

Geological map of southern Malaŵi and the Lupata area of Mozambique (after Vail, 1963a and b; Woolley and Garson, 1970; Woolley *et al.*, 1979).

The southernmost swarm appears to be related to the large intrusive complex of Gorongosa (Coelho, 1959b) and is traceable for 180 km to the north and at least 100 km to the south (Vail, 1963a). Most of the dykes are fine-grained dolerites but there are some of porphyritic granophyre and microgranite. Vail (1963b) also identified dykes with north-north-west and north-north-east trends in the Zambezi valley approximately 50 km downstream from Tete, which may represent a discontinuous extension of the Gorongosa swarm. If this is so then the swarm has a total length approaching 400 km.

Vail (1963a) notes a second swarm, termed Inhamangombe, which appears abruptly 30 km north of Changara (see Fig. 15) and strikes north-north-west for a further 65 km. In this northern area a few dykes striking north-east are also seen.

The north-east-trending Cholo dyke swarm in the Blantyre area of Malaŵi (Woolley *et al.*, 1979) has a very distinctive geometry in that it is some 140 km wide but, in its main development, only about 100 km long. The rocks are doleritic and in the densest part of the swarm there are about four dykes per kilometre. In the extreme south of Malaŵi a further group of dykes is found cutting the basement on the west bank of the Shire River and having a roughly north–south trend. We shall term this the Nsanje swarm.

Woolley *et al.* (1979) point out several particularly interesting features of the geochemistry of the Malaŵi dykes. Firstly, the most basic specimens analysed, all from the Nsanje swarm, define an olivine fractionation trend but are aphyric. They contain up to 15% MgO and thus represent distinctly picritic liquids. This is one of the very few instances where picritic magma, believed to be representative of the parental liquids of most Karoo basalts (Cox, 1980), has reached the surface outside the south-east Zimbabwe–northern Lebombo area. However, the incompatible element geochemistry of all the Malaŵi dolerites could hardly be more different from that of the latter area. The Malaŵi dolerites are relatively depleted in K, Ti, P, Ba and Sr and are thus much more similar to the basalts of Lesotho and the southern Lebombo. As Woolley *et al.* (1979) suggest, this greatly changes the simple picture of north–south geochemical zonation proposed by Cox *et al.* (1967). Some of the fine detail of the pattern is seen within Malaŵi itself, because although all the rocks are incompatible element-depleted the effect is much more marked in samples from the Cholo swarm than in Nsanje samples (see Table VI).

P. The Lupata Volcanics

The Lupata volcanics overlie Karoo basalts and rhyolites in the Lupata Gorge area of the Zambezi, about 70 km downstream from Tete (Fig. 15). Age determinations summarized by Woolley and Garson (1970) lie in the range 106–130 m.y. and indicate the volcanics to be of approximately the same age as the Chilwa Province plutons to the north. An underlying Karoo rhyolite has been dated at 166 ± 10 m.y. (Flores, 1964). The whole Karoo volcanic sequence appears to consist of about 600 m of basalts, overlain by 100 m of sandstone and finally by 80 m of rhyolite (from literature review by Woolley and Garson, 1970). Above the unconformity the Lupata volcanics themselves consist of about 300 m of lavas overlying 150 m of conglomeratic sandstones and tuffs. The whole sequence is overlain by the conglomeratic Sena Sandstones, believed to be of Cretaceous age.

The Lupata volcanics consist of phonolites, kenytes, analcite kenytes, and very rare blairmorites containing analcite phenocrysts up to 1 cm in diameter. Six analyses of trachytes and phonolites are given by Coelho (1959a) and five further analyses are available in Woolley and Garson (1970), including one of a foyaite (see Table VI for representative analyses).

Q. Barotseland

Seven boreholes drilled by the Geological Survey of Zambia (Ridgway and Money, 1978) show that an area of at least 36,000 km^2 in Barotseland (western Zambia) consists of basic lavas beneath a younger cover. The lavas are the presumed continuation of the Karoo basalts of the Victoria Falls area, known locally as the Batoka Formation. The southernmost borehole, near the Zambezi about 300 km north-west of Victoria Falls, penetrates the greatest thickness of lavas, 390 m. However, 100 km to the north-east a thickness of only 40 m is present. Many analyses have been carried out but only averages are available at present. Two striking features emerge. Firstly, in the southernmost borehole the lower part of the sequence contains highly sodic rocks which are normatively basanites. As Ridgway and Money point out, comparison with the nephelinite occurrences of south-east Zimbabwe and the northern Lebombo is invited. Secondly, in the tholeiitic rocks which make up most of the sequence potassium contents are low and similar to those of the *southern* province defined by Cox *et al.* (1967), although these are the most northerly Karoo lavas known. Geochemical details are not clear at present and are obviously complex since the Barotseland basalts are quite high in Ti and P, unlike typical southern province rocks. Nevertheless, to an extent the Barotseland data confirm the impression gained from the geochemistry of the Malaŵi dolerites discussed previously. The northernmost occurrences of Karoo basaltic rocks show a tendency to resemble the southernmost, and the area in which the distinctive K-rich geochemistry predominates lies in an intermediate position.

R. Northern Mozambique

Volcanic rocks have been known from the coastal region of northern Mozambique (near Mozambique Island and António Enes, see Fig. 16) for some time (Holmes and Wray, 1912; Holmes, 1971; Moura, 1935) but were until recently regarded as Tertiary in age. However, a study by Jaritz *et al.* (1977), on whose work the following account is based, has shown that most K-Ar ages lie in the range 177–157 m.y. and are thus typical of the Karoo, though possibly somewhat younger than the main phase of activity in the Lebombo region to the south. Ages of 120 ± 2 m.y. and 130 ± 3 m.y. from a single outcrop in the upper part of the sequence at Lunga are not mutually consistent but may indicate a genuine phase of Lower Cretaceous activity in this area.

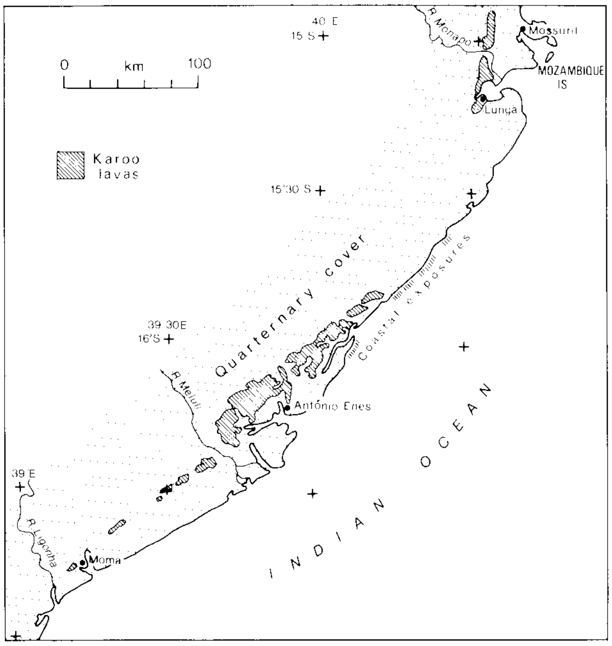

Figure 16

Karoo lava occurrences (diagonal shading) of the northern coast of Mozambique (after Jaritz *et al.*, 1977).

The volcanic rocks are on the whole not well exposed because of an extensive cover of Quaternary sediments, and are generally rather weathered. Flow relationships are seen in exposures in the tidal zone and indicate an average seaward dip of about 10°. On this assumption the 15 km-wide outcrop at António Enes may represent a stratigraphic thickness of as much as 2500 m, while the outcrop west of Mozambique Island and at Moma represent 500 m and 200 m sections respectively. Collectively these occurrences extend along strike for approximately 275 km, with a possible extension, so far uninvestigated, to the north of Mossuril.

The different rock types, which appear to be closely interbedded, are referred to by Jaritz *et al.* (1977) as tholeiitic basalts and rhyolites though, as can be seen from Table VI, the former have strongly andesitic affinities. Petrographically these rocks exhibit unusual degrees of departure from equilibrium and contain several generations of plagioclase and clinopyroxene showing varying degrees of resorption. Coarse-grained aggregates of plagioclase, bronzite, and diopsidic augite make up textural regions of gabbroic structure. The rhyolitic rocks, in contrast, appear to be aphyric.

VI. REGIONAL GEOCHEMISTRY

The Karoo volcanics are an excellent example of the acid-basic association in which SiO_2 shows a strongly bimodal distribution (Fig. 17) with SiO_2 maxima corresponding to basalts and rhyolites (*sensu lato*). The acid rock types are only developed in areas such as the Etendeka Plateau, Lebombo, Nuanetsi and Lupata regions which form the western and eastern margins of the Karoo Ingneous Province. In the central portions of the province rock types with >66 % SiO_2 are totally absent but very small volumes of intermediate rocks with compositions in the andesite–

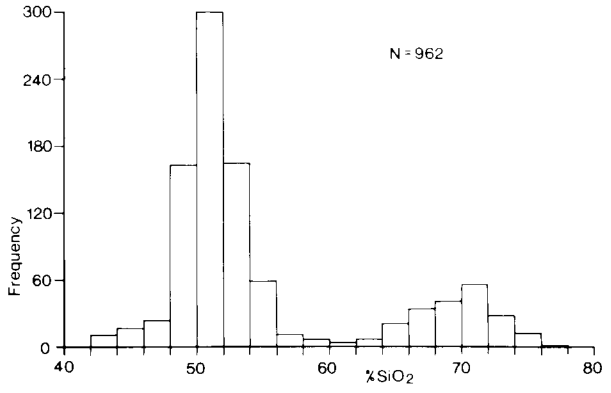

Figure 17
Histogram of per cent SiO_2 contents for intrusive and extrusive rocks in the Karoo volcanic province. All data are listed on Microfiche Cards 1 and 2 included with this volume. Data in the figures have been recalculated on a volatile-free basis (Microfiche Card 2).

dacite range are known from the north-eastern Cape Province near Barkly East and Jamestown.

By far the most common basic rock type in the Karoo volcanics is tholeiitic basalt as has been mentioned in previous sections of this chapter. Some of the rocks, particularly from the Lebombo, are relatively evolved, silica-rich types and the term tholeiitic andesite (Wilkinson and Binns, 1977) is perhaps more appropriate (see Bristow and Cox, 1984). The relatively evolved character of many Karoo basaltic rocks is shown by typically low Mg-numbers (generally <65) and rather low Ni values (see Fig. 18). Other basic rock types which are found in the Karoo volcanics include picritic basalts, shoshonitic basalts and nephelinites.

The basaltic rocks of the Karoo Igneous Province were subdivided by Cox *et al.* (1967) into northern and southern provinces on the basis of some distinctive differences in minor and trace element composition. With the enormous increase in the availability of compositional data for the Karoo volcanics, much of it obtained during the course of the present project, it has become possible to refine and extend these compositional subdivisions. We no longer believe that it is approproate to subdivide the Karoo basalts into simple geochemical provinces with specific geographic limits. Rather, we prefer to define a number of specific magma types where some of these have rather restricted geographic distribution (e.g. the magma type which corresponds to the Kraai River Formation of the north-eastern Cape Province) and others that occur over enormous areas of the subcontinent (e.g. the magma type which corresponds to the Lesotho Formation). The details of definition and distribution of these magma types are discussed in later chapters in this volume, but an outline of the major features can be considered here. Clans of magma types from the Etendeka, Central Karoo (e.g. Lesotho, north-eastern Cape, etc.), southern Lebombo and northern Lebombo–Nuanetsi show marked compositional

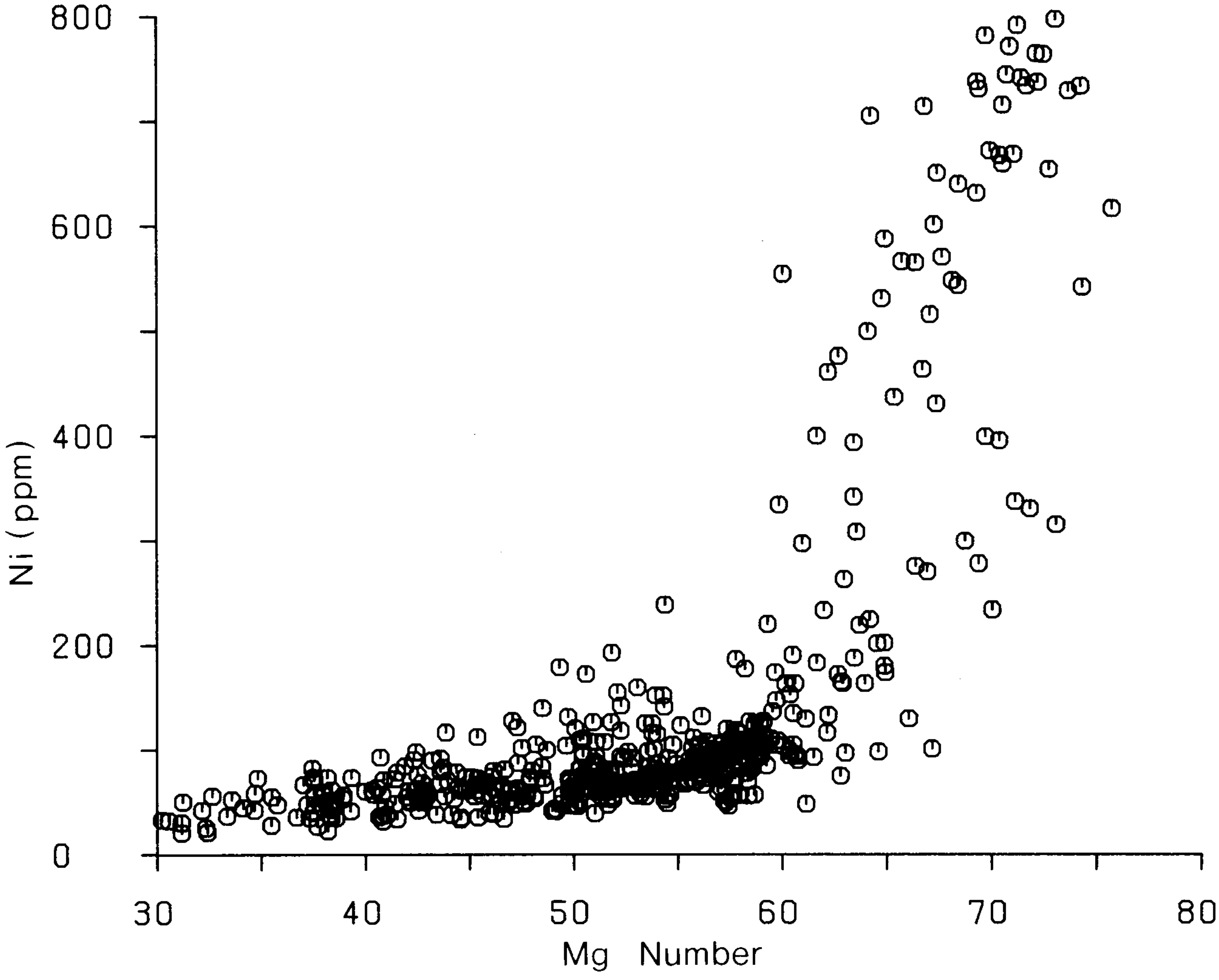

Figure 18
Plot of Ni concentration *vs.* Mg-number (atomic ratio of Mg/(Mg + Fe^{2+}) for rocks of Karoo volcanic province. If a basalt were derived directly from the mantle and was in equilibrium with presumed mantle olivine (Fo_{92}) its Mg-number should lie in the range 68–72. Note that a few samples with high Ni concentrations (>800 ppm) have been excluded from the diagram.

differences. Histograms of elemental abundances in these magma types indicate systematic differences between them for many minor and trace elements (e.g. Ti, K, P, Rb, Ba, Sr, Zr, Cr, V and Ga). The rare earth elements also show systematic differences in both pattern and total abundance between the different types. The compositional differences between these basaltic magma types could be due to differences in one or more of the following:

a. mantle composition varying in either a lateral or vertical fashion;
b. degree of partial melting;
c. degree of fractional crystallization;
d. contamination processes in either the crust or the mantle.

The compositional differences between the basaltic magma types are such that they cannot readily be explained by different degrees of partial melting or fractional crystallization alone. It therefore seems probable that many of the compositional differences between the types are either the product of *systematic* differences in the degree of contamination of the primary magmas or that they reflect mantle inhomogeneity. This generalized conclusion can also be supported by isotopic evidence, but this will be discussed in later chapters.

The acid and intermediate magma types in the Karoo volcanics consist of the latite and quartz latite magmas in the Etendeka Formation; the "dacite" magmas in the north-eastern Cape Province and dacite, rhyodacite and rhyolite magmas in the Lebombo–Nuanetsi region. The bulk of the Lebombo–Nuanetsi acid volcanics are quite different from the other acid volcanics in the Karoo Province in having higher SiO_2 (averaging about 70%), much higher REE, Zr, Y and Ba together with much lower Ti and P. They also have much lower initial $^{87}Sr/^{86}Sr$ ratios (Manton, 1968).

In contrast, the acid and intermediate magma types in the Etendeka volcanics, north-eastern Cape and in two minor formations in the southern Lebombo (Mkutshane Beds in Swaziland and Kuleni rhyolites in Zululand) all have lower SiO_2 and relatively high initial $^{87}Sr/^{86}Sr$ ratios.

In later chapters the field relationships together with these chemical and isotopic characteristics are used to evaluate various petrogenetic models for the acid and intermediate volcanics. In general, models whereby the silicic volcanics are generated by fractional crystallization of associated basic magmas cannot be supported by chemical data. More compelling models invoke anatexis of crustal material or derivation by re-melting mantle-derived basic rocks.

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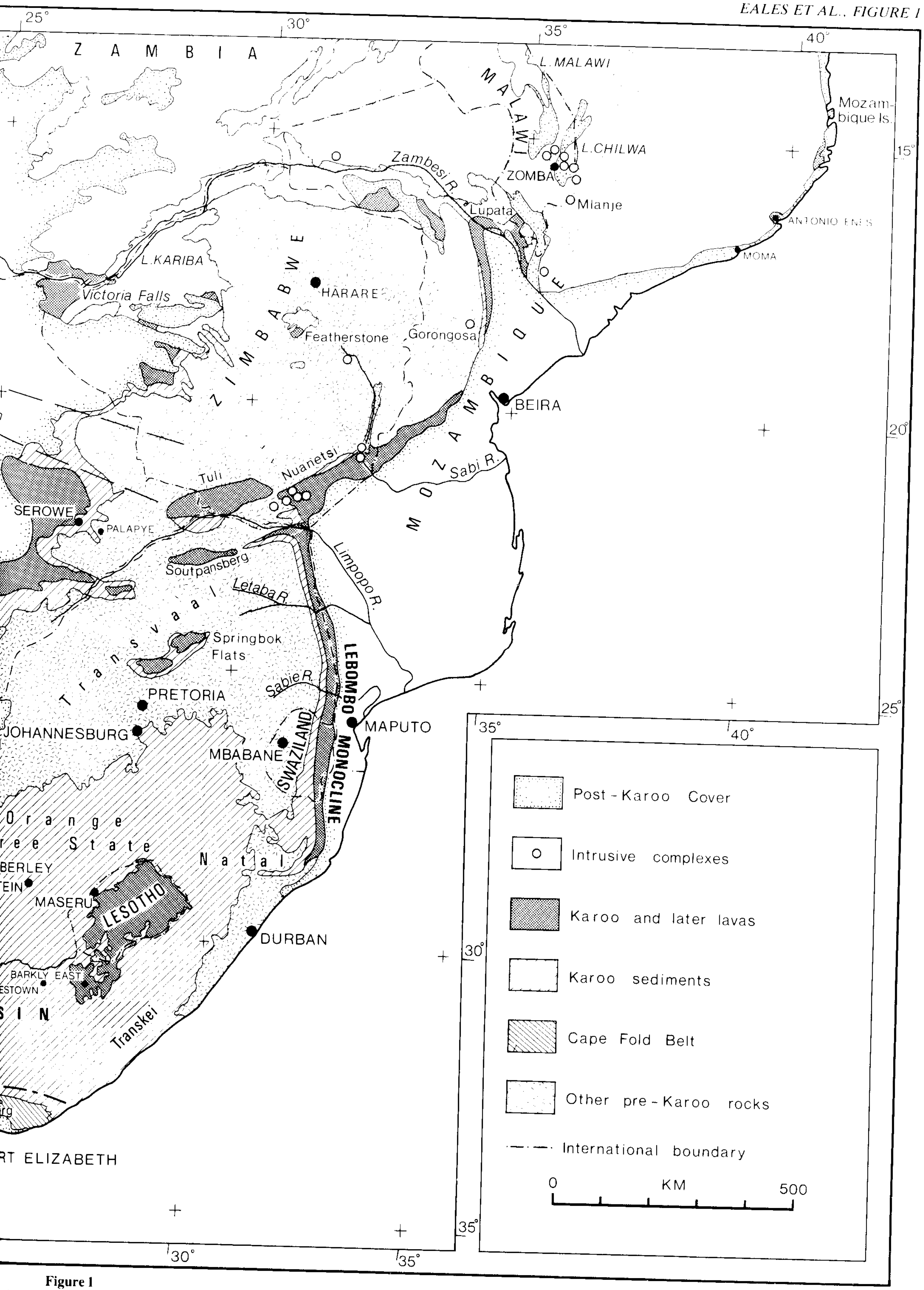

Figure 1

al map showing distribution of Karoo rocks.

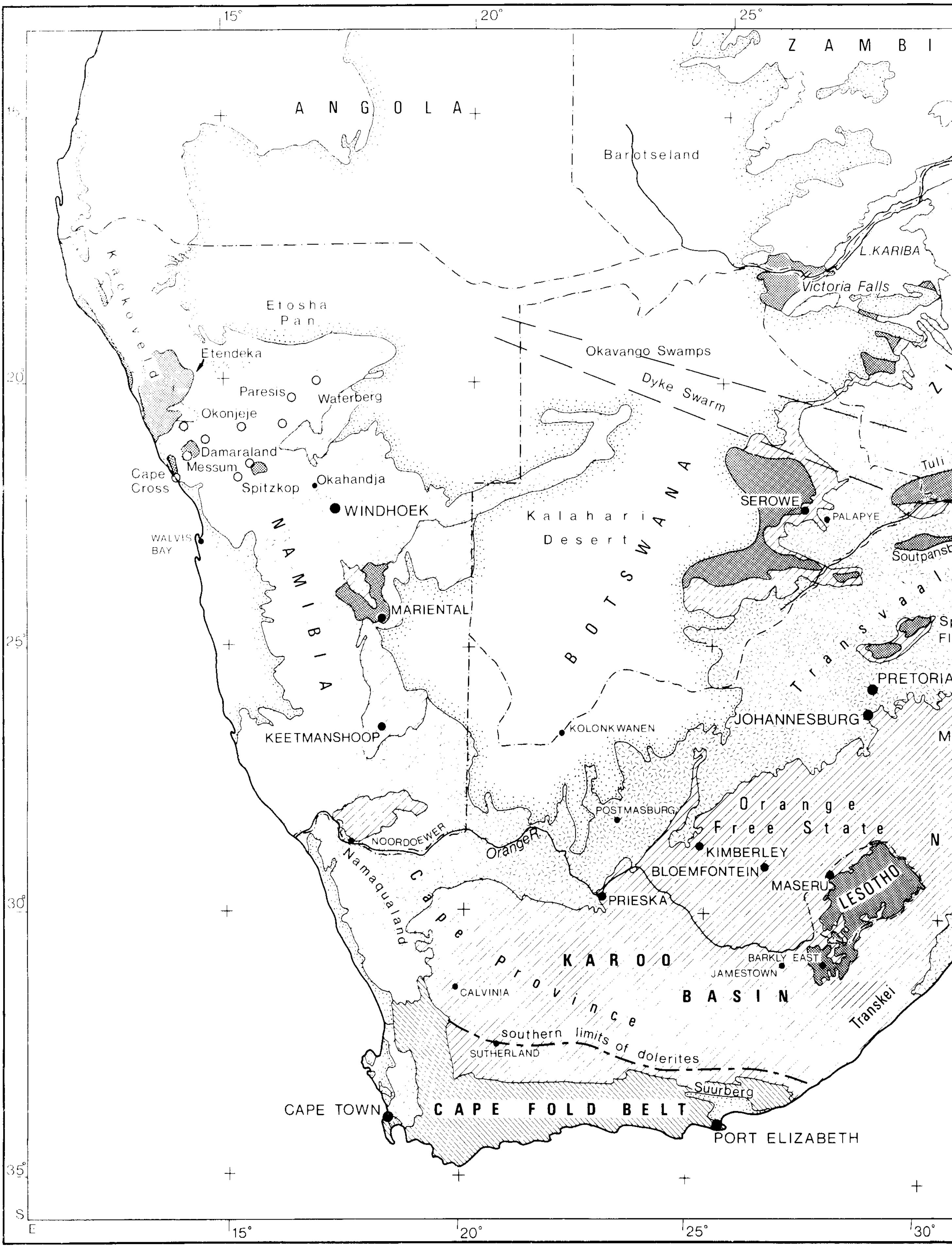

Figure 1

Simplified geological map showing distribution of Karo