THE GEOLOGY OF THE NUANETSI IGNEOUS PROVINCE

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[Plates 2 to 8, and a coloured map]

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The Nuanetsi Igneous Province is situated in the south-eastern corner of Southern Rhodesia and marks the intersection of the Limpopo lineament with the volcanic monocline of the Lebombo. The latter is part of a zone of intense Karroo and post-Karroo volcanicity which lies along the boundary between the uplifted central portion of southern Africa and the depressed Mozambique geosynclinal area to the east. With interruptions, due to the overlap of Cretaceous sediments, the volcanic zone can be traced from Natal to the Zambezi.

In the Nuanetsi area a number of late-Karroo ring complexes are found, cutting a thick (*ca.* 25000 ft.) succession of Karroo lavas consisting predominantly of basalts and rhyolites.

A brief description is given of the gneissose Basement complex rocks lying unconformably beneath the Karroo. By plotting Basement trends from aerial photographs it has proved possible to link areas which had previously been mapped by Söhnge (1945) in the Messina area, immediately to the south-west of the province, and by Swift *et al.* (1953) at the northern end of the province. A general picture has thus emerged of the extent and trend of the Limpopo orogenic belt, a basement orogeny provisionally dated at 2000 My (Holmes & Cahen 1955).

The belt can be divided into three longitudinal zones which have an immense significance in the interpretation of subsequent geological events. The central zone is characterized by the great diversity of the trends shown by individual beds. Folds tend to run oblique to, or even normal to, the overall east-north-east trend of the belt. Flanking the central zone on each side is a zone in which strikes are uniformly parallel to the elongation of the belt. The central zone is about 30 miles wide and the transition to the marginal zones is comparatively sharp, taking place in a matter of 2 to 3 miles. The whole belt is well over 100 miles wide.

During the Karroo period the marginal zones were the sites of sedimentary troughs and, later, of intense volcanicity and faulting. The central zone, in contrast, remained as a comparatively stable, positive, unit, termed the Messina Block, and was covered only by a thin veneer of sediments and lavas. The centre line of this zone was marked, during the culmination of the volcanism, by the intrusion of 7 ring complexes lying on a straight east-north-east line.

Details of Karroo sedimentation are then given and particular attention is paid to the variations in thickness reflecting the underlying basement structure. Following this, the distribution and general nature of the volcanics and their associated dyke rocks are discussed. Small amounts of nephelinite and allied rocks were erupted at a very early stage and were succeeded by great thicknesses of limburgitic lavas, passing upwards into normal tholeiites. The lower part of the basaltic succession contains numerous intrusions of picritic rocks, many with strong alkaline affinities. The later lavas were of rhyodacitic and rhyolitic composition and were to a large extent erupted as ignimbrites.

A brief account is given of the late-Karroo intrusive rocks, viz. the rocks of the ring complexes and the regionally developed Main Granophyre. The latter is an immense sill with an inferred extent of at least 100 miles along the strike. In the south-western part of the province the sill is preserved in the Nuanetsi syncline, a deep and extensive volcano-tectonic fold. The discordance of the sill suggests that, though it has itself a synclinal structure, the folding affecting it is less intense than that affecting its country rocks. Hence it is concluded that the intrusion took place towards the close of deformation of the syncline.

All the ring complexes contain granitic or granophyric rocks and many in addition contain earlier intrusions of gabbro. Nordmarkites are occasionally present, falling between the gabbros and granites in time. One complex, Marangudzi, includes a post-granite intrusion of nepheline syenite.

The section on tectonics deals first with the descriptive aspects of the structural geology and covers the main tectonic units of the province and surrounding areas. The principal fold structures affecting the Karroo rocks are the Lebombo monocline and its extension northwards in the Mateke–Sabi monocline. The Tuli syncline and Nuanetsi syncline jointly form an approximately

east–west structure lying on the north side of the Messina Block and meeting the Lebombo at the southern end of the province. South of the Messina Block lies the Northern Transvaal fault-zone which again contains considerable thicknesses of Karroo rocks.

Structural features are summarized on the basis of trend and age-relations and a structural interpretation based on this is suggested. It is concluded that the Northern Transvaal fault-zone and the Tuli syncline owe their location to the zonal structure of the Limpopo orogenic belt in the underlying basement. The Nuanetsi syncline, on the other hand, runs somewhat obliquely across the basement structure and overlaps Limpopo-trend (east-north-east) structural features, such as faults and the line of ring complexes, in both time and space. Hence the fold cannot be envisaged as localized by basement structure in the same way as the Tuli syncline. The uplifted shield area of southern Africa has, however, a deep indentation in its edge, represented by the change of direction of the Lebombo monocline as it swings into the Mateke–Sabi monocline. The Nuanetsi syncline lies in the shield area and meets the shield-margin at the point of the re-entrant, almost bisecting the angle. The syncline, moreover, is filled with volcanic rocks which were largely erupted from fissures parallel to the synclinal axis. Hence the fold can be envisaged as a tensional feature, localized as the result of the concentration of stress at the point of the re-entrant in the margin of the shield. Such stress appears to have been caused by essentially lateral tectonic movements affecting the shield. A very close analogy may be found in the Kangerdlugssuaq area of East Greenland (Wager 1947).

A general tectonic synthesis, involving an assessment of vertical and lateral tectonics, cannot be attempted until more information is available on antithetic fault-zones such as that of the Northern Transvaal. Such zones are of wide occurrence in Africa and consist essentially of groups of parallel, apparently normal, faults all of which throw and hade in one direction and tend to offset the dip of the beds. Interpretation in terms of pure vertical tectonics fails to account for the antithetic nature of the faulting; interpretation in terms of pure lateral tectonics, however, does not explain the uniformity of hade. It is considered that a possible interpretation may be made by postulating a crust held relatively rigidly in position in its upper levels, overlying a mobile substratum which can flow laterally. Oblique shear planes transecting the whole crust could be formed by such a mechanism, rather in the way in which an incompetent formation is sheared in a folded sedimentary sequence.

The petrography and geochemistry of the Karroo igneous rocks of the province and surrounding areas are then discussed. The basalts can be shown to form a continuous series from limburgites, carrying normative olivine, to oversaturated quartz-bearing types. This is termed the Tholeiitic Series, the limburgites and olivine-basalts being designated high-magnesia tholeiites, and the oversaturated types, low-magnesia tholeiites. The latter correspond with the original tholeiites of Kennedy (1933).

A continuous series can also be established for the acid rocks and includes both extrusives and intrusives, the two types being chemically indistinguishable. It is considered that the rhyolites of the Lebombo and Nuanetsi areas represent primary acid magma and are not the differentiation products of Karroo basaltic magma. The Tholeiitic Series, too, is difficult to interpret in terms of conventional crystallization differentiation, mainly because the observed chemical variation cannot be explained by reference to the observed phenocrysts. It is therefore considered possible that the major variations in the Lebombo–Nuanetsi zone are due to a thermal disturbance causing the production of a large range of primary magmas by refusion or partial refusion of the substructure at differing levels.

This leads to the concept of the Karroo volcanic cycle, an essentially thermal event consisting of a waxing phase during which geo-isotherms rise, a culmination when the geothermal gradient has reached its steepest inclination, and a waning phase during which thermal normality is regained. Deep-seated rocks of alkaline affinities are erupted at the beginning and the end of the cycle. Rhyolites correspond with the culmination. It may be said that the waxing phase represents the ideal environment for rock-variation by melting processes, whereas the waning phase is the environment of crystallization differentiation. The waning phase of the Karroo volcanic cycle is represented by the basalt–trachyte–phonolite association found overlying the Karroo rhyolites in the Lebombo and in the Lupata area on the Zambezi. The cycle therefore includes rocks of Cretaceous age and hence transects the normal stratigraphic time-divisions.

Finally, some problems of carbonatite genesis are discussed in terms of the Karroo volcanic cycle.

FOREWORD

This memoir deals with a hitherto unmapped area situated along the southern border of Southern Rhodesia, immediately to the north of the Limpopo River. It is a region of very considerable interest in that it marks a northern deflected continuation of the great structural line of South Africa, known as the Lebombo monocline, made famous by Du Toit. The present investigation shows that the Limpopo lineament was in existence in Pre-Cambrian times and that subsequent movements along this lineament have controlled the much later Karroo sedimentation, volcanicity, and the emplacement of late Karroo igneous complexes.

The region as a whole illustrates many important aspects of the tectonic control of igneous activity, the manner of emplacement of intrusive igneous rocks, petrogenesis, and the generation of acid magmas in non-orogenic areas. The results have been obtained by the authors working individually and as a team, under the auspices of the Research Institute of African Geology in the University of Leeds. The work is, therefore, dedicated to the late Sir Ernest Oppenheimer and the Anglo-American Corporation of South Africa whose generous endowment of the Research Institute of African Geology enabled these researches to be carried out.

W. Q. KENNEDY

PART I. GENERAL GEOLOGY AND TECTONICS

I. Introduction

The Nuanetsi Igneous Province is situated in south-east Southern Rhodesia, and covers an area approximately 50 miles wide, running from near Beitbridge, on the Limpopo, to the Lower Sabi valley, 150 miles to the north-east. The Province may conveniently be divided into two parts, the south-western, or Mateke region and the north-eastern, or Sabi–Lundi region. The location of the Province and an outline of the geology of the surrounding areas are shown in figure 1.

Access to the Mateke region is from the Fort Victoria–Beitbridge road via a number of tracks leading eastwards or south-eastwards. The most important of these leaves the main road at the Nuanetsi police post and Native Commissioner's office and follows the north bank of the Nuanetsi River to Chikombedzi. Beyond this point a number of tracks are

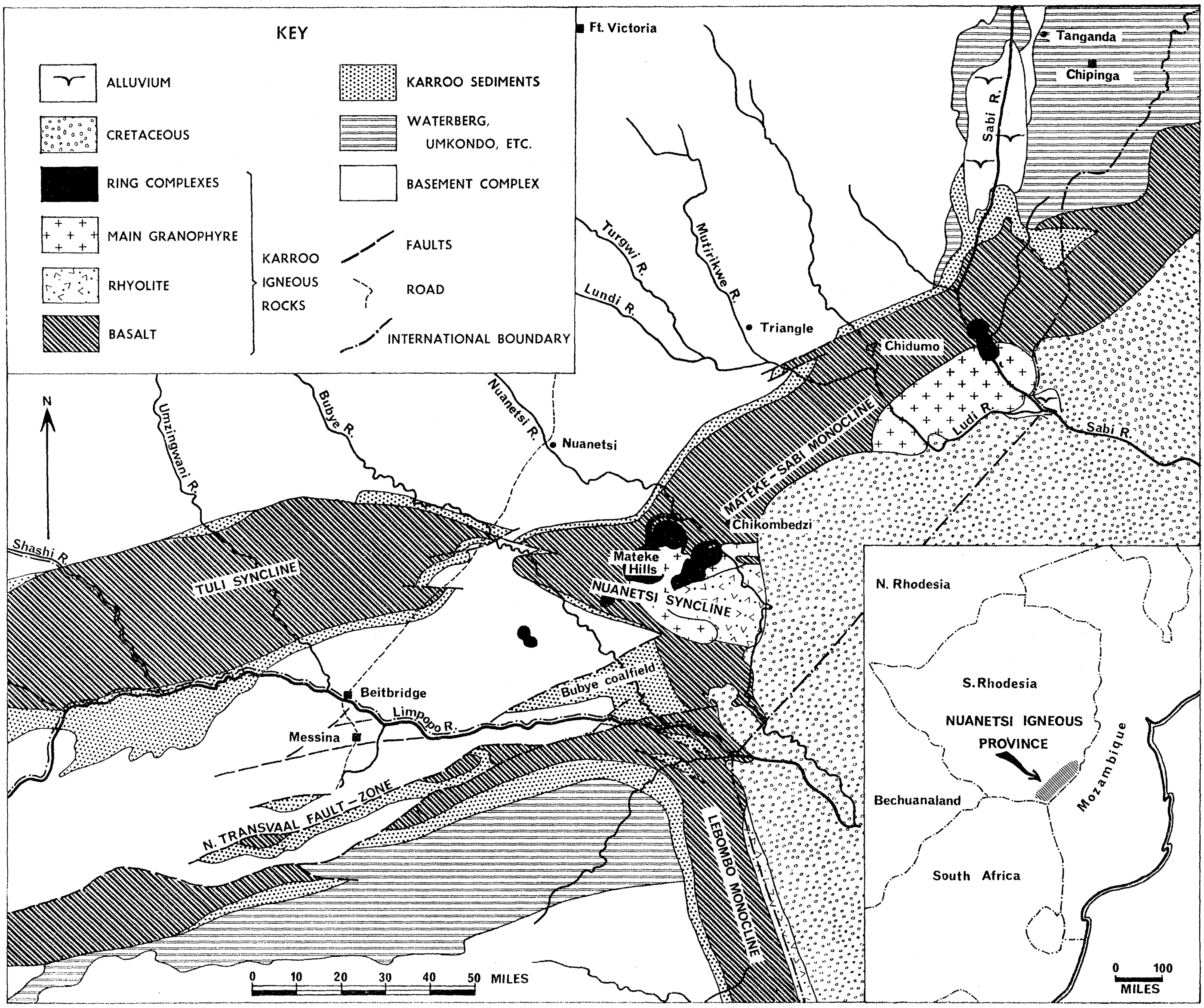


Figure 1. General geology of the Nuanetsi Igneous Province and the surrounding area.

available and give reasonable access to the Mateke Hills and the lower reaches of the Nuanetsi River.

The Sabi–Lundi region is best approached via the Triangle sugar estates and Chidumo Clinic. Access to the extreme north-eastern part of the area is, however, from Tanganda Halt on the Birchenough Bridge–Chipinga road, and thence down the east bank of the Sabi.

The Province lies entirely in the Rhodesian low-veld, for the most part between 1000 and 2000 ft. above sea-level, and the country, viewed from a distance, appears monotonously flat with occasional isolated hills and several larger plateaus rising above the plains.

The dry season, when even the largest rivers are apt to cease flowing, lasts from April to November. Field work has been confined to periods from May to October when the vegetation has dried off sufficiently to expose outcrops, and the tracks and stream-courses are dry enough to be passable.

A geological map of the Nuanetsi Igneous Province and the surrounding area is given in figure 1. The information outside the province has been derived from the published maps of the Geological Surveys of South Africa, Southern Rhodesia and Mozambique. The geological formations present in the province are summarized in table 1.

TABLE 1. GEOLOGICAL FORMATIONS OF THE NUANETSI IGNEOUS PROVINCE

alluvium	Recent
unconformity	
Malvernia Beds—sandstones and conglomerates	? Cretaceous
unconformity	
Acid intrusives of the ring complexes	late-Karroo intrusive rocks
Main Granophyre sill	
Basic intrusives of the ring complexes	
Rhyolitic Group	Karroo extrusive rocks
Upper Basalt Group	
The Olivine-rich Group	
Cave Sandstone	Karroo Sediments
Lower sediments—shales and sandstones including coal	
unconformity	
Granites and orthogneisses	Basement complex
Paragneisses of the Messina System	

The principal structural features controlling the distribution of the Karroo Rocks are:

The Lebombo monocline, which runs north–south along the border between Mozambique and South Africa. The Karroo rocks dip steeply eastwards and pass beneath the Cretaceous and Tertiary sediments of the Mozambique geosyncline.

The Nuanetsi syncline, a large east–west synclinal fold with a pronounced eastward axial plunge. The southern limb of the fold swings into the Lebombo monocline. The *Tuli syncline* is the westward continuation of the Nuanetsi syncline, separated from it by a culmination in the vicinity of the Beitbridge–Fort Victoria road.

The Mateke–Sabi monocline, which is the continuation to the north-east of the northern limb of the Nuanetsi syncline.

Northern Transvaal fault-belt, which repeats the northward-dipping Karroo rocks of the south side of the Limpopo valley, causing them to crop out in several elongated strips.

The Sabi syncline, a comparatively small north–south fold which intersects the Mateke–Sabi monocline at the north-eastern end of the Nuanetsi Igneous Province.

The Karroo succession consists of a lower series of sediments of very variable thickness, the maximum development of which is in the vicinity of the Limpopo, that is to say in the area of the Bubye Coalfield and in the Northern Transvaal fault-belt. The sediments are again comparatively thickly developed in the Sabi syncline, a much thinner sequence being present round the margins of the Nuanetsi syncline.

The overlying volcanics also appear to vary considerably in thickness, and reach an estimated 25 000 ft. at the eastern end of the Nuanetsi syncline. Here the upper part of the sequence consists of several thousands of feet of rhyolites with small amounts of interbedded basalt.

The chief geological feature of the province is the occurrence of numerous intrusive igneous bodies which cut the Karroo volcanics. These comprise ring-dyke complexes, together with an extremely widespread major sill, termed the Main Granophyre, which has an inferred extent of slightly over 100 miles along the strike of the Mateke–Sabi monocline. The ring complexes are made up mainly of gabbroic and granitic rocks with subordinate quartz- and nepheline-syenites, and their age has conveniently been referred to as late-Karroo, since they clearly belong to the later stages of the igneous cycle which commenced with the eruption of the Karroo basalts. The only other direct evidence of their age is provided by the fact that the Main Granophyre is overlain by the Malvernia Beds, believed to be of (? Upper) Cretaceous age.

In the course of the present study it has become clear that the Nuanetsi Igneous Province is an area *par excellence* in which the relations between tectonism and volcanism are displayed and in which the control of Karroo structural evolution by existing basement structures can be demonstrated with unusual clarity. This work deals first with descriptive geology and then with aspects of the relations existing between tectonics, igneous activity, and sedimentation during the evolution of the Province in the Karroo period. Finally, the geochemistry and petrogenesis of the igneous rocks are discussed and the concept of the Karroo volcanic cycle is put forward.

It is hoped to publish a separate account of the post-Karroo geology of the area comprising a study of the Malvernia Beds and geomorphology.

II. The Basement complex

The older crystalline rocks on which the Karroo rests unconformably can conveniently be grouped together as the Basement complex. In the present study no attempt has been made to produce a geological map of these rocks, work having been confined to the plotting of basement trends from aerial photographs and to the collection of samples. By this means, however, it has been possible to link up areas which had previously been mapped in detail by the Geological Survey of South Africa in the Transvaal (Söhnge 1945, sheet 2228 Beit Bridge and sheet 2230 Messina, 1:250000 series, 1957), and by the Geological Survey of Southern Rhodesia in the Sabi Coalfield area (Swift, White, Wiles & Worst 1953). A general picture of the Basement over much of the Northern Transvaal and the southern part of Southern Rhodesia can therefore be put forward and this leads to the conclusion that the Basement structure has had a very marked influence on the subsequent geological evolution of the area.

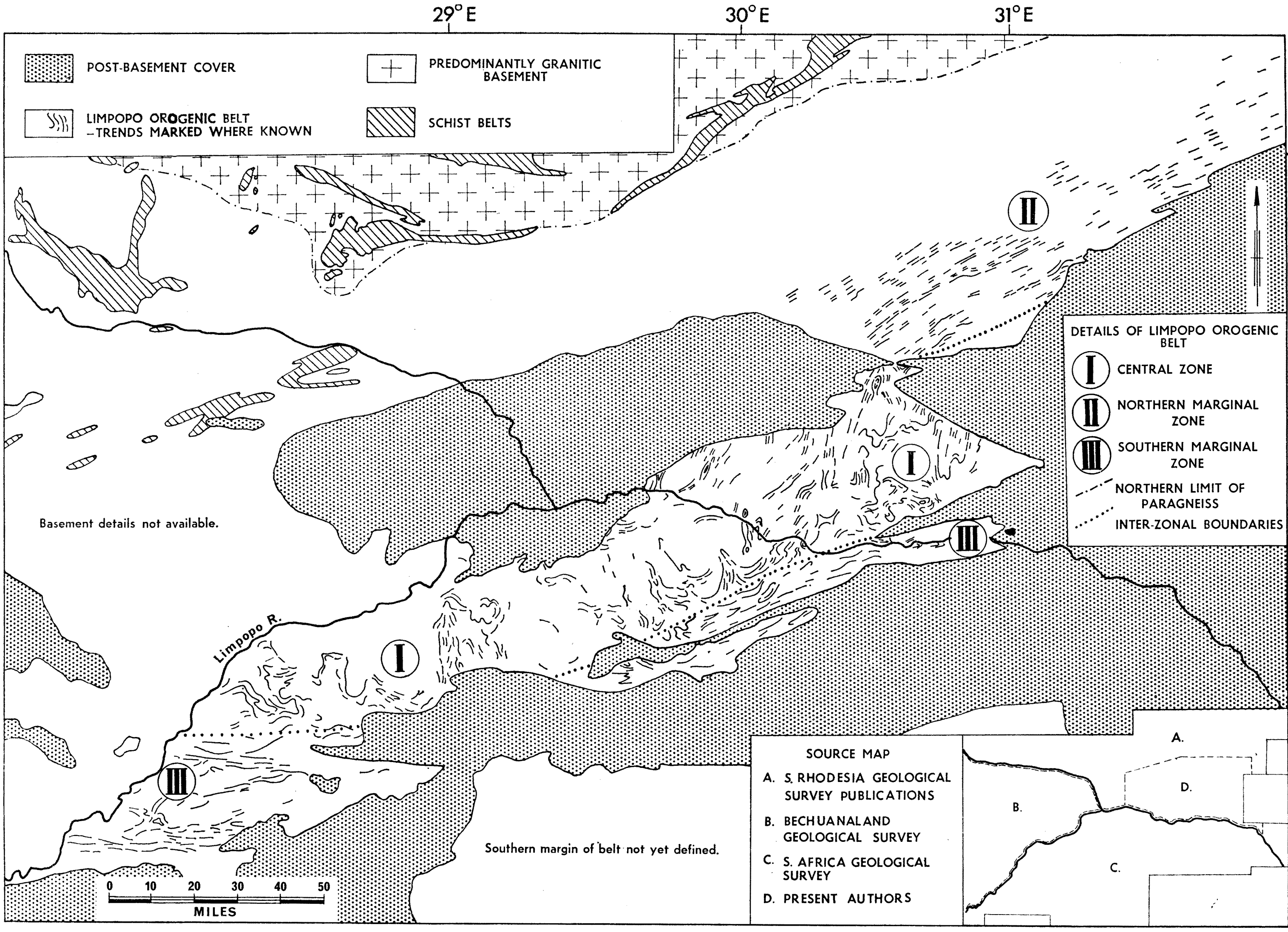


FIGURE 2. Basement complex trends within the Nuanetsi Igneous Province and surrounding areas.

It has been known for some time that the Basement complex of the Limpopo area differed from that found more towards the centres of Southern Rhodesia and the Transvaal in containing appreciable amounts of paragneisses. The 1962 edition of the 1:1000000 geological map of Southern Rhodesia shows an approximate boundary, running east-north-east and passing about 80 miles north of the Mateke Hills, separating a zone of paragneisses on the south from the predominantly granitic basement further north. The first representation of this zone as an orogenic belt was made by A. M. MacGregor (1953). Holmes & Cahen (1955) have given an adopted age of 2080 My, for the orogeny (termed the Limpopo orogeny) and Brock (1959) has discussed the belt in terms of the major structure of southern Africa, envisaging it as a 'hinge-zone' between the stable blocks of Southern Rhodesia and the Transvaal.

In figure 2 all the available trends for the whole of the Limpopo area are assembled and two points of interest emerge.

First, the Limpopo orogenic belt can be distinguished, running from Bechuanaland in an east-north-easterly direction to the lower Sabi valley via Messina and the Nuanetsi area and including all the areas where paragneissic rocks are commonly found in the Basement complex. North and south of the belt the Basement is predominantly granitic, though frequently gneissic, and includes sedimentary and volcanic remnants in the form of schist belts.* The boundaries between the Limpopo belt and the granitic blocks lying to north and south are at present poorly defined and the structural and age relations are unknown. Similarly, the correlation of the para-metamorphic rocks of the belt with less-metamorphosed sequences elsewhere must remain speculative.

Secondly, it is clear that the Limpopo orogenic belt itself can be divided into three distinct zones. These are:

The central zone in which the gneisses are very irregularly deformed and the strike of the rocks tends to run oblique to the overall east-north-east trend of the belt. The axes of many of the larger folds appear to run approximately north–south.

Two marginal zones in which the strike of the rocks is generally parallel to the trend of the belt.

The boundaries between the zones are surprisingly well defined, the southern margin of the central zone being particularly easy to see on the Geological Survey of South Africa, 1:250000 maps of Beit Bridge and Messina.

The origin of the zonal structure, i.e. whether it is due to more than one orogenic phase, is a matter of speculation, as are the precise structural relations within the belt. However, as is shown later there is a very close relationship between the Limpopo orogenic belt, with its constituent zones, and the post-Basement complex geological evolution of the area.

III. The Karroo sedimentary rocks

Sedimentary rocks of Karroo age were described by Lightfoot (1938) from the eastern part of the Nuanetsi province, and at a later date further information from the area to the west of the Nuanetsi River was published by Tyndale-Biscoe (1949). Lightfoot recognized that to the north-east of the Matibi homestead (figure 3) the Karroo basalts rest on Karroo sandstones which in turn overlie the Basement complex. On his map of the region west of the Nuanetsi River, Tyndale-Biscoe showed the thin sequence of Karroo sediments underneath the basalts near the Bubye homestead, and indicated fairly accurately the limits of the wider outcrop of sediments to the south of Shurugwe Hill.

Sutton & Bond (1962) have recently described the stratigraphy of the Karroo System in the Bubye Coalfield, and have provided good palaeontological evidence for the Ecca age of the coal measures in this region.

In the course of the present investigation it has been shown that the relatively thick sequence of sediments in the *Bubye Coalfield* contrasts markedly with the much thinner development in the region to the north which is here designated *The Nuanetsi shelf area* (see figure 3).

* For the use of the term 'schist belt,' see Macgregor (1951, p. xxix).

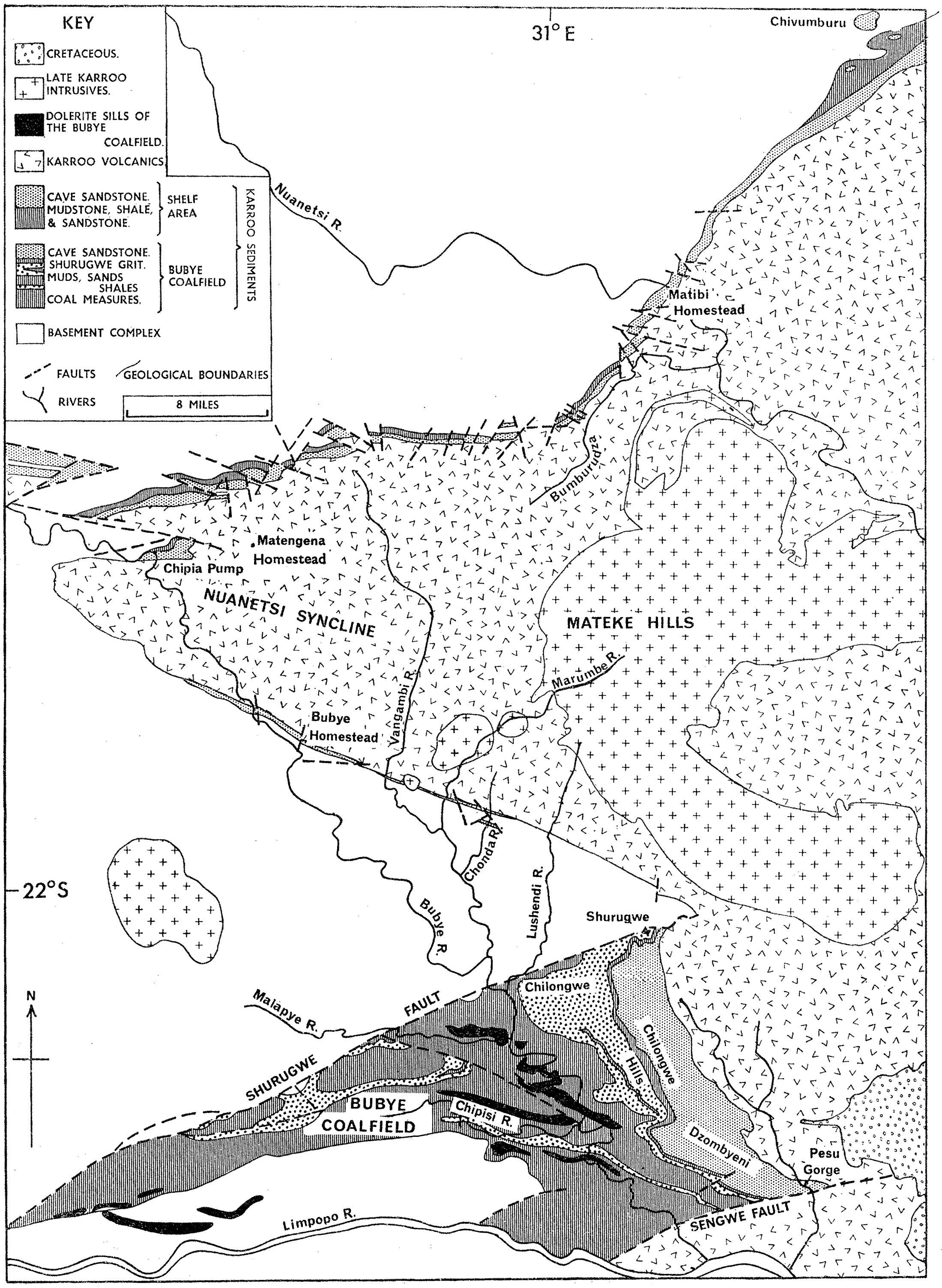


FIGURE 3. Distribution of the Karroo sediments in the Mateke region.

The Bubye Coalfield

The succession and approximate thicknesses of the rocks in the Bubye Coalfield are as follows:

		ft.
Cave Sandstone	massive, fine sandstone	+350
Shurugwe Grits	coarse sandstones	300–600
Red Beds	red shales, mudstones and sandstones	+400
L. Beaufort	mudstones, sandstones and coaly shales	600
Ecca	coal measures	370

The Beaufort and Ecca groups are those of Sutton & Bond, but the present writers have subdivided the sandstones at the top of the succession on lithological grounds into a lower Shurugwe Grit Group and an upper Cave Sandstone formation. The rocks of the lower part of the sequence have been intruded by a number of dolerite sills, the largest of which are of the order of 100 or 150 ft. in thickness and give rise to escarpments which extend for 5 or 10 miles.

The Nuanetsi shelf area

The thin sequence of Karroo sedimentary rocks north of the coalfield crops out over a narrow strip between the basalt country to the east and the ground underlain by the Basement complex to the west. From Chivumburu in the extreme north the outcrop extends south-westwards across the Nuanetsi River to the Bumburudza River and then west-south-westwards towards Chipia Pump. West and south-west of Chipia Pump, the Karroo sediments are overstepped by the basalts, but reappear about 10 miles north-west of the Bubye Homestead and extend in an east-south-easterly direction to a point about half way between the Chonda and Lutshendi Rivers. Beyond that locality the basalts again rest on the Basement complex. Field investigation of the Karroo sediments has not been carried out north of Chivumburu, but they are known to crop out over a narrow, north-east trending strip which continues, with only minor interruptions due to faulting, to the Sabi Coalfield. The sediments of the shelf area vary considerably in thickness from place to place, but in the investigated area are nowhere more than 350 ft. thick and are more commonly 100–200 ft. in thickness. The following lithological sequence has been established at a number of localities: Basal Sandstones, Shale Group, Quartzite Group, Cave Sandstone.

This succession has been recognized at several places along the flanks of the Nuanetsi syncline, although at a number of exposures one or more of the groups is missing. The Cave Sandstone and the Shale Group have distinctive lithologies and may readily be identified in the field. The other two groups cannot always be distinguished from one another on lithological grounds, but a sandstone of less distinctive type can in most cases be referred to the appropriate horizon on the basis of its position either above or below the Shale Group.

In the west, at the nose of the syncline, the sedimentary rocks appear to be absent, and the Karroo basalts rest unconformably on the Basement complex. The sediments do not thin progressively towards the west, but are very irregular in thickness within one or two miles of the points where they disappear. This variation in thickness is due to the extreme irregularity of the upper contact of the Cave Sandstone where it is overlain by the basalts. The form of this surface is similar to the corresponding Cave Sandstone–Karroo Basalt contact along the eastern side of the Chilongwe Hills (see figure 33*b*, plate 3).

By contrast, the reduction in thickness and disappearance of the Karroo sediments east of the Marumbe River is progressive in character. The Cave Sandstone which is about 150 ft. in thickness at the Matibi Homestead becomes gradually thinner east of here, and between the Vangambi River and the Marumbe River is only sporadically developed and only a few feet in thickness when present. The Basal Sandstone and Shale Group disappear about 1 mile east of the Chonda River and about 2 miles east of this river the most persistent formation, the Quartzite Group, thins and disappears. From the latter locality to Shurugwe Hill the basalts rest directly on the Basement complex. Since the above changes affect all the groups in the sequence and take place gradually, they are more likely to be due to non-deposition or intraformational erosion, than erosion after the deposition of the whole sedimentary sequence.

IV. The Karroo volcanics and associated minor intrusions

1. *General*

Volcanic rocks of the Karroo period cover a very large area in the southern part of Southern Rhodesia, where they are preserved in the Nuanetsi–Tuli syncline, and along the Mateke–Sabi monocline. South of the Nuanetsi area the volcanics continue southwards along the Lebombo monocline and west-south-westwards along the south side of the Limpopo into Bechuanaland. Here the spread of basalts becomes wider again, though extensively covered by the Kalahari sands, and extends back into western Southern Rhodesia where the volcanics occur widely north-west of Bulawayo and in the Victoria Falls area (see figure 27).

The present study deals with the volcanics of the Nuanetsi syncline and the Mateke–Sabi monocline. In the latter area a considerable amount of information is already available due to the work of Swift *et al.* (1953) in the Sabi coalfield area.

The Karroo Volcanic succession of south-east Southern Rhodesia is particularly interesting for two reasons: first, rhyolitic rocks similar to those of the Lebombo monocline are found in the Mateke area, and, secondly, a great variety of olivine-rich rocks, including limburgites, picrites, alkaline-picrites and olivine-monzonitic types, is found towards the base of the sequence, overlain by the more usual olivine-free basalts.

The succession in the Nuanetsi syncline may, therefore, be divided, on a mineralogical basis, into three broad groups. These are as follows: (1) An early group of olivine-rich extrusive and hypabyssal rocks. (2) A group of olivine-free basalts (tholeiitic in the sense that they are saturated or slightly oversaturated with respect to silica); together with intrusive equivalents. This group is termed the Upper Basalts. (3) A later group of rhyolitic extrusives interbedded with thin basalt flows of tholeiitic type.

The thicknesses of the groups vary considerably, but it is probable that all three attain their greatest development at the eastern end of the Nuanetsi syncline (see figure 4). Here, the total thickness, calculated using the widths of outcrop and average dips, is of the order of 22000 to 26000 ft., made up as follows:

	ft.
rhyolitic extrusives	5500
Upper Basalts	10000
Olivine-rich Group	6500

This sequence is similar to the one described by du Toit (1929, p. 189) and Lombaard (1952, p. 175) from the Lebombo belt north of the Letaba River. A little south of the Limpopo, the rhyolites of the Lebombo are overstepped by Cretaceous sediments, but reappear in the Nuanetsi syncline some 40 miles further north.

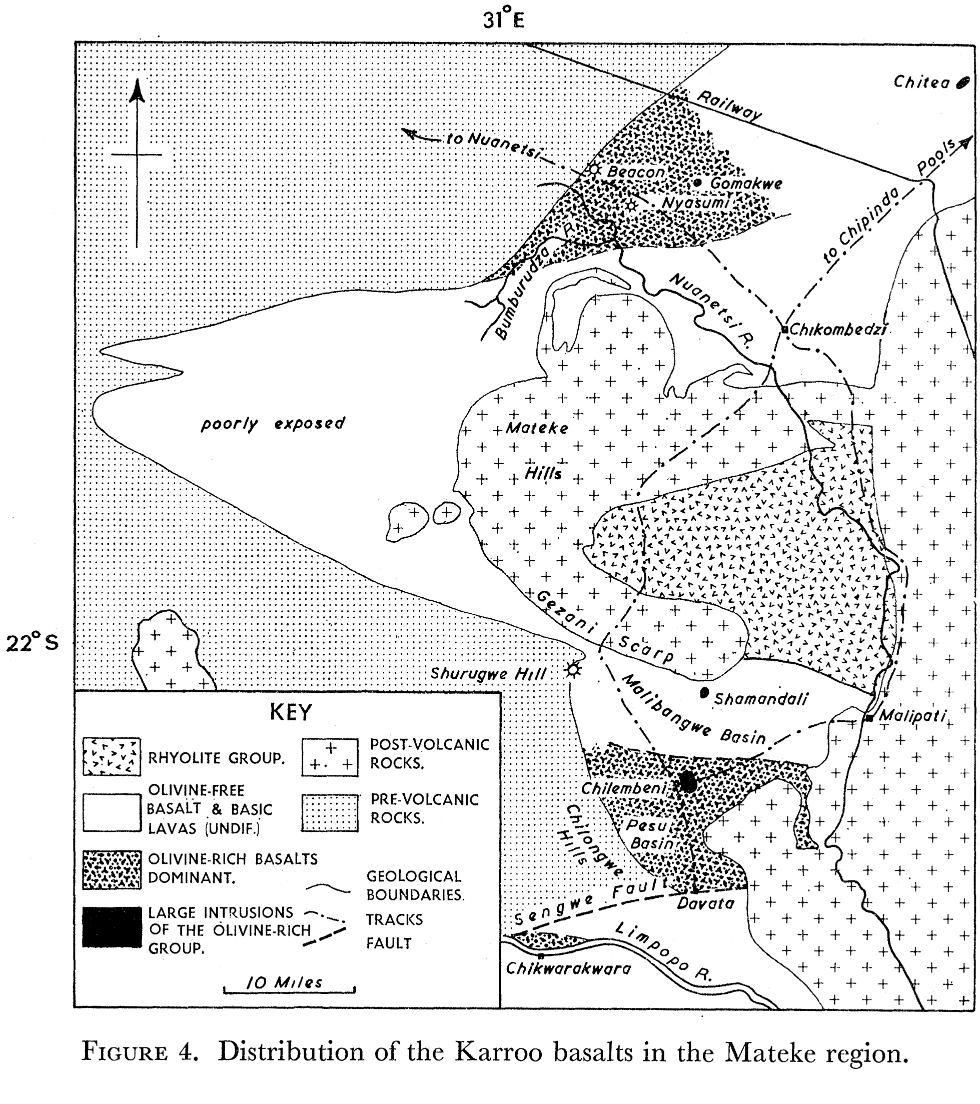


FIGURE 4. Distribution of the Karroo basalts in the Mateke region.

Over most of south-east Southern Rhodesia the Karroo volcanics rest with slight disconformity on the Cave Sandstone. The contact between the basalt flows and the sandstone is usually highly irregular, showing that the latter had been somewhat eroded or perhaps piled into dunes before the extrusion of the lavas. Figure 33*b*, plate 3, shows the contact along part of the east side of the Chilongwe Hills where the basalts lap up against a steep, indented, slope of Cave Sandstone.

As the basalts are traced northwards along this boundary, progressively younger horizons are in normal contact with the Cave Sandstone. Eventually over a small area north of Shurugwe Hill the basalts overstep the sediments completely and rest directly on the Basement complex. The total thickness of basaltic rocks in the area north of Shurugwe cannot be determined accurately, as no suitable dip-measurements could be obtained. The outcrop width, however, is reduced to barely a mile and it is clear that the thickness must be only a small fraction of the 16500 ft. succession of basalts recorded 20 miles to the east. The intense thickening towards the east explains the marked divergence between the northerly strike of the Cave Sandstone in the Chilongwe Hills and the easterly strike of the overlying basaltic rocks.

The northern limb of the Nuanetsi syncline demonstrates similar changes in the thickness of the lavas though the effect is less marked. The lower, olivine-rich, volcanics overlying the Cave Sandstone in the vicinity of the Nuanetsi River appear to be overlapped in the Bumburudza area. Hence, the long tongue of basalts preserved in the western part of the Nuanetsi syncline, that is to say, west of a line drawn from the Bumburudza to Shurugwe Hill, is probably made up only of the higher horizons, and the succession is considerably thinner than further east. It should be noted that throughout this area the underlying Karroo sediments are also at their thinnest and appear to be absent completely round the nose of the syncline.

Mode of eruption of the lavas

A general character of the basaltic part of the volcanic sequence is the almost complete absence of pyroclastic material. A volcanic bomb associated with ash and scoriaceous material was found at Gozonya near the Chiredzi River by Swift *et al.* (1953, p. 38) and several bands of 'andesitic ash' were recorded by the same authors in the neighbourhood of the Mutandawhe complex also in the Sabi–Lundi region. In the Mateke region, however, no certain pyroclastic rocks have been discovered, although layers of volcanic breccia are frequently found at the bases of the flows. These are the normal types of breccias formed during the extrusion of flows and are not true pyroclastics.

It appears, therefore, that the extrusion of the basaltic volcanics was generally non-explosive and the countless dolerite dykes roughly parallel to the synclinal axis seem to be the most likely feeders to the flows. Many of the dykes are, in fact, similar petrographically to distinctive types of extrusive rocks, and they are not infrequently amygdaloidal.

A period of more violent explosive activity followed the extrusion of the basalts, and during this period the rhyolites, which show abundant evidence of ignimbritic origin, were erupted.

Only one true volcanic vent, the Zoguvira crater within the rhyolites south of the Divula complex, has been found in the area.

2. *Description of the volcanic succession*

(*a*) *The Olivine-rich Group*

(i) *Extrusive rocks.* The rocks of the Olivine-rich Group, exposed on the northern and southern limbs of the Nuanetsi syncline (figure 4) are largely restricted to the lower part of the Karroo basalt succession and include both lava flows and abundant associated hypabyssal intrusions. The group consists of a variable series of olivine-basalts, picrite-basalts and limburgites, together with more coarse-grained rocks generally of a picro-doleritic or picritic nature. The latter types frequently contain interstitial alkali feldspar which may occasionally be abundant enough to form monzonitic rocks. In addition to the rocks listed above, Swift *et al.* (1953) record nepheline-basalts and related rock-types from the lower part of the succession in the Sabi area.

The Olivine-rich Group cannot strictly be regarded as forming a stratigraphic unit, as, especially towards the middle of the basaltic sequence the lavas are frequently interbedded with olivine-free types of the Upper Basalts (referred to by Swift (1953) as andesites). Moreover, occasional representatives of the group, such as the metamorphosed limburgite found in the aureole of the Main Granophyre north of Gezani, and the Shamandali picrite sill of the same area, may be found high up in the Upper Basalt sequence. Nevertheless, the distribution of the group is restricted in general to the areas shown on the map (figure 4).

The Olivine-rich Group appears to be poorly represented in the western half of the Nuanetsi syncline, although a few limburgite dykes have been found cutting the basalts near Chipia Pump on the Bubye River, while limburgites have been found in the aureole of the Marumbe granite. Despite the poor outcrop, however, it does seem certain that the great masses of picrite and limburgite, such as those near the base of the sequence in the Beacon area and in the Pesu basin, are not represented further west.

(ii) *Minor intrusions*. In addition to the flows, numerous dykes have been mapped. Many of these are limburgites and are indistinguishable in hand specimen from the extrusive rocks. Other, larger, dykes are mainly composed of holocrystalline rocks of picro-doleritic or picritic composition and are much coarser in grain.

In the olivine-rich areas the limburgite dykes show no particular orientation, but in the Upper Basalt areas they are commonly alined east–west, roughly parallel to the strike of the basalts, and to the trend of the massive quartz-dolerite dykes. Occasionally, limburgite dykes are found intruding basalts high up in the Upper Basalt succession; these dykes are probably the feeders to the rare limburgite lava-flows locally interbedded with the Upper Basalt lavas.

Two of the larger dykes are worthy of special mention. One of these, termed the Bezi dyke (see main map), is a fine-grained augite picrite nearly $\frac{1}{2}$ mile wide, which crosses the Nuanetsi–Chikombedzi track about 2 miles north-west of Nyasumi.

The second large dyke, formed of a comparatively coarse-grained picrite, has a notably polygonal outcrop-pattern. It is 100 to 300 yards wide and crosses the track 9 miles south-east of Nyasumi as a low, but prominent ridge. The general trend is approximately north-east with a north-west trending branch immediately south of the track. One-and-a-half miles further south-west the main dyke turns abruptly and continues towards the west-north-west. The form of this dyke illustrates a general character of the dykes of the Olivine-rich Group, namely, their variety of strike-directions as compared with the later olivine-free dykes which tend to be in well-defined swarms in a mainly east-west direction.

In addition to the large dykes, two large picrite bodies, probably plug-like in form, have been found in the northern area. These form the hills of Chitea, 21 miles north-east of Chikombedzi and Gomakwe, $3\frac{1}{2}$ miles east-north-east of Nyasumi. Further large masses of intrusive rock are also probably present at the base of the volcanic succession near the Nuanetsi River.

In addition to the olivine-rich lavas and minor intrusions described previously, several large intrusive bodies of olivine-rich rocks have been found on the southern limb of the Nuanetsi syncline. Two of the largest are those of the Chilembeni and Shamandali hills, both of which are sill-like bodies. The former is a differentiated body of olivine-bearing monzonite and olivine-monzonite intruded into volcanics of the Olivine-rich Group, whilst the latter is a picrite-gabbro body within the Upper Basalt Group.

The *Chilembeni Hill intrusion* crops out as a series of small grey kopjes in the southern part of the Malibangwe valley, on the track two miles west of the Davata–Gezani–Malapati track junction. The intrusion straddles the Malapati track and is elongated in a north-west to south-east direction; it is $2\frac{3}{4}$ miles long by 1 mile wide. The intrusion is in the form of a slightly discordant sheet or sill which can be divided into two portions; a marginal portion, 350 to 800 yards wide, composed of mafic olivine-monzonite; and a central portion, over 900 yards in diameter, composed of leucocratic olivine-bearing monzonite. The mafic marginal portion or zone probably extends beneath the leucocratic central zone, and represents the floor of the sheet, the leucocratic rocks being preserved above in the centre. Crystal fractionation and gravitational differentiation of the light and heavy crystals of the magma within the cooling body are thought to be responsible for the present mode of occurrence of the rock types.

The Shamandali intrusion crops out as five or six small flattish-topped conical hills, the upper two-thirds of which consist of picrite-gabbro, and the lower third of country rock basalt. The Malibangwe river flows through the hills, which are alined north-north-east to south-south-west, and lie about 5 miles north of Chilembeni Hill. The intrusion is possibly the remnant of a formerly much larger ultra-basic body intruded into the middle horizons of the Upper Basalt Group, the present body representing only the basic selvage of an original, possibly cigar-shaped, intrusion whose upper portion has been eroded away.

(*b*) *The Upper Basalts*

The Upper Basalts overlie the previously described Olivine-rich Group and are themselves overlain by the Rhyolite Group, which, however, contains interbedded basaltic horizons.

The Upper Basalts contain little or no olivine and are slightly oversaturated with respect to silica. They are mildly alkaline and, in common with the olivine-rich rocks, have a rather high content of TiO_2. Characteristically, they are highly amygdaloidal and occur as rather thin flows, the succession reaching an estimated thickness of at least 10 000 ft. in the Malibangwe basin and along the Mateke–Sabi monocline. The outcrop of these rocks is, however, poor and, unlike the limburgites and olivine-basalts, individual flows very seldom form topographic features.

On the northern limb of the syncline the basalts in the Chikombedzi region are generally thin (individual flows are probably less than 50 ft. in thickness) and dip to the south except where deflected by the basin structure of the Northern Ring complex. To the north-east, in the direction of Chipinda Pools, distinctive hard, non-amygdaloidal basalts, known as the Chikwedziwa type, crop out in several cuestas, dipping to the south-east at 2 to 3°.

On the southern limb of the syncline, within the Malibangwe basin, the upper basalts occupy a belt of country, measuring over 20 miles from east to west and 5 miles from north to south, lying immediately south of the Mateke uplands. Stratigraphically, they occupy the same position as the Chikombedzi basalts of the northern limb of the Nuanetsi syncline. They appear to overstep the Olivine-rich Group westwards so that, at the northern end of the Chilongwe Hills, they come to rest directly on the Karroo sediments and Basement complex. The general strike of the basalts in the Malibangwe area is east-south-east. The dip varies from 12° to the north-north-east, in the lower part of the succession, to 20° to 30° in the upper part. The flows are estimated to be of the order of 30 to 40 ft. thick. Outcrop is on the whole poor and the rocks are deeply weathered.

The top of the Upper Basalt Group consists of rather distinctive rocks containing large tabular plagioclase phenocrysts (5 to 40 mm in diameter). In exceptional cases the phenocrysts reach 75 mm in diameter and form large pod-like masses within otherwise non-porphyritic basalts. These very characteristic basalts, distinguished as the Uche–Guwini type, crop out on both flanks of the Nuanetsi syncline and lie stratigraphically in each case immediately at the base of the Rhyolite Group. On the northern limb of the syncline the Uche–Guwini division comprises some 300 ft. of lavas which dip southwards at 40° to 50°. On the southern limb, the thickness increases to a total of approximately 650 ft. and the rocks here dip at an angle of 17° to the north-north-east and are interbedded with normal basalts and rhyolites.

The highest part of the Karroo volcanic succession in the Mateke region of the Nuanetsi Igneous Province is predominantly rhyolitic, but interdigitating with the acid extrusives are a number of basaltic flows.

In the Lower Rhyolitic Group the basaltic horizons are thinly and irregularly developed and rarely exceed a few score feet in thickness. On the southern flank of the Nuanetsi syncline, where the flows are particularly thin, the dip of the basalts is towards the north-north-east, and the amount varies between 25° in the lowest flows to 12° in the middle parts of the succession. On the northern flanks of the syncline the basalts are exposed westwards from south of the Guwini flats to the Main Granophyre intrusion; here, the flows are somewhat thicker and the dip more variable. The latter is always to the south and is approximately 25° in the lowest horizons, 50° in the middle flows and 12° in the upper part of the succession.

The basalts of the Upper Rhyolitic Group are more prominent and persistent and because of their shallower dip crop out over relatively large areas. Three extensive horizons have been recognized and in order of extrusion are: (1) the Mawanga–Umvumvu basalts, (2) the Maose–Hlangalungwe and Machow basalts, and (3) the Mjanja basalts.

The Mawanga and Umvumvu basalts lie beneath the Tchovi ignimbrite flow and occupy broad subsequent strike valleys on the north and south sides of the Nuanetsi syncline respectively. They reach a maximum development (1250 ft. thick) in the western portion of their outcrop and, in common with the other basaltic horizons, thin in an easterly direction. The Mawanga basalts dip south at between 15° and 20° and the Umvumvu basalts dip north at between 15° and 28°. The outcrops are terminated in the west by the Main Granophyre intrusion and it is thus impossible to trace one group into the other around the nose of the syncline.

The Maose–Hlangalungwe basalts are the youngest of the interbedded basalts in the western half of the rhyolite outcrop. Because of their similar stratigraphic position (both underlie the Zamzamkonde ignimbrite flow) they are correlated with the Machow basalts to the east. The basalts attain their maximum thickness of 450 ft. in the western area.

The Mjanja basalts are the youngest in the area and are confined to the Mjanja Plains in the eastern part of the syncline. They have a maximum thickness of 600 ft. and by virtue of their shallow dip crop out over an area of 20 square miles.

Within the Sabi–Lundi region, in the neighbourhood of the Mutandawhe complex (see figure 7) the basalts are practically devoid of olivine and can be correlated with the Upper Basalts of the Mateke region. Swift *et al.* (1953) describe olivine-rich volcanics from the lower part of the sequence a few miles further to the north and it is therefore clear that the succession in the Sabi–Lundi region is essentially the same as that of Mateke.

The lavas near Mutandawhe mainly dip at about 6° towards the south-south-east and strike east-north-east, parallel to the overall trend of the Mateke–Sabi monocline. South-east of the complex, however, the strike swings in a more southerly direction. This is due to the presence of the very shallow, southward-plunging, Sabi syncline, a north–south fold which intersects the monocline almost at right angles.

The basalt-country is on the whole very flat and poorly exposed. The flows are thin, are highly amygdaloidal, and are usually darker in colour and fresher than those of the Chikombedzi area.

Siltstones and silcretes. The interbedded basalts of the Maose–Malibangwe area are sometimes overlain by thin siltstones or mud-stones with silcretes. The sediments rest on the highly irregular vesicular tops of the basalt flows, with sedimentary dykes of silcrete fingering downwards for several feet into the flows.

(*c*) *The Rhyolitic Group*

The rhyolitic extrusives of the Mateke Uplands are the youngest of the volcanic rocks in the Nuanetsi Igneous Province and are equivalent to the middle or acid effusive phase of Stormberg volcanicity as represented in the Lebombo Mountains of South Africa. The rhyolitic extrusives of the Lebombo crop out in a long, narrow belt, 5 to 15 miles wide, along the Transvaal–Swaziland–Natal border with Mozambique, from the coast of Zululand in the south, almost to the Limpopo River in the north, a total distance of about 350 miles. Some 40 miles south of the Southern Rhodesian outcrop, the Lebombo rhyolitic extrusives disappear beneath Cretaceous and Tertiary sediments and only reappear again to the north of the Limpopo River in the Mateke Uplands (see main map).

Various estimates of the thickness of the rhyolitic extrusives have been made; in the Lebombo Range estimates of over 10000 ft. are common and J. J. Frankel (1960) quotes 15000 ft. In the Mateke Uplands, however, the full succession is not seen and a thickness of 5000 to 7000 ft. is more likely.

The Rhyolitic Group of Mateke is composed predominantly of acid extrusives varying from rhyodacitic to rhyolitic in composition. As described previously, thin and impersistent horizons of basalt occur interbedded with the acid extrusives.

In the Mateke Uplands the rocks are disposed in two centripetally dipping tectonic basins, an eastern and a western, developed along the axis of the Nuanetsi syncline (see main map). The succession in the eastern basin is continuous, but in the western basin only the upper part is exposed, the lower half being concealed by the Main Granophyre intrusion.

The rhyolitic extrusives may be divided into indurated volcanic tuffs or ignimbrites, and rhyolitic lavas; the former accounting for at least 99 % of the total.

The indurated tuffs occur as sheet deposits, from 100 ft. to more than 750 ft. in thickness, covering several tens of square miles, and maintaining essentially regular and horizontal upper and lower surfaces, except where deformed by later tectonic movements. Throughout each sheet, except for a thin basal zone, there is an absence of bedding, and a uniform fine felsitic texture is developed. The tuffs are completely indurated and 'ring' with a blow from a hammer.

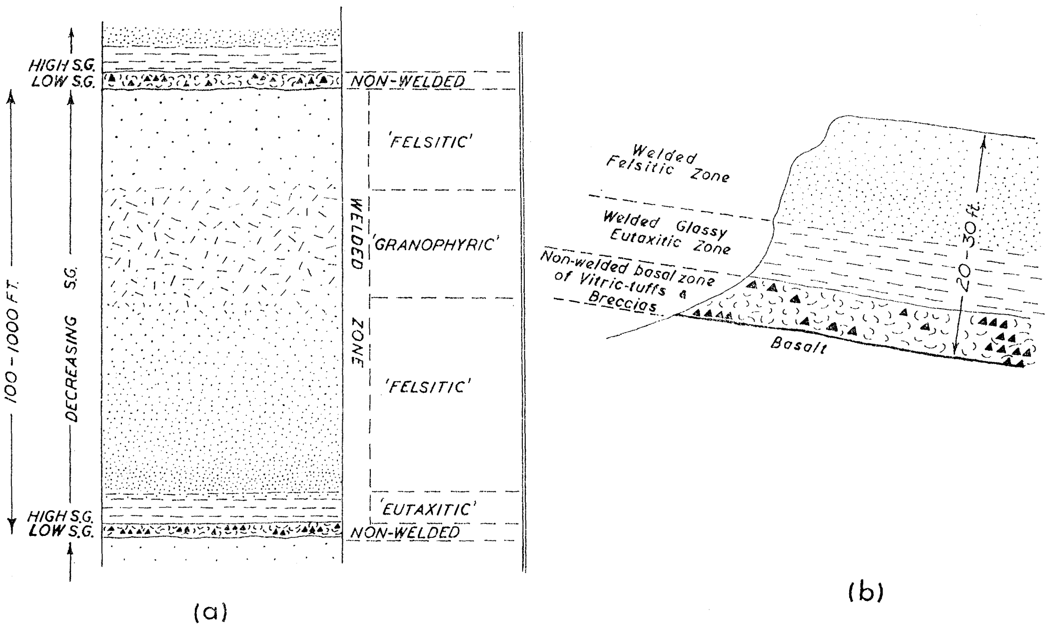


FIGURE 5. (*a*) Idealized section through a typical ignimbrite sheet. (*b*) Idealized section through the base of the Tchovi ignimbrite.

The base of each deposit is marked by a pyroclastic horizon which varies from several inches to over 30 ft. in thickness. The horizon consists of very fine glass dust in a coherent form, with pumice- and lithic-breccias. The breccias are commonly cemented by fine rhyolitic material.

Immediately overlying the pyroclastic horizon, is a horizon of vari-coloured, horizontally banded and streaked rocks. The vari-coloured streaks or bands are from 1 to 10 mm wide and are developed parallel to the base of the deposit. This horizon grades into the even-textured, non-banded upper and main part of the deposit by the elimination of the streaky bands and the formation of a felsitic texture (see figure 5*a*).

Macro-structures associated with these lower horizons of the deposit include macro-spherulites, vesicles, distorted vesicles and collapsed and flattened pumice and lithic fragments. Correlation of deposits from different areas is frequently possible because of the tendency for particular macro-structures or groupings of macro-structures to be peculiar to one deposit. Textures are illustrated in figures 34, 35, plates 4 and 5.

The whole of the basal zone, comprising the pyroclastic and the streaky vari-coloured horizons, forms less than one-tenth of the total thickness of the deposit.

The upper nine-tenths is formed of massive, well-jointed, evenly and finely textured rocks, with a felsitic texture. In the thickest sheets the felsitic texture is partially masked by a fine granophyric texture developed patchily throughout. The spread of these interstitial granophyric patches gives rise to a fine-grained rock of granophyric appearance, almost identical to the chilled varieties of rocks from the Main Granophyre intrusion.

Features displayed by these deposits (see figure 5), such as the complete induration of the tuffs, the felsitic and micro-granophyric texture of the upper zone, and the streaky horizon of the basal zone with its associated macro-structures, cannot be explained satisfactorily by recourse to a simple airborne tuffaceous origin. An ignimbritic origin for the rocks is accordingly proposed.

The term *ignimbrite* is used in the sense of its originator, P. Marshall (1935), who gave the name to rocks formed by an eruptive process similar to that visualized by C. N. Fenner (1920) in the Katmai eruptions of Alaska. The process is a nuée ardente eruption of fissure type, rather than from a central volcanic vent, as in the Peléan type of nuée ardente. It is employed in a genetic sense and is applied to the whole rock unit of a single nuée ardente deposit as suggested by E. F. Cook (1955) and R. C. Martin (1959). Thus, a non-welded or poorly welded tuff deposit of nuée ardente origin is included in this definition.

The term *welded tuff* is strictly a rock or textural term referring to those parts of an ignimbrite deposit that have developed characteristic and diagnostic features of welding. This is contrary to the usage of the term as a synonym for ignimbrite, and the restricted usage adopted here follows that suggested by E. F. Cook (1955).

An ignimbrite deposit is commonly made up of several texturally different types of rock, the different lithologies having developed as a result of differences in the cooling environment within the deposit. E. F. Cook (1955) suggests that the Wentworth & Williams (1932) pyroclastic classification, together with terms describing the degree of welding and chemical composition is sufficient for description of rock types found within an ignimbrite. Thus, the terms *crystal tuff*, *vitric tuff*, *tuff breccia*, *welded tuff* and *vitrophyre*, etc., are used, and following R. C. Martin (1959), an ignimbrite which shows zones of different lithology or texture is described as *heterolithic*.

Normal terminology is used to describe the macro-structures of the ignimbrites, for example, *spherulites*, *lithophysae* and *intratelluric* crystals.

The acid extrusives of the Mateke Uplands have been erupted in four principal stages. The earliest extrusives are altered tuffs and tuff breccias, cropping out in the Uche and Guwini areas respectively. These deposits are thin and impersistent and occur interbedded with olivine-bearing basalts high up in the succession of the Upper Basalts. The Lower Maose and Guwini porphyries form the second series of acid eruptives, and crop out over a wide area along the northern and southern flanks of the Nuanetsi syncline. They are much more massively and persistently developed than the earlier series. The third series, the Lower Ignimbrites, spread over an even larger area, and crop out in both the eastern and western basins. This series is unmistakably of ignimbritic origin. The Upper Ignimbrites form the fourth series, and are the best exposed of the acid extrusives, occupying a central position in both the eastern and western basins. They are separated from the Lower Ignimbrites by a thick series of basalt flows, the Mawanga–Umvumvu basalts, and are partially subdivided by the Maose–Hlangalungwe basalts in the western basin and by the Machow and Mjanja basalts in the eastern basin.

A tuff-filled vent, the Zoguvira crater, situated near the centre of the Western rhyolite basin, is the only known volcanic vent in the Mateke Hills. Two other possible vents occur, one close to the Mawanga–Nuanetsi confluence and the other close to the small granophyre intrusion north-west of Makonde pool on the Nuanetsi river.

A warm spring at Machow, close to the confluence of the Umvumvu and Hlangalungwe rivers, is the only present day sign of thermal activity in the Mateke Hills. The waters of this spring contain sulphates and bicarbonates of lime and magnesia, with a little salt.

The rhyolitic succession determined in the Mateke Uplands is as shown in table 2.

TABLE 2. THE RHYOLITIC SUCCESSION IN THE MATEKE AREA

Western basin		Eastern basin
Upper Ignimbrites		
		Samalema flows
Zoguvira flows		Majanja basalts
Zamzamkonde flows	...	Malipanda flows
Gujamyi sandstone*	...	Machow red mudstone*
Maose-Hlangalungwe basalts	...	Machow basalts
Maose rhyolite*		
Bakuji flow		Undifferentiated flows with interbedded basalts
Chasitchi flow		
Tombwanani flow		
Shavani rhyolite*		
Shavani flow		
Tchovi flow		
Mawanga-Umvumvu basalts		
Lower Ignimbrites		
Undifferentiated flows with interbedded basalts making up the Lower Ignimbrites in both the Eastern and Western basins		
Rhyolites obscured by Main Granophyre intrusion		Lower Maose and Guwini porphyries
		Uche–Guwini basalts
		Uche–Guwini rhyolitic tuffs and breccias
		Upper basalts

* Not shown on main map.

A comparison with ignimbrites from other areas

Many of the features shown by the ignimbrites of the Mateke area are characteristic of large scale outpourings of rhyolitic ignimbrites elsewhere. For example, the ignimbrites of North Island, New Zealand (Marshall 1932, 1935); of Eastern California (Gilbert 1938); of Crater Lake, Oregon (Williams 1942); and of Chiracahua National Monument, Arizona (Enlows 1955).

The features which suggested a mechanism different to that envisaged for the extrusion of rhyolitic lavas and tuffs in the case of the New Zealand ignimbrites (Marshall 1932, 1935) was the apparent contradiction between the seemingly fluidal nature of the ignimbrites, which enabled them to spread out evenly and uniformly over a great area without forming scoriaceous surfaces, and all the known physical characteristics of a rhyolitic lava flow, such as its extreme viscosity and the impossibility for such a lava to flow evenly and regularly over long distances. Furthermore, the presence of pronounced vertical columnar jointing indicated that the deposits had cooled slowly from a high initial temperature and were at rest during cooling. Thus the ignimbrites were not normal airborne volcanic tuffs which are much cooled or even cold when laid down.

The Mateke ignimbrites show a similar fluidal nature in the regular and horizontal disposition of individual flows and in the uniformity of character within each flow, both vertically through the welded felsitic units, less so in the lower units, and horizontally over the entire area of outcrop of each ignimbrite flow.

The columnar prismatic jointing present in the New Zealand flows is, however, rarely present in the Mateke ignimbrites and such is also the case in the ignimbrite flows of the Chiricahua National Monument, Arizona. Enlows (1955) concludes after study of these deposits 'that the development of prismatic jointing or columnar structure in welded tuffs is of local importance. A welded-tuff origin for volcanic strata is possible even though prominent structure or prismatic jointing are missing'. This appears to be the case in the Mateke ignimbrites.

P. Marshall examined the New Zealand ignimbrites under the microscope and showed that they were fine tuffs, formed mainly of glass particles, in which intratelluric crystals were embedded. They differed from ordinary vitric tuffs in that the particles were often seen to bend around the intratelluric crystals; from this Marshall concluded that the glass particles were in a viscous condition when deposited, and that the viscous condition was due to high temperature.

Owing to the subsequent natural devitrification of glass in the much older Mateke ignimbrites, Karroo age instead of Recent, only rarely is similar evidence available. However, the microeutaxitic texture has been demonstrated in ignimbrites from the Mabgwamachena valley, and in addition there are several lines of indirect evidence which suggest that the glass particles forming the Mateke deposits were in a viscous state and at a high temperature when deposited. These are as follows:

(1) The alternation throughout the succession of both non-welded and welded tuff deposits precludes the possibility that the welding is due to induration caused by the weight of the superincumbent load. Further indirect evidence is provided by the unlikelihood of there ever having been any great thickness of younger deposits above the rhyolitic extrusives.

(2) The increase in specific gravity from top to bottom of the welded units, contrasting with the lower specific gravity of the non-welded basal unit, suggests that the welded rocks were originally in a more readily susceptible state to compaction, than were the non-welded rocks. This could have been the case if the glass shards forming the deposit had remained in a viscous state for a sufficient length of time following deposition.

(3) The pumice and lithic fragments forming the basal consolidated ashes and breccias in certain ignimbrites show marginal remelting. The fine rhyolitic material, similar to that forming the streaky welded unit, cementing the fragments, was presumably the source of the heat. The remelting took place after the deposition of the ashes and breccias, as is shown by the completeness of the 'glassy' rim around even the most highly shattered fragments. This suggests that the remelting took place after the explosive forces had ceased, after the fragments had come to rest.

(4) The presence of discoid compaction structures and spherulitic and lithophysal structures in the transitional zone between the streaky welded and the felsitic welded units

shows that the temperature of the deposit was sufficiently high for these structures to form after deposition.

(5) The crystallization of tridymite in certain spherulitic and axiolitic rocks from the base of the Zamzamkonde flow, shows that the temperature of the deposit was high for some time after deposition.

(6) The progressive change in degree and type of crystallization from the base towards the middle of each ignimbrite, from the non-welded vitric tuff unit, through the streaky welded unit into the felsitic welded unit and in the centre of the thickest flows, into the welded granophyric unit, corresponds to the normal trend of devitrification and crystallization of glassy rocks, on slow cooling from a high temperature.

The observed recrystallization in the welded units of the ignimbrite deposits is thought to be due to the spontaneous devitrification and recrystallization of the glass, aided by high temperatures existing in the flow centres for a period of months or years after deposition

Following on from this, the basal unit of non-welded vitric tuffs is thought to be formed by the rapid chilling of the nuée ardente deposit by contact with an underlying cold surface, which precluded welding and flattening of the glass and pumice fragments.

The streaky welded unit is thought to represent a zone in which the rate of cooling was sufficiently slow to allow compaction of the glass and pumice fragments to take place, but not sufficiently prolonged to allow for crystallization.

As the individual deposits are texturally uniform over considerable areas this, coupled with the above evidence, implies the deposition of very hot, viscous glassy tuffs over a wide area in a very short space of time. The mechanism invoked by Marshall (1935) to explain this type of deposition was that of a nuée ardente eruption of the Katmaiian type; similar to the eruption which gave rise to the 'indurated sand flow rock' of Katmai, described by C. N. Fenner (1925). Subsequent workers on ignimbrites have invoked the same mechanism with only slight modification.

The conclusion is also reached that the material forming each deposit is derived from one magma. This appears to be the only possible explanation, when the evidence is considered that an individual deposit may be traced for many miles solely on colour shade and degree of crystallization, and yet be distinguished from other deposits of similar origin by such subtle distinctions. This implies a constancy of character which could not arise fortuitously again and again. Such a constancy requires a common magma and similar conditions of extrusion for all the rocks of an individual ignimbrite. The method of eruption envisaged is that of simultaneous fissure eruptions of nuée ardente type, in which explosive rhyolitic material was poured out over a large area and coalesced to form laterally extensive deposits.

Slight differences in the temperature of extrusion, in the degree of oxidation, and in the thickness of the individual deposits, with consequent differences in rate of cooling, have resulted in the subtle differences seen between the individual rhyolitic ignimbrites.

The Zoguvira explosion crater

The Zoguvira explosion crater is sited just east of the Zoguvira River, within the area of outcrop of the youngest ignimbrite sheet of the western basin of rhyolitic extrusives.

The explosion crater or volcanic pipe forms a hollow below the general level of the land surface and shows unmistakably on the aerial photographs as an area of denser vegetation amidst the sparse vegetation covering the surrounding rhyolitic extrusives. The hollow is elliptical in plan, and is 550 yards in length by 440 yards in width.

The outcrop in the floor of the hollow consists of a few, irregular, impersistent 'whale back' features formed by smoothly weathering explosion breccia. The explosion breccia contains angular blocks and fragments of both rhyolitic and altered basaltic material, with microphenocrysts of resorbed quartz and of tabular felspar in a brownish or pale buff coloured, finely comminuted, quartzo-felspathic matrix. The matrix also contains abundant calcite, present largely as an alteration product of the basaltic fragments.

The blocks and fragments forming the breccia are representative of the underlying series of interbedded rhyolitic and basaltic extrusives, through which the volcanic pipe passes, the fragments being presumably derived by the tearing from the wall of the pipe, of such material.

The finely comminuted state of the material cementing the breccia and the lack of lava suggests that the main activity within the volcanic pipe was explosive, and the lack of equivalent deposits outside the crater suggests that the activity was largely gaseous.

The Zoguvira ignimbrites immediately surrounding the crater are texturally unchanged although they do show a change in colour, from the normal pale lilac or purple to a yellowish-white.

Another, similar hollow, slightly smaller in size, occurs in the southern part of the Samalema ignimbrite sheet. The floor of this hollow is covered by talus debris and except for a quartz porphyry dyke trending 5° T across the centre of the hollow, there is no outcrop. The ignimbrites surrounding the hollow are slightly reddened.

3. *Dykes and dyke Swarms*

Several types and ages of dyke can be distinguished within the region and, with the aid of aerial photographs, their distribution can be indicated. A number of distinct swarms can be defined (see figure 6), separated by areas where dykes either appear to be absent or are at least less common. In the present section attention is confined mainly to the descriptive geology of the dykes, since the significance of their distribution and age relations can not be discussed without reference to the pattern of folding and faulting.

In the *Mateke region* of the province the dykes can be classified as follows:

(i) Olivine-rich dykes associated with the Olivine-rich Group of lavas. The dykes are petrographically indistinguishable from the lavas and sills of the group and have therefore been described previously. There is little doubt that these dykes, although covering a long time range since they are occasionally found cutting the Upper Basalts, are the earliest group in the area. The dykes are mainly confined to the lower parts of the basalt succession, being most prominent in the areas of the outcrop of the olivine-rich lavas.

As mentioned earlier, the olivine-rich dykes within the northern limb of the Nuanetsi syncline have very variable trends and are occasionally branching and polygonal in form. On the southern limb there appears to be more regularity and most of the dykes run approximately west-north-west to east-south-east, roughly parallel to the strike of the lavas.

(ii) Olivine-free dolerite dykes make up the Duvi, Bubye, and Malibangwe swarms and include many dykes suspected of being feeders to the Upper Basalts. They appear to pre-date the intrusive complexes.

(iii) The Marangudzi swarm. This consists of various alkaline dolerites trending east–west and probably post-dating the acid intrusives.

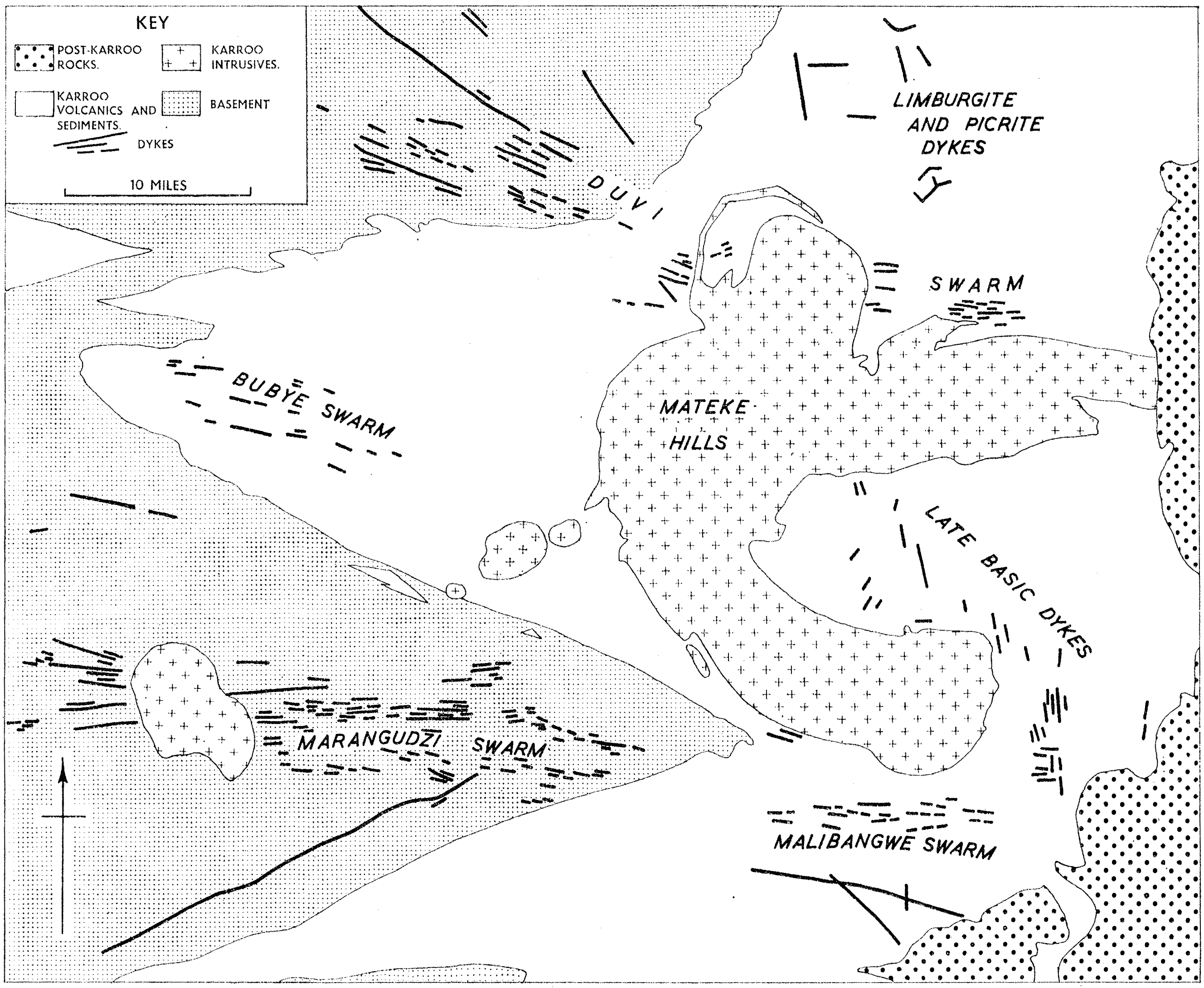


FIGURE 6. The basic dyke swarms of the Mateke region.

(iv) Late basic dykes. The late basic dykes are mainly basaltic and are found cutting the rhyolites, and occasionally the granophyres, in the eastern part of the Nuanetsi syncline. The approximately north–south trend is a unique feature of the swarm.

(v) The acid dyke swarm south of the Marumbe complex.

In the *Sabi–Lundi region* of the province olivine-free dolerite dykes are abundant within the Upper Basalts in the neighbourhood of the Mutandawhe complex. In the main they strike approximately east-north-east to west-south-west, parallel to the strike of the basalts, and pre-date the intrusive rocks of the complex. Further north Swift *et al.* (1953) have mapped numerous dykes, including many olivine-rich and alkaline types, cutting the Karroo sediments and the lower basalt horizons. As in the northern part of the Mateke region, irregular trends are common. Late dykes, having very variable trends, are also found and cut the Main Granophyre and the intrusive complexes. The rock-types include normal fine-grained dolerites, glassy olivine-bearing dyke-rocks, and kersantites. Nothing similar to the Marungudzi swarm is present in the region.

Basic dykes of the Mateke region

The Duvi swarm. The Duvi swarm is comparatively well defined and is bounded on either side by areas in which dykes are much less common. The swarm is traceable from an area a few miles south of the Nuanetsi Ranch headquarters to the vicinity of the Masukwe complex, a total distance of about 40 miles. The trend is west-north-west near the ranch headquarters but swings to east–west at the eastern end of the swarm. At its widest point, near the western end, the swarm consists of at least 30 large dykes, some of them reaching as much as 75 yards in width. Doubtless many smaller dykes are present but are not well exposed.

The swarm is intrusive into the Basement complex in the western sector and passes into the Karroo rocks in the vicinity of the Bumburudza River. The Northern Ring complex stands in the direct path of the swarm but is not cut by it and is therefore probably younger.

The eastern end of the Duvi swarm is one of the few areas where it has been possible to find evidence of the hade of dykes. Here the swarm is intrusive into the gently dipping basalts on the northern limb of the Nuanetsi syncline and it is surprising to find that the dykes consistently hade southwards at 70° to 80°, i.e. in the same direction as the dip of the basalts. This finding is quite at variance with the usual situation found on monoclinal flexures such as those of the Lebombo (du Toit 1929) and East Greenland (Wager 1947). In the case of the Lebombo monocline, du Toit ascribes the westward hade of the dykes to post-intrusive eastward tilting. For the Duvi swarm an explanation of this type can not be applied since the dykes and the country rocks dip in the same direction. There is, in contrast, some evidence that the hade of the Duvi dykes is original. One particular dyke, cropping out in the Nuanetsi River about $\frac{1}{2}$ mile west of the Chikombedzi rest hut, hades southwards at 75°. Small, spherical, quartz-filled amygdales are concentrated in a narrow marginal zone along the 'hanging-wall' contact and are completely absent in the rest of the dyke. Clearly, gas bubbles forming in the liquid have been floated up and collected along the upper contact. The hade is, therefore, undoubtedly an original feature of the dyke, though possibly post-intrusive tilting of the basalts has reduced its magnitude slightly.

A further characteristic feature of the Duvi swarm is the common abundance of xenoliths of basement gneiss included in the dolerites. This feature is mainly confined to the western end of the swarm where the dykes are intrusive into the Basement complex itself. A few dykes cutting the lower part of the basalt succession do, however, also contain xenoliths and one in particular, situated on the right bank of the Nuanetsi, 3 miles south-east of the Matibi Homestead, has carried up large angular blocks of acid gneiss through an estimated 750 ft. of basalt. The xenolith content varies remarkably from dyke to dyke; certain dykes are choked with abundant xenoliths and others are almost entirely free of them. It may well be, therefore, that the xenolithic dykes have been intruded along planes of contemporaneous movement.

Other evidence suggesting movement along the dykes is found in the Nuanetsi River north of the Masukwe complex. Here the dykes are often crushed parallel to their length and in one particular instance a dyke of feldspar-phyric dolerite is irregularly veined by a chilled rock identical with its own chilled edge. It must also be pointed out that the Duvi swarm is paralleled throughout its length by, presumably, later faults.

There is therefore a considerable amount of evidence which links the Duvi swarm with faulting. First, the dykes were probably intruded in a non-vertical attitude, secondly many of them were possibly intruded along planes of movement, and thirdly they are parallel to a later zone of faulting which swings in direction just as the dyke-swarm does.

The Malibangwe and Bubye swarms. The dykes of these swarms are petrographically similar to those of the Duvi swarm.

The Bubye swarm runs along the axis of the Nuanetsi syncline and is most strongly developed near the western end of the syncline, being particularly well seen in the bed of the Bubye River. In the same general area powerful faults are developed and have the same trend as the swarm. The direction of both faults and dykes has swung slightly westward compared with the neighbouring area of the Duvi swarm.

The Marangudzi dyke-swarm. The Marangudzi swarm of basic dykes runs approximately east-west through the triangular area of Basement complex outcrop which is bounded by the Nuanetsi syncline on the north and the Bubye coalfield on the south. The dykes can be traced on aerial photographs from about 5 miles west of the Marangudzi complex to the Lushendi River in the east, a distance of 30 miles. At its widest point, south of the Marumbe complex, the swarm is about 8 miles wide. The general trend of the swarm is east–west but there appears to be a slight tendency for the dykes to focus on Marangudzi. There is no noticeable association of the Marangudzi dykes with faulting although this may be due to the difficulty of tracing faults in the Basement complex.

In the present study the swarm was sampled in the vicinity of the Bubye River and provided a variety of fine-grained, usually porphyritic, doleritic rock types.

The age of the Marangudzi swarm relative to other igneous rocks in the area can not be determined directly as the main body of the swarm cuts only the Basement complex. However, several dykes of typical Marangudzi type have been found further afield and suggest that the intrusion of the swarm was one of the latest episodes in the Karroo igneous cycle. One of these dykes, situated a few miles to the north of the main swarm, cuts the Marumbe complex, which itself is undated but which is, by analogy with other complexes, believed to be a post-rhyolite intrusion. Others found near the Maose east of the south-east end of the Main Granophyre cut rhyolites and are intruded along north–south faults.

The Malignite dyke of the Shurugwe fault area. This large dyke appears to be related to the alkaline igneous activity of the Marangudzi complex. It is intrusive into the Basement complex and can be traced on aerial photographs for a distance of over 20 miles. The dyke runs parallel to the Shurugwe fault, the northern boundary fault of the Bubye coalfield, and lies 2 to 3 miles north of it.

A microcrinanite dyke. A solitary microcrinanite dyke has been found in the Malibangwe area. Like the malignite dyke it is possibly related to the Marangudzi swarm.

The north–south swarm of late basic dykes. This swarm is moderately well defined and runs through the Upper Basalts and Rhyolites, in the eastern part of the Mateke Uplands, with occasional members intruding the late-Karroo intrusive rocks. The rocks concerned are of two types; non-porphyritic fine-grained dolerites and porphyritic dolerites with alkaline affinities. The latter are petrographically similar to the dykes of the Marangudzi swarm.

The association of the dykes with faulting is shown more clearly in this area than elsewhere in the Nuanetsi Igneous Province. It is likely, in view of what has been said about the Duvi swarm, that this is mainly due to the fact that the alternating beds of rhyolite and basalt which form the country-rocks are ideal for the demonstration of faulting. A similar relationship may equally well hold elsewhere but the homogeneity of the country rocks makes detection considerably more difficult.

In general, the late basic dykes trend a little west of north and many of them run along strong joints and minor faults which displace the rhyolites. The most prominent fracture in this area is the Maose crush zone, and the majority of dykes although lying several miles further east, are parallel to it.

The late basic dykes vary from 2 ft. to over 20 ft. in width. Most are non-porphyritic and slightly amygdaloidal. They are almost always heavily altered, with the clinopyroxene altered to calcite, limonite, and chlorite and the plagioclase highly epidotized or sericitized. Quartz, calcite and chlorite occur interstitially with occasional potash feldspar. The amygdales contain quartz, epidote and calcite. In the less altered portions the plagioclase is identifiable as labradorite (An_{65}) and the clinopyroxene as probable augite.

The porphyritic varieties are akin to the Marangudzi dykes.

Basic dykes of the Sabi–Lundi region

A broad parallelism of the types and ages of dykes exists between the Sabi–Lundi and Mateke regions. In the present study the olivine-rich dykes of the lower part of the succession have not been examined but they are mentioned by Swift *et al.* (1953) and are clearly very similar to those of the Mateke region. It seems probable that many of them have irregular forms but insufficient information is available to show whether they form a swarm or not. Only one such dyke has been found during the present work. This cuts the Upper Basalts 1 mile north-north-east of the Hippo Mine (see figure 14) and is a rather coarse-grained hypidiomorphic olivine dolerite containing 25% of olivine.

The remainder of the dykes in the Upper Basalts of this area (the vicinity of the Mutandawhe complex) are non-porphyritic olivine-free dolerites generally very similar to the surrounding basalts. The trend is mainly a little north of east, parallel to the strike of the basalts and parallel to the most important local fault-direction.

Late basic dykes, cutting the intrusive complexes, are well developed in the Mutandawhe area (see figure 14) but unlike those of the Mateke region do not appear to form swarms and have very variable trends. They are mainly narrow, varying from a few inches to 6 ft. in width, and can rarely be traced more than 30 yards. The rock types recognized comprise:

(i) Non-porphyritic fine-grained dolerites. These are mainly rocks with an intergranular to intersertal, basaltic texture and are composed of pale brown augite, tiny plagioclase laths, chlorite, calcite and epidote.

(ii) Feldspar-phyric fine-grained dolerites similar to the above but containing highly sericitised tabular phenocrysts of plagioclase up to 5 mm in diameter.

(iii) Feldspar-phyric kersantites are the only known occurrences of lamprophyric rocks within the province. They have been emplaced into the Sabi granite, the earliest of the acid intrusions in the Mutandawhe complex.

In addition to the above types it should be noted that Swift *et al.* (1953) record olivine- and pyroxene-bearing glassy dyke-rocks cutting the Main Granophyre south of the Mutandawhe area.

The acid dyke rocks

Acid dyke rocks are mainly associated with the ring complexes and are therefore described under the appropriate headings. Only in one locality is a dyke swarm developed, and this passes immediately south of the Marumbe complex (see main map). The dykes have not been studied in detail, but appear to be mainly porphyritic rocks containing small feldspar phenocrysts set in a very fine-grained granophyric or microgranitic matrix. The swarm runs east-north-east and is therefore a characteristic Limpopo-trend feature. The majority of the dykes appear to have a considerable southward hade.

V. A general description of the late-Karroo intrusive rocks

1. *General*

The existence of large intrusive bodies, mainly of granitic composition, cutting the basalts of south-east Southern Rhodesia has been known for some time. The first reference to them is that of F. P. Mennell (1930; in Lightfoot 1938), who mentions that the basalts are cut by 'felsite and porphyry'. In 1931 the field manager of the Victoria Prospecting Company, Dr E. G. Bishop, referring to the area of the Sabi–Lundi junction, stated: 'A belt of basaltic lavas has been invaded by a granitic plutonic complex. A later intrusion of syenite porphyry has cut both' (quoted from Lightfoot 1938).

In 1938 the Geological Survey of Southern Rhodesia published the results of the Company's mapping (Geological map of the country between Bikita, Zaka, Chipinga and the Lundi River, 1:250000), showing, in outline, the intrusive rocks of the area of the Sabi–Lundi junction as 'granite, syenite and more basic differentiates'. Later Mennell (1938) again mentioned these rocks and commented that granophyre was an important rock type. He considered that the granophyre could be in the form of a sheet, but if so it was a thick one as deep dissection failed to expose the floor.

Lightfoot (1938) surveyed the country between the Lundi and Nuanetsi Rivers and showed approximately the form of the intrusive granophyre in the Mateke Hills area. In 1939 Tyndale-Biscoe (1949) made a reconnaissance of the area east of Beitbridge and, apart from mapping the western end of the Mateke Hills granophyre body, partially mapped the marginal ring-dyke of the Northern Ring complex and noted the intrusion breccias of the Dembe complex. The Southern Rhodesia Geological Survey later refined the Victoria Prospecting Company's mapping of the intrusive rocks of the Sabi–Lundi junction during the mapping of the adjacent Lower Sabi Coalfield (Swift *et al.* 1953).

In 1956 Tyndale-Biscoe again visited the Mateke Hills accompanied by P. Padget and C. J. Stillman of the Research Institute of African Geology, and Tyndale-Biscoe (1956) later, on the basis of this combined reconnaissance, prepared a map showing the form of the Northern Ring complex with its central layered gabbro and marginal acid ring-dyke, and the outlines of the Dembe, Divula and Masukwe complexes.

As a result of the work subsequently carried out by the authors of this paper the Nuanetsi Igneous Province is now known to include an extensive sill-like body of granophyre, the Main Granophyre, together with a number of intrusion ring-complexes. These comprise the following (see main map and figure 7):

name of complex	principal rock types	principal structures, etc.
Marangudzi	nepheline-syenite, granite, gabbro	a ring complex—not described in detail
Vangambi	nordmarkite, gabbro	structure unknown
Marumbe	granite, nordmarkite	an early plug and a later ring-dyke with partially complete roof-sheet
Marumbe Gabbro	gabbro	unknown structure
Dembe	granite, granophyre, gabbro	gabbro probably sill-like, later acid ring-intrusions
Divula	granite, granophyre	Ring-dykes with roof-sheets
Masukwe	granophyre, micrograniter, gabbro	Ring-dykes?, cone-sheets and irregular polygonal intrusions
Mateke Granite	granite	unknown structure: probably complex
Northern Ring	micrograniter, quartz-monzonite, gabbro	a large, basinal, layered gabbro with marginal quartz-monzonite ring-dyke
Chakumba	micrograniter	probable cone-sheets
Mutandawhe	granite, nordmarkite	ring-dykes and plugs, ring-dykes
Chiwonje	granite	partial ring-dykes with roof-sheets

Despite the number of complexes the variety of rocks is small, and similarities of structure and evolution commonly exist between one complex and another. Gabbros and granites or granophyres are by far the most usual rock-types, the nepheline-syenite of Marangudzi being the most noteworthy exception.

The presence of the Main Granophyre fortunately enables the probable age-relations of the more common types to be established. In this connexion, it is significant that gabbroic rocks are seen in contact with the Main Granophyre in the Northern Ring, Dembe and Masukwe complexes and, in all cases, the gabbro is the older rock. Since the Main Granophyre is the earliest of the major acid intrusives it is probable that the majority of the gabbroic rocks of the province were intruded before acid intrusive activity began. Certainly no case has been found of a *gabbroic* rock intrusive into any of the granites or granophyres, although a single *basaltic* intrusion is found cutting the earlier acid intrusives of the Mutandawhe complex.

The intrusive cycle in the province is therefore essentially a simple one of basic rocks followed by acid rocks. Intermediate types are rare, and when present usually appear to be hybrids formed by the reaction between acid magma and basic country-rocks.

A brief return to basic magmatic activity is indicated by small numbers of late basic dykes cutting the acid intrusives.

To summarize, it appears that the intrusive activity of the province can be divided into four main phases:

(1) The intrusion of gabbroic rocks at various centres.

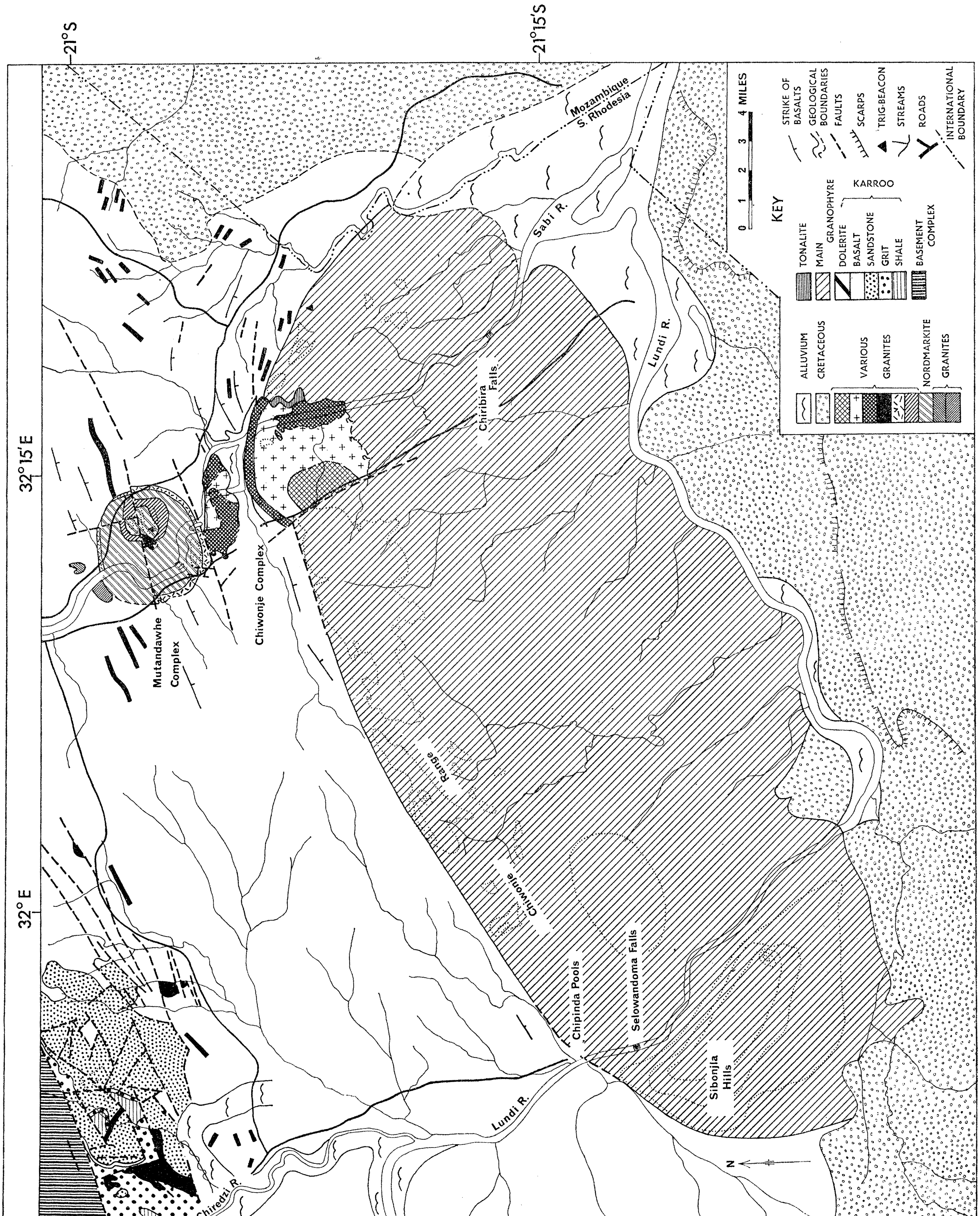


FIGURE 7. Geological map of the Sabi–Lundi region.

(2) The intrusion of the regionally developed Main Granophyre.

(3) The intrusion of the later acid rocks in part, at least, at the same centres as the gabbros.

(4) The intrusion of late basic dykes.

It is worth pointing out that this sequence leads to a slightly curious age relationship between some of the complexes and the surrounding Main Granophyre since they are in part younger than it and in part older.

2. *The Main Granophyre*

The Main Granophyre is the name given to the very extensive multiple sill which, in area of outcrop, is by far the largest late-Karroo intrusion of the Nuanetsi Igneous Province.

The sill is intrusive into the Karroo volcanic rocks and crops out in the south-western part of the province, in the Mateke Hills region, and in the north-eastern part of the province, in the Sabi–Lundi area. Between these two regions, on the Lundi–Nuanetsi watershed, the sill is overlapped by the (Cretaceous) Malvernia Beds. Assuming its continuity beneath this cover, the total extent of the sill along strike is over 100 miles, the outcrop reaching a maximum width of 15 miles in the Sabi area. The exact thickness is not known, but as seen in individual sections, it must reach at least several hundreds of feet.

The granophyre gives rise to comparatively high ground separated from the basalt-country by a prominent escarpment.

The intrusion is made up of moderately or slightly inclined sheets of microgranite and granophyre which, in the Mateke region, allow of the following subdivisions:

(i) *The Danje and Chakumba sheets*, which underlie the other members and are the oldest of the group.

(ii) *The Gezani hornblende–microgranite*, a major component which forms the main part of the escarpment at the southern edge of the Mateke Uplands and overlies and intrudes the Danje and Chakumba sheets.

(iii) *The Red Granophyre*, which overlies and intrudes the Gezani sheet in the southern limb of the Mateke outcrop. It has a much larger outcrop area than the other divisions and is the only phase present in the northern part of the Mateke Uplands.

In the Sabi–Lundi area the granophyre is mainly a rather mafic variety, which corresponds most closely with the Danje granophyre of Mateke, but here also there is some suggestion that the sill is multiple.

That the Main Granophyre is intrusive into the Karroo volcanics is evident from innumerable occurrences of contact veining, intrusion brecciation and contact metamorphism. It is, however, chemically very similar to the rhyolites and it is only known to cut their lower horizons. It is therefore possible that its intrusion was contemporaneous with, or earlier than, the eruption of the higher rhyolites.

As pointed out above, by virtue of its great extent, the Main Granophyre is an invaluable datum for relating the ages of the intrusive complexes of the province. On this basis, over the province as a whole, the basic rocks of the complexes are seen to be older than the Main Granophyre, whereas the acid rocks of the complexes are younger. Certain exceptions are found such as the Hanyani Granophyre and Causeway microgranite of the Masukwe complex. The former pre-dates the Main Granophyre but is an *in situ* differentiate of one of the gabbroic intrusions of the complex; the latter phase appears to be contemporaneous with the Main Granophyre. The Mutandawhe, Marumbe and Marangudzi complexes do not come into contact with the granophyre and hence cannot be dated directly.

That the Main Granophyre intrusion as a whole is somewhat discordant is abundantly clear in several areas, notably in the vicinity of the Masukwe complex; in the area on the synclinal axis south of Dembe; and in the blunt termination of the southern limb of the Granophyre near the Mundilakose River. A less obvious but important discordance is present along the northern limb of the outcrop where the upper contact of the sheet rises progressively through the rhyolite succession when traced westwards from Litsotsoma towards Dembe.

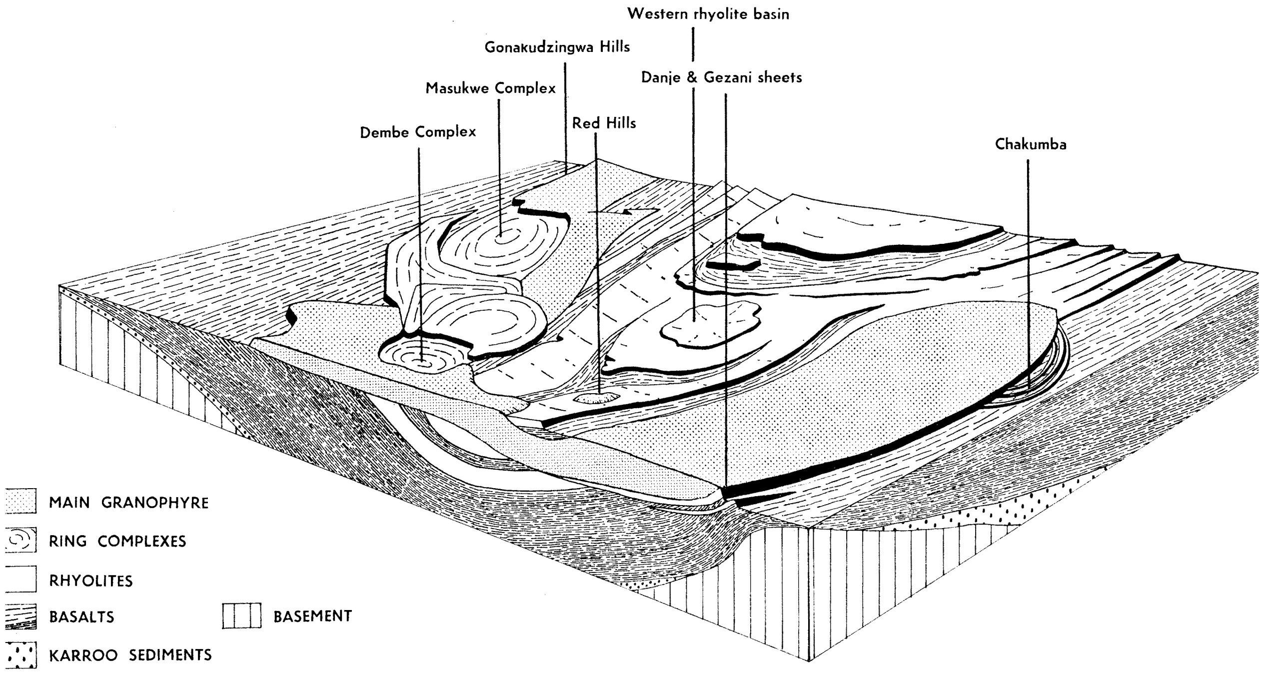


FIGURE 8. Block diagram illustrating the structure of the Main Granophyre in the Nuanetsi syncline.

Along the southern limb of the granophyre outcrop the strike of the intrusion is strictly parallel to the strike of the country rocks. This suggests that the intrusion is concordant, but it is clear that a large part of the volcanic succession, represented further east in the Nyavasikana Pools area, is missing here. If the southern limb of the granophyre is a sheet-like intrusion it follows that its dip must be considerably less than that of the country rocks. The blunt termination of the granophyre in the Mundilakose area is a feature difficult to interpret but it must be due to a comparatively rapid thinning and fading out of the sill eastwards. The bluntness of the outcrop pattern is then largely due to the low angle at which the sill dips, and is perhaps accentuated by faulting and by the culmination which separates the eastern and western rhyolite basins and draws out the northern contact of the granophyre into a slight bulge a little west of the termination.

The granophyre reaches its highest stratigraphical level when it crosses the axis of the Nuanetsi syncline in the Red Hills area (see figure 8). The volcanic succession along the synclinal axis appears to be at its most complete for only on this line are rhyolites, in the form of screens, found both above and below the Red Granophyre. Nevertheless, it is doubtful if even here the complete succession of volcanics is seen and it must be concluded that the granophyre on the synclinal axis dips eastward less steeply than do the country-rocks.

On the northern limb of the syncline the lower part of the Rhyolite Group is completely missing west of the Masukwe complex. Here again it is probable that the granophyre dips more gently than the volcanics.

In summary, the following seem to be the essential structural relations of the sill.

It has a synclinal form with an eastward axial plunge and it is intruded into a similarly eastward-plunging synclinal fold in the volcanic country-rocks. The generally low dip of the sill compared with its country-rocks indicates that the fold-structure in the former is shallower and the amount of plunge is probably less than that of the country rocks.

The relationship can best be interpreted by assuming that the Main Granophyre sill was originally a horizontal intrusion which owes its present form to subsequent deformation. This implies that the intrusion took place during the evolution of the Nuanetsi syncline, a conclusion which provides a firm link in time between the igneous activity of the province and its tectonic events.

The principal post-granophyre effect appears to have been the formation of the western rhyolite basin, with most of the displacement taking place along an arcuate flexure now revealed as the zone of high dips in both granophyre and country-rocks running from Sheba, past Danje, to the vicinity of Chakumba.

In addition a general sagging along the synclinal axis took place and the existing eastward plunge of the fold was probably accentuated. Some of the higher rhyolite formations may have been erupted during this period.

3. *The ring complexes*

Detailed descriptions of the ring complexes will be published elsewhere but a brief summary of the salient features will be given here.

The complexes are made up of gabbroic and granitic or granophyric rocks with lesser amounts of nordmarkite, nepheline syenite, granodioritic and dioritic rocks.

The principal gabbroic types are quartz-hypersthene gabbro, olivine-gabbro and troctolitic types with quartz-hypersthene microgabbro appearing as the earliest intrusive phase in several complexes. Amphibole-bearing gabbros are also found, notably in the Masukwe complex. Chemical analyses of gabbroic rocks are given in tables 15 and 17.

The granitic and granophyric rocks are generally extremely leucocratic and carry a variety of feldspar microphenocrysts amongst which the most noteworthy is anorthoclase. Most of the granitic rocks are biotite bearing but the marginal ring-dyke of the Northern Ring complex carries fayalite and several of the microgranites contain clinopyroxene. Almost all the acid intrusive rocks contain notable amounts of fluorite and they are also characteristically miarolitic, suggesting a high level of emplacement. New chemical analyses of acid rocks from the Nuanetsi Igneous Province are given in tables 25 and 29.

Among the most striking rocks of the complexes are the breccias formed by the intrusion of granite or nordmarkite into basaltic and gabbroic country rocks (Vail 1964). These are particularly well represented in the Mutandawhe complex and are illustrated in figure 38, plate 8.

From a structural point of view the complexes are of great interest since they exhibit a

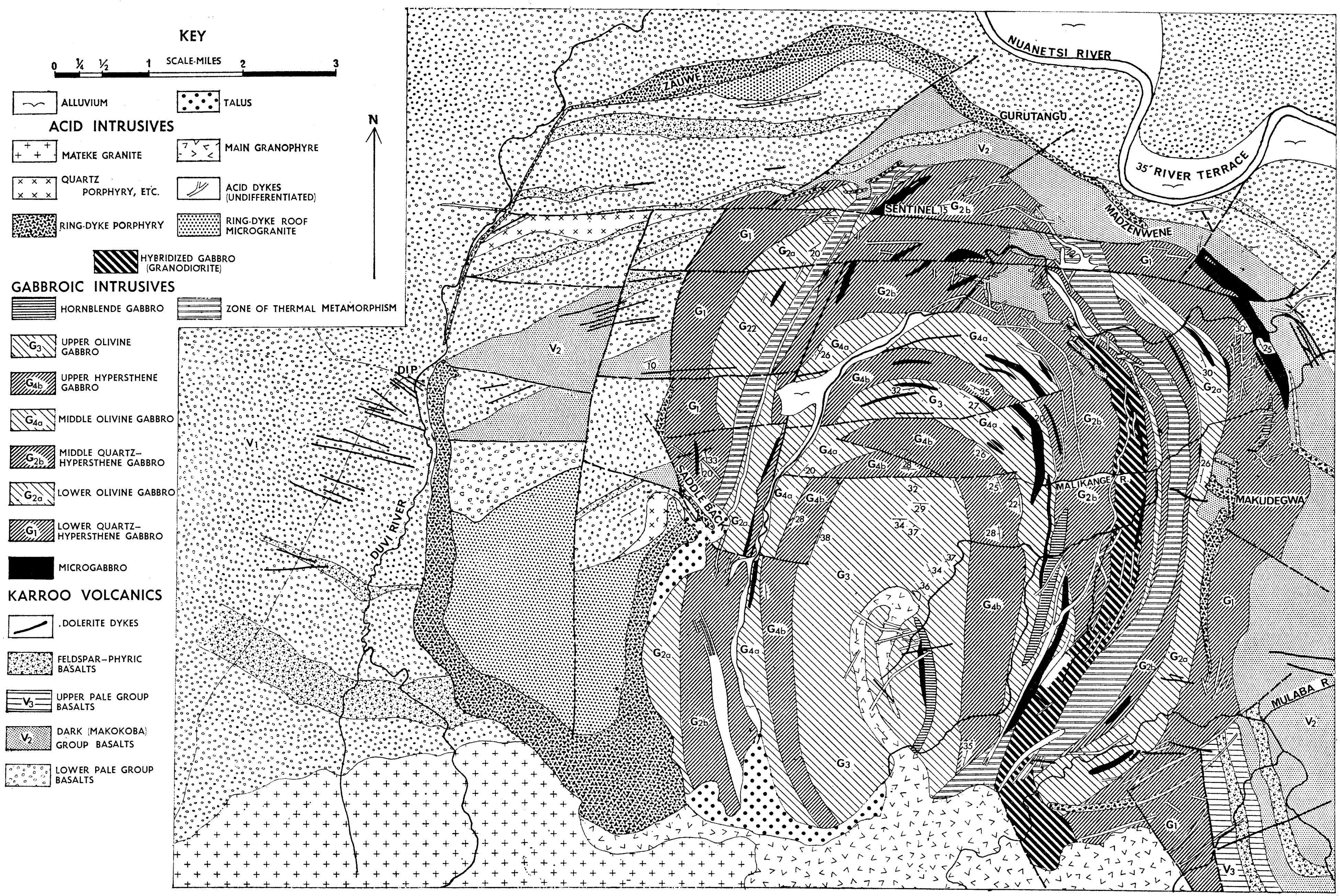
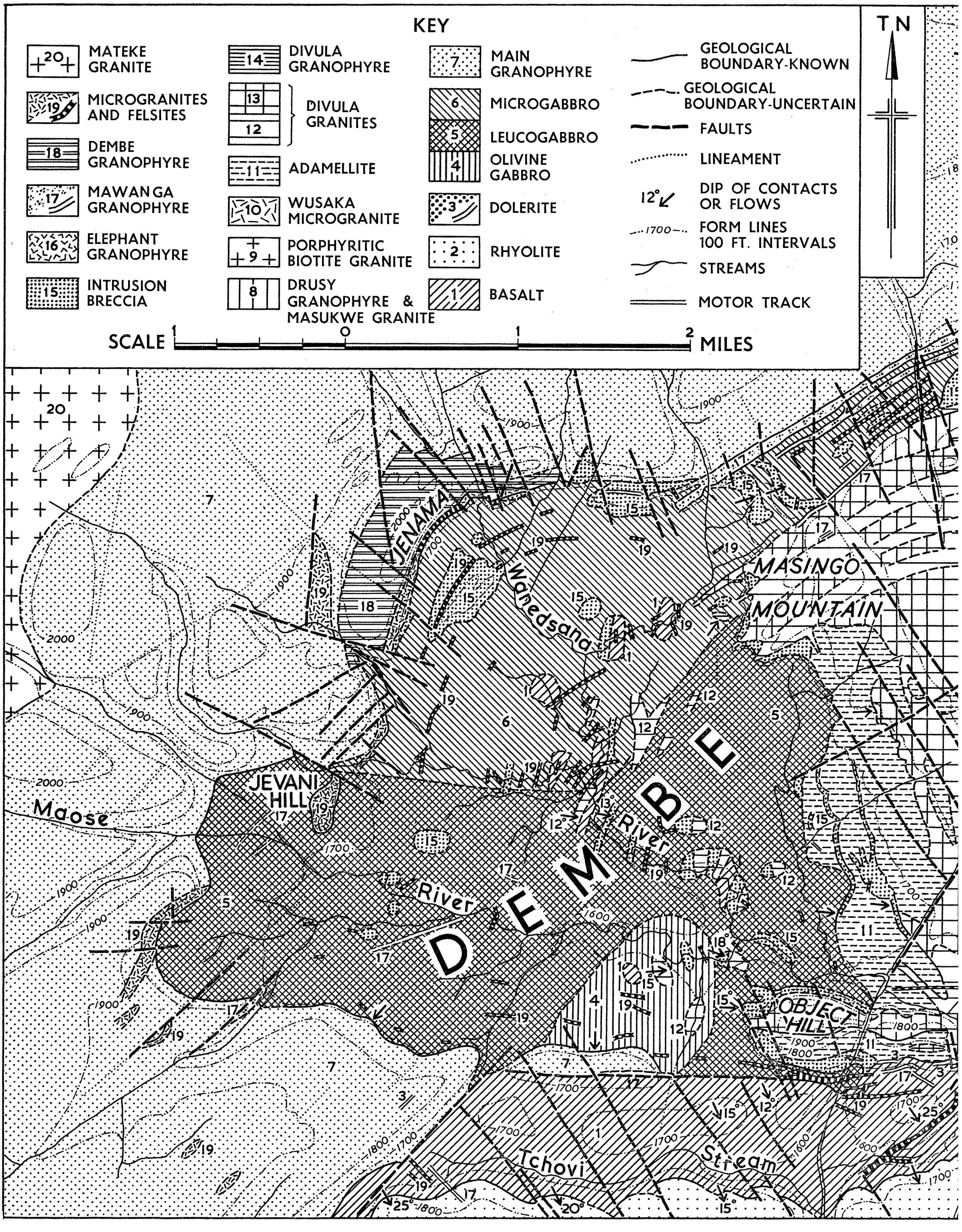


FIGURE 9. Geological map of the Northern Ring complex.


KEY
20 MATEKE GRANITE
19 MICROGRANITES AND FELSITES
18 DEMBE GRANOPHYRE
17 MAWANGA GRANOPHYRE
16 ELEPHANT GRANOPHYRE
15 INTRUSION BRECCIA
14 DIVULA GRANOPHYRE
13, 12 DIVULA GRANITES
11 ADAMELLITE
10 WUSAKA MICROGRANITE
9 PORPHYRITIC BIOTITE GRANITE
8 DRUSY GRANOPHYRE & MASUKWE GRANITE
7 MAIN GRANOPHYRE
6 MICROGABBRO
5 LEUCOGABBRO
4 OLIVINE GABBRO
3 DOLERITE
2 RHYOLITE
1 BASALT
GEOLOGICAL BOUNDARY-KNOWN
GEOLOGICAL BOUNDARY-UNCERTAIN
FAULTS
LINEAMENT
12° DIP OF CONTACTS OR FLOWS
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TN
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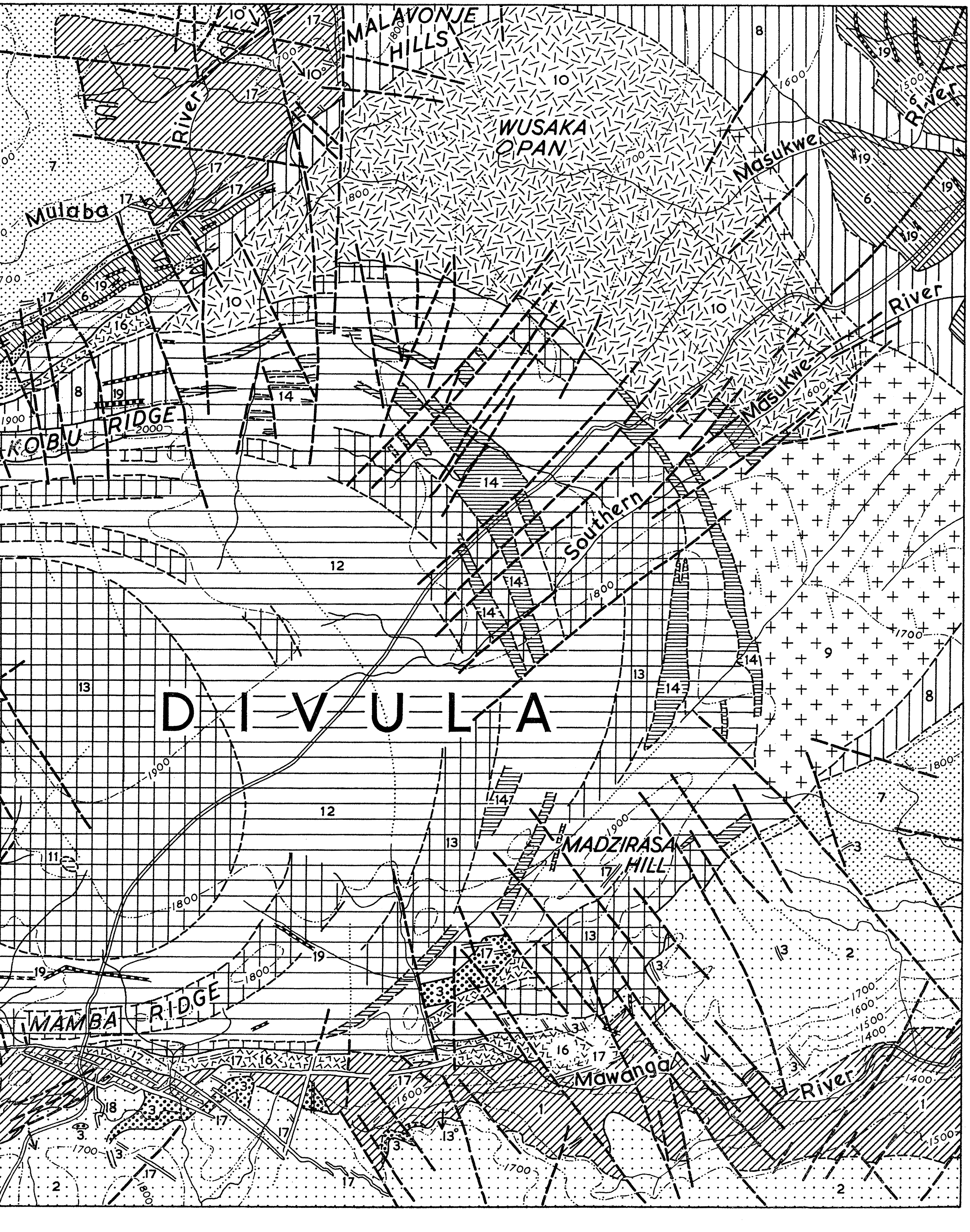
MALAVONJE HILLS
WUSAKA PAN
River
Masukwe
River
Mulaba
KOBU RIDGE
Masukwe
River
Southern
DIVULA
MADZIRASA HILL
MAMBA RIDGE
Mawanga
River

variety of intrusive forms and in particular provide excellent examples of ring-dykes with their associated sub-horizontal roof-sheets, the latter due to intrusion above the foundering blocks of country rock let down on ring-fractures.

Perhaps the most impressive ring-dyke is that of the Northern Ring complex (see figure 9). This has a hexagonal plan, with a diameter of some 8 miles, and is incomplete on the eastern side of the complex. In the north and south-west, where the ring-dyke is continuous, some subsidence of the enclosed country rocks evidently took place since the intrusive rock spreads out into a horizontal sheet overlying the country-rock basalts and linking the vertical ring-dyke with a vertical septum penetrating the subsiding block in the south-west.

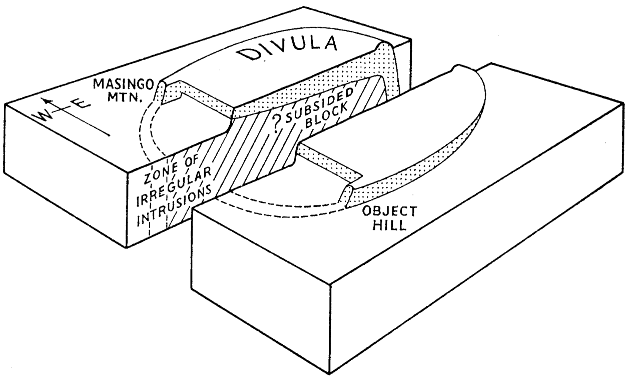

FIGURE 11. Diagram illustrating the structure of the Divula granites.

A somewhat similar structure is shown by the granites of the Divula complex (figure 10) which, as is shown in figure 11, are present as large vertical dykes at Masingo Mountain and Object Hill but form gently dipping sheets in the intervening area. In the Dembe area the ring-fracture passes into a zone of small and irregular intrusions again suggesting incomplete detachment of the subsiding block.

The transition from vertical ring-dyke to horizontal roof-sheet is, however, perhaps best seen in the western part of the Marumbe complex near Key Kopje (see figure 12). Here a thin basalt screen separates the granite from the underlying nordmarkite showing that the cross fracture bounding the top of the subsiding block very nearly coincided with the original top of the nordmarkite intrusion. In a number of other localities within the complex the sub-horizontal contact between the granite and the nordmarkite can also be convincingly demonstrated (Johnson 1964).

A similar structural relation also holds in the Chiwonje complex where the Gombi granite forms a fine partial ring-dyke running from Duradzimu to Duiker Hill. Within the ring, the roof-sheet is found where the same granite overlies the Chikwaka granite in the Chiribira Gorge area. Other good examples of ring-dykes are found in the Mutandawhe complex (figure 14).

In the Masukwe complex a solitary examples of a gabbroic ring-dyke (see figure 15) is exposed at both dyke- and roof-sheet-levels due to faulting. This is the hornblende gabbro intrusion and is of particular interest because the gabbro grades upwards into the Hanyani Granophyre, a clear case of differentiation *in situ*.

In general, however, the gabbros are characterized by a sheet-like form of intrusion rather than by ring-dykes. In both the Masukwe and Northern Ring complexes the earliest intrusive phase took the form of a microgabbro sill. In the latter complex this has been almost entirely obliterated by subsequent intrusions but is preserved as screens within the later gabbro mass. The main gabbro mass of the Northern Ring complex is a very thick basinal sequence of alternating layers of quartz-hypersthene gabbro and olivine gabbro. The microgabbro screens dip concordantly inwards with the layering of the gabbros and it therefore seems probable that the gabbros were intruded as a series of sheets along the level of the existing microgabbro sill. The general inward dip is interpreted as being due

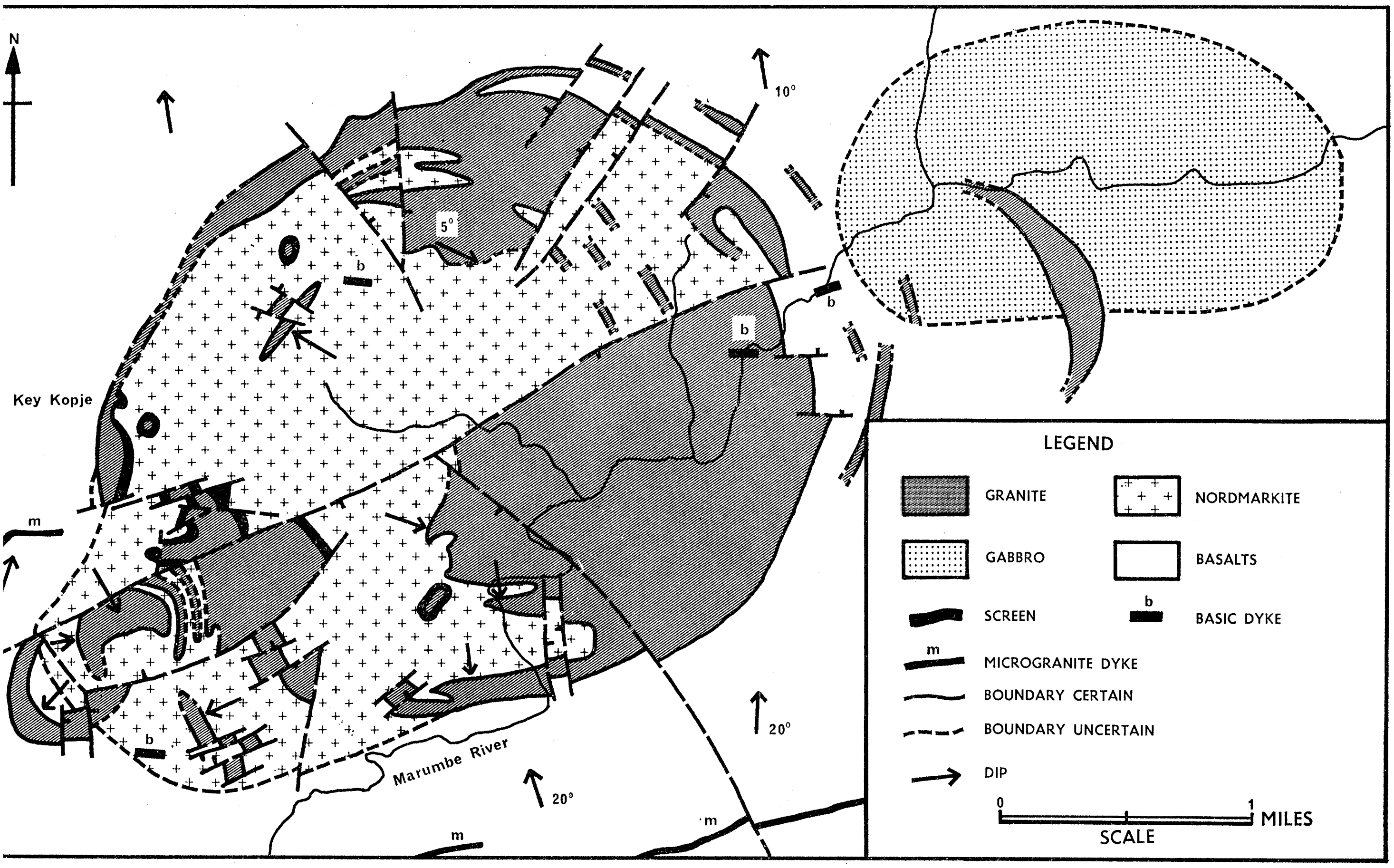

FIGURE 12. Geological map of the Marumbe complex.

to a downward sagging of the centre of the complex after intrusion had taken place. The structure is closely comparable with that of the late-Karroo Messum complex in South-west Africa (Korn & Martin 1954).

The cone-sheet form of intrusion is a rarity within the Nuanetsi Igneous Province but is possibly represented by the concentric swarm of dykes, the Causeway microgranites, found in the Masukwe complex. The outcrop pattern is that of a typical cone-sheet swarm yet the individual intrusions are vertical in attitude, not inward-dipping.

Two arcuate features of the Northern Ring complex are worthy of special mention. One of them, a zone of gabbro injected and hybridized by granitic material is found in the eastern part of the complex. The other is an almost complete elliptical zone of contact metamorphism running through the gabbros. This must be presumed to overlie a ring intrusion just below the present erosion level.

Figure 13. Geological map of the Chiwonje complex.

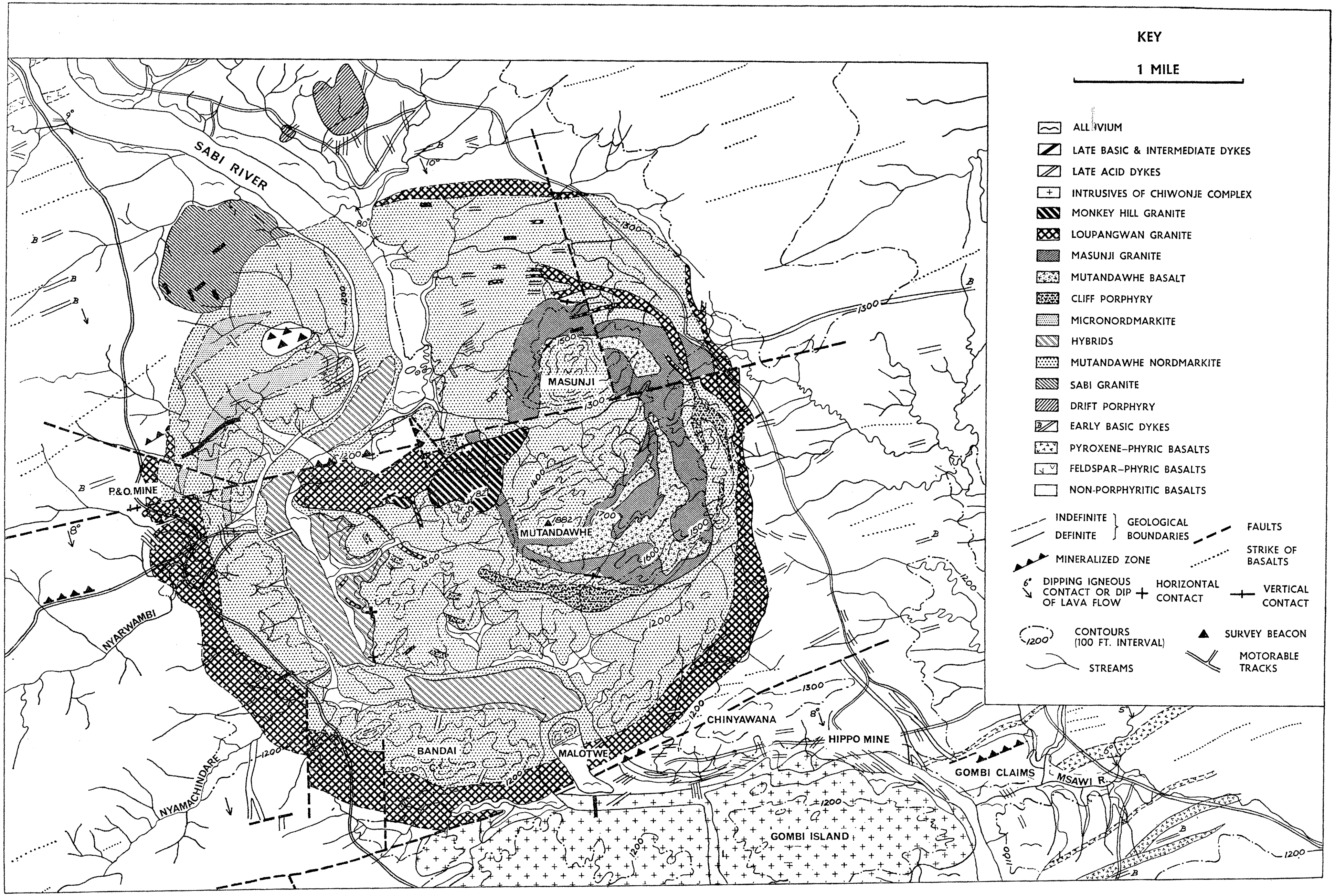

FIGURE 14. Geological map of the Mutandawhe complex.

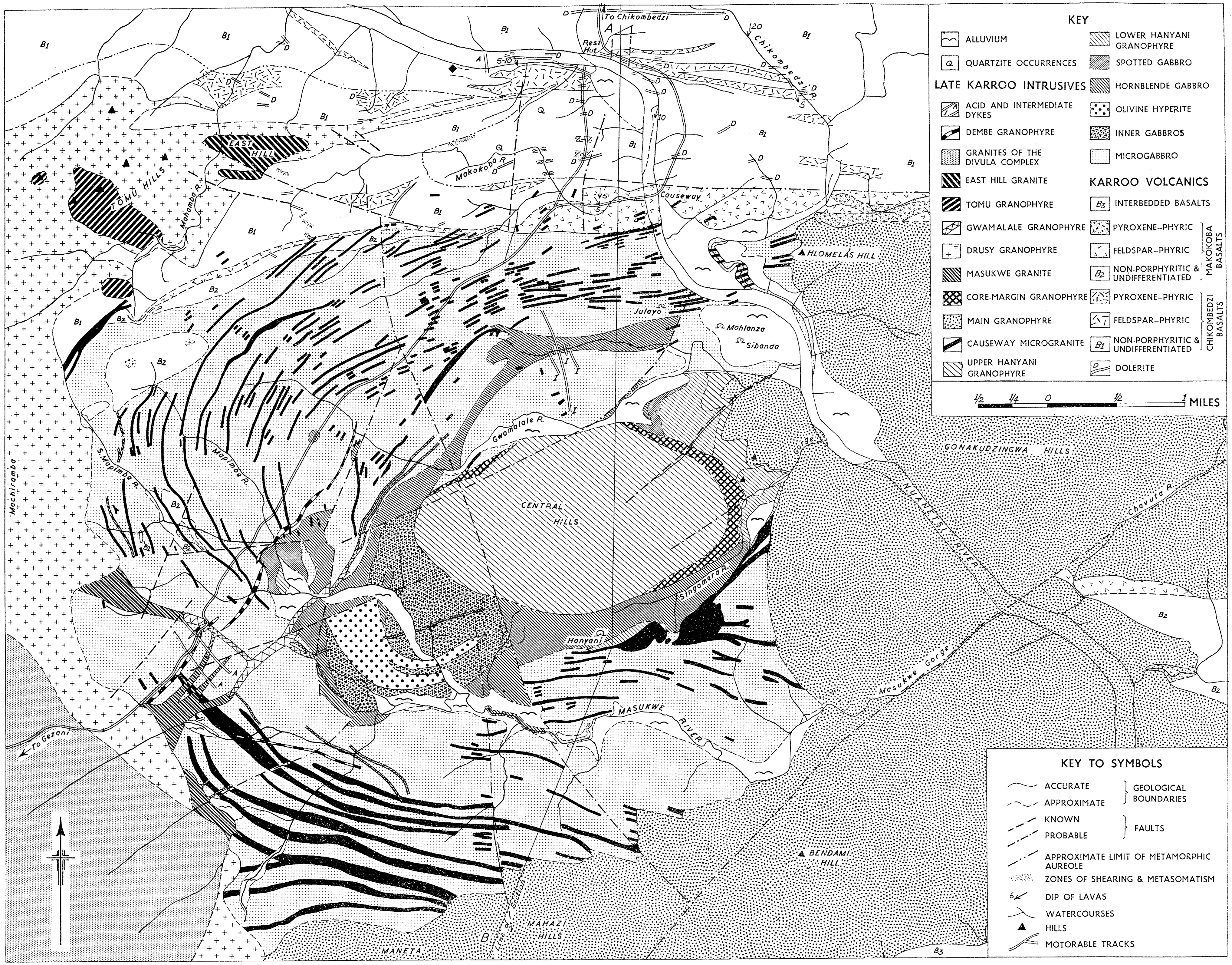

FIGURE 15. Geological map of the Masukwe complex.

The geology of the individual complexes may be summarized as follows:

Marangudzi. Not studied in detail during the present investigation, it consists of an early gabbro mass followed by a ring intrusion of granitic rocks with a later central mass of nepheline syenite. It is the only complex of the Nuanetsi Igneous Province to show this late alkaline igneous activity though similar rocks both extrusive and intrusive may be found in the Lupata Gorge and Lebombo areas of Mozambique.

Vangambi. An extremely small complex consisting of an early gabbro of circular outcrop and in part layered, with a central plug of nordmarkite.

Marumbe. An elliptical complex made up of an early nordmarkite intrusion followed by coarse grained biotite granite. The granite forms a marginal ring dyke with several parallel minor dykes and overlies the nordmarkite as a sub-horizontal sheet in the central parts of the complex.

The Marumbe Gabbro is a poorly exposed intrusion lying east of the Marumbe complex. It has not been studied in detail.

Dembe. The Dembe complex forms a topographic basin within the Mateke uplands and consists largely of leucogabbro, olivine gabbro and amphibolized microgabbro. An arcuate intrusion of granophyre partially frames the complex in the north-west and is paralleled by microgranite dykes cutting the gabbros. The Main Granophyre intrudes and overlies the gabbros along the west side of the complex and the complex is limited in the east by the Divula granites.

Divula. The north-eastern part of the complex contains the earliest intrusions comprising large masses of microgranite and porphyritic biotite granite of unknown structure. These are succeeded to the south-west by the complex ring-dyke and roof-sheet assemblage made up by the Divula granites, arcuate masses of granophyre and gently dipping sheets of hybrid rocks (adamellites) and intrusion breccia overlying the Dembe gabbros.

Masukwe. The early gabbros of the complex comprise an extensive sill of quartz-hypersthene microgabbro penetrated by ring-dykes of hornblende gabbro and olivine hyperite. A poorly exposed group termed the Inner Gabbros includes anorthositic and noritic types. Much of the central part of the complex is covered by the Hanyani granophyres which occupy the upper part of the hornblende gabbro roof sheet. The completely gradational nature of the contact between the gabbro and the overlying gabbro suggests strongly that the sequence has been differentiated *in situ*. The cauldron subsidence of the central hills has resulted in the preservation of extensive tracts of the granophyre.

The acid rocks of the complex consist of the Causeway microgranite 'cone-sheet' swarm followed by a variety of granophyres and granites forming a complex of polygonal dykes in the south-west. The Drusy Granophyre is an extensive body consisting of dyke-like and sub-horizontal sheet-like portions. The whole of the eastern and southern sides of the complex is overlain by the Main Granophyre sill.

Northern Ring. The principal feature of the complex is the layered basinal gabbro intrusion which crops out over an area of 45 square miles and reaches an estimated thickness of 10500 ft. A sevenfold division of the gabbros has been determined, the main feature being the alternation of olivine-bearing and olivine-free layers. Rhythmic layering is well developed within the individual units.

The gabbros are cut by a well-developed ring-dyke of fayalite-bearing quartz monzonite and by a considerable variety of smaller micrograntic dykes. Also present are zones of hybridization where granodioritic rocks are found, and an extensive zone of thermally metamorphosed gabbro. The complex is overlain by the Main Granophyre in the south.

The Mateke granite. This intrusion lies immediately south-west of the Northern Ring complex and forms the Mateke Hills. The main rock type is a coarse-grained granite but the intrusion has not been mapped in detail. The eastern contact dips gently beneath the Main Granophyre suggesting that the intrusion may have the form of a roof-sheet. Steeply dipping granite sheets are found as an offshoot in the south-west.

The Mutandawhe complex. Situated on the Sabi River at the north-eastern end of the province, this complex is made up largely of nordmarkite. The latter forms an almost circular outcrop about four miles in diameter and frequently grades into intrusion breccias marginally. Contaminated varieties underlie the nordmarkite in the interior of the complex and are extensively exposed in the bed of the Sabi. It is probable that a basalt floor lies not far beneath the present erosion level and the nordmarkite thus appears to have the typical form of a combined ring-dyke and roof-sheet.

Subsequent intrusions were largely granitic but include a very fine-grained basaltic rock occurring east of the centre of the complex. The Loupangwan granite, one of the later phases of intrusion, forms a ring-dyke which almost surrounds the earlier rocks.

The Chiwonje complex. The Chiwonje complex lies immediately south of Mutandawhe and is made up of three different intrusions of granite. These form irregular, partially sheet-like, masses in the Gombi Island area but are more arcuate in their occurrences further south. The principal features of the latter area are the ring-dyke and roof-sheet of the Gombi Granite intrusion.

VI. Tectonics

1. *Descriptive structural geology*

In the preceding sections structural aspects of the Nuanetsi Igneous Province and the surrounding areas have only been mentioned in so far as they concerned the distributions of the rock-groups dealt with. The present section, therefore, consists of a summary of the available structural information, first on the faulting and secondly on the flexures affecting the Karroo rocks. The tectonic setting of the intrusive rocks is then briefly considered.

(*a*) *Faulting*

The picture of the fault-pattern (see figure 16) has many gaps in it largely because of the absence of detailed mapping in the areas of Basement complex and Karroo basalt outcrop. Fortunately, however, because of the presence of the important flexures, the Karroo rocks are widely distributed and the fault-pattern can be traced over a considerable part of the area, mainly by its effects on the boundary between the Karroo and the Basement complex or between the Karroo sediments and the Karroo basalts.

The most important faults affecting the Karroo rocks can be grouped, on the basis of distribution and trend, as follows:

(i) *Faults with the Limpopo trend.* These strike generally east-north-east and are the most important and widespread in the whole region, except in the area of the Lebombo monocline.

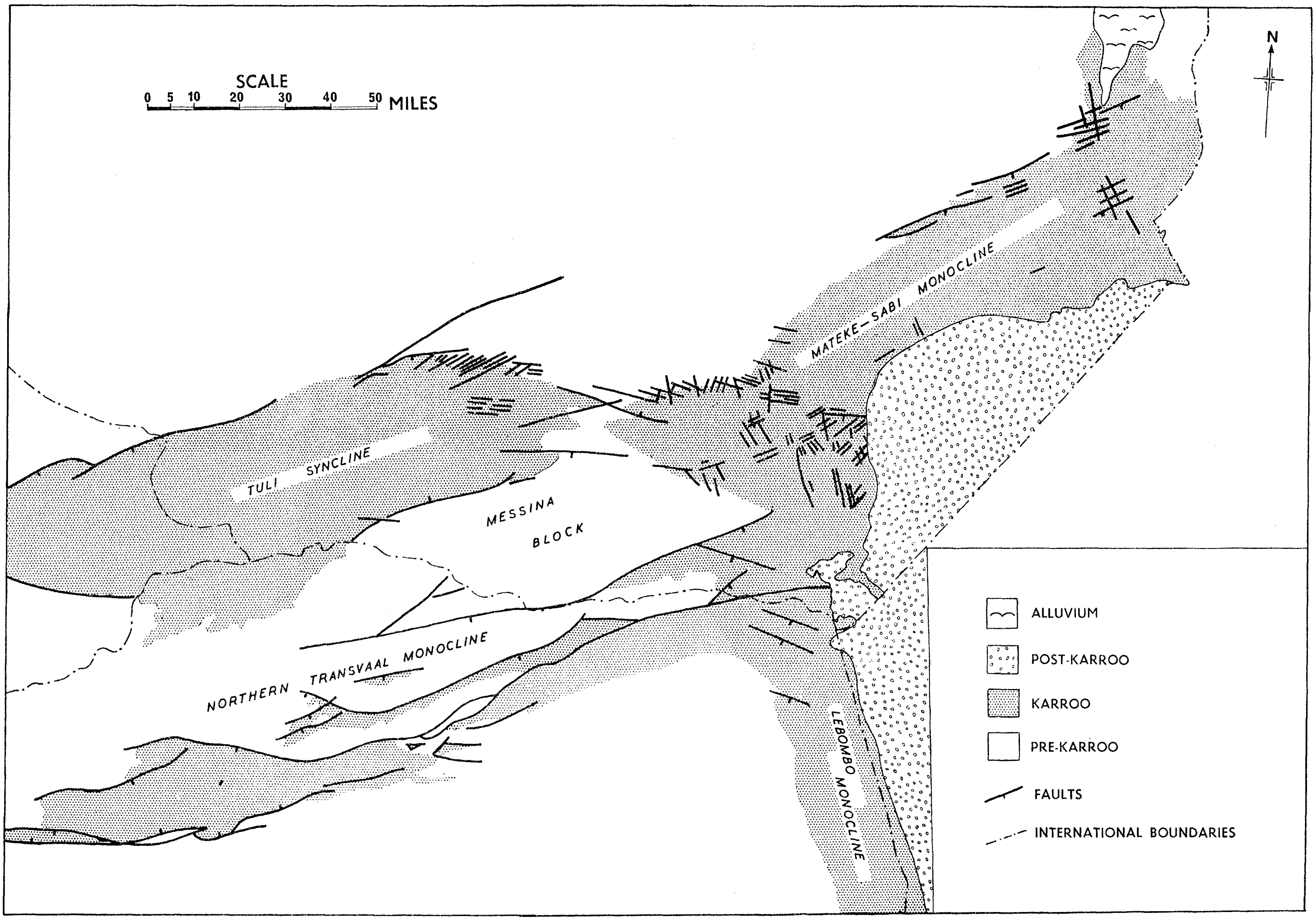

FIGURE 16. The fault-pattern of the Nuanetsi Igneous Province.

(ii) *Faults with the Nuanetsi trend.* These strike approximately east-south-east and are confined to the general area of the Nuanetsi syncline and the eastern end of the Tuli syncline.

(iii) *Approximately north–south faults.* These are mainly confined to the Nuanetsi syncline and the Sabi–Lundi region.

(i) **Faults with the Limpopo trend.** The term 'Limpopo' is given to the east-north-east trend because this is the direction of the axis of the Limpopo Orogenic Belt. The following descriptions cover the various areas in which the Limpopo-trend faults are developed.

The Northern Transvaal. Information on faulting in this area is largely derived from the works of the South African Geological Survey (e.g. Söhnge 1945; van Eeden *et al.* 1955). The following features have been clearly demonstrated.

(1) There is both intense post-Karroo and post-Waterberg faulting with the same (Limpopo) trend.

(2) Most of the faults, irrespective of age, throw down to the south. The post-Karroo faults appear to be mainly of normal type and the post-Waterberg of reverse type.

The great Dowe–Tokwe strike-slip fault cutting the Basement complex in the Messina area, on the other hand, has a dextral displacement of between half a mile and a mile.

(3) In some cases (e.g. The Tshipise fault) a large post-Karroo displacement is a rejuvenation of the earlier, post-Waterberg, faulting.

The area of the Tuli syncline. Information on faulting in the Tuli syncline has been largely derived from a photo-geological study undertaken during the present work. Details of faulting at the extreme western end of the fold are taken from the work of the Geological Survey Department of Bechuanaland (Annual Report 1960) and some information concerning the eastern end of the fold has been taken from the Provisional Geological Map of the Federation of Rhodesia and Nyasaland (published in Salisbury in 1960 on a scale of 1:2500000).

Faults with the Limpopo trend are well developed in the syncline, particularly near the eastern end where the northern margin of the Karroo outcrop is intensely dissected by closely spaced east-north-east fractures. In addition, the fold has something of the character of a graben, as, over much of the area, the Karroo basalts are faulted directly against the Basement complex.

At the eastern end of the syncline the Nuanetsi trend becomes dominant and the fold itself swings away from the Limpopo trend. The northern boundary fault of the syncline can, however, be traced through the Basement complex, continuing as an obvious photo-geological feature for at least 40 miles to the east-north-east.

The Mateke region. The Northern Transvaal belt of Limpopo-trend faults is represented in the extreme south-eastern part of Southern Rhodesia by the Shurugwe and Sengwe faults, marking respectively the northern and southern boundaries of the Bubye Coalfield. In common with the general tendency further west, both faults throw down to the south, the Shurugwe fault probably only a few hundred feet and the Sengwe probably at least 2000 ft. The latter may have suffered a slight post-Malvernia Beds rejuvenation.

In the Mateke Uplands the Limpopo trend is represented by numerous smaller faults and by an intense jointing, the latter being particularly marked in the Mateke Hills proper and in the Tomu Hills at the north-western side of the Masukwe complex. Faults with the same trend are found in the Marumbe, Northern Ring, Dembe–Divula and Masukwe complexes and in the rhyolites in the eastern part of the upland area. In practically all cases which can be determined, the faults throw down to the south, as in the Northern Transvaal fault-belt.

Strike faulting with the same trend has also been detected in the basalts north-east of the Mateke Uplands on the Lundi–Nuanetsi watershed.

The Sabi–Lundi region. The work of the Southern Rhodesian Geological Survey (Swift *et al.* 1953) shows that Limpopo-trend faults are extremely well developed in the area of Karroo sediments lying north of the basalt outcrop between the Lundi and Sabi Rivers. These faults mainly throw down to the south though there are several exceptions. Further south, two of the faults cut the Mutandawhe complex and a third probably marks the northern margin of the Main Granophyre in this area. Faulting on the same east-north-east trend is also detectable in the basalt outcrop, though the directions and amounts of throw are not known.

(ii) **Faults with the Nuanetsi (east-south-east) trend.** The Nuanetsi-trend faults are those which run parallel to the axis of the Nuanetsi syncline, many of them being concentrated within the syncline and at the eastern end of the Tuli syncline. The two most important faults effect considerable displacements on the Karroo outcrop and probably have throws of several thousand feet. The northerly one crosses the main road from Beit Bridge to Fort Victoria at the Bubye drift and throws down to the north. The southerly one crosses the road 14 miles further south and throws down to the south. This fault can be traced east of the road by its shifting of features in the Basement complex. The country between these two faults clearly has the nature of a planed-off horst and it may be significant that it coincides with the culmination separating the Tuli syncline from the Nuanetsi syncline.

In the eastern end of the Tuli syncline itself, the Nuanetsi trend is also represented by an intense zone of fracturing, without significant displacements, lying on the synclinal axis about 30 miles west of the Bubye drift (12 miles east of Mazunga).

On the northern limb of the Nuanetsi syncline the Karroo sediments in the east–west trending outcrop stretching from near the Bubye drift to the Bumburudza River 30 miles to the east, are similarly cut by innumerable small faults and joints parallel to the synclinal axis. The direction of throw is not consistent. This swarm of faults can again be picked up in the Northern Ring complex and in the basalts along the northern edge of the Masukwe complex where it has swung to a more nearly east–west direction. In the latter area, throws in general are down towards the south as is the throw of the east–west faulting contemporaneous with the intrusion of the Main Granophyre.

Further afield, several powerful Nuanetsi-trend faults, all throwing down to the south, are found cutting the Karroo sediments and basalts in the Bubye Coalfield and further south in the extreme north-eastern part of the Transvaal. These faults are themselves within the Northern Transvaal swarm of Limpopo-trend faults and their parallelism with the Nuanetsi axis may perhaps be coincidental.

(iii) **Faults with approximately north–south trends.** Faults with approximately north–south trends are found in the Nuanetsi syncline, in the Sabi area, and along the Lebombo monocline. Whereas the Limpopo-trend faults are all probably genetically related to each other and are controlled by a common Basement structure, the north–south faults must be considered separately in the three areas mentioned.

The Lebombo area. Faulting on the whole is not conspicuous along the Lebombo monocline. It must be borne in mind, however, that strike faulting would be extremely difficult to detect in the basalt outcrop west of the axis of the flexure. It has indeed been argued (Way 1957; de Blij 1961) that the Swaziland lowveld, towards the southern end of the Lebombo, is a rift-valley. This is a somewhat controversial point and it is certain that strike faulting is not a necessary adjunct of great volcanic monoclines. The flexure forming the east coast of Greenland (Wager 1947), for example, is almost devoid of faulting. In the Lebombo, du Toit (1929) noted only minor amounts of faulting, by which slices of basalt caught between dolerite dykes were uniformly displaced downwards to the west. He noted the curious point that the faults do not throw down in the same direction as the monocline, but in the opposite direction.

The Nuanetsi syncline area. The eastern part of the Mateke Uplands is cut by numerous small faults, trending a little west of north. As has been noted, the faults are associated with late basic dykes. The faults cut the basalts and rhyolites of the central part of the syncline and can also be traced through the Masukwe complex and into the basalts to the north. In this area they appear to throw down to the east.

The most important fracture in this swarm is the Maose crush zone, which forms one of the principal topographic features of the Mateke region. The crush zone runs south-south-east across the axis of the Nuanetsi syncline (see figure 33*a*, plate 3) and can be traced for 18 miles, reaching a maximum width of over 600 yards. The zone has been excavated, over most of its length, to form a parallel-sided, flat-bottomed valley cutting through the rhyolite hills and affording a means of access to the central parts of the Mateke upland area. The rhyolites and basalts in the zone are intensely shattered and are mineralized by hydrothermal quartz, epidote and calcite. This, taken in conjunction with the evidence of late basic dykes associated with neighbouring faults parallel to the crush zone, suggests that the swarm of approximately north–south fractures was formed towards the close of the volcanic activity.

Displacement on the Maose crush zone is negligible, horizontal offsets of approximately 1 cm seen on individual joints being the only detectable movements. How such an extensive zone of intense fracturing has been formed without significant displacement of the country rocks remains an unsolved problem.

Joints following the south-south-east trend are common north of the Maose crush zone in the Mateke granite in the north-western part of the uplands. Further north and west, the Karroo sediments on the northern limb of the Nuanetsi syncline between the Fort Victoria–Beitbridge road and the Bumburudza River are also cut by numerous faults in this direction. Several of these are also seen on the southern limb of the syncline in the vicinity of the Marumbe complex. In addition, the western part of the syncline is cut by faults with a trend slightly east of north. These appear to be almost confined to the northern limb of the fold.

The Sabi area. Faulting in an approximately north–south direction is also seen in the vicinity of the Sabi River in the north-eastern part of the Nuanetsi Igneous Province. The trend varies from somewhat west of north in the neighbourhood of the Mutandawhe complex to more nearly north–south in the Karroo sediment outcrop to the north (Swift *et al.* 1953). The direction probably continues to swing slightly, to a more north-north-easterly direction, along the Sabi valley north of the province (S.R. Geol. Survey 1:1 000 000 map). The faulting seems to be concentrated into a diffuse fault-swarm roughly following the Sabi valley.

(*b*) *Flexures*

The principal flexures and fold-structures affecting the Karroo rocks of the Limpopo region have been indicated in figure 17. The present section deals in more detail with structures within the Nuanetsi Igneous Province and also gives a brief summary of the information available concerning the Tuli syncline, the Lebombo monocline and the Northern Transvaal fault-zone.

Figure 17, a map showing the deformation of the sub-Karroo erosion surface, has been constructed by taking all the best available information on surface dips, and drawing a series of sections by the standard methods. The result can only be an approximation but probably gives a minimum estimate of the amplitudes of the structures since such evidence as is available indicates a general tendency for volcanics and sediments to thicken towards the downwarped or downfaulted areas. In the diagram, minor faults have been omitted since there is no evidence that groups of small faults collectively effect significant displacements.

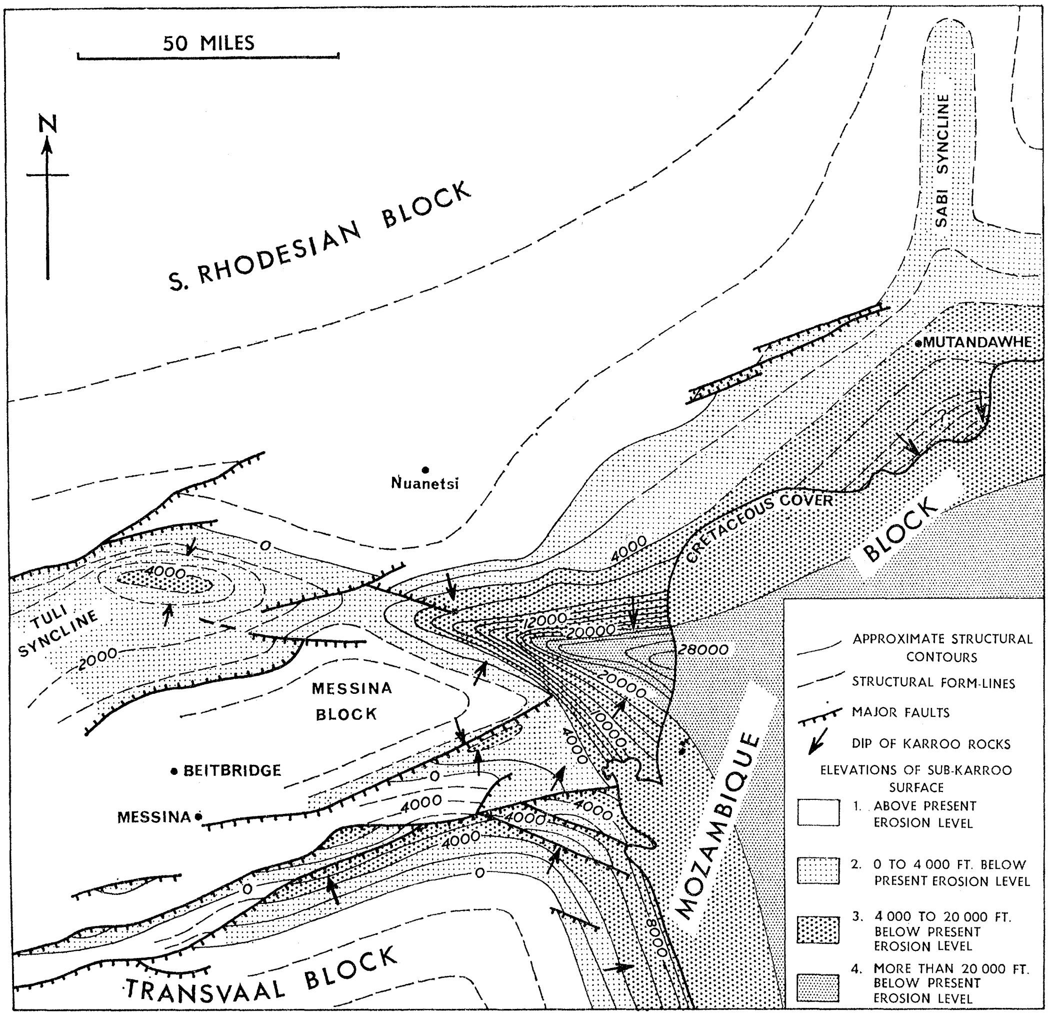

FIGURE 17. Flexures in the sub-Karroo floor.

The Tuli syncline is treated diagrammatically as no information is available regarding thicknesses or the magnitudes of dips. In this case the photogeological interpretation indicates only the position of the synclinal axis in the east end of the syncline, apart from the abundant data on faulting previously referred to.

(i) *The Nuanetsi syncline*. This is a fold of enormous proportions and is estimated to contain something approaching 30 000 ft. of volcanic rocks at its eastern end. The axis of the fold trends east-south-east and has an average plunge in this direction of approximately 5°. The cross-section of the fold appears to have a rather V-shape, judging from the outcrop pattern at the western end. Further east the structure is complicated by the superimposition of the western rhyolite basin on the main fold. In addition, the unconformities within the rhyolite group prevent any accurate extrapolation of surface data. Although the shape of the cross-section cannot be inferred with confidence in this area it is clear that the fold is somewhat asymmetrical and is more steeply dipping on the northern limb. The southern limb is marked by a wide zone of moderate dips and it is probable that because of the marked eastward thickening of the basalts east of the Bubye Coalfield the present east-south-east strike of the basalts exposed cannot be parallel to the strike of the sub-basalt surface. On the map, this is evident from the divergence in direction between the base of the basalts, striking south-south-east along the east side of the Chilongwe Hills, and the general east-south-easterly strike of individual flows.

(ii) *The Tuli syncline*. The Tuli syncline has an overall east-north-east trend and is 140 miles long by approximately 30 miles wide. Except at the eastern end the fold is parallel to the Basement-structure of the Limpopo orogenic belt. Little detailed work has been done on the fold but it is probable that the northern boundary and the eastern end of the southern boundary are to a large extent faulted. The fold therefore has some of the characters of a large graben. Photogeological studies show that at the eastern end of the structure the synclinal axis is asymmetrically placed within the outcrop. This is indicated in figure 17 where it will be seen that the axis has the Nuanetsi (east-south-east) trend and is a direct continuation of the axis of the Nuanetsi syncline. The culmination separating the two synclines is accentuated by faulting.

(iii) *The Mateke-Sabi monocline*. This is a prolongation of the northern limb of the Nuanetsi syncline which swings from the Nuanetsi to the Limpopo trend. Unlike the Lebombo monocline, it does not contain a zone of high dips. For example, at the western end the basalts dip uniformly south-eastwards at 2 to 3° and are then overlain by the Malvernia Beds. Further east, in the Sabi–Lundi region, dips are higher but probably do not exceed 10° except very locally. It is possible, however, that the structure is essentially similar to that of the Lebombo monocline and that rhyolites and a zone of high dips are both present beneath the cover of the Malvernia Beds. East of the Sabi, in Mozambique, the Cretaceous rocks are more transgressive than further south, and the Karroo is eventually overlapped completely.

(iv) *The Northern Transvaal fault-zone*. This is a faulted, monoclinal structure in which the northward-dipping Karroo rocks are repeated several times by southward-throwing faults. The following quotation from H. N. Visser (in van Eeden *et al.* 1955) summarizes the structure:

'A comparison of the elevations at which the base of the Karroo System is encountered at various places in the Soutpansberg Area, shows that the Karroo sediments should have a dip of less than 1° towards the north or the north-east, apart from minor irregular deviations due to an uneven floor. In reality the dip is invariably about 12½° to the north. This dip must, therefore, be ascribed to the beds being tilted at the same time that they were being faulted. The total downthrow at the various faults amounts to tens of thousands of feet but the Karroo rocks are not thereby lowered in a southerly direction to lower places, as the tilting towards the north compensates for the downthrow towards the south'.

The belt of faulting and monoclinal flexuring maintains its identity for a distance of approximately 160 miles and, relative to the Basement structures, occupies an analogous position to that of the Tuli syncline. The latter lies parallel to and immediately north of the central, highly deformed zone of the Limpopo orogenic belt whilst the Northern Transvaal fault-zone borders the central zone on its southern side.

(v) *The Messina block.* The Messina block is the area of Basement complex rocks, occupied by the highly deformed zone mentioned above, which lies between the Northern Transvaal monocline and the Tuli syncline. Since, at its extreme eastern end, in the vicinity of Shurugwe Hill, the Karroo basalts and sediments become considerably thinner as they pass northwards on to the block, it is suspected that the block has acted as a consistently positive area during the evolution of the Limpopo region. Hence the Karroo outcrops along the Northern Transvaal fault-zone cannot be regarded simply as a repetition of the southern limb of the Nuanetsi–Tuli syncline.

(vi) *The Lebombo monocline.* The Lebombo monocline extends southwards from the Nuanetsi region for a distance of over 400 miles and is one of the world's best developed volcanic monoclines. Over much of this distance, its course is marked by the Lebombo Range, made up of the Karroo rhyolites. Dips in this zone are frequently high, reaching up to 60°. In the general vicinity of Lourenço Marques the Cretaceous cover falls back from the east side of the Lebombo Range and reveals the much more gently dipping rhyolites and upper basalts on the downthrow side of the monocline. The total vertical displacement across the flexure is at least 10000 m according to du Toit (1929).

(*c*) *The tectonic setting of the intrusive rocks*

The distribution of the majority of the intrusive rocks of the Nuanetsi Igneous Province is very clearly tectonically controlled. Hence a description of structural features of the region would be incomplete without reference to this feature.

In the Mateke region the ring complexes are situated mainly on a straight line parallel to the Limpopo trend. The line stretches from the Marangudzi complex in the south-west, to the Masukwe complex in the north-east, via the intrusive centres of Vangambi, Marumbe, Mateke, Dembe and Divula. The swarm of acid dykes near the Marumbe complex may also be included in the line.

A second line, of more hypothetical existence, may be imagined to run approximately northwards from the Chilembeni intrusion via the centre of the inclined sheets of Chakumba to Dembe and the Northern Ring complex. This line may perhaps extend northwards to include the very wide Bezi picrite dyke and it should be noted that it also includes the Maose crush belt.

Neither of these lines is closely related to the flexures affecting the Karroo rocks, but a comparison of the distribution of the intrusive centres with the structure of the Basement complex reveals a spatial relationship so exact that it can hardly be coincidence. This is the identity of the Marangudzi–Masukwe line with the centre line of the Limpopo orogenic belt.

Hence the structure of the Basement appears to have controlled the position of the intrusions in much the same way as it has controlled faulting. The Marangudzi–Masukwe line is a Limpopo-trend tectonic feature and must be considered as such in the structural interpretation.

In the Sabi–Lundi region the Mutandawhe and Chiwonje complexes similarly show an alinement parallel to a well-defined structural direction, in this case, the faulting and gentle synclinal folding which marks the Sabi trend. It may also be significant that these complexes lie roughly on the extension of the Mateke line of ring complexes.

(*d*) *Time relations in the tectonic evolution*

In the preceding sections the space relations of the tectonic features of the Limpopo region have been described. Before attempting to draw any structural conclusions it is next necessary to discuss the historical development of these features.

(i) **Pre-Karroo tectonics.** The earliest tectonic event of which there is any evidence in the Limpopo region was the formation of the Limpopo orogenic belt. The belt itself, although it has apparently to a large extent controlled the subsequent evolution of the Limpopo valley, is not necessarily the most fundamental local feature of the earth's crust, but may have formed in response to a disposition of crustal units of even greater age.

The geology of the pre-Karroo rocks of the Northern Transvaal, described by Söhnge, le Roex & Nel (1948) and van Eeden *et al.* (1955), shows clearly that the line of the Limpopo orogenic belt, what may be termed the Limpopo geosuture, was intensely reactivated in the post-Waterberg, pre-Karroo period. During the deposition of the Dominion Reef, Loskop and Waterberg systems the area was the site of thick sedimentation and basaltic vulcanism. Subsequently these rocks were tilted to the north and intensely faulted by reverse faults following the Limpopo trend and throwing down to the south. The geological history was therefore similar in many respects to that of the ensuing Karroo period except that the faulting was evidently, due to compression rather than tension—a fact noted for example by Truter (1946). Just as in the Karroo period the Messina block at least locally marked the northern limit of Karroo sedimentation, so it marked the northern limit of the pre-Karroo volcanic and sedimentary formations. The Tshipise fault for example, one of the principle fractures marking the southern edge of the block, was active in both the post-Waterberg and Karroo periods. South of this fault the Karroo rests on a considerable thickness of Waterberg sediments whereas a few miles further north it rests directly on the Basement complex.

(ii) **Early-Karroo tectonics.** After the faulting of the Waterberg rocks a long period of erosion ensued before the deposition of the Karroo sediments. These vary considerably in thickness from place to place partly as a result of irregularities in the sub-Karroo floor (see, for example, Visser 1961) and probably also due to differential down-warping during the period of sedimentation. The latter effect can only be inferred as a probability in the Limpopo region although Gair (1956) has put forward evidence to suggest that the accumulation of the Karroo sediments of the mid-Zambezi valley was entirely due to Karroo subsidence.

The evidence from the Limpopo region is fragmentary but there are, at least, clear indications that the areas of relatively thick Karroo sedimentation coincide closely with areas which were subsequently intensely faulted or down-warped. In other words, at least part of the pattern of negative and positive areas which was intensified during the later Karroo period, was in existence during or before the deposition of the Karroo sediments. Whether the sedimentary troughs and basins, therefore, were pre-Karroo depressions or only developed during the early Karroo period, it must be surmised that they have an essentially tectonic origin.

The evidence bearing on this point will be reviewed by reference to specific areas:

The Bubye Coalfield. It has been shown that the relatively thick sequence of sediments in the Bubye Coalfield contrasts remarkably with the absence or extreme thinness of the sediments only a few miles further north on the southern limb of the western part of the Nuanetsi syncline. From this it is clear that the Messina Block was in existence as a relatively positive area during the deposition of the Karroo sediments. The exact coincidence, at the north-eastern end of the coalfield, of the Shurugwe fault with the boundary between the areas of thick and thin sedimentation strongly suggests that the fault was operative, possibly as a monoclinal flexure rather than a fracture, during the sedimentary period.

The Zoutpansberg region of the Northern Transvaal. The Karroo sediments here are preserved in the faulted strips of the Northern Transvaal fault-zone and have recently been described by Visser (1961) following the earlier description of van Eeden *et al.* (1955). Visser concludes that the sediments in this region were deposited in an elongated basin, separated from the main Karroo basin of South Africa, and that they did not extend over the Zoutpansberg area to the south. It is likely also, in view of the evidence from the Bubye Coalfield, which represents the eastern continuation of Visser's basin, that they were also thin or absent to the north, over the Messina Block. Thus, the present site of the Northern Transvaal fault-zone was marked by a depositional trough in the pre-volcanic period, a convincing demonstration of the existence of one of the principal late-Karroo tectonic features at an earlier stage.

The Waterberg Coalfield. This area lies approximately 170 miles west-south-west of Messina and is, strictly, outside the scope of the present work. The geology, summarized recently by Visser (1961), does, however, confirm the close spatial relation between sedimentary basins and later faulting as seen in the Bubye Coalfield. The Waterberg Coalfield is a basinal structure, about 30 miles long, somewhat elongated parallel to the Limpopo trend. The basin contains a thicker sequence of sediments than in the surrounding area, hence the subsequent slight warping to form a structural basin is superimposed on a sedimentary basin. In addition, the northern margin of the coalfield is marked by a direct continuation of the Tshipise fault, one of the main, southward-throwing, faults of the Northern Transvaal fault-zone.

(iii) **Late-Karroo tectonics.** In the preceding section it has been shown that at least some of the main tectonic features of the Karroo period in the Limpopo region developed during the period of sedimentation, before the onset of volcanicity. The main tectonic movements, however, strongly affect the volcanic rocks and must therefore have taken place during or after the period of volcanism. The available evidence indicates that at least the Nuanetsi syncline developed *during* the volcanic period.

The evidence for this rests mainly on the structure of the Nuanetsi syncline in the eastern and central parts of the Mateke Uplands. Here there is a marked tendency for the rhyolitic volcanic horizons to overstep towards the flanks of the fold. Thus in the western basin the Tombwanani flow oversteps the more steeply dipping Shavani flow, and both the Shavani and Tombwanani flows are overstepped on the northern flank of the syncline by the Chasitchi flow.

Similarly, in the eastern basin, the Samalema flow, the youngest extrusive in the area, progressively oversteps the older and more steeply dipping Majanja basalts, and the

Malipanda ignimbrites below. The Samalema flow, at its northern margin, dips at 7 to 8° southwards, the underlying rocks dipping in the same direction at 15 to 25°.

From this evidence it seems clear that the main period of deformation of the Nuanetsi syncline took place during the eruption of the rhyolites since the lowest horizons are steeply tilted and the youngest, the Samalema flow, lies mainly horizontal.

In considering the age of the main period of deformation of the Lebombo and Mateke–Sabi monoclines the evidence is less satisfactory since structural information of the type available in the Nuanetsi syncline is lacking. Du Toit (1929) has argued, on the basis of the hade of basic dykes, that the Lebombo flexuring took place during the eruption of the rhyolites. It should, however, be pointed out that du Toit's assumption that the dykes were originally vertical is not necessarily valid. Evidence suggesting the non-vertical intrusion of dykes in the Mateke region has already been mentioned and the very close association between dykes and faults indicates strongly that certain of the dykes were probably intruded along non-vertical shear-planes rather than along vertical tension-fractures. Furthermore, Wager's interpretation of the dykes of the East Greenland monocline (Wager 1947) also involves original non-vertical emplacement, in this case along tensional fractures normal to the deformed basalts of the flexure.

Apart from the flexuring discussed above, the volcanic period was also probably a time of major faulting. As has previously been mentioned, the Shurugwe fault, forming the northern margin of the Bubye Coalfield in the Mateke region, was probably in existence as a monoclinal flexure during the period of Karroo sedimentation. This fault cuts the Karroo sediments and the lower parts of the basalt sequence but can not be traced into the Main Granophyre or the overlying rhyolites. The main faulting movement therefore probably took place during the extrusion of the basalts.

Later faulting and joint formation was, however, widespread on a smaller scale, particularly on the Limpopo trend.

The Marangudzi–Masukwe line of complexes can also be regarded as a late-Karroo tectonic feature. The acid rocks of the complexes are so similar to the Main Granophyre that they were probably intruded only shortly after the latter, towards the close of deformation of the Nuanetsi syncline. Indeed, the Causeway microgranite sheets of the Masukwe complex appear to have been intruded at the same time as the Main Granophyre. The basic rocks of the complexes pre-date the latter but the time-interval is unlikely to have been a long one.

2. *Some structural conclusions and problems*

In the preceding descriptive section structural features have been subdivided on the basis of trends, and time relations have been established. This information is summarized in table 3 and its interpretation is attempted in the present section.

(*a*) *The block structure of the crust*

Undoubtedly one of the most important structural conclusions to emerge from the present study, is the dependence of Karroo structural evolution in the Limpopo region on the disposition of crustal blocks and mobile zones on a variety of scales. The close correspondence of these units with structural features of the Basement complex makes it certain that many of them were already in existence in the pre-Karroo period.

The concept of Basement-control of Karroo geological evolution in the Limpopo region fits into the general pattern of African structural geology. Dixey (1937, 1946) for example, has stressed the parallelism of the East African rifts to ancient Basement structures and has suggested that many of them originated as fault-bounded troughs of Karroo rocks. Similar views relating to the trends of the rifts to local Basement structures have also been given by Harpum (1954) and McConnell (1950), who expressed the view that the whole pattern of the rift system was laid out in the pre-Cambrian. Brock (1954) has described pre-Cambrian rifts from the Orange Free State.

TABLE 3. TIME RELATIONS OF TECTONIC FEATURES OF VARIOUS TRENDS

	Limpopo trend (E.N.E.)	Nuanetsi trend (W.N.W.)	Sabi trend (N.S.)	others
pre-Karroo period	evidence of activity of Messina Block and North Transvaal fault-belt (post-Waterberg faulting)	—	—	—
period of Karroo sedimentation	present site of Northern Transvaal fault-zone marked by depositional trough. Major faulting initiated (e.g. Shurugwe fault). Messina Block acted as relatively positive area. ? Initiation of Mateke–Sabi Monocline	no evidence available. The trend may not have developed at this stage	possible initiation of the Sabi syncline	—
period of basalt eruption	continuation of positive character of Messina Block. Probable major faulting	initiation of folding in Nuanetsi syncline. Possibly major faulting. Dyke intrusion	—	—
early rhyolite period	—	main period of folding of Nuanetsi syncline	—	probable main deformation of Lebombo
late rhyolite period	emplacement of ring-complexes along Marangudzi–Masukwe line. Acid dykes intruded near Marumbe complex	—	Probable period of emplacement of ring complexes and late acid dykes	—
post rhyolite period	relatively minor faulting and joint formation over whole area	—	minor faulting and joint formation	north–south and minor faults of Mateke

The block concept is itself an old one stemming from the works of Krenkel (1928) and Cloos (1937) and more recently elaborated by Brock (1955).

The most easily defined and largest crustal blocks, relevant to the evolution of the Limpopo area are those of the Southern Rhodesia–South Africa area, on the one hand, and the depressed Mozambique Block on the other. The preoccupation of the present work with details of structure and volcanism in the Limpopo area should not obscure the fact that it is along the boundary of the Mozambique Block that the most intense warping and volcanism have taken place.

The Southern Rhodesia–South Africa shield can itself be divided into the Southern Rhodesian Block, on the north, and the Transvaal Block on the south. The mutual contact of these units in the Limpopo area has had a further effect on the localization of Karroo volcanic activity.

The Transvaal Block, referred to by Krenkel (1928) as the Transvaal 'Schüssel', is a dish-shaped structure with a raised rim of ancient Basement-rocks. The Southern Rhodesian Block is a more consistently positive unit of which the most authoritative description is given by Macgregor (1951).

The broad mobile zone lying between these two major units is itself divisible into smaller parts, each of which probably maintained its identity throughout the Karroo period. The Messina block, recognized by Krenkel (1928) as a minor structural unit which he referred to as the Messina-Zwischenmassiv, lies between the Northern Transvaal fault-zone and the Tuli syncline. The disposition of these units reflects the underlying structure of the Limpopo orogenic belt.

The first stage in the reconstruction of Karroo tectonic evolution clearly lies, therefore, in the recognition of the fundamental block-structure of the crust. No mention, however, has been made so far of the Nuanetsi syncline which appears to be a structure of a type quite unique in the area.

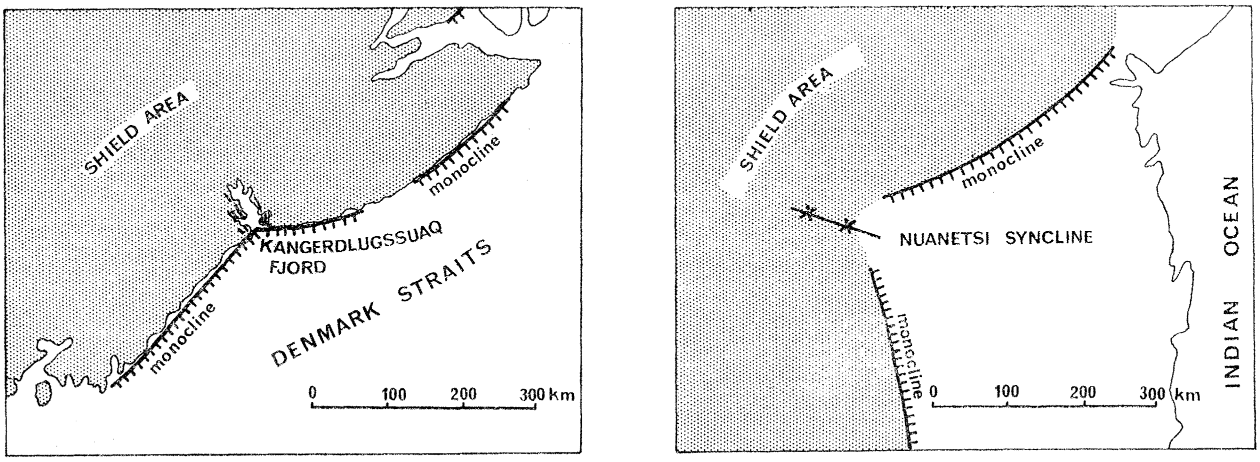

FIGURE 18. Comparison of the East Greenland and Lebombo–Mateke–Sabi monoclines showing positions of Kangerdlugssuaq Fjord and the Nuanetsi syncline.

(*b*) *The Nuanetsi syncline*

The Nuanetsi syncline with its attendant Nuanetsi-trend faults and dykes is quite unlike the other structural features of the Limpopo region in showing no apparent dependence on Basement structure. There is no evidence, for example, that the Limpopo orogenic belt fails to continue beneath the syncline, maintaining its east-north-east trend. Furthermore, reference to table 3 shows that the Limpopo-trend features, such as the Marangudzi–Masukwe line of complexes, were formed obliquely across the synclinal axis after the main period of folding. Features of the Nuanetsi and Limpopo trends therefore overlap in both time and space, crossing each other at an angle of some 30°. It must be concluded that the former structure is not dependent on the type of Basement-control affecting the latter.

If, however, the overall shape of the combined Southern Rhodesian–Transvaal shield is considered, the position of the Nuanetsi syncline, almost bisecting the re-entrant angle where the Lebombo swings into the Mateke–Sabi monocline, appears to be more significant. It is extremely relevant to refer at this stage to the Kangerdlugssuaq area of East Greenland (Wager 1947) which forms an almost perfect analogy to the Nuanetsi area. A diagrammatic comparison is made in figure 18.

In both areas a volcanic monocline, paralleled by dyke swarms, changes direction suddenly. In both cases, at the point of the re-entrant angle formed in the positive block, a subsidiary, apparently tensional, structure, lying within the positive block, is present.

In Southern Rhodesia it is the Nuanetsi syncline with its dykes and faults. In Greenland it is the Kangerdlugssuaq swarm of dolerite dykes, which can be traced for approximately 35 km in a north-north-westerly direction and includes dykes up to 150 m in width. It may also be significant that in both areas there is a tendency for the dykes to fan-out away from the re-entrant.

It is clear that, given a certain rigidity in the positive blocks, a variety of essentially lateral stresses acting non-uniformly on the blocks as a whole could cause a great concentration of tensional stress in the positions occupied by the Nuanetsi syncline and the Kangerdlugssuaq dyke-swarm.

In the Nuanetsi area it seems likely that tension across, and dyke intrusion parallel to, the present synclinal axis were the most important factors leading to the formation of the syncline. The latter appears to have been the inevitable consequence of the extrusion of enormous amounts of lava, and represents the subsidence of the original land-surface in response to the transfer of material from below to above. The fold may therefore be referred to as a volcano-tectonic feature. If the tri-zonal structure of the Limpopo orogenic belt is regarded as the main contribution of the Limpopo orogeny to the permanent structure of the region, the Nuanetsi syncline may similarly be regarded as the main contribution of the Karroo Period.

(*c*) *The problem of the North Transvaal fault-zone*

The Nuanetsi Igneous Province forms only a small part of the African continent and any genetical structural interpretation of the area must be viewed in the context of the continental structure. Such a synthesis is outside the scope of the present work, but there is, nevertheless, one aspect of the structural geology of the Nuanetsi and Limpopo regions which deserves special comment since it may ultimately contribute towards such a synthesis.

The Northern Transvaal fault-zone is one of the most curious structural features of the area. This extensive zone consists of numerous parallel normal faults all of which throw down to the south, thereby almost exactly offsetting the northward dip of the Karroo rocks. Such faulting, generally termed antithetic, is frequently encountered on a much smaller scale accompanying more important normal faults in rifts (e.g. see de Sitter 1956, p. 154). In the case in question, however, no master-fault is present and the origin of the fault pattern remains obscure. A simple lateral tension, for example, fails to explain the uniformity in direction of throw. An explanation in terms of purely vertical tectonics is similarly somewhat unsatisfactory because of the antithetic nature of the faulting. The consistent southward downthrow of the faults suggests that any causative upward block-movement must have taken place to the north of the fault zone. The Messina Block, a consistently positive unit, occupies an appropriate position but an explanation in these terms fails to explain the uniform northward dip of the Karroo rocks within the fault-zone.

The problems presented by the Northern Transvaal fault-zone, however, are by no means confined to the Limpopo region. Gair (1956), for example, draws a section across the northern limb of the mid-Zambezi Karroo trough showing Karroo beds dipping at about 20° towards the centre of the trough and repeatedly cut by powerful normal faults tending to offset the effects of the dip. Ellis (1956) describes very similar faulting from the south side of the Zambezi valley. A further example is found in the South Morondava basin in South-west Madagascar (Cliquet 1956) where it is aptly termed 'factory roof' structure ('en toit d'usine'). Here the Sakamena and Sakoa formations of the Karroo dipping in at the western side of the basin are cut by numerous faults throwing down away from the basin. The Natal monocline, the faulting of which has recently been discussed by Maud (1962), also shows broadly similar features.

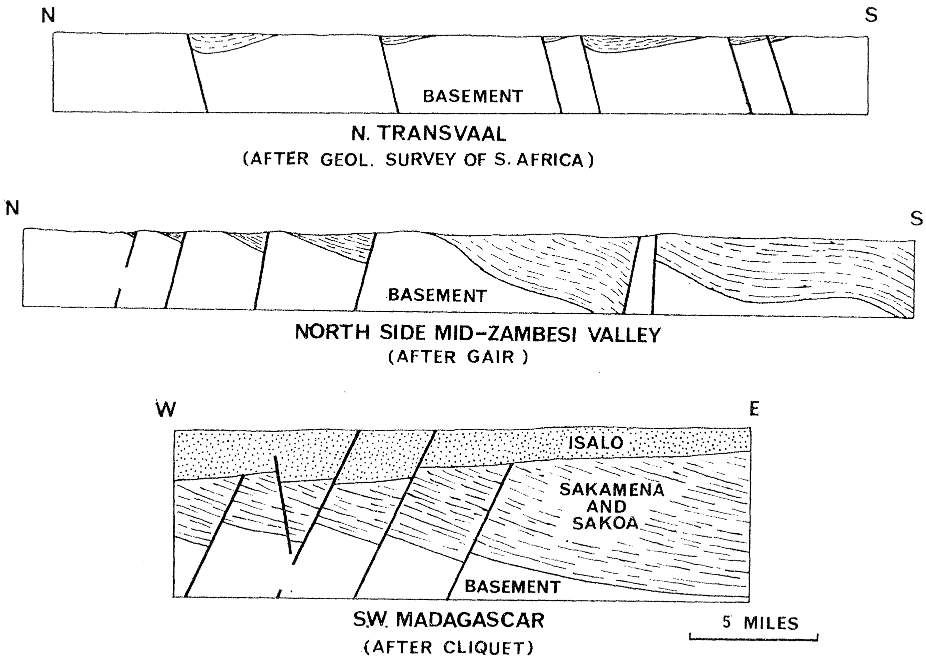

FIGURE 19. Sections of antithetic fault-zones.

The Northern Transvaal, mid-Zambezi and South Morondava structures are illustrated in figure 19. The importance of this type of structure can not be over-emphasized in any study of Karroo tectonics. The existence of fault-zones showing uniformity in direction of throw and apparently not related to local vertical movements, may perhaps be explained by relative lateral movements between the crust and its substratum. It is necessary, therefore, to visualize a crust, held relatively rigidly in position, above a more mobile foundation capable of effecting both lateral and vertical tectonic processes.

PART II. PETROGRAPHY, GEOCHEMISTRY AND PETROGENESIS

VII. THE PETROGRAPHY OF THE KARROO BASIC VOLCANICS AND ASSOCIATED MINOR INTRUSIONS

1. *Petrography of the Olivine-rich Group*

For descriptive purposes the rocks of the Olivine-rich Group have been divided as follows:

Limburgites—rocks containing abundant glass and no feldspar;

Olivine-basalts and picrite-basalts—rocks containing both glass and feldspar crystals;

Holocrystalline rocks from the larger intrusive bodies.

(*a*) *The Limburgites*

The limburgites are amongst the most abundant rocks of the Olivine-rich Group and occur as widely distributed flows and minor intrusions throughout the lower part of the Karroo basalt succession. They are also amongst the most interesting rocks of the Nuanetsi area by virtue of their high glass content and the great variety of skeletal forms which the crystalline constituents show. In hand-specimen they are a dull black or reddish colour with abundant, easily visible, small olivine phenocrysts set in a featureless matrix which occasionally shows a slightly pitchy lustre. Amygdales are rarely conspicuous. In thin section the limburgites are seen to consist most commonly of euhedral olivine phenocrysts and smaller clinopyroxene crystals, usually more or less lath-like, or occasionally, dendritic, set in a matrix of glass containing abundant skeletal ore (figure 36*d*, plate 6). More rarely clinopyroxene forms large euhedral phenocrysts and in a few specimens orthopyroxene was found as an additional constituent. Modal analyses of some typical limburgites are presented in table 4.

TABLE 4. MODAL ANALYSES OF LIMBURGITES

(volume %)

specimen no. ...	LM 452	KC 94	LM 432	KC 46	LM 428
olivine	14·4	16·7	25·0	29·1	19·4
clinopyroxene	26·0	22·8	24·5	15·7	47·0
ore	5·2	5·4	10·0	8·9	} 33·6
glass	52·3	53·8	39·2	46·3	
amygdale material	2·1	1·3	1·3	—	—

The *olivines* in the limburgites have $2V_x$ in the range 88°–92° corresponding with compositions of Fa_{15}–Fa_{27}. Slight zoning is occasionally found, the margins of crystals being somewhat more fayalitic than the centres. The sizes of the olivine crystals usually vary considerably within any one specimen. Commonly the range is from about 0·4 mm to about 2·0 mm in diameter. The clinopyroxene phenocrysts are almost always much smaller.

In the majority of the specimens examined the olivine tends to be euhedral, and perfect six-sided longitudinal sections and rectangular cross-sections are moderately common. In many cases, however, the form exhibited in thin section is modified by deep, rounded and sinuous embayments filled by the groundmass glass. In several specimens, all rocks of a highly chilled appearance, the olivines are markedly skeletal (see figure 36*c*, plate 6) and very similar to those described by Drever (1956) and Drever & Johnston (1957) from other localities. In the great variety of olivine-rich rocks examined from the Nuanetsi area the impression is gained that the highly chilled rocks, that is to say, the rocks with a high glass content and with skeletal pyroxenes and dendritic ore minerals, contain the highest proportions of skeletal olivines. This seems to support the view, stressed by Drever, that the form of the olivines is likely to be due to rapid growth and not necessarily to magmatic corrosion.

The olivines in most of the specimens examined were partially altered to a variety of minerals, including antigorite, chrysotile, iddingsite and talc. In addition, pale yellowish and brownish micaceous alteration products with moderate pleochroism, very low relief and high birefringence are abundant.

The *clinopyroxene* in the majority of the limburgites is present as small sub-hedral or euhedral crystals from 0·1 to 0·3 mm in length. In certain dyke-rocks, however, it occurs as phenocrysts up to 3 mm in length and shows almost perfect euhedral form (figure 37*a*, plate 7).

The more commonly found small crystals are mainly somewhat elongated and in several specimens where chilling appears to have been most intense the form is acicular and the glass matrix is packed with bundles of clinopyroxene needles. Occasionally groups of another, unidentified, mineral are present. These are slightly pleochroic in shades of brown and have straight extinction, high birefringence and positive elongation.

The clinopyroxenes very commonly show a tendency towards skeletal crystallization. This is manifest in the ragged and hollow ends which otherwise euhedral, prismatic and microlitic crystals often show. Occasionally skeletal crystals may be moderately large. In such cases it appears that two generations of clinopyroxene are present, the earlier occurring as colourless euhedral microphenocrysts and the later as deep pinkish-coloured microlites and overgrowths on the microphenocrysts. In the latter case the earlier pyroxene crystals acts as a foundation for large skeletal crystals. Occasionally, instead of being microlitic in chilled rocks the pyroxene is dendritic in form. Such rocks are particularly striking when viewed between crossed nicols (see figure 36*b*, plate 6).

The composition of the clinopyroxene is difficult to determine because of the small size of the crystals and the prevalence of zoning. The pinkish or violet colouration which is often present suggests that it is titan-augite. The centres of crystals commonly have $2V_z$ in the range 50° to 54° and margins have $2V_z$ as low as 42°, suggesting a lower calcium content. In addition to the above variation, very occasional crystals may be found which appear to be almost uniaxial centrally. Extinction angle may vary considerably in the range 44° to 52° within a single crystal.

Orthopyroxene is present as phenocrysts in a few of the limburgites. The crystals are usually euhedral, giving slightly elongated rectangular sections, and may reach a rather larger size (up to 4 mm in length) than the olivines. The crystals are clear and colourless with a low birefringence. One specimen gave $2V_x = 83°$ indicating a composition of approximately Fs_{25} (hypersthene). The most characteristic feature of the hypersthene phenocrysts is their patchy marginal replacement by clinopyroxene. Occasionally replacement may result in complete pseudomorphs of clinopyroxene after the orthopyroxene, but such crystals are easily distinguished from the primary clinopyroxene phenocrysts by their patchy texture. Another feature, commonly but not invariably present, is the inclusion by the hypersthene of small, rounded olivine crystals.

The *ore minerals* of the limburgites show particularly interesting forms. Two ore minerals appear to be represented—probable kennedyite and ilmenite.

The probable kennedyite is found in prismatic crystals, usually opaque but with brown translucent patches showing straight extinction and high birefringence exactly like the kennedyite from the type rocks of the Beacon area. The crystals vary considerably from minute needles to slender prisms up to $\frac{1}{2}$ mm long showing rectangular, square and rhombic cross-sections. The termination of the crystals are usually ragged and occasionally hollow. The prismatic ore mineral occurs in about half the specimens examined, sometimes as the only ore mineral present, and sometimes accompanied by the ilmenitic type of ore.

The latter is characterized by a structure which might be termed dendritic. Most characteristically it is found in comb-like plates up to 0·5 mm in diameter, appearing as thin elongate crystals in thin section. Each plate consists of closely packed parallel lobes of ore growing from a central branch. The specimens vary considerably and in some the parallel lobes are separate and distinct giving a truly comb-like appearance, whereas in others the lobes have almost completely coalesced to give a more solid plate which retains a crenulated margin.

Each of these combs frequently appears to belong to a larger dendritic crystal so that in many of the thin sections examined small areas where all the combs are parallel are frequently found. This is particularly so in the vicinity of the olivine phenocrysts which often seem to act as a nucleus for the large dendritic ore crystals. The texture is most distinctive and is illustrated in figure 36*a*, plate 6. It is not found in the typically olivine-free basalts.

The *glass*, which forms the matrix in the limburgites, is frequently grey or reddish in thin section owing to the presence of crowds of minute globulites, probably of ore minerals. Occasionally it may be so full of minute inclusions as to be almost opaque. It is quite clear that in the majority of cases the glass must have approximately the composition of basic plagioclase. This can be deduced from the fact that specimens containing abundant glass and tiny microlites of basic plagioclase are commonly found as varieties texturally intermediate between the true limburgites and the picrite-basalts in which comparatively little glass remains. In fact, a complete range of specimens is found illustrating the transition from pure glass to basic plagioclase with a little glass. The small amount of glass remaining in the latter rocks, however, may well be more alkaline in view of the common occurrence of a small amount of interstitial alkali feldspar in the holocrystalline rocks of the suite.

Amygdales are usually present in the limburgites but are almost always very small (less than 1 mm in diameter) and rarely make up more than a small percentage of the volume of the rock. In this respect they differ considerably from the usually highly amygdaloidal olivine-free basalts. In the limburgites the occurrence of subspherical or almond-shaped amygdales is rare. The common shape is somewhat angular the amygdales being interstitial to the microphenocrysts of the rock. Mineralogically the amygdales in the limburgites are remarkably uniform. A variety of fibrous zeolites has been found in a few specimens but the great majority of the rocks contain monomineralic amygdales filled by nontronite, identified by X-ray powder photographs. This is a pale yellowish-green micaceous mineral with low relief and refractive indices above balsam. The cleavage traces are length slow and the birefringence is moderate, larger flakes giving mid second order colours. The mineral was present as the only amygdale mineral in nearly all the specimens examined. It is also common in the picrite-basalts, olivine-basalts and holocrystalline rocks of the suite.

(*b*) *The Olivine-basalts*

The rocks described under this heading differ from the limburgites in containing plagioclase feldspar in addition to a glassy groundmass. They are perhaps the most abundant rocks of the Olivine-rich Group and occur both as flows and minor intrusions. The petrography will be described briefly in view of the more detailed account of the limburgites already given.

Texturally many of the olivine-basalts are very similar to the limburgites in their phenocrysts, in the distinctive habit of the ore minerals, and in the presence of a glassy groundmass. In these types the plagioclase occurs as minute acicular prisms, usually with hollow centres, set in the glassy groundmass with an irregular flow structure (see figure 37*b*, plate 7). In what are presumably less chilled varieties, the plagioclase crystals are larger and become more tabular in form, occasionally enclosing smaller pyroxenes. In common with the holocrystalline rocks of the Olivine-rich Group, the olivine-basalts frequently contain visible apatite needles.

TABLE 5. MODAL ANALYSES OF OLIVINE-BASALTS
(volume %)

specimen no. ...	LM 338	LM 434	LM 430	LM 447	KC 32	KC 42(*a*)	LM 592
olivine + alteration products	5·0	5·7	6·9	9·4	21·2	25·2	26·7
clinopyroxene	46·0	28·7	27·2	35·3	4·0	31·1	16·2
orthopyroxene	—	—	—	—	1·2	—	0·8
plagioclase	44·7	23·3	33·1	35·3	—	—	17·5
ore	4·6	14·9	6·9	3·0	—	9·6	5·5
glass	—	26·9	25·4	16·9	—	—	28·4
groundmass (undifferentiated)	—	—	—	—	73·5	34·1	—
amygdale material	—	0·7	0·5	—	—	—	5·0

LM 338, dyke—Chilembeni Hill—cutting complex; LM 434, flow—Davata Dip; LM 430, probable flow—2 miles west of Chilembeni; LM 447, dyke—Chilembeni Hill—cutting complex; KC 32, dyke—Chisume River; KC 42 (*a*), flow—north of Bumburudza River; LM 592, dyke—east of Shamandali.

Modal analyses of some olivine-basalts are given in table 5. In addition, the olivine content of several more specimens which were too fine-grained to be suitable for full analysis was determined. The highest olivine content recorded was 55 %, in a rock differing only from the augite-picrites in its small content of glass. In contrast, several specimens with all the textural features of the olivine-basalts were found to contain little or no olivine. In this respect, therefore, the olivine-basalts differ considerably from the limburgites which apparently never have low olivine-contents.

The plagioclase crystals are zoned. Centres are of labradorite and the margins are of andesine composition.

An interesting point arises regarding the sizes of the crystals. The plagioclase microlites, when they first appear in the most chilled olivine-basalts, are considerably elongated. Despite their small bulk they are frequently up to 0·75 mm in length. The tabular plagioclase crystals in the more crystalline rocks have about the same diameter. The combs of ore are frequently up to 1 mm in diameter and the olivines are commonly 2 mm in diameter.

These sizes contrast considerably with those found in the typical Chikombedzi basalts of the Upper Basalt Group. The latter rocks are holocrystalline and do not show any features, such as skeletal crystallization, to indicate intense chilling. At the same time the individual crystals are very much smaller than in the olivine-basalts and limburgites. The apparently less-chilled rock-type therefore is the more fine-grained. This apparent anomaly could be accounted for by the high volatile content of the Chikombedzi basalts which, by reducing the viscosity of the magma, could have accounted for the fine-grained crystallization of the entire rock on moderately rapid cooling. That the Chikombedzi basalt magma was volatile-rich is suggested by the generally highly amygdaloidal nature of the rocks.

The pyroxenes of the olivine basalts consist of sparse, large, phenocrysts of hypersthene, and small sub-hedral crystals of clinopyroxene. The latter are usually somewhat tinted and, as in the limburgites, appear to be augitic in composition and are commonly zoned.

(*c*) *The holocrystalline rocks from the larger intrusive bodies*

For descriptive purposes the holocrystalline intrusive rocks of the Olivine-rich Group have been subdivided into:

Augite-picrites. These are perhaps the most common of the intrusive rocks and consist essentially of olivine and augite, making up about 75 % of the rock, accompanied by basic plagioclase. Alkali feldspar is, however, frequently present in subordinate amounts.

TABLE 6. MODAL COMPOSITIONS OF AUGITE-PICRITES

(volume %)

specimen no. ...	KC 51	KC 52	KC 42	LM 339	LM 591
olivine + alteration products	30·4	36·1	48·3	23·4	43·9
augite	33·5	29·9	24·3	25·6	13·4
hypersthene	7·4	8·0	2·8	3·7	12·8
basic plagioclase	24·5	22·1	19·5	}36·3	19·9
alkali feldspar	1·2	1·5	1·1		—
ore	3·1	2·4	2·3	5·1	1·1

Localities: KC 51, Chitea; KC 52, Chitea; KC 42, large dyke crossing track 9 miles south-east of Nyasumi; LM 339, large north-west–south-east dyke ½ mile south of junction of Gezani–Davata track with Malipati track; LM 591, Shamandali.

Alkaline augite-picrites. Types similar to the above except that alkali feldspar predominates over basic plagioclase. Occasional specimens are entirely free of plagioclase. There is little doubt, however, that the alkaline picrites grade into the normal picrites via intermediate types.

The rocks of the Chilembeni intrusion. Rocks in many respects similar to the alkaline augite-picrites but including more leucocratic types classified as olivine-monzonites. They are described separately as the intrusion has been studied in more detail than the other occurrences.

(i) **The Augite-picrites.** Modal compositions of rocks referred to this group are given in table 6. It should be noted that in one case it was not possible to distinguish the two types of feldspar during the modal analysis and the total feldspar content is therefore shown. Within this group, however, alkali feldspar is present only in minor amounts. Olivine and pyroxene are present in varying amounts and either may predominate. Orthopyroxene is always subordinate to clinopyroxene.

Texturally the rocks consist of comparatively large (up to 3 mm long) euhedral to sub-hedral olivine crystals set in a matrix which, in the finer-grained varieties, is similar to an intergranular dolerite or, in the coarser varieties, is more gabbroidal. In the latter case, however, the basic plagioclase usually assumes a poikilitic form. Alkali feldspar, where present, is interstitial and only shows faces when in contact with patches of minutely crystalline, green, micaceous material which may represent altered glass in some cases or, perhaps more likely, amygdale material. Apatite and ore minerals, either kennedyite (von Knorring & Cox 1961) or ilmenite, are prominent accessories.

Orthopyroxene (hypersthene) occurs as large (up to 5 mm long) phenocrysts in many of the specimens examined. In the majority of cases these phenocrysts are considerably replaced by a mosaic of smaller clinopyroxene crystals. In the chilled marginal facies of the Chitea intrusion, orthopyroxene is also present as small granules in the groundmass and, mixed with fine-grained ore, forms well-defined reaction rims round strongly resorbed olivine crystals. The reaction rims frequently reproduce the original euhedral form of the olivines.

The orthopyroxene phenocrysts usually enclose small, rounded olivines and, occasionally, plagioclase crystals. The crystallization appears to have taken place at a very late stage in fine-grained specimens where comparatively large crystals enclose large numbers of plagioclase laths giving a sieve-structure of almost metamorphic appearance.

The *olivines* in the augite-picrites are usually more or less altered along cracks to serpentine and iddingsite. In most of the specimens examined the olivine had $2V_x$ in the range 87° to 88°, corresponding with a composition of Fa_{28}. Zoning was found rarely and one crystal investigated ranged in composition from approximately Fa_{24} ($2V_x = 89°$) centrally to Fa_{37} ($2V_x = 84°$) marginally.

The *clinopyroxene* is usually colourless to very pale yellow and is frequently slightly zoned. $2V_z$ varies from 45° to 50° for crystal centres and may be 5° lower marginally. $Z \wedge C$ is in the range 50° to 56°. Refractive indices have not been determined but it seems probable that the pyroxene is augite.

The *orthopyroxene* has usually only the faintest pink to neutral pleochroism. Measurements of $2V_x$ on several specimens gave results in the range 62 to 76° corresponding with a composition of Fs_{30}–Fs_{40} (hypersthene) (data in Winchell & Winchell 1951, p. 406).

The *plagioclase* is frequently zoned. Centres of crystals are mainly An_{70} (labradorite-bytownite) and margins may occasionally be as sodic as An_{50}.

The *alkali feldspar* has not been identified positively because of the difficulty of separation but is characterized by extremely low birefringence, refractive indices below balsam, and $2V_x$ in the range 44° to 48°; from the low $2V$ it would appear to be anorthoclase. An extremely irregular wavy extinction is present in many of the specimens. Crystals show rectangular outlines against amygdale minerals and have a prominent rectangular cleavage picked out by thin layers of what is probably sericite.

The *ore minerals* are variable in form and range from dark brown and translucent prisms (kennedyite) to more irregular, granular or skeletal, opaque, grains which are probably ilmenite.

Apatite is frequently a most prominent and striking accessory mineral. It is often extremely abundant running through the feldspars as hair-like acicular crystals. Some of the curious forms encountered have been described by Wyllie, Cox & Biggar (1962).

The foregoing petrographic description applies to many of the picritic rocks of the area. Certain slight variants are, however, worthy of special mention. The very large Bezi Dyke, crossing the track 2 miles north-west of Nyasumi consists of a rather more fine-grained and melanocratic type of picrite. A specimen from this dyke has the following modal composition: olivine 35·2%, augite 47·6%, ilmenite 5·9%, feldspar (approximately equal proportions of labradorite and possible anorthoclase) 11·3%. Texturally the rocks consists of very irregularly shaped olivines up to 1 mm long set in a mass of small augite and ilmenite granules with interstitial feldspar. The olivines have $2V_x = 85°$ to $87°$ corresponding with a composition in the range Fa_{28} to Fa_{34}. The alkali feldspar has a $2V_x$ of 48° and is therefore assumed to be anorthoclase.

(ii) **The alkaline augite-picrites.** The alkaline augite-picrites are not clearly divided from the more normal types described above. It is very probable that the alkali feldspar-free picrites such as LM 591 in table 6 and the plagioclase-free picrites like C 888 in table 7 are end-members of a series in which there is continuous gradation. Several specimens of highly alkaline picrite have been collected from the vicinity of the Beacon beside the Nuanetsi–Chikombedzi track. Modal analyses of two of these are given in table 7.

TABLE 7. MODAL ANALYSES OF ALKALINE AUGITE-PICRITES

(volume %)

specimen no. ...	C 888	KC 201
olivine + alteration products	41·0	53·9
clinopyroxene	25·9	27·0
basic plagioclase	—	5·9
alkali feldspar	24·4	9·9
ore	3·8	3·3
interstitial micaceous material	4·9	—

Localities: both specimens are from the Beacon beside the Chikombedzi–Nuanetsi track.

In texture the rocks are very similar to the picrites already described with the exception that no phenocrysts of orthopyroxene have been noted. In some specimens a comparatively large amount of interstitial, green, micaceous material is present and in these the rectangular form of the alkali feldspar crystals is conspicuous. Apatite is particularly abundant in this type of rock and occurs as hosts of tiny needles in the feldspar and in the interstitial micaceous patches.

The olivines, corresponding with a composition of Fa_{20} have $2V_x$ in the range 88° to 92°, and appear to be a little more magnesian than those in the normal picrites. This may not be a significant difference, however, as the number of specimens of alkaline picrite available was comparatively small.

The alkali feldspar again has the low $2V$ characteristic of anorthoclase. Specimen C 888 has been analysed (see table 12) and it is interesting to compare normative feldspar with the modal feldspar. As is shown in table 7, the rock contains 24·4 % of alkali feldspar, believed to be anorthoclase. The norm contains 11·7 % *or*, 11·5 % *ab* and 4·7 % *an*, a result which is consistent with the identification of the modal feldspar as anorthoclase.

In several of the specimens of alkaline picrite containing basic plagioclase a curious texture is often present. The plagioclase occurs in a series of small blebs in the alkali feldspar, often with a roughly rectangular arrangement. The impression is given that original small euhedral plagioclase crystals have been fritted away either by the magma or possibly by later metasomatic processes.

The ore mineral in the alkaline picrites, as in the normal picrites, is sometimes of the kennedyite type and sometimes ilmenite.

(iii) **The olivine-monzonites of Chilembeni.** As mentioned previously the Chilembeni intrusion is characterized by a marginal zone of mafic olivine-monzonites and a central zone composed of leucocratc monzonites.

The *melanocratic rocks* are holocrystalline and are typically medium- to coarse-grained, with a porphyritic or poikilitic texture. The phenocrysts are predominantly euhedral ilmenite and olivine crystals ($2V_x = 84°$), the former occurring in skeletal form and the latter ranging from 0·2 to 2 mm in diameter. Titaniferous augite ($2V_z = 47°$ to $49°$) occurs as subhedral crystals which range up to 4 mm in diameter and which often enclose numerous small crystals of olivine, ilmenite and occasionally apatite. Plagioclase (usually partially altered to prehnite) forms subhedral laths with a maximum length of 2 mm. The crystals are usually zoned and have a core composition of An_{72} and margins of calcic andesine. The groundmass of the rock is composed of alkali felspar with a very low birefringence and a refractive index slightly below that of balsam. Two measured crystals gave $2V_x = 51°$ and $53°$ respectively and this fact together with the C.I.P.W. norm of the

TABLE 8. AVERAGE MODAL ANALYSES OF OLIVINE-MONZONITE FROM CHILEMBENI HILL (volume %)

	1	2
olivine and serpentine	25·1	2·4
titaniferous augite	24·7	8·4
plagioclase	13·8	44·0
alkali felspar	25·6	37·6
ilmenite	7·1	3·9
biotite	2·2	0·7
apatite	0·4	1·1
rest	1·1	1·8

1, Average of four specimens of melanocratic olivine-monzonite. 2, Average of three specimens of olivine-bearing monzonite.

rock (LM 436) (see table 12) suggests that the feldspar is probably anorthoclase. Accessory minerals include biotite, sericite and chlorite. An average modal analysis of four typical specimens of melanocratic olivine monzonite is given in table 8 and a chemical analysis together with the C.I.P.W. norm of specimen LM 436 is presented in table 12. Both chemically and mineralogically the Chilembeni rock is very similar to the Kentallen-type olivine monzonite as defined by Williams, Turner & Gilbert (1954).

The *leucocratic rocks* are very similar both in texture and mineralogy to the more melanocratic monzonite, the main difference being that olivine, clinopyroxene and ilmenite occur in much smaller amounts and that the plagioclase content is correspondingly higher. An average modal analysis of three specimens is presented in table 8.

2. *The petrography of the Upper Basalts*

(*a*) *Basalts of the Chikombedzi area*

Certain general characteristics distinguish the Chikombedzi basalts from those of the Olivine-rich Group. First, olivine is represented only by pseudomorphs which make up a small percentage (normally less than 2%) of a few of the rocks examined. In most specimens it is absent completely. Secondly, the rocks are in the main exceedingly fine-grained though glass is present only in very small amounts. In this respect they are texturally quite distinct from the olivine-basalts. Thirdly, the ore minerals tend to be granular or disseminated as a dust in contrast to the well formed combs, plates and spicules in the olivine basalts.

A high degree of deuteric alteration is characteristic of the Chikombedzi basalts and the rarer unaltered varieties will be described first. The unaltered basalts are normally dark bluish-black in colour and somewhat harder and more resistant to weathering than the altered basalts. A distinctive group of unaltered basalts, termed the Makokoba Group, can be mapped towards the top of the succession in the Chikombedzi area and is found in the vicinity of the Masukwe complex and along the eastern side of the Northern Ring complex.

(i) *Non-porphyritic basalts.* These are generally extremely fine-grained rocks with an intersertal texture. Dusty granules of clinopyroxene are set in a plexus of minute plagioclase laths arranged with little or no flow-structure. Identifiable glass is rarely present. The ore minerals are arranged in discrete equidimensional grains or in elongated ragged crystals. The clinopyroxene is usually too fine-grained (about 0·05 mm) for optical determinations to be made. In the few cases where it has been possible to determine the $2V$ however, this has proved to be of moderate size. Pigeonite has not been found in any of the Upper Basalts. The plagioclase laths are usually 0·1 to 0·2 mm in diameter and are strongly zoned. Determination of compositions is again difficult but it is clear that crystal centres are mainly of composition An_{50-60} whilst margins may be as sodic as An_{30}.

(ii) *Feldspar-phyric basalts.* These are most distinctive rocks, the mapping of which has been almost the only means of determining the strike direction in poorly exposed ground. The texture is glomeroporphyritic, the feldspar phenocrysts being arranged in aggregates (see figure 37*c*, plate 7). The individual crystals are flattened parallel to 010 and may be up to 1 cm in diameter. They are slightly zoned labradorite, ranging in composition from An_{56-60} marginally, to An_{60-65} centrally, and usually make up about 15% of the rock. Several cases of inhomogeneity have, however, been noted in feldspar-phyric flows and dykes. A 3 ft.-thick flow, for example, was found to contain 11% of feldspar phenocrysts at the base, 6% in the centre and none at all in the top few inches. This suggests that settling of feldspar crystals could be a differentiation mechanism in these basalts. Similarly, several feldspar-phyric dykes have been found to have non-porphyritic margins. In these, the groundmass is quite continuous from centre to margin and feldspar phenocrysts are only present to within approximately 6 in. of the actual contact. The phenocrysts are platy and show conspicuous parallelism with the contact and were, therefore, clearly present in the liquid at the time of intrusion. The marginal non-porphyritic rock is perhaps due to filter-pressing in the magma chamber causing pure liquid to be injected up the fissure shortly before the whole plexus of crystals and liquid followed.

The groundmass of the feldspar-phyric basalts is similar to the non-porphyritic type described previously.

(iii) *Pyroxene-phyric basalts.* The phenocrysts in this type are clinopyroxenes ($2V_z$ approximately 45°), again arranged in glomeroporphyritic aggregates (see figure 37*d*, plate 7). The individual crystals are clear, almost colourless, euhedral in contact with the groundmass and sub-hedral in contact with each other. They vary in size from 0·1 to 1·0 mm in diameter, the aggregates being 3 to 4 mm in diameter and hence easily visible in the hand-specimen. A few flows in the aureole of the Main Granophyre east of the Nuanetsi River contain larger (up to 5 mm) clinopyroxene phenocrysts and have a normal porphyritic texture. In several of the pyroxene-phyric basalts examined chlorite-serpentine-magnetite pseudomorphs after olivine were present. These rarely make up more than 2 to 3% of the rock.

(iv) *Altered Chikombedzi basalts.* The majority of the basalts in the area south and west of Chikombedzi suffer from deuteric alteration and are generally pale in mottled greys, brown, purplish, greenish colours. In hand-specimen the feldspar phenocrysts when present are frequently pink or red. This is due to the dissemination in them of a fine red dust, presumably an iron ore, which has accompanied the breakdown of basic plagioclase into epidote and sodic plagioclase. Although epidote is widely spread throughout the rocks it is frequently concentrated in the feldspar phenocrysts and may form partial pseudomorphs. Irregular streaks and patches of untwinned feldspars run through the original labradorite and are occasionally coarse enough to be identified by optical methods as albite or oligoclase. Pyroxene phenocrysts in the altered basalts, in contrast, are little affected.

In the groundmass of the altered basalts the principal changes are the breakdown of the pyroxene and the dissemination of the iron ore as a dust. Pyroxenes become replaced by uralite, chlorite and ore. In addition, epidote and calcite are widely scattered through the groundmass. The oxidation of the ore to a reddish dust accounts for the brownish and purplish colouration of many of the basalts. The optical determination of the felspar composition is usually impossible because of the degree of alteration.

The changes are attributed to deuteric action in view of the following points:

(1) The altered and non-altered basalts appear to be stratigraphically distinct, a factor which seems to rule out the presence of a zone of regional pneumatolysis such as that described from the Hebridean basalts of Mull (Bailey *et al.* 1924).

(2) The distribution of the altered basalts is not related to the intrusive rocks which might have exerted an essentially retrograde effect on the mineral facies.

(*b*) *The Chikwedziwa basalts*

The Chikwedziwa basalts are like the Chikombedzi basalts in being very fine-grained. They differ primarily in being much fresher in appearance than even the least altered Chikombedzi basalts and in addition are much less amygdaloidal. The texture is intersertal without flow structure. Small laths of basic plagioclase (0·1 mm long), granules of clinopyroxene (0·2 to 0·4 mm diameter) and iron ore are the principle minerals present. The pyroxene is probably augite as it has a moderately large $2V$. The ore occurs in rather large ragged plates similar to a type found in the olivine-basalts and limburgites. Small amounts of pinkish or colourless glass are present.

The brownish bands observed in many of the hand-specimens are due to zones of what appears to be haematite staining. This is an orange-red colouration affecting the minerals selectively. Zeolites in amygdales, clinopyroxenes and glass tend to be stained in preference to feldspar.

(*c*) *Basalts of the Malibangwe area*

These basalts in general are very similar to those of Chikombedzi, being pale in colour, highly amygdaloidal, and practically devoid of olivine. Non-porphyritic varieties predominate but feldspar-phyric basalts with the typical glomeroporphyritic texture found in the Chikombedzi area are also common. Pyroxene-phyric types seem to be comparatively rare.

In thin section, however, the Malibangwe basalts are seen to be coarser than those of Chikombedzi. The texture is intergranular or intersertal though any original glass present is now altered to chlorite and calcite, magnetite and other secondary minerals. The clinopyroxene has a moderately large $2V$ and the feldspar-laths, where identifiable, are labradorite. The ore minerals tend to be crystallized in comparatively large ragged plates, though some specimens with finely granular ore are also found. Small chlorite-magnetite pseudomorphs after olivine are not infrequently present though never in large amounts. Alteration is usually intense and takes the form of sericitization rather than epidotization of the feldspars. Ferromagnesian minerals are to a large extent replaced by chlorite or calcite and magnetite.

(*d*) *Basalts of the Mutandawhe area*

Both porphyritic and non-porphyritic lavas are found but as in the areas of the upper basalts the latter predominate. In general the basalts are similar to those found in the Malibangwe area.

(i) *Non-porphyritic basalts.* The texture is intersertal, consisting of euhedral tabular plagioclase crystals 0·2 mm to 1·0 mm in diameter, somewhat smaller granules of augite ($Z \wedge C$ *ca.* 44°, $2V_z = 46°–51°$), and abundant plates of ore up to 1·8 mm in diameter. The interstices are filled by dark brown glass, which occasionally make up as much as 50% of the rock, and by chlorite, cancrinite, quartz and calcite. In general, therefore, the rocks are much coarser in grain than the Chikombedzi basalts. The feldspar is andesine or labradorite and there is some evidence that the higher flows in the sequence tend to contain the former (about An_{45}) whilst the lower flows are characterized by labradorite (An_{50-55}).

(ii) *Feldspar-phyric basalts.* The glomeroporphyritic texture typical of the feldspar-phyric rocks of the Upper Basalts is again common. The individual phenocrysts are tabular and vary from 2 to 12 mm in diameter. They appear to be more sodic than those of the Mateke region, having compositions of approximately An_{45}.

(iii) *Pyroxene-phyric basalts.* These contain euhedral phenocrysts of colourless or pale green clinopyroxene ranging from 2 to 3 mm. The texture is only rarely glomeroporphyritic.

(*e*) *The Uche–Guwini basalts*

This group of basalts is characterized by a high degree of alteration. Phenocrysts consist of large tabular, ragged and broken, plagioclase crystals (An_{60-70}) which are usually heavily sericitised (Uche Pool area) or epidotized (Guwini) with with formation of secondary albite and a red coloration. In addition, euhedral pseudomorphs after olivine and titanaugite phenocrysts are occasionally found. The groundmass has an intersertal texture, reaching doleritic grain-size in certain cases, and consisting of tabular and prismatic plagioclase crystals, granules or, occasionally, small euhedral crystals of clinopyroxene, patches of devitrified glass, granular and platy iron ore, and apatite. The form of the ore minerals is generally similar to that found in the limburgites and olivine-basalts.

(*f*) *Interbedded basalts*

Detailed petrographic descriptions of the basalts interbedded with the rhyolitic extrusives are given by Monkman (1961) and only a brief summary will be given here. Like the great majority of the Upper Basalts they are very fine-grained almost holocrystalline rocks, and generally rather amygdaloidal. Deuteric alteration is also fairly widespread. Porphyritic types are not common and the characteristic feldspar- and pyroxene-glomero-porphyritic varieties, found in sequences of Chikombedzi type, are absent. A micro-porphyritic type carrying small, somewhat rounded, pseudomorphs after olivine is, however, fairly common amongst the Mawanga–Umvumvu basalts.

(*g*) *Metamorphism of the basalts*

Contact-metamorphic aureoles are almost ubiquitously present where the acid intrusives of the province cut basaltic country-rocks. The aureoles form somewhat higher ground than the plains underlain by the unmetamorphosed basalts, and the outcrop is usually good. In some cases, for example round the Marumbe complex, the meta-basalts form prominent hills. Usually, however, they form low pedestals bordering the higher hills formed by the intrusive rocks. The outer boundaries of the aureoles are often sharp and there is a sudden transition from the plains to the broken well-exposed ground within the aureoles.

In thin section, metamorphic changes, except in specimens from close to the igneous contact, are by no means easy to detect. This is partly due to the fine grain of many of the basalts and partly due to the difficulty of distinguishing thermal alteration, in the early stages essentially retrogressive, from the already widespread deuteric changes. In specimens collected from within a few yards or tens of yards from the intrusive contacts, however, recrystallization is well advanced and the rocks assume a fine-grained crystalloblastic texture most clearly revealed by the intergrowing of feldspar phenocrysts with groundmass minerals. The groundmass texture of the unmetamorphosed basalts is largely destroyed.

In these rocks the clinopyroxene is usually clear and colourless in contrast to the dusty, tinted crystals normally found, and is accompanied by biotite. It is likely to have formed by recrystallization of amphibole, either a deuteric or early metamorphic derivative of the original pyroxene. Large crystalloblasts of pyroxene growing in originally chloritic amygdales support the impression that pyroxene-hornfels conditions of metamorphism have been realized in many instances. In other cases, notably in the aureole of the Mutandawhe complex where the basalts are comparatively coarse-grained, a series of changes involving the partial replacement of original pyroxene, first by hornblende and then by biotite, can be demonstrated. In this area, metamorphic pyroxene fails to appear even in intensely recrystallized rocks. The ore minerals in the meta-basalts frequently become gathered into well-defined grains and the general dustiness so common in the unaltered basalts disappears. In some specimens, however, the opaque ore forms an almost continuous network of small interconnected blebs and scales. In others, orange-red haematite is disseminated throughout the rock. Feldspar phenocrysts appear very dark in hand-specimen due to increased transparency on the absorption of sericite, epidote and other inclusions. Thermal clouding, consisting of minute opaque inclusions is common.

In addition to purely thermal effects the basalts are locally metasomatized along linear fracture zones. There may also be some general metasomatism in the vicinity of igneous contacts but this is mainly apparent in the amygdale mineralogy and will be discussed in the next section.

In the Mateke area the fracture-zones are found commonly in the basalts lying immediately north of the Masukwe complex and north of the Main Granophyre of the Gonakudzingwa Hills. The altered basalts are intensely jointed and in some instances granophyre veins are present and are slightly displaced by the joint planes. Textural features such as amygdales and glomeroporphyritic aggregates of feldspar crystals are perfectly preserved. Various types of altered basalt are found, perhaps the most common being a grey flinty rock which has essentially granitic compositions. This type has a very fine-grained crystalloblastic texture and staining techniques show it to be composed of pyroxene, alkali feldspar and quartz. Other altered basalts from such zones are brown or red in colour and consist of abundant haematite and an excessively fine-grained groundmass of feldspar and, probably, quartz.

In the Mutandawhe area metasomatism along linear fracture zones has given rise to a fine-grained quartz epidote rock. Epidote forms 70% of the rock, quartz 13% and the rest is composed of ore (11%), pyroxene (5%) and calcite (1%).

(*h*) *Amygdales in the Upper Basalts*

The amygdale minerals found in the Upper Basalts are immensely varied when compared with those of the Olivine-rich Group. Despite the variety, however, a characteristic of the province appears to be the extreme rarity of zeolites and related minerals.

Practically all the Upper Basalts are highly amygdaloidal and in most cases the amygdales contain a zoned arrangement of two or more minerals. The amygdale minerals can be divided into three groups on the following basis:

(1) *Endogenetic*—those minerals emanating from the basalts themselves.

(2) *Exogenetic*—those found in amygdales but introduced from hydrothermal veins emanating at least in part from the acid intrusives.

(3) *Metamorphic*—new minerals formed in amydgales in metabasalts.

The endogenetic minerals are recognized by their constant occurrence, and their absence from hydrothermal veins. The chief amongst these are chlorite (penninite), chalcedony, disseminated magnetite, and the rare zeolites. In addition quartz, calcite and epidote are so abundant in amygdales that they must in many cases be of endogenetic origin although they are also found in hydrothermal veins.

The zeolites found include natrolite, gmelinite, chabazite and analcite. The only area so far found where they could be said to be common is in the vicinity of Chitea Hill on the Lundi–Nuanetsi watershed. Here both the Chikwedziwa basalts and the more amygdaloidal interbedded basalts contain them in comparative abundance.

The chief vein minerals encountered are quartz, epidote, and garnet, found associated in veins near the granite contacts. The garnet occupies the centres of the veins and is pale yellow and anhedral. Identical garnets are occasionally found in amygdales in the neighbouring basalts and must certainly be of exogenetic origin together, no doubt, with some of the associated amygdale quartz and epidote.

In the general area of Chikombedzi, and at various scattered localities, hydrothermal calcite veins are found. These contain fluorite where they are found cutting the intrusive rocks of the Masukwe complex. Fluorite, however, has not been found as an amygdale mineral in the basalts. Calcite, possibly partly exogenetic, on the other hand is common and figures predominently in the basalts at Chikombedzi Dam. Here, large amygdales up to 20 cm in diameter are zoned by an outer layer of chalcedony followed by a layer of euhedral quartz prisms projecting into a central cavity. Complexly formed calcite crystals are perched on the tips of the quartz crystals, bridging but not filling the open centres of the amygdales.

Within the metamorphic aureoles tremolite appearing in chloritic amygdales is usually the first sign of metamorphism. In intensely recrystallized rocks large crystals of hornblende and clinopyroxene sometimes appear and in other cases, instead of ferromagnesian minerals, a mixture of magnetite with phlogopite porphyroblasts is occasionally found. Rarely, small, euhedral, orange garnets are formed.

In some instances, in the neighbourhood of the contacts of the granites and granophyres with the basalts, metasomatic effects are suspected. The amygdales assume a pinkish look due to the presence of orthoclase and quartz-orthoclase intergrowths. Biotite is also commonly present.

3. *The petrography of the dykes*

(*a*) *The Duvi swarm*

The rocks of the Duvi swarm vary from fine-grained dolerites to rocks with an almost gabbroidal texture, depending on the width of the dyke. The coarser types are commoner at the western end of the swarm where the erosion level is deeper, and it is suspected that the more chilled, less regular and narrower dykes of the eastern end may pass downwards into similar coarse-grained rocks.

The gabbroidal types of the western end of the swarm are frequently somewhat porphyritic, containing tabular basic plagioclase crystals of composition An_{65-70}, ranging up to 1 cm in diameter. The groundmass is usually holocrystalline but occasional specimens contain appreciable amounts of glass. The texture is sub-ophitic in the coarser varieties and intergranular in finer varieties. In the former, pinkish- or yellowish-tinted clinopyroxene partially encloses euhedral plagioclase crystals and the ore is crystallized in roughly hexagonal skeletal plates. Characteristically, chlorite pseudomorphs after olivine are present in small amounts together with interstitial, possibly secondary, quartz. Many of the specimens also contain small patches of interstitial quartz-orthoclase micropegmatite. Apatite, in acicular crystals, is a common accessory.

At the eastern end of the swarm gabbroidal dykes are absent though many moderately coarse dolerites remain. Dykes petrographically similar to the basalts are also found, particularly a feldspar-phyric type with the glomeroporphyritic texture so common in the basalts. The narrower dykes are not infrequently amygdaloidal and tend to be irregular in detail though maintaining the general trend of the swarm.

(*b*) *The Marangudzi swarm*

The petrographical features of the rocks of the Marangudzi swarm may be summarized as follows.

Phenocrysts. Most of the dyke-rocks collected were porphyritic. Phenocrysts may consist of any combination of olivine, basic plagioclase and clinopyroxene. No fresh olivine was found but a number of specimens contain pseudomorphs of chlorite, tremolite, and calcite, after euhedral olivine. Clinopyroxene is usually fresh and almost invariably greenish in tinge, especially marginally; it is sometimes pleochroic. Marginal zones tend to have an extinction angle, $Z \wedge C$, of 55° to 60°; this is somewhat higher than in the crystal centres and suggests that there may be some sodium enrichment. Plagioclase phenocrysts are commonly found and appear to be rather basic, anorthite having been determined in one instance.

Features indicating intense resorption of phenocrysts are found not infrequently. In some cases pyroxene or plagioclase crystals are smoothly rounded, showing no trace of faces.

TABLE 9. NEW ANALYSES OF BASALTS AND ALLIED ROCKS OF THE NUANETSI IGNEOUS PROVINCE

specimen no. ...	LM 432	KC 37	LM 428	LM 434	C 868	DW 389	LM-619 (*a*)	KC 58	LM 341	C 922	LM 126
SiO_2	48·98	49·58	49·11	49·61	50·05	50·37	47·27	52·90	50·55	51·00	52·05
TiO_2	3·34	2·87	2·99	3·54	2·54	2·22	4·46	2·69	1·62	1·90	1·70
Al_2O_3	7·74	9·17	9·39	11·28	12·33	14·16	13·23	13·05	16·20	16·30	12·43
Fe_2O_3	3·75	2·47	1·83	2·13	3·84	3·03	4·36	3·58	1·65	4·00	5·18
FeO	6·53	8·49	7·90	10·11	7·69	9·53	7·97	8·20	8·13	7·62	10·08
MnO	0·13	0·15	0·14	0·18	0·15	0·15	0·17	0·14	0·10	0·14	0·24
MgO	15·52	14·82	12·84	7·67	6·74	6·19	5·72	4·85	3·80	3·39	3·95
CaO	6·44	7·36	7·18	9·66	9·18	9·29	7·40	8·69	3·89	7·25	7·33
Na_2O	1·40	2·07	2·31	2·37	2·45	2·04	3·49	2·36	3·53	3·20	2·76
K_2O	2·44	1·98	1·42	1·83	1·58	0·47	1·98	1·63	3·38	2·55	2·07
H_2O^+	2·36	0·52	3·59	0·80	1·74	1·64	2·76	1·35	3·49	1·71	1·90
H_2O^-	0·91	0·18	0·62	0·42	0·27	0·75	0·78	0·18	0·62	0·26	0·36
P_2O_5	0·54	0·52	0·83	0·52	0·36	0·29	0·59	0·39	1·07	0·58	0·28
CO_2	n.f.	n.f.	n.f.	n.f.	n.f.	n.f.	n.f.	n.f.	2·15	n.f.	n.f.
total	100·08	100·18	100·15	100·12	99·92	100·13	100·18	100·01	100·18	99·90	100·33
Fe/Mg index	40·0	42·5	43·0	61·5	63·0	67·0	68·5	70·7	72·0	77·5	79·5

n.f., not found.

Key to analyses presented in table 9

LM 432	Limburgite	Gezani–Davata track, Pesu River basin. Analyst: J. R. Baldwin. (See table 4)
KC 37	Limburgite (dyke)	Bezi River drift. Nuanetsi–Chikombedzi track. Analyst: J. R. Baldwin
LM 428	Limburgite	junction of the Gezani–Davata track with the Malipati track south-west of Chilembeni. Analyst: J. R. Baldwin. (See table 4)
LM 434	Limburgite	Davata Dip. Immediately overlying the Cave Sandstone. Analyst: J. R. Baldwin
C 868	Basalt (Chikombedzi type)	near the Mahamba River between the Masukwe complex and the Nuanetsi River. Analyst: M. H. Kerr
DW 389	Basalt	near east side of Mutandawhe complex, Sabi–Lundi area. Analyst: J. R. Baldwin
LM 619 [*a*]	Basalt (interbedded)	Maose River. Interbedded with rhyolites. Analyst: J. R. Baldwin
KC 58	Basalt (Chikwedziwa type)	near main bend in railway north-east of Chikombedzi village. Analyst: M. H. Kerr
LM 341	Basalt	Chakumba River. Malibangwe area. Analyst: J. R. Baldwin
C 922	Basalt (Chikombedzi type)	Nuanetsi River north of Masukwe complex. Analyst: M. H. Kerr
LM 126	Basalt (interbedded)	from borehole in Maose crush zone near Maose River. Analyst: J. R. Baldwin

TABLE 10. C.I.P.W. NORMS OF ANALYSES GIVEN IN TABLE 9

specimen no. ...	LM 432		KC 37		LM 428		LM 434		C 868		DW 389		LM 619 (*a*)		KC 58		LM 341		C 922		LM 126	
Q	—		—		—		—		4·14		6·48		—		9·12		6·37		2·16		5·88	
or	14·47		11·69		8·35		10·57		9·45		2·78		11·69		9·45		20·03		15·03		12·24	
ab	12·06		17·30		19·40		19·92		20·96		17·29		29·36		19·91		29·89		27·26		23·59	
an	7·51		10·01		11·13		15·02		17·79		28·08		14·46		20·29		—		22·53		15·30	
C	—		—		—		—		—		—		—		—		6·73		—		—	
di *wo*	8·71	16·40	9·52	18·16	7·90	15·09	12·19	23·77	10·44	20·08	6·73	12·97	7·78	14·95	8·35	16·32	—		4·06	8·02	8·01	15·97
di *en*	7·03		6·93		5·67		7·23		7·00		3·60		5·32		4·80		—		2·11		3·61	
di *fs*	0·66		1·71		1·52		4·35		2·64		2·64		1·85		3·17		—		1·85		4·35	
hy *en*	27·91	30·55	14·96	18·65	22·23	28·10	11·04	17·64	9·80	14·16	11·80	20·51	5·47	7·38	7·30	11·92	9·44	20·52	6·32	12·12	6·22	13·74
hy *fs*	2·64		3·69		5·87		6·60		4·36		8·71		1·91		4·62		11·08		5·80		7·52	
ol *fo*	2·60	2·91	10·55	13·40	2·82	3·64	0·56	0·97	—		—		2·43	2·58	—		—		—		—	
ol *fa*	0·31		2·85		0·82		0·41		—		—		0·15		—		—		—		—	
mt	5·33		3·47		2·55		3·01		5·57		4·41		6·25		5·34		2·32		5·79		7·41	
il	6·37		5·46		5·61		6·68		4·86		4·26		8·50		5·17		3·03		3·64		3·19	
ap	1·34		1·34		2·02		1·34		1·01		0·67		1·34		1·01		2·35		1·34		0·67	
cc	—		—		—		—		—		—		—		—		4·60		—		—	
Fe/Mg index	40·0		42·5		43·0		61·5		63·0		67·0		68·5		70·7		72·0		77·5		79·5	

In other cases resorption has been followed by re-growth giving a crystal of more normal shape but containing a zone or zones of inclusions indicating a former ovoid shape.

Alteration. All the rocks collected were intensely altered. The alteration has produced abundant epidote, calcite, chlorite, and fibrous amphibole in the groundmass. It appears to be a deuteric phenomenon.

Groundmass. The groundmass, apart from the alteration products mentioned, commonly consists of plagiocase, lesser amounts of alkali feldspar, pyroxene mainly altered, ilmenite in small hexagonal skeletal plates, sphene and acicular apatite as accessories. One specimen examined contained large brown spinels.

TABLE 11. SPECTROGRAPHIC ANALYSES OF BASALTS FROM THE NUANETSI IGNEOUS PROVINCE

index no. ...	1	2	3	4	5
specimen no. ...	LM 434 (p.p.m.)	LM 619 (*a*) (p.p.m.)	LM 341 (p.p.m.)	LM 126 (p.p.m.)	DW 21 (p.p.m.)
Ba	700	850	1800	750	400
Li	< 5	11	< 5	30	< 10
Sr	700	900	700	160	350
Co	45	40	25	40	35
Cr	1100	60	< 10	< 10	300
Ga	30	30	20	25	15
La	< 100	< 100	~ 100	< 100	< 100
Mo	< 3	< 3	< 3	< 3	< 3
Mn	2100	2100	1500	2600	n.d.
Nb	50	90	170	55	< 30
Ni	300	100	45	35	90
Pb	25	30	25	30	~ 10
Ti	> 1000	> 1000	> 1000	> 1000	> 3000
V	300	350	250	300	200
Y	60	75	50	60	~ 30
Zr	450	500	400	350	350
Sc	~ 10	~ 10	~ 10	~ 10	n.d.
Be	< 10	< 10	< 10	< 10	< 3
Ge	< 30	< 30	< 30	< 30	n.d.
Ta	< 300	< 300	< 300	< 300	< 100
Rb	n.d.	n.d.	n.d.	n.d.	< 100
Cu	n.d.	n.d.	n.d.	n.d.	~ 30

n.d., not determined.

Analysed by Miss J. M. Rooke and Mrs A. M. Fisher. Nos. 1–4 have also been fully analysed (see table 9). No. 5, basalt from the Hippo Mine, Mutandawhe complex.

To summarize, the Marangudzi dykes appear to be dolerites, frequently olivine-bearing, with slightly alkaline affinities. They are therefore petrographically more similar to the dykes of the Olivine-rich Group than to the later, olivine-free dolerites. The alkaline character is hardly surprising in view of the apparent structural relation of the swarm to the Marangudzi complex.

(*c*) *Miscellaneous dykes*

The malignite dyke. In thin section this rock has a very distinctive appearance owing to the colour of the titaniferous clinopyroxene which is the main mafic mineral and makes up about 30% of the rock. The crystals are subhedral prisms up to 3 mm in length and are strongly zoned from neutral-coloured centres to moderately deep purple margins. Colourless, euhedral olivines are also present and a green-brown hornblende replaces some of the pyroxenes marginally. The groundmass consists of a sericitized mass of bladed orthoclase aggregates and irregular, rarely euhedral, nepheline crystals with some interstitial analcite. The ore appears to be in slightly skeletal, roughly hexagonal, plates and skeletal apatite needles are abundant.

TABLE 12. NEW ANALYSES OF PICRITIC AND RELATED ROCKS FROM THE NUANETSI IGNEOUS PROVINCE

index no. ...	1	2	3	4
specimen no. ...	LM 593	KC 42	C 888	LM 436
SiO_2	43·89	44·97	46·59	45·61
TiO_2	1·54	1·48	2·83	4·81
Al_2O_3	5·51	5·74	5·89	10·31
Fe_2O_3	6·50	3·45	3·54	3·51
FeO	7·32	10·18	8·31	9·80
MnO	0·17	0·18	0·16	0·14
MgO	25·53	24·15	21·00	10·97
CaO	4·51	6·26	5·79	7·90
Na_2O	0·81	0·91	1·37	2·21
K_2O	0·59	0·75	1·97	2·62
H_2O^+	2·77	0·87	1·76	1·13
H_2O^-	0·56	0·29	0·10	0·52
P_2O_5	0·28	0·23	0·46	0·70
CO_2	n.f.	0·50	n.f.	n.f.
Cr_2O_3	n.d.	n.d.	0·19	n.d.
	99·98	99·96	99·96	100·23

n.f., not found; n.d., not determined.

Norms of analyses

	1	2	3	4
or	3·34	4·45	11·7	15·88
ab	6·82	7·86	11·5	18·87
an	9·73	9·17	4·7	10·29
di	8·30	14·58	16·9	19·23
hy	31·03	21·56	18·1	1·36
ol	24·33	32·57	24·2	17·35
mt	9·49	5·10	5·1	5·09
il	2·88	2·89	5·3	9·10
ap	0·67	0·34	1·0	1·68
cc	—	0·08	—	—
H_2O	3·33	1·16	1·86	1·65

Key to analyses presented in table 12

1 Picrite. Shamandali Hills, Malibangwe area. Analyst: J. R. Baldwin.
2 Picrite. 'Polygonal' dyke, 9 miles south-east of Nyasumi, Nuanetsi–Chikombedzi track. Analyst: M. H. Kerr.
3 Alkaline picrite. 29 miles east-south-east of Nuanetsi near the Beacon on the Nuanetsi–Chikombedzi track. Analyst: O. von Knorring.
4 Olivine monzonite. Chilembeni Hill. Analyst: J. R. Baldwin.

The microcrinanite dyke. This is a fine-grained doleritic rock-type containing approximately 9% olivine, 45% clinopyroxene, 30% basic plagioclase and 10% analcite.

The kersantite dykes. In hand-specimen the kersantites possess a fine-grained groundmass of basaltic appearance and are conspicuously porphyritic. Quartzo-feldspathic xenoliths are sometimes present. The phenocrysts consist of euhedral buff-coloured plagioclase crystals up to 13 mm long, occasional crystals of hornblende and abundant small crystals of biotite. Thin-section examination shows the feldspar to be oligoclase (An_{16}). The groundmass in some specimens is almost entirely composed of biotite and plagioclase while in others a strongly pleochroic blue-green hornblende is also present. The biotite occurs in fine shreds and may make up 30 % of the groundmass in those rocks without groundmass hornblende. Quartz is also present, interstitially and as rounded crystals up to 0·1 mm in diameter. The latter are possibly derived from the granitic country rocks.

TABLE 13. NEW ANALYSES OF RHYOLITIC ROCKS FROM THE NUANETSI IGNEOUS PROVINCE

index no. ...	1	2	3
specimen no. ...	LM 242	LM 466	LM 389
SiO_2	66·91	70·61	71·85
TiO_2	0·63	0·22	0·47
Al_2O_3	14·09	12·47	11·15
Fe_2O_3	6·15	2·61	4·50
FeO	0·15	0·09	0·73
MnO	0·14	0·06	0·05
MgO	0·23	0·57	0·19
CaO	0·72	2·17	1·67
Na_2O	4·76	2·14	3·03
K_2O	5·60	6·09	4·95
H_2O^+	0·47	0·74	0·29
H_2O^-	0·19	0·83	0·18
P_2O_5	0·15	0·04	0·07
CO_2	n.f.	1·41	1·08
	100·19	100·05	100·21

n.f., not found.

Norms of analyses

	1	2	3
Q	16·94	32·88	34·14
or	32·83	36·17	29·49
ab	40·37	18·35	25·69
an	0·56	3·89	2·78
C	—	1·53	0·20
wo	0·70	—	—
en	0·60	1·41	0·50
mt	—	—	0·93
hm	6·23	2·56	3·83
il	0·61	0·15	0·91
ap	0·34	—	—
cc	0·17	3·20	2·50
rutile	0·32	0·16	—

Key to analyses

1 Rhyolite-porphyry. Nyavasikana Pools, Maose River. Analyst: J. R. Baldwin.
2 Rhyolite tuff. Makwakwane Pools, Nuanetsi River. Analyst: J. R. Baldwin.
3 Ignimbrite. Tchovi Ridge, south of the Divula complex. Analyst: J. R. Baldwin.

4. *New chemical and spectrographic analyses of the Karroo volcanic rocks and associated minor intrusions*

During the course of the present work several new chemical and spectrographic analyses of the Karroo volcanic rocks and their associated minor intrusions have been made. These are presented in tables 9 to 14. A discussion of the chemistry of these and previously analysed related rocks has been reserved until the geochemistry section.

Table 14. New spectrographic analyses of rhyolitic rocks from the Nuanetsi Igneous Province

index no. ...	1	2	3
specimen no. ...	LM 242 (p.p.m.)	LM 466 (p.p.m.)	LM 389 (p.p.m.)
Ba	200	2000	2000
Li	< 5	9	< 5
Sr	50	80	80
Be	< 10	< 10	< 10
Cr	25	45	30
Ga	25	25	20
La	100	< 100	< 100
Mo	6	4	< 3
Nb	140	70	120
Ni	< 10	< 10	< 10
Pb	17	20	25
V	10	< 10	11
Y	60	90	110
Zr	450	300	900

Analysts: Miss J. M. Rooke and Mrs A. M. Fisher. For chemical analyses and localities of these rocks see table 13.

VIII. The petrography of the late-Karroo intrusive rocks

1. *Basic rocks of the ring complexes*

Gabbroic rocks make up the earliest phases of intrusion in the Vangambi, Dembe, Northern Ring and Masukwe complexes where in all cases they pre-date the granitic and granophyric intrusives, In the Mutandawhe complex, a single basaltic ring-intrusion is however, found cutting the nordmarkites, though it is post-dated by the majority of the granitic phases of intrusion within the complex.

The Northern Ring layered-gabbro intrusion has been studied in some detail (Stillman 1959), as have certain of the gabbroic phases in the Masukwe complex. Elsewhere outcrops of gabbroic rocks are generally poor and only brief petrographic details are therefore given.

(*a*) *The Northern Ring layered gabbro*

(i) **Mineralogy.** *Olivine.* This is the first mafic mineral to crystallize, sometimes being preceded by some plagioclase. The resorption of olivine is to be observed at all horizons, and hypersthene mantles are almost ubiquitous. The replacement, however, is more extensive in the coarser, slower-cooled rocks. The amount of olivine in the gabbros never exceeds 25 % (see figure 22) and only rarely are layers with this concentration met with. Such layers are found in the upper and middle olivine gabbros. The troctolite has up to 22 % olivine, but the mineral is unusual in that it is poikilitic to feldspar, and enters into symplectic intergrowths with magnetite. Olivine grains are usually rounded and larger than those of other mafic minerals. The composition varies from Fa_{15} to Fa_{35}. Coronas or kelyphitic borders of fibrous amphibole are sometimes developed where olivine is in contact with plagioclase and has not been mantled by hypersthene. Magnetite is often found as an exsolution product in the form of dendrites, similar to those described by Du Toit (1910; see Bruynzeel 1957). This may be the only iron ore in the rock.

Feldspar. Plagioclase forms over 50 % of the majority of the gabbros (see figure 22). The crystals are lath-shaped and tabular, the form and proportion varying approximately with grain size. In the coarser rocks, tabular, anhedral intergrown crystals with complex twinning are the rule. In these rocks also, the colour index is low, which suggests that they have formed by crystal accumulation, subsequent crystallization resulting in the formation of complex intergrowths. The period of crystallization of the plagioclase is longer than that of the mafic minerals, and generally starts earlier. Where this is not so, notably in the main zone of the middle olivine gabbro, later plagioclase forms a fine-grained granular mosaic of equidimensional grains. The composition of the normal plagioclase varies from bytownite (An_{84}) to labradorite (An_{64}). In general, olivine gabbros carry a more calcic plagioclase than olivine-free rocks. Anorthositic gabbros in all units have plagioclases more calcic than usual. It will be noted that there is no overall change in basicity throughout the intrusion

Two generations of plagioclase commonly occur, the older being more calcic and often a little larger. Despite this and the long period of crystallization, zoning is nowhere so abundant as in Karroo dolerites (Walker & Poldervaart 1949). Where observed it is usually continuous. A few phenocrysts in glomeroporphyritic rocks may show absorption and repair, or oscillatory zoning, but such features are never found in olivine-bearing rocks.

In some cases late stage marginal replacement by oligoclase has occurred. This appears to be associated with the acid residuum which in olivine-free gabbros crystallizes as micropegmatite or potash feldspar.

*Pyroxenes**. Both clinopyroxenes and orthopyroxenes are present in all units with clinopyroxenes predominant in the majority. The clinopyroxene is usually augite; pigeonite is rare, and is only found as cores or exsolution lamellae in orthopyroxenes. The orthopyroxene varies from bronzite to hypersthene.

Augite maintains a fairly regular volume percentage throughout the intrusion the highest percentage noted being 49 % from the G4 upper olivine gabbro. Finer rocks often have hypersthene and augite in almost equal amounts, but in the coarser gabbros augite is predominant.

The crystal form is related to the grain size and cooling history of the rock. Finer rocks have early formed small granular and sub-ophitic crystals, whereas the coarser rocks have large, strongly ophitic, even poikilitic augites, sometimes up to 10 cm in diameter. Normal prismatic cleavages are present together with a very well developed basal cleavage. Simple (100) twinning is common.

The composition of the augites shows little systematic variation, but there is a distinction between augites from olivine-bearing and olivine-free gabbros, as shown in figures 20*a*, *b*. The augites from olivine gabbros form a group with average Mg/Fe ratio of 75/15, and a marked variation in Fe/Ca ratios. The augites from olivine-free units have a steady Fe/Ca ratio around 26/74 but show some variation in Mg/Fe ratios. The data indicate a decrease in lime and increase in iron in more differentiated, less basic gabbros. Similarly, zoning, where detected, suggests a decrease in lime towards the margins of the crystals. These observations are in accord with those of Walker & Poldervaart (1949) who state that in the

* Nomenclature used is that of Poldervaart & Hess (1951).

middle period of crystallization, pyroxene is enriched in iron at the cost of lime. The Mateke gabbros show this enrichment at a stage much nearer the En/Wo line than is usual in Karroo dolerites, and this may well be related to a difference in the chemistry of the intrusions as a whole since the Mateke rocks are poorer in lime than average Karro dolerites.

Orthopyroxenes are distinguished by their clear colour, strong pleochroism and, in olivine-free gabbros, by the almost ubiquitous presence of exsolution lamellae.

The fluctuation in amount throughout the intrusion is considerable and shows a close antipathetic relation to olivine. True norites are never developed but zones of augite

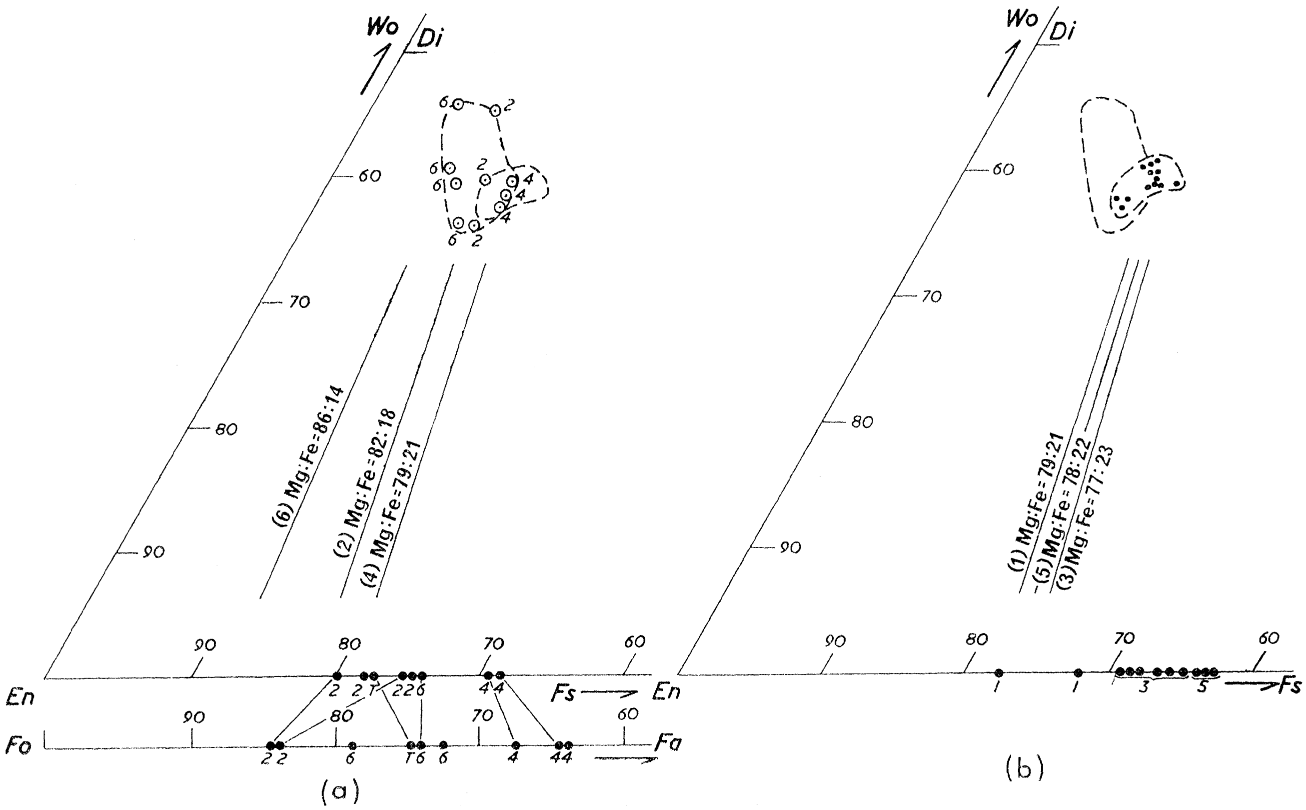

FIGURE 20. Composition of co-existing olivines, hypersthenes and augites in the Northern Ring gabbros.

norite are present in all three olivine-free units. Hypersthene may exceed augite in olivine gabbros but the total percentage of pyroxene in these cases is very small. The crystal form is usually strongly ophitic and even poikilitic in some olivine gabbros, and it is probable that orthopyroxene has crystallized later than augite in most cases. Cleavage is similar to that in augite but twinning is more abundant, and a herringbone texture produced by simple twinning parallel to the *c* (crystallographic) axis combined with basal cleavage or exsolution lamellae is very common. The pleochroism scheme is: *X*, pale brown-pink; *Y*, pale clear pink; *Z*, pale clear green. The absorption varies from one horizon to another, but the general pleochroism scheme remains essentially unchanged.

The orthopyroxenes show a distinct compositional change throughout the intrusion.

An upward trend towards iron enrichment is noticeable, with depression of Of values in olivine rocks, as follows:

average composition ...	Of_{25} no olivine	Of_{23} olivine	Of_{33} no olivine	Of_{25} olivine	Of_{32} no olivine	Of_{31} olivine	Of_{36} no olivine
phase	G1	G2(*a*)	G2(*b*)	G3(*a*)	G3(*b*)	G4(*a*)	G4(*b*)

This does not correspond entirely with height in the intrusion owing to the inverted positions of G3 and G4 gabbros.

Relationship of orthopyroxene and olivine. Orthopyroxene clearly has a reaction relationship with olivine for it is seen to mantle it in all the olivine gabbros, and in some cases appears

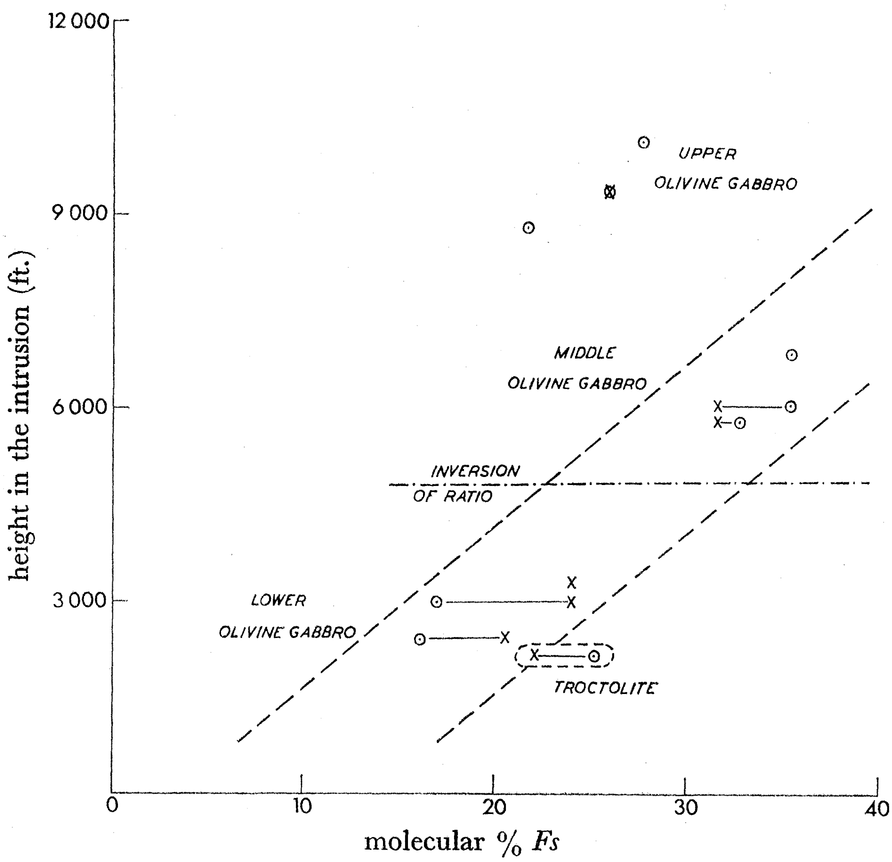

FIGURE 21. Co-existing olivines (⊙) and orthopyroxenes (×) of the Northern Ring complex, plotted against height in the intrusion.

to have totally replaced it. This reaction accounts for the late crystallization of orthopyroxene and the antipathetic variation of the two minerals, and suggests that totally resorbed olivines may in part be the source of abundant orthopyroxene in olivine-free rocks.

The composition of co-existing olivines and orthopyroxenes in the various members of the Northern Ring gabbro differentiation sequence (see figure 20*a*) show a striking correspondence with the results quoted by Ramberg & de Vore (1951) in their paper on the distribution of Mg^{2+} and Fe^{2+} ions in these co-existing minerals. However, if these compositions are plotted against height in the intrusion the inverted positions of G3 and G4 are again apparent (see figure 21).

Ramberg & de Vore plot the mineral compositions (in terms of Fe:Mg) against position in a differentiation sequence, and show that as crystallization proceeds the Fe:Mg ratio of the early olivines (which are more magnesian than the orthopyroxenes) approaches that of the orthopyroxenes, until an inversion takes place at a point where the ratio is in the region of 20:80/30:70. Beyond this point the compositions diverge again but with the olivines more iron-rich than the corresponding orthopyroxenes. Ramberg & de Vore ascribe this to a mutual interchange of magnesium and iron between the two phases when they cool in the absence of free silica. The plot of the Mateke gabbros agrees closely with these figures and suggests that all three olivine gabbros definitely belong to one single differentiation sequence. The diagram also suggests that the troctolite, presumed from field evidence to be intrusive into the lower olivine gabbro of G2, possibly belongs to the middle olivine gabbro of G4.

Relationship of orthopyroxene and clinopyroxene. The composition range of augites is small compared with the ranges of orthopyroxenes and olivine, a common phenomenon in basic rock suites as pointed out by Hess (1941). Further, the composition ranges of orthopyroxene and olivine are almost equal. Within the olivine gabbros, hypersthene and augite both show a gradual increase in iron with respect to magnesia, but in the augites this is concealed by the much greater increase in calcium with respect to the other components. This may be related to the upward curve in the early part of the course of crystallization of clinopyroxenes given by Hess (1941). In the olivine-free units both show a parallel gradual increase in iron over magnesia, but here there is little variation in the lime content of the augites.

Intergrowths and exsolution phenomena. The orthopyroxenes of the Mateke gabbros show very complex intergrowth and exsolution phenomena. Simple exsolution lamellae of pigeonite on (100), or relict augite lamellae on a plane near (101) are produced by early formed pigeonite exsolving augite plates parallel to (001). The subsequent inversion of pigeonite to orthopyroxene retains the lamellae of the now-relict (001) plane, producing lamellae on a plane near (101) when referred to the crystallographic directions of the orthopyroxenes. Some of these latter orthopyroxene crystals show, in addition, a new set of fine diopside lamellae parallel to (100). This is due to the fact that orthopyroxene, having inverted from pigeonite, normally retains a small percentage of Ca^{2+} ions. These are expelled on slow cooling to produce fine lamellae of diopside. In addition to these well-developed lamellae, there is a great abundance, in the finer grained more rapidly crystallized rocks, of 'graphic intergrowths' (Walker & Poldervaart 1949) in which irregular, unoriented blebs of clinopyroxene are expelled from the orthopyroxene.

With regard to the origin of the orthopyroxene in these gabbros, it is noteworthy that far fewer of the bronzites in the olivine-bearing rocks show exsolution lamellae than do the hypersthenes of the olivine-free gabbros, and this must be due to the production of orthopyroxene in the olivine gabbros, mainly by the resorption of olivine rather than by the inversion of pigeonite.

Accessory minerals. The minor mineral constituents of the gabbro are iron ores, a little apatite, quartz and alkali feldspar, and replacement minerals such as serpentine, chlorite, biotite, and amphiboles. The iron ore is mainly magnetite and no undoubted ilmenite has been found.

Quartz and alkali feldspar frequently occur in micropegmatitic intergrowths, in which the proportion of quartz to orthoclase varies from 45:55 to 50:50, the latter being more common. The distribution of this acid residuum is uniform throughout the main part of the lower two olivine-free gabbros, but is highly concentrated in the gabbro pegmatites where it may constitute more than 50% of the rock.

(iii) **Mineralogical variation within the intrusion.** A summary of the variation in modal composition with height in the gabbro intrusion is given in figure 22, and variations in mineral composition with height in figure 23.

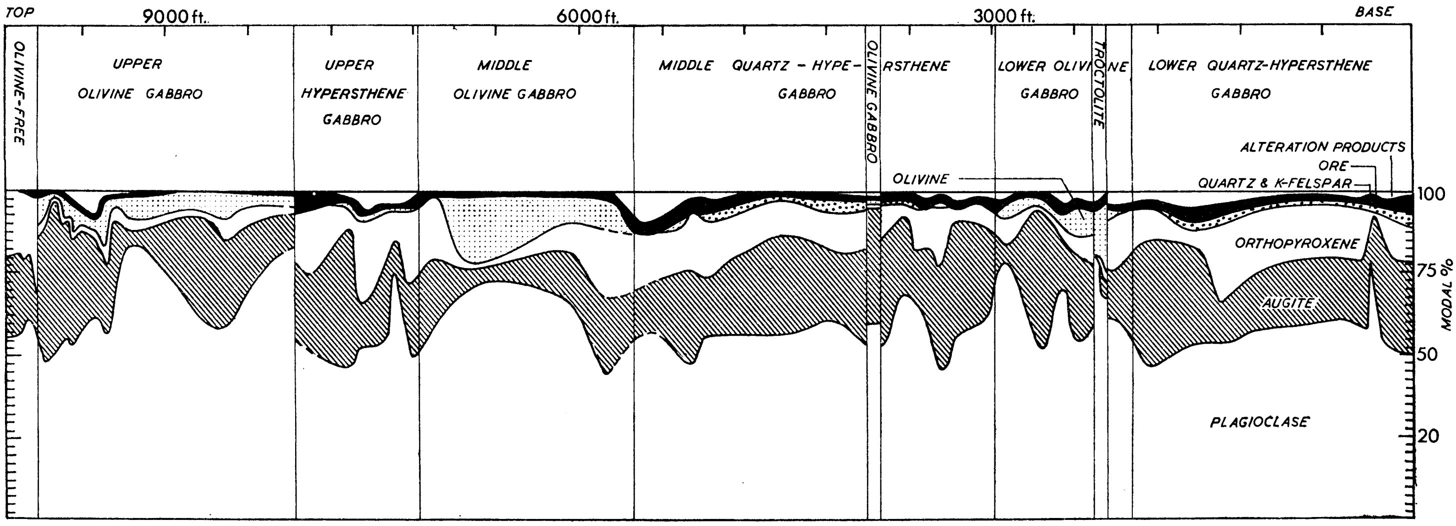

FIGURE 22. Modal compositions of Northern Ring gabbros.

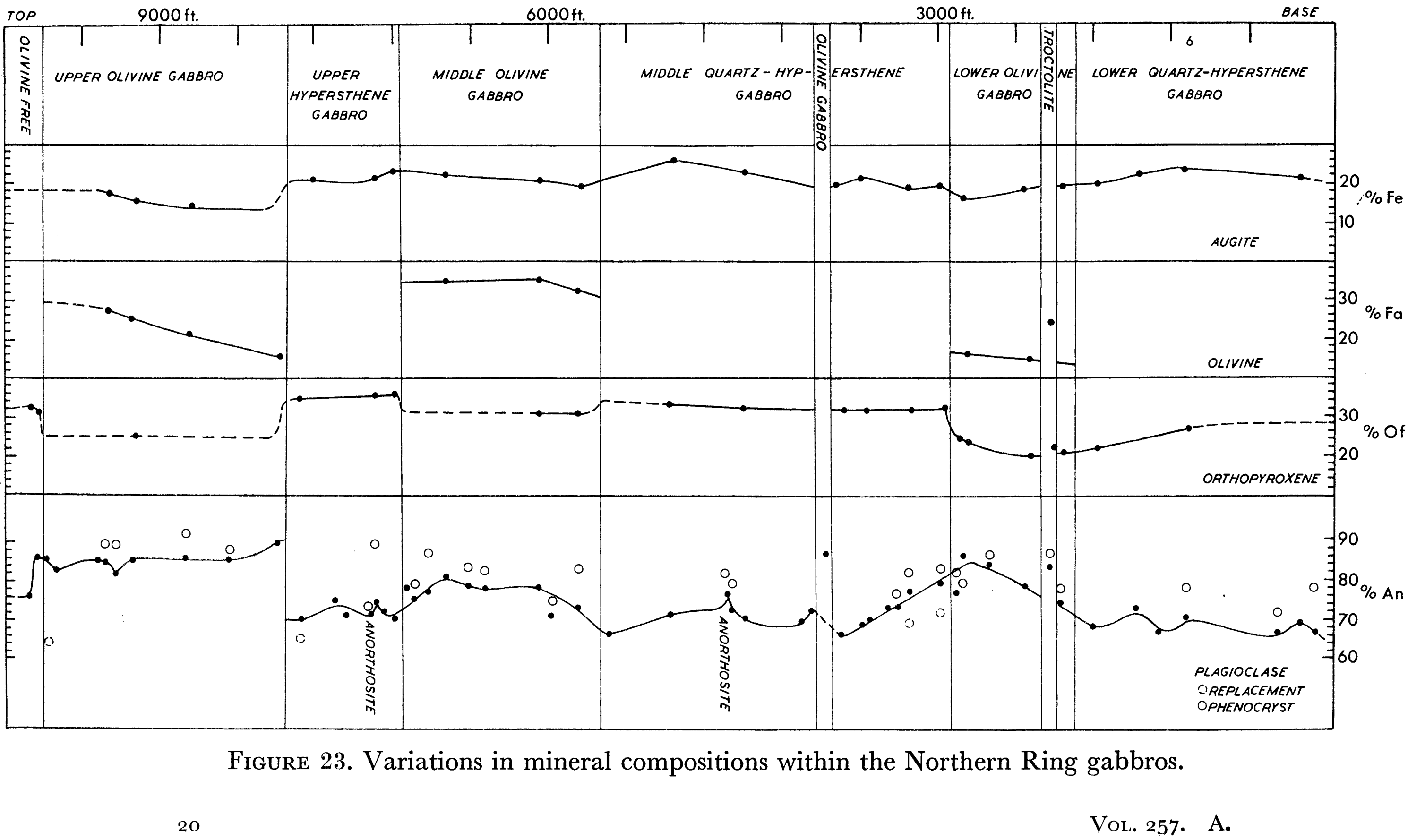

FIGURE 23. Variations in mineral compositions within the Northern Ring gabbros.

(iii) **Chemical variation within the intrusion.** Full chemical and spectrographic analyses have been made of representative specimens from four of the major gabbro units. These, together with their C.I.P.W. norms, are presented in tables 15 and 16. The samples have been selected from those gabbros considered to be most typical of each unit, and which have been subjected to a full mineralogical investigation. Two additional analyses have been calculated from modal analyses on the basis of mineral compositions deduced

TABLE 15. NEW CHEMICAL ANALYSES OF GABBROS FROM THE NORTHERN RING COMPLEX

index no. ...	1	2	3	4
SiO_2	51·82	52·26	47·68	48·26
TiO_2	0·66	0·91	0·22	0·15
Al_2O_3	18·38	15·89	19·48	19·95
Fe_2O_3	2·60	1·89	1·70	0·93
FeO	5·94	6·65	5·24	3·57
MnO	0·15	0·15	0·13	0·09
MgO	5·25	6·76	9·29	8·45
CaO	11·68	11·82	14·13	15·86
Na_2O	2·58	2·20	1·55	1·30
K_2O	0·47	0·61	0·08	0·13
H_2O^+	0·57	6·88	0·91	1·16
H_2O^-	0·13	0·02	0·12	0·22
P_2O_5	0·08	0·15	0·05	0·00
	100·31	100·19	100·58	100·07
C.I.P.W. norms				
Q	2·8	3·87	—	—
or	2·78	3·34	—	—
ab	22·01	18·34	13·10	11·00
an	36·97	31·97	46·43	48·37
di *en*	5·2	6·8	6·7	9·1
di *fs*	3·17	3·7	2·38	2·38
di *wo*	8·82	11·14	9·86	12·64
hy *en*	4·75	5·54	5·6	6·6
hy *fs*	7·9	10·1	1·98	1·72
ol *fo*	—	—	7·6	3·79
ol *fa*	—	—	2·96	1·12
mt	3·71	2·78	2·55	1·39
il	1·22	1·67	0·46	0·3

Key to analyses

1 Quartz-hypersthene gabbro (G1). Specimen no. N 723. Analyst: J. R. Baldwin.
2 Quartz-hypersthene gabbro (G2(*b*)). Specimen no. N 334. Analyst: M. H. Kerr.
3 Olivine gabbro (G2(*a*)). Specimen no. N 81. Analyst: J. R. Baldwin.
4 Olivine gabbro (G3). Specimen no. N 357. Analyst: M. H. Kerr.

from optical data. Since the compositions so determined are not precise, nor are the proportions of such oxides as titania and manganese-oxide determinable by this method, these analyses have been used with caution. In order to check their degree of accuracy, compositions of two analysed gabbros were calculated by the same method, and the agreement proved to be sufficiently close to warrant the use of the calculated analyses in Niggli variation diagrams. The grouping of oxides in the Niggli classification reduces many of the errors inherent in the calculated analyses. It must be noted, however, that owing to the extremely small amount of chemical data available at present, conclusions drawn from them must be regarded as tentative, and are mainly useful in providing corroborative evidence to that obtained from the mineralogy and petrography.

To study the variation within the gabbro intrusion the Niggli values for *c*, *al*, *alk*, *mg*, *k* and *qz*, etc., have been plotted against *si* (figure 24*a*). This shows the variation with increasing acidity of the rock. Smooth curves indicate a steady rise in *alk*, *k* and *qz*, and a fall in *mg*, whilst the ratio $FeO/(FeO+Fe_2O_3)$ remains almost constant. This implies a slight degree of differentiation involving enrichment in total alkalis and increase of potash over soda, and decrease in magnesia relative to total iron oxide. The iron enrichment is shown more clearly by the curve $(FeO+Fe_2O_3)/(MgO+FeO+Fe_2O_3)$. Within the composition range of the gabbros the iron enrichment is largely balanced by decrease in magnesia as shown by the *fm* curve which has no overall upward gradient.

TABLE 16. NEW SPECTROGRAPHIC ANALYSES OF GABBROS NORTHERN RING COMPLEX

	1 (p.p.m.)	2 (p.p.m.)	3 (p.p.m.)	4 (p.p.m.)
Ba	180	100	30	12
Li	~ 3	< 3	< 3	< 3
Rb	< 30	< 30	< 30	< 30
Sr	150	170	140	100
Be	< 1	< 1	< 1	< 1
Co	30	20	30	10
Cr	300	20	100	600
Cu	200	200	30	30
Ga	11	12	10	10
Ge	< 30	< 30	< 30	< 30
La	< 80	< 80	< 80	< 80
Mn	1100	1100	850	450
Mo	< 10	< 10	< 10	< 10
Ni	100	55	190	170
Nb	< 30	< 30	< 30	< 30
Pb	11	8	9	8
Ta	< 100	< 100	< 100	< 100
Ti	> 3000	> 3000	900	600
V	150	130	55	55
Y	45	35	< 30	< 30
Zr	70	50	14	4

For key to analyses see table 15.

The values for *al*, *c* and *fm* give very irregular curves, with no discernable overall trend. *al* and *c* are sympathetic and *fm* is antipathetic to these. This is a reflexion of the modal antipathetic variation between plagioclase and pyroxene+olivine, suggesting that the variation of *c* is based entirely on variations in the plagioclase and that the lime held in augite varies little throughout the intrusion, a fact confirmed by the mineralogy of the pyroxenes.

The colour index varies directly with the *fm* value, a phenomenon likewise seen at Insizwa, but Bruynzeel (1957) points out that this relation is best displayed in undersaturated rocks with olivine as the chief ferromagnesian mineral. In the Northern Ring rocks the relation holds good for more siliceous rocks in which orthopyroxene is developed in place of olivine, again suggesting that the *fm* variation is related to the orthopyroxene rather than to the augite.

If the same values are plotted against height in the intrusion (figure 24*b*), an overall but discontinuous differentiation is again seen, which appears to take place in a series of pulses with reversals of trends, a situation difficult to reconcile with the concept of a single intrusion followed by *in situ* differentiation, and it seems more probable that there may have been several phases of injection.

It is believed that the portions of the Niggli value curves between G 2 (*a*) and G 2 (*b*), and between G 4 (*a*) and G 4 (*b*) indicate *in situ* differentiation producing an olivine gabbro below and an olivine-free gabbro above. If this is so the olivine-bearing member of phase G 4 is less basic than G 2 or G 3, and thus breaks the sequence.

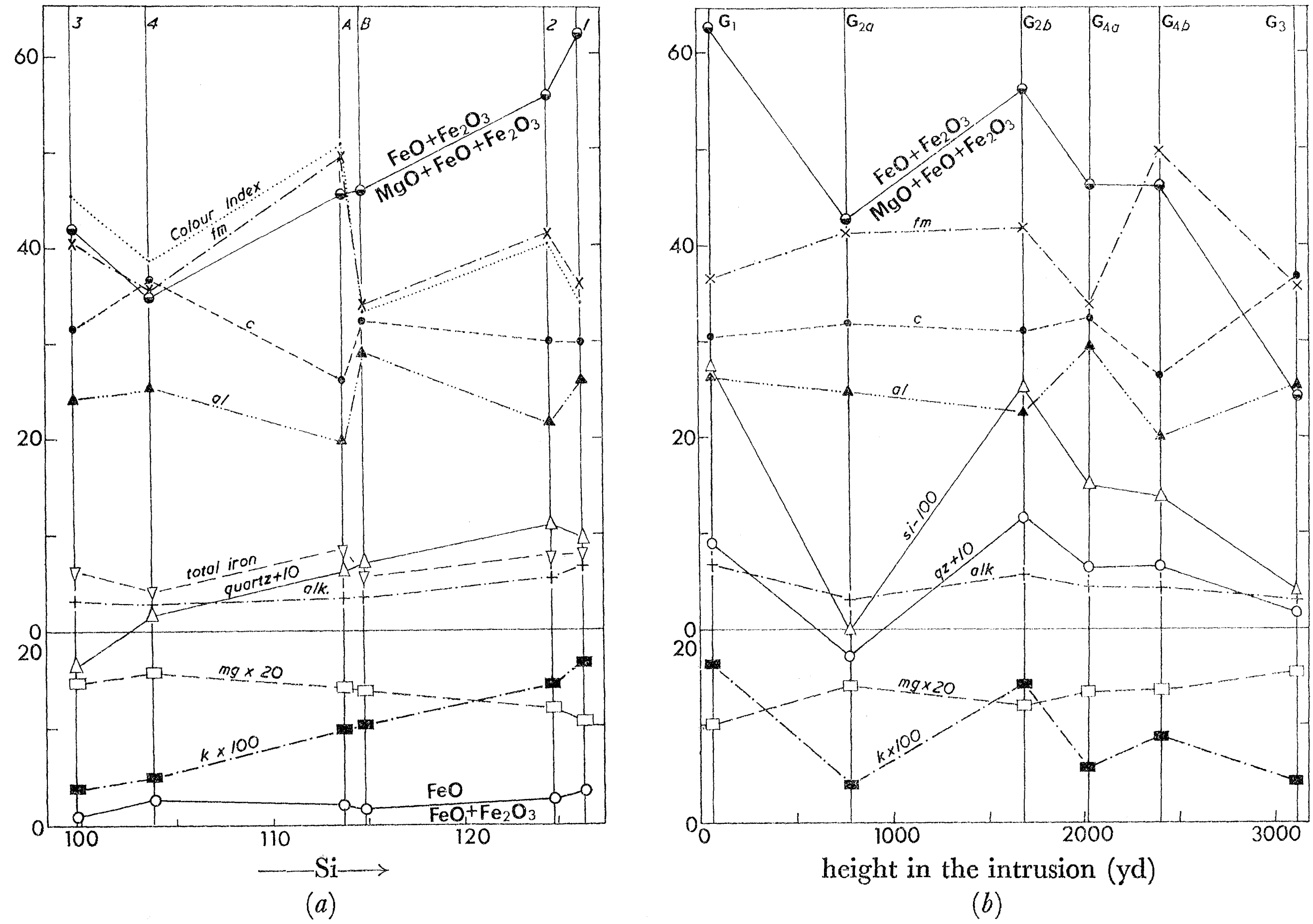

FIGURE 24. (*a*) Niggli values for analysed Northern Ring gabbros. (*b*) Niggli values for Northern Ring gabbros plotted against height in the intrusion.

The main features of the gabbro chemistry may thus be summarized as follows:

(1) Increasing basicity from base to top with a reversal between the top two phases.

(2) Differentiation towards iron enrichment within each phase subsequent to intrusion.

These considerations lead to the conclusion that the gabbro may have been emplaced as a series of pulses of magma fed from a reservoir below, and the complex repetition of units was governed by differentiation both within the reservoir, and *in situ*, after intrusion.

(iv) **Layering within the intrusion.** *Description.* Layering in the gabbro is marked largely by alternations of normal gabbro with bands rich in basic plagioclase. There are no complementary olivine- or pyroxene-rich bands.

In the lower quartz hypersthene gabbro, rhythmic layering is common. A typical sequence exposed in the Malikange River shows the following characters:

(1) The basal layer is a thin anorthosite with a sharp contact against normal gabbro below. It is composed of a jumbled confused mass of broken plagioclase crystals. The upper part grades by increase of pyroxene into:

(2) a fine-grained gabbro with rather granular pyroxene and plagioclase similar to that in the anorthosite. Towards the top a normal gabbroic texture is resumed together with a strong directional element, producing a lamination of tabular feldspars parallel to the dip and strike. This persists for some 15 ft. then is succeeded abruptly by:

(3) another anorthosite with sharp base and texture as before, indicative of accumulation by crystal settling. The upper part of this layer, which is over 35 ft. thick, contains rounded interstitial augite grains as before. The upper surface of this layer forms a well-defined, though very irregular, plane with the succeeding gabbro filling in the hollows, suggesting that the anorthosite has acted as a new floor for crystal accumulation.

(4) Subsequent accumulation is at first largely of plagioclase, with clumps of crystals giving a glomeroporphyritic texture, but higher up, abundant pyroxene appears.

In the lower olivine gabbro anorthositic gabbro is produced by feldspar accumulation due to crystal settling, and is followed by a darker gabbro produced by *in situ* crystallization of the residue. A transition zone of feldspar glomeroporphyritic gabbro is sometimes developed. In this, a darker fine-grained groundmass is developed within the feldspar mesh, containing late stage feldspar, pyroxene and olivine in more normal proportions. With increase in size of the interstices, the plagioclase network is disrupted and clumps of feldspar phenocrysts are dispersed. By a progressive reduction in the number of phenocrysts, the rock grades into the finer equigranular gabbro.

This gradation seems to imply a period of quiet accumulation of feldspar phenocrysts with the crystallization of interstitial pyroxenes and some olivine, followed by agitation which allows fewer phenocrysts to settle, and induces the break up of the feldspar network, together with the partial resorption of the feldspar. This finally causes the gabbro to crystallize without any further accumulation. It is perhaps important in this respect that the most calcic plagioclase is to be found in the coarse pale gabbro.

Also in this unit, igneous lamination is found at varying horizons. This is indicated by strong parallel orientation of the feldspar laths, with the still ophitic pyroxenes sometimes roughly segregated into layers parallel to the feldspar. This texture is named 'igneous lamination' after Wager & Deer (1939), but in contrast to the Skaergaard rocks, only a minority of the Northern Ring gabbros are laminated. The lamination was originally sub-horizontal, parallel to the surface of the gabbro, and probably caused by magma flow. Similar lamination is again seen in the upper hypersthene gabbro, where the feldspars do not have a strongly tabular crystal habit.

In the upper olivine gabbro, banding or layering is characteristic of the upper part of the unit (see above). This seems precisely similar to the gravitation layering in thin bands, separated by thicker layers of average rock showing no crystal sorting, seen at Skaergaard. It may well have been produced by periodic agitation of the magma during crystallization dislodging early formed heavy crystals from their position in the partly formed crystal mesh, and allowing them to accumulate at a lower level.

The mechanism of layering. Theories on the mechanism of layering in gabbro bodies are numerous and a consensus of opinion seems to support a method of crystal differentiation by gravity settling either combined with a winnowing effect caused by convection currents within the magma, as at Skaergaard (Wager & Deer 1939), or in a stagnant magma as at Stillwater (Hess 1939). Certain authors however, notably Lombaard (1935) and Cooper (1936), favour multiple injection of magma drawn at intervals from a concealed reservoir of differentiating magma. Gravity settling as described by Bowen (1915) produces layering by the precipitation over prolonged periods of time of particular minerals in a more or less constant ratio to one another. Variation in temperature and pressure produces breaks or repetitions of the sequence. Many other factors must also affect the type of layering produced, such as rate of sinking, partial resorption of crystals and the effect of this endothermic reaction on the thermal gradient, whether magma conditions are turbulent or quiescent, and so on. It is concluded that in addition to the ferromagnesian minerals, basic plagioclase (labradorite-bytownite) would also sink slowly, and Coates (1936) has suggested that accumulation could be effected elsewhere than on the floor of the intrusion, by upward currents in the magma produced by upward movements of the fluid phase compensating the settling of heavy crystals. These currents would support the plagioclase crystals as a raft suspended within the magma chamber. Such a raft would probably be of no great extent, and thus the mechanism could not explain the extensive anorthosite layers found for example in the Bushveld complex. The theory nevertheless might explain the presence of small layers.

If the plagioclase does not sink far, it will not suffer the same degree of igneous corrosion as the heavier minerals. In fact, intergrown relations might be expected between crystals in suspended rafts.

Textural studies on the Mateke gabbros indicate that olivine and plagioclase are the main early formed minerals, as the pyroxene usually shows an ophitic relationship to them. The plagioclase-rich layers are frequently formed by the accumulation of glomerophenocrysts, which are rounded clusters of crystals with the outer margins slightly corroded, and with the crystals intergrown within the cluster. This suggests that the gabbro may have been intruded in a partly crystalline form and that the glomero-phenocrysts were derived from a differentiating reservoir below. The form and internal texture of the clusters indicate that they may originally have formed parts of anorthosite layers—possibly the rafts described above—which suffered disruption during intrusion whereby the broken fragments were carried upwards into the new chamber.

If this is indeed the case, the absence of complementary olivine-rich accumulative layers at the base of the intrusion is to be expected, since many of the rapidly settling olivines produced in the reservoir may well have sunk below the level of the magma tapped by the intrusion. There is no doubt that the gabbros (see table 15) are generally much richer in CaO and Al_2O_3 than the majority of the basalts (see table 9), a fact which tends to support this view.

Three types of feldspar layers have been noted in the gabbros:

(1) a coarsely crystalline layer with a sharp base, and intergrown texture;

(2) a variant of type 1 with both base and top clear-cut, the top being irregular with small hollows in which crystals have accumulated from the overlying gabbro;

(3) a layer formed by the accumulation of glomerophenocrysts, gradational both above and below into normal gabbro with occasional phenocrysts.

The third type is the most common, and is apparently due to alternating conditions of turbulence and quiescence, which permitted the deposition of the suspended glomerophenocrysts inherited from the reservoir below.

The first two types are rarer, and appear to be due to precipitation of new phenocrysts, forming accumulative layers on the floor of the chamber, possibly with continued crystallization giving rise to the interlocking texture.

(v) **Petrogenesis.** The Northern Ring gabbro intrusion is believed to have been fed by repeated injections from a differentiating magma reservoir having the form of a cupola, within which differentiation by settling of olivine and basic plagioclase has produced an upper zone more siliceous than the normal gabbro. The reservoir was tapped near the top so that successive phases drew off progressively more basic magma for phases G 1, G 2 and G 3. Each phase has been intruded through the previous ones prior to their complete consolidation with the result that, while a certain amount of mixing and desilication has taken place there is now no evidence of intrusive contacts. Differentiation *in situ* produced an acid upper zone to phase G 2, but this is less acid than in the case of G 1 as it was derived from a more basic portion of the initial reservoir magma, and underwent differentiation on a more restricted volume of magma.

Phase G 3 shows differentiation *in situ*, but to a lesser extent, and the whole phase is more basic than the others.

Phase G 4 appears to have been injected after a longer pause and subsequent to the solidification of the previous intrusions. The contacts are consequently sharper and the hiatus in injection permitted further differentiation within the magma reservoir so that an upper zone, intermediate in basicity between phases G 2 and G 3 was formed. This is shown by the constituent minerals of G 4. Differentiation *in situ* has also taken place producing different textural conditions from those in the other phases. Strong magma currents may have been set up in the restricted space below G 3 to produce the igneous lamination seen in the upper unit of G 4. The spatial position of phase G 4 has been discussed above.

This petrogenetic synthesis compares with those of Lombard (1935) and Cooper (1936), and the sequence of intrusion, from acid to basic members of a dolerite magma suite is consistent with the theories put forward by Holmes (1931) in his paper on the association of acid and basic rocks in central complexes.

(b) Microgabbros of the Northern Ring and Masukwe complexes

The earliest phase of intrusion in both the Northern Ring and Masukwe complex is represented by micrograbbo. This is well preserved in the latter but occurs only as scattered, highly metamorphosed, screens in the Northern Ring. The Masukwe microgabbro is a very uniform rock over the whole area of the complex. The microscopic texture is intergranular verging on hypidiomorphic and the grain size is 0·2 to 0·5 mm. The majority of the specimens examined showed signs of thermal metamorphism owing to the host of minor acid intrusions which cut the microgabbro, the main effect being the uralitization of the pyroxenes.

A comparatively unaltered specimen gave the following modal composition: augite, 26·4%; hypersthene, 12·2%; labradorite, 59·7%; iron ore, 1·7%. A small amount of acid material is also commonly present and usually consists of separate interstitial patches of quartz and micropegmatite.

The plagioclase crystals usually show thermal clouding and a moderate degree of normal zoning. Apatite is a common accessory. The zoning of the plagioclase indicates that some fractionation has taken place during crystallization and the interstitial micropegmatite probably owes its presence to this process.

The chemical analysis of the modally analysed specimen above is given in table 17.

In the Northern Ring complex the microgabbros are dark grey-brown fine-grained and equigranular. They have a granulose texture and consist of stumpy laths and equant crystals of labradorite (An_{60-62}) normally well-twinned, together with abundant evenly distributed pyroxene and magnetite granules. The dark minerals are in general smaller and more idiomorphic than the plagioclases. Both diopsidic augite and hypersthene are present in varying proportions, the hypersthene sometimes being ophitic to the augite.

TABLE 17. NEW ANALYSES OF THE MASUKWE AND NORTHERN RING MICROGABBROS

	Masukwe	Northern Ring
SiO_2	51·38	46·73
TiO_2	0·23	0·73
Al_2O_3	13·16	14·45
Fe_2O_3	5·77	7·00
FeO	5·56	8·64
MnO	0·15	0·21
MgO	8·21	7·08
CaO	12·13	12·19
Na_2O	2·49	2·49
K_2O	0·22	0·15
H_2O^+	0·52	0·19
H_2O^-	0·07	0·08
P_2O_5	0·04	0·00
	99·93	99·94

Analyst: M. H. Kerr

Where feldspars are lath-like, a flow texture may be developed. Lenticles or schlieren of coarse pyroxenes are also occasionally found, and in them hypersthene may be ophitic to augite and plagioclase, and the crystals have their *c*-axes oriented parallel to the lineation. Parallel strings of magnetite grains are also found. Characteristic of all these rocks is the freshness and freedom from dust or inclusions of the clear unaltered minerals, which have a regular, almost decussate, texture. In a number of cases the microgabbro has been broken up and fragments are incorporated in the gabbro, producing a mixed rock of very irregular composition and texture.

An analysis of the microgabbro is given in table 17. It compares closely with an analysis of the microgabbro sheet intrusion in the Masukwe complex, which is intruded in an analogous position in the Karroo basalt succession and pre-dates the other basic intrusions of the complex. A characteristic of both is the high Fe_2O_3 content, which is unusual in Karroo dolerites, and reflects the large amount of magnetite present in the rocks.

That the microgabbro is metamorphosed has been deduced from its texture and mineralogy. The texture is distinctly granulose, and quite typical of recrystallized textures produced by thermal metamorphism of basaltic rocks, such as those described from the patches of basic rock with 'granulitic structure' enclosed in the Tertiary gabbros and eucrites of Ardnamurchan and Mull (Richey & Thomas 1930; Bailey *et al.* 1924).

The mineral phases apparently in equilibrium in these rocks are labradorite, augite, hypersthene, and magnetite. Hornblende is only found in the metabasalts, and is sometimes replaced by augite. These are the stable phases of the 'pyroxene hornfels' facies of contact metamorphism.

(*c*) *Metagabbros of the Northern Ring complex*

These rocks which occur as narrow arcuate bands within the layered gabbros comprise both 'olivine' and quartz-bearing gabbros. No olivine is present as such, since it is replaced by aggregates of chlorite, biotite, serpentine and magnetite. The major metamorphic changes seen are:

(1) clouding of the feldpsar, which causes the darkening of the rock;

(2) slight granulation of the pyroxene, together with an increase in the complexity of exsolution phenomena;

(3) recrystallization of quartz and orthoclase and the occasional production of new sodic plagioclase which mantles the clouded crystals.

The granulation of pyroxene is not invariably seen and is mainly restricted to the inner zones of most intense darkening. The exsolution phenomena are particularly well developed, and an unusual feature is the frequent development of pigeonite lamellae in augite. This contrasts with the normal gabbros where augite may carry orthopyroxene lamellae, and suggests that re-heating may have occurred under relatively dry conditions so permitting the inversion of orthopyroxene to pigeonite as a continuation of the course of crystallization halted by solidification of the gabbro.

(i) *Net-veining.* Abundant net-veining by granophyric microgranite is found in many central parts of the black gabbro arcs. This veining is identical both in form and petrography with that seen in association with the red microgranite dykes. Normal gabbro adjacent to the black gabbro seldom possesses it, nor are the marginal areas of the arcs much affected. The net-veining is seldom related to major red microgranite dykes, but the western arc of black gabbro is intruded throughout much of its length by a buff microgranite dyke.

(ii) *Feldspar clouding.* The plagioclase for the most part consists of normal gabbroidal crystals which do not differ in form from those of the ordinary gabbros, apart from the presence of minute inclusions arranged in lines, loops and whorls. A narrow clear zone is present at the crystal boundaries, at the junctions between crystals, and sometimes along twin planes. The clouding is obvious under low magnification, and the feldspars appear almost black in hand-specimen. In most cases the crystals are strongly zoned from centre to margin, and the narrow unclouded rim has a composition less calcic than the centre of the crystal. Specimens from the middle quartz-hypersthene gabbro with clouded feldspars show cores of composition An_{64-70} and margins An_{45-50}. Occasionally the margin is zoned still further and mantles of oligoclase (An_{25}) may be present.

A. G. Macgregor (1931) described similar clouded feldspar, and attributed the clouding to thermal metamorphism, but Poldervaart & Gilkey (1954) suggests that this is not necessarily so. They conclude that the requisites for plagioclase clouding are: prolonged elevated temperatures, presence of water, and a supply of iron from the original rocks. These conditions may or may not be met with in thermal or regional metamorphism. Frequently they are met, especially where basaltic rocks normally of high iron content are metamorphosed. Clouding may also be caused by extended iron-rich deuteric activity in basic intrusives.

(iii) *The cause of the metamorphism.* The arcs of black gabbro in the Northern Ring comprise different types of gabbro and are uninfluenced by faulting. They are not peculiar to any particular layer of gabbro, that is, they are not the product of auto-metamorphism. In addition, the curvature is parallel with a great number of microgranite dykes, intrusive into the gabbro, and the black gabbros are themselves net-veined. Other features of the rock, such as the granulation and development of exsolution lamellae of pyroxene, do not suggest deuteric alteration as there is little more replacement of pyroxene by biotite or hornblende than in normal gabbros. On the other hand, these features together with the replacement of plagioclase margins by sodic plagioclase, and the recrystallization of interstitial quartz and orthoclase, may be explained by conditions of raised temperature and slight stress with little addition of water, which may be the conditions of low grade thermal metamorphism. As gabbros are relatively iron-rich, two of Poldervaart & Gilkey's conditions for the production of clouded plagioclase are met with, but there is little evidence of the presence of water.

Table 18. Modal compositions of specimens of the Hanyani gabbro

(volume %)

specimen no.	amphibole	augite	plagioclase	ore	micropegmatite
C 430	32·9	8·3	49·1	2·3	7·7
N 9	36·6	9·6	52·0	1·4	0·6
C 361	25·0	8·1	49·6	3·5	13·9
C 334	22·6	10·6	42·0	10·3	14·9

These factors taken together with the field evidence, particularly the abrupt termination of acid net-veining at the edges of the metagabbro, suggest that the arcs are underlain by an acid intrusive, either related to the ring-dyke or to the microgranite dykes. This unexposed acid intrusion has metamorphosed the gabbro above and around it, and where it has penetrated most nearly to the present surface has net-veined the gabbro with granitic fluids.

(*d*) *The Hanyani gabbro* (*hornblende gabbro*) *of the Masukwe complex*

The normal Hanyani gabbro is a mesocratic rock made up of amphibole (tremolite-actinolite), augite, and plagioclase with small amounts of iron ore and quartz-orthoclase micropegmatite. The texture is usually sub-ophitic but can vary to ophitic or intergranular. Table 18 above shows the modal compositions of several specimens.

The amphibole is pseudomorphous after augite and is usually well crystallized. Partial replacement of augite crystals is common and in these cases it can be seen that the twin planes and schiller structures in the amphibole are inherited from the original augite. Amphiboles can also be found showing typical eight-sided pyroxene cross-sections. The amphibole has the following optical properties. Absorption: X, very pale yellow; Y, yellow-green; Z, medium blue-green. $Z \wedge C = 21°$; $2V_x = 62°$; N_z was determined for one specimen as $1{\cdot}653 \pm 0{\cdot}003$.

The optics indicate that the amphibole belongs to the tremolite-actinolite series, the refractive index suggesting, using the data of Sundius (1946), that the actinolite content is approximately 30%. Amphibole similar to the above occurs less commonly in a finely divided, typically uralitic, state. Occasionally, however, euhedral crystals of what is possibly primary brown hornblende are found.

The pyroxene of the Hanyani gabbro is crystallized interstitial to and partly enclosing the plagioclase crystals. It is colourless and has a moderate $2V$ and $Z \wedge C = 52°$. Schiller structure is common and alteration to magnetite dust and amphibole is usually marked. The plagioclase crystals are euhedral and slightly flattened parallel to (010). Slight zoning is common, crystal centres being labradorite of composition An_{62} to An_{66} while narrow marginal zones may be andesine. Micropegmatite is almost always present interstitially but in varying amounts. Accessory minerals include apatite and occasional epidote.

As has been mentioned in a previous section, p. 115 the gabbro passes vertically upwards into the Hanyani Granophyre. In order to demonstrate that the transition from gabbro to granophyre is in fact gradual the specific gravities of fifteen specimens, each weighing approximately 50 g, have been determined. Figure 25 shows the specific gravities plotted against distance along a traverse line. The ground rises gently and fairly uniformly along this line so that distance is roughly proportional to height in the intrusion. Figure 25 also shows the amounts of some of the minerals present plotted against distance along the same traverse line. Plagioclase and amphibole show a fairly steady decrease in amount as the proportions of quartz and alkali feldspar rise. Iron ore, apatite and epidote all show peak concentrations, mainly in the lower zone of the granophyre.

In the spotted gabbro zone and in the lower zone of the granophyre, labradorite is the principal plagioclase as it is in the normal gabbro. It is, however, considerably epidotized, the intensity of this effect increasing with height in the intrusion and causing the epidote peak in figure 25. The labradorite crystals become almost unrecognizable towards the top of the lower zone of the granophyre due to partial replacement by more sodic plagioclase, the abundance in them of epidote and dusty iron ore, and perhaps their partial absorption by the magma. In contrast, the andesine crystals which appear in the upper zone of the granophyre, show little alteration other than slight epidotization and reddening due to the presence of minute inclusions of presumed hematite. They are, therefore, regarded as being the result of primary crystallization. A remarkable feature of these crystals is the frequency with which they are twinned on a combination of the Carlsbad and Manebach laws.

Pale green or colourless amphibole is the only important ferromagnesian mineral in the Hanyani Granophyre, pyroxene being very rare. There is much evidence in the Hanyani gabbro that a similar amphibole is pseudomorphous after pyroxene and this may be the case in the granophyre also. Although the amphibole is always acicular in the granophyre it is possible that it has replaced original acicular pyroxene. In the lower zone of the granophyre the amphibole is very similar to that found in the normal gabbro and has absorptions: X, very pale yellow; Y, pale yellow-green; Z, pale blue-green. These colours become paler with height in the intrusion and in the upper zone of the granophyre much of the amphibole is practically colourless. Liberation of magnetite accompanies the colour change and accounts for the iron ore peak of figure 25. At the same time changes in optical properties take place, $2V_x$ increasing from about 70° in the Spotted Gabbro to about 80° in the Upper Hanyani Granophyre. Birefringence, however, remains throughout in the range 0·018 to 0·026 and no significant changes could be detected in $Z \wedge C$. The refractive index (N_z) of a specimen from the middle of the Lower Hanyani Granophyre was determined as $1{\cdot}653 \pm 0{\cdot}003$.

It is concluded that the amphiboles in the granophyre belong to the tremolite-actinolite series and all lie fairly close to the magnesian end of the series. The loss of colour, increase of $2V_x$ and the liberation of iron ore are all features which point to the magnesium enrichment of the crystals with height in the intrusion.

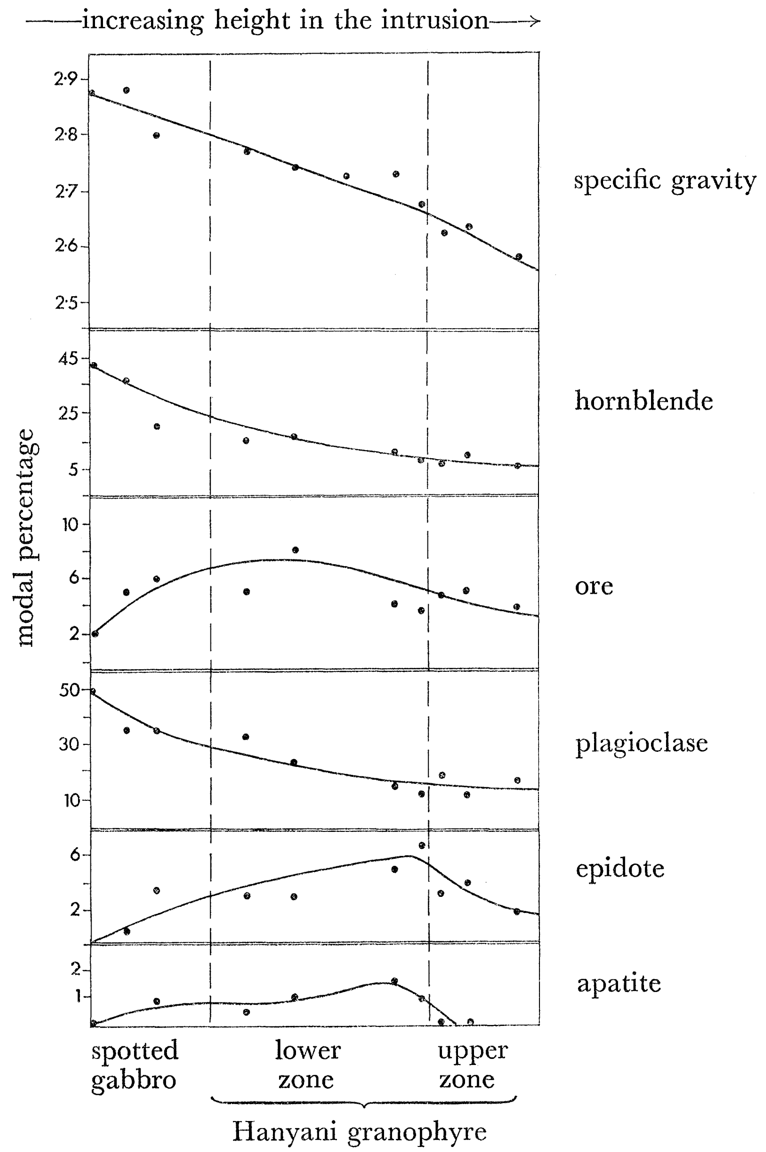

FIGURE 25. Variations in specific gravity and modal composition within the Hanyani gabbro.

(e) Olivine-hyperite, Masukwe complex

(i) *Petrography.* With the exception of a picritic selvage, the olivine-hyperite intrusion is entirely made up of a very uniform mesocratic gabbroidal rock with a grain-size of approximately 5 mm. The rock is attractive in hand-specimen, being composed of dark brown olivine crystals set in a matrix of white feldspar with occasional large poikilitic crystals of pyroxene. The picrite selvage is probably of the order of a foot thick and grades into the olivine-hyperite. The picrite is a dark brown, heavy rock, composed mainly of olivine and small amounts of interstitial feldspar. Thin-section examination shows the minerals to be rather altered and the modal analyses given in table 19 represent, as far as possible, the original mineralogical compositions of the rocks. The commonest alteration products are serpentine, tremolite, magnetite and biotite in the mafic minerals and prehnite in the feldspars. Texturally both rocks consists of euhedral and sub-hedral olivines, 3 to 5 mm long, set in a matrix of plagioclase. The pyroxenes have crystallized late as large poikilitic plates.

The olivine is considerably altered and a few crystals are completely pseudomorphosed by iddingsite. Wide cracks filled with serpentine and magnetite are common in the slightly fresher crystals and each crystal is usually bordered by a narrow rim of finely divided serpentine, tremolite and magnetite. The composition of the olivine has been determined as

Table 19. Modal compositions of the olivine-hyperite and the picrite (volume %)

	olivine-hyperite	picrite
plagioclase (bytownite)	55·8	26·6
olivine	32·9	71·0
orthopyroxene	6·4	0·2
clinopyroxene	4·0	2·0
iron ore (primary)	0·6	0·4

chrysolite, in the range Fa_{13} to Fa_{17}, in both the olivine-hyperite and the picrite. The orthopyroxene has a faint pink to green pleochroism and in a few cases contains irregular exsolution lamellae of clinopyroxene. The crystals usually show marginal alteration to tremolite and biotite. The $2V_x$ of specimens from the olivine-hyperite is 78° indicating a composition of En_{83}. The clinopyroxene is colourless and exhibits marked schiller structure and polysynthetic twinning. Specimens from the olivine-hyperite have $2V_x = 50°$. The plagioclase in the rock is comparatively fresh and is for the most part unzoned. Colourless epidote is a fairly common alteration product and patches of feldspar are almost completely replaced by fine-grained masses of flaky prehnite. The composition of the plagioclase is in the range An_{78} to An_{83}.

(ii) *Origin of the picrite selvage.* Field observations show that the picrite selvage, although thin, is always present at the contacts of the intrusion. It is therefore unlikely that the picrite represents a separate intrusive phase. It also seems unlikely to have been formed by crystal-settling, especially since the main mass of olivine-hyperite is uniform and free from banding. A diffusion hypothesis is therefore suggested as being most likely to account for the presence of the picrite.

Such a marked basic selvage could be due to a rather critical degree of chilling at the contacts, sufficient to accelerate the crystallization of early formed olivines yet not sufficient to reduce the viscosity of the magma to a point where diffusion rates would be excessively low. Under these conditions the magma near the contact would become impoverished in magnesium and iron as olivine crystallized. Magnesium and iron ions would therefore tend to diffuse towards the contact and a marginal, olivine-enriched rock would result.

(f) The inner gabbros of the Masukwe complex

The *leucogabbros* are coarse-grained, pale green to white in colour and sometimes well laminated due to the parallel orientation of platy felspar crystals. Poikilitic augite is the main dark mineral and in typical specimens makes up 12 to 15 % of the rock.

The *ophitic gabbros* contain large poikilitic crystals of augite which are frequently uralitized and give the rock a green-spotted appearance. The plagioclase in these rocks is distinctly more calcic than in, for example, the Hanyani gabbro and usually has a composition in the range An_{70} to An_{80}.

The *hypersthene-bearing gabbros* have a generally dark and granular appearance in the field and consist of well-formed hypersthene crystals, ophitic augite, basic plagioclase and minor amounts of iron ore, quartz, orthoclase and biotite. They are generally mesocratic, and hypersthene (22 %), exceeded augite (18 %) in the one slide modally analysed. This rock is in effect an augite-norite.

(g) Gabbros of the Dembe–Divula complex

Under the microscope the *leucogabbros* show a coarse gabbroidal texture. The grain size of the plagioclase crystals ranges up to 5 mm, and they are coarsely intergrown with green, platy pyroxene, and flakes of biotite. The composition of the plagioclase varies, due to zoning, from about An_{53} to An_{69}. Labradorite usually makes up about 70 % of the rock. Ophitic clinopyroxene plates account for about 20 % of the rock, and are altered to a greater or lesser degree to biotite, hornblende, and chlorite (penninite). Small patches of calcite and sericite are also alteration products. Accessory minerals include hematite, chalcopyrite, probably magnetite and ilmenite, rare epidote, quartz, and sphene.

In thin section the outstanding feature of the *microgabbro* is the high degree of alteration. The main constituents are plagioclase (54 %), and amphibole (30 %). The feldspar crystals have a lath-like form, are zoned, and have a composition varying between An_{42} and An_{52}. Pyroxene (augite) is in some cases completely altered to brown biotite, chlorite and hornblende. Small amounts of K-feldspar, apatite, and iron ore, (probably magnetite) are also present.

The *olivine gabbro* contains slightly zoned labradorite (approximately An_{69}), in part traversed by systems of closely spaced fractures, which radiate out from the olivines. Large plates up to 5 mm across, of colourless or pale green augite make up about 27 % of the rock, while rare (about 1 %) orthopyroxene is present in some of the rocks. Green chlorite and brown pleochroic biotite occur as alteration products, and magnetite, calcite, sericite, and apatite are also present.

(h) The Vangambi gabbro

The Vangambi gabbro is composed essentially of labradorite, augite and a little quartz, the latter occurring as small but discrete grains. These minerals are developed in amounts which are typical of other gabbros in the province. In addition, however, the rock contains unusually large quantities of microperthite and biotite. In most of the gabbros of the province in which potassium feldspar is present, it occurs as a component of micropegmatite, but here it forms large grains a millimetre or more in diameter. The biotite forms large poikilitic tabular crystals 2 cm or more across, which are very conspicuous in hand-specimen. Rather more than the usual amounts of epidote, secondary amphibole, and chlorite are also developed. It is possible that the unusual amounts of potassium feldspar and biotite in the gabbro and the large amounts of secondary ferromagnesian minerals may be due to potash metasomatism associated with the emplacement of a later intrusion of nordmarkite.

(*i*) *The Mutandawhe basalt*

The Mutandawhe basalt is a heterogeneous rock whose variable composition has resulted from its modification subsequent to and during emplacement. During intrusion the basalt magma was apparently modified to a varying degree by the incorporation of rock fragments and crystals derived from the rocks into which it was emplaced. At a later date the basalt was invaded and thermally metamorphosed by the younger Masunji granite in which it is now found as screens. In certain places only thermal effects can be recognized and the rocks then resemble the metabasalts which encircle the complex. In other localities the metabasalt is distinctly xenolithic.

The degree of thermal metamorphism induced by the Masunji granite varies from place to place. In some instances original basalt structures and textures are still preserved whilst in others the rock has completely recrystallized and a crystalloblastic texture has developed.

The contamination of the basalt by enclosed xenoliths and xenocrysts has resulted in the production of a series of rocks, the end members of which vary greatly in appearance. At one end of the series is an unmistakable breccia consisting of nordmarkite and basalt fragments, and constituent crystals of the former, set in a metabasalt matrix. Presumably owing to there having been insufficient time for equilibrium to be established only the occasional xenolith or xenocryst shows any signs of having reacted with the enclosing basic magma. At the opposite end of the series is a rock which is more leucocratic than the normal basalt and which in places almost resembles a felsite in hand specimen. In thin section, however, it can be seen that the rock is a fine-grained metabasalt whose light colour is due to the presence of innumerable tiny xenocrysts of plagioclase, perthite and quartz.

2. *The nordmarkites*

Rocks of intermediate composition are comparatively rare in the Nuanetsi Igneous Province. However, quartz-syenites, mainly of nordmarkitic type, are present in the Mutandawhe, Marumbe and Vangambi complexes. In the general intrusive time-sequence they probably lie between the earlier gabbros and the later granites.

(*a*) *The Mutandawhe nordmarkite*

The rock varies in colour from buff to salmon pink, and in grain size from medium-grained to coarsely pegmatitic. The pegmatite occurs in veins and in irregularly shaped segregations, and is found mainly in the north-east part of the complex. The localization of the pegmatites probably indicates that the magma in this part of the intrusion was relatively rich in volatiles at the time of its crystallization. Possibly, therefore, the north-eastern section of the intrusion represents the highest level still exposed in the nordmarkite body.

In hand-specimen the nordmarkite is seen to be composed largely of subhedral to euhedral feldspar and amphibole crystals together with a little interstitial quartz and some biotite. In the pegmatitic varieties prismatic crystals of hornblende range up to 2 in. in length and tabular crystals of feldspar up to 4 in. in diameter. The presence of two types of feldspar in the rock is suggested by the colour; the majority is either pink or buff-coloured but in addition a greenish white feldspar also occurs. Some specimens contain markedly zoned feldspars and these are usually white in the centres and pink around the margins. An average modal analysis of five specimens of the Mutandawhe nordmarkite, all of which where very similar, is as follows: microperthite, 67·59 %; plagioclase, 15·95 %; hornblende and biotite after hornblende, 8·59 %; quartz, 6·13 %; magnetite, 1·54 %; and minor accessories.

In thin section the dominant mineral is seen to be microperthite (the pink feldspar of the hand-specimen) occurring as subhedral crystals. Both vein- and patch-perthite occur but the latter predominates. The plagioclase lamellae are usually too small to enable their composition to be determined, but in some instances they attain 1 mm in diameter and exhibit multiple twinning. In some such crystals the lamellae have the composition of oligoclase (An_{26-28}). The host mineral of the perthite is orthoclase with $2V_x = 71°$. It occasionally exhibits simple twinning on the Carlsbad law.

In addition to the oligoclase lamellae of the perthite, plagioclase feldspar also occurs as separate crystals and is presumably the white feldspar seen in hand-specimen. It is multiply twinned oligoclase-andesine and forms relatively clear, euhedral, lath-like crystals which are invariably mantled by microperthite. This mantle appears to be a replacement phenomenon for in some instances the original twinning of the plagioclase is still partially preserved.

Amphibole occurring as euhedral crystals is the most common of the ferromagnesian minerals. Twinning is rare but some crystals with twin plane (010) have occasionally been seen. The mineral has the following optical properties: $2V_x = 56°$; $Z \wedge c = 23°$; $N_x = 1{\cdot}701$; $N_z = 1{\cdot}723$; pleochroism X, light greenish brown; Y, brownish green; Z, dark bluish green (almost opaque). Following Billings (1928) and Sahama (1948) these data, especially the high refractive index of the mineral, suggest that it is ferrohastingsite, a fact which supports the contention of Billings (1928) that 'ferrohastingsite...is the common amphibole in nordmarkites'.

Biotite is usually associated with magnetite and ferrohastingsite and in some instances is seen to be replacing the latter. It is usually strongly pleochroic from light to dark brown but is sometimes intergrown with green biotite. Quartz occurs interstitially. Apatite and allanite are the most common accessory minerals. Both occur as euhedral crystals and the allanite is further characterized by its marked zonary structure. Sericite, rutile, sphene, and epidote occur rather more rarely. A chemical analysis of the Mutandawhe nordmarkite is presented in table 20.

The *Mutandawhe micronordmarkite* is a fine- to medium-grained rock and is mineralogically almost identical to the Mutandawhe nordmarkite—and average modal analysis being as follows: quartz, 7·9 %; perthite, 67·5 %; plagioclase, 13·4 %; ferrohastingsite, 10·0 %; biotite, 1·2 %. Accessory minerals include magnetite, allanite, apatite and zircon.

The *Cliff Porphyry*, also of the Mutandawhe complex, is a pink porphyritic nordmarkite consisting of feldspar and ferrohastingsite phenocrysts set in a fine-grained dominantly feldspathic groundmass which also contains some quartz and a little ferromagnesian material. The phenocrysts constitute from 5 to 15% of the rock, are euhedral and range from 1·5 mm to 2·0 cm in length.

TABLE 20

CHEMICAL ANALYSES OF NORDMARKITES

	Mutandawhe nordmarkite (analyst: J. R. Baldwin)	Marumbe nordmarkite (analyst: M. H. Kerr)	average nordmarkite (7 analyses, Daly)	average of 11 analyses taken from the literature
SiO_2	61·48	62·73	64·36	64·25
TiO_2	0·67	0·35	0·45	0·50
Al_2O_3	17·28	16·25	16·81	17·27
Fe_2O_3	1·98	1·52	1·08	1·75
FeO	3·70	4·48	2·71	2·42
MnO	0·12	0·15	0·15	0·11
MgO	0·64	0·33	0·72	0·53
CaO	2·33	2·05	1·55	1·74
Na_2O	4·46	5·36	5·76	5·59
K_2O	6·10	6·26	5·62	5·31
H_2O^+	0·46	0·49	0·70	0·58
H_2O^-	0·25	0·08	—	—
P_2O_5	0·17	0·13	—	0·11
totals	99·64	100·18	99·91	100·16

C.I.P.W. norms

Q	5·12	1·8	4·2	6·06
or	36·14	36·7	33·36	31·14
ab	37·20	45·06	48·72	47·16
an	9·5	1·95	3·34	6·39
di	1·12	6·57	3·7	3·67
hy	5·54	3·96	3·14	1·86
mt	2·32	2·32	1·62	2·55
il	1·22	0·61	0·91	0·91
ap	0·34	0·34	—	0·67

SPECTROGRAPHIC ANALYSIS OF THE MARUMBE NORDMARKITE

(amounts in p.p.m.)

Ba 400	Cr 10	Ni $<$ 10
Li 3	Ga 35	Pb 20
Rb $\sim$ 100	La 100	V $<$ 3
Sr 45	Mo $<$ 3	Y 45
Be 3	Nb 110	Zr 250

(*b*) *The Marumbe and Vangambi nordmarkites*

In hand-specimen the nordmarkite from both these complexes is a pink or grey rock characterized by tabular phenocrysts of orthoclase up to 2 cm in length, which are distributed throughout a medium-grained feldspathic groundmass containing dark hornblende and a little quartz. A chemical and spectrographic analysis of the Marumbe nordmarkite is presented in table 20. Three specimens gave the following average modal composition: quartz, 7·0%; feldspar, 80·2%; hornblende, 11·4%; biotite, 0·9%; magnetite, 0·4%; apatite and zircon, 0·1%.

The orthoclase phenocrysts contain patches of microperthite and are enclosed by a groundmass composed largely of microperthite crystals averaging about 5 mm across. The feldspars of the groundmass show good crystal faces where they are in contact with interstitial quartz, and in parts of the rock an ophitic relationship is developed between these two minerals. A few independent grains of albite are present, but they are small and may have formed by exsolution. The subhedral prisms of hornblende are pleochroic with: *X*, pale brown; *Y*, dark brown; and *Z*, dark green-brown; and have an extinction angle $X \wedge C = 15$ to 20°.

(c) Nomenclature and chemistry of the nordmarkites

Owing to the absence of quantitative mineralogical data on the nordmarkite from the type area it is impossible to compare it with the quartz syenites from the Nuanetsi Province. The latter, however, stand a fairly close comparison with Johannsen's definition of a nordmarkite (1937, p. 6) and have accordingly been so named.

Chemical analyses of the Mutandawhe and Marumbe rocks are given in table 20 together with the average chemical composition of 7 nordmarkites (Daly 1910) and the average of 11 nordmarkites taken from the literature. A comparison with these shows no significant differences and there can be no doubt that chemically at least, the Nuanetsi rocks are true nordmarkites.

3. *Hybrid rocks*

In numerous localities within the province abundant evidence is found of the contamination of granitic or granophyric intrusive rocks by the incorporation of basic material. Such contamination may result, especially in intrusion breccias, simply from the mechanical disintegration of xenoliths, notably of gabbro, and gives rise to xenocrystic hybrids. In other instances more complete assimilation of the basic material has taken place to give somewhat more uniform rock types such as the Dembe–Divula adamellites or, locally, the grey tonalites of the Masukwe complex. In the Northern Ring complex large areas of gabbro show signs of *in situ* metasomatism by granitic emanations.

A general characteristic of the hybrid rocks is their variability compared with the normal acid intrusions. Though of very widespread occurrence they form only a small proportion of the rocks in any complex.

(a) The contaminated causeway microgranite, Masukwe complex

Modal analyses of two specimens are given in table 21. The high content of intermediate plagioclase is typical of the tonalitic type. The andesine crystals are mainly euhedral and make up most of the rock, the quartz being almost entirely interstitial.

(b) The adamellites of the Dembe–Divula complex

Under the microscope the texture is generally subhedral granular, but a trachytoid texture is developed where feldspar crystals are locally alined. The major mineral components of these rocks are the feldspars; plagioclase and orthoclase occurring in roughly equal proportions. In the specimens examined the amount of plagioclase varied from 24 to 44 %, and K-feldspar from 28 to 44 % (see table 22). Most of the plagioclase laths are rimmed by orthoclase. The plagioclase exhibits normal zoning, the centres of crystals being largely unzoned and of composition An_{57}, while the outer rim has a sharp change in composition to An_{12}. Some microperthite is present. Early formed hornblende occurs as euhedral or subhedral crystals up to 1·5 mm in length. It is pleochroic brown in colour, but some grains are green, and others both patchy green and brown. The hornblende alters to fibrous amphiboles, chlorite, and brown biotite. Between the major components

Table 21. Modal analyses of contaminated varieties of Causeway Microgranite, Masukwe complex

(volume %)

	tonalitic type	granodioritic type
quartz	8·6	11·8
orthoclase	7·6	22·2
plagioclase (andesine)	72·6	53·4
clinopyroxene	1·6	—
hornblende	3·8	7·4
ore	5·8	5·2

Table 22. Modal analyses of adamellites

(volume %)

specimen no. ...	V 264	V 255	V 160	V 261	V 67
quartz	25·7	22·0	10·3	10·7	7·5
orthoclase and perthite	44·0	38·2	33·4	27·6	29·5
plagioclase	23·6	26·3	37·7	40·0	44·5
biotite	0·8	—	tr.	0·7	0·2
chlorite	0·3	—	4·0	1·9	1·8
hornblende	3·6	7·7	10·6	15·0	13·3
ore minerals	1·6	3·5	2·3	2·5	2·5
zircon	0·3	0·4	0·2	0·4	0·1
sphene	—	1·5	0·2	0·7	0·4
epidote	0·1	—	—	0·3	tr.
apatite	tr.	0·4	0·4	0·2	0·2
calcite	—	—	0·9	—	tr.

V 264, Between Dembe and Divula, $\frac{1}{2}$ mile north of Object Hill; V 255, west end of Mamba Ridge; V 160, north bank Maose River, north side Object Hill; V 261, north bank Maose River, north side Object Hill; V 67, north end Maose gorge.

interstitial quartz is present, amounting to from 7 to 26% in the sections examined (see table 22). Ore minerals account for up to 3·5% of the rock and consist of magnetite and ilmenite, with which is associated sphene. Other accessories include small amounts of apatite, epidote and allanite, calcite and zircon.

(*c*) *Hybrids of the Northern Ring complex*

The petrography of this extremely variable group of hybrids can best be illustrated by describing the two end members, granodiorite and slightly altered gabbro, then listing the changes which take place in passing from one to the other.

(i) *Granodiorite hybrid.* In its most extreme form the hybrid gabbro becomes a granodiorite with over 20% by volume of quartz. The rock is speckled pale and dark grey, is equigranular (average grain size 1 to 2 mm) and has a uniform granitic texture. It consists of zoned plagioclase laths (average length 2 to 3 mm) and sub-ophitic pyroxene crystals largely replaced by hornblende. These are set in a groundmass of quartz and orthoclase together with hornblende and magnetite. Granophyric intergrowth is frequently developed in the groundmass.

Dark xenoliths of microgabbro are not uncommon, and appear to be unaffected by the hybridization, although often surrounded by a narrow rim of epidote and quartz.

Plagioclase is the dominant original mineral of the hybridized gabbro, and occurs as large laths zoned from calcic centres to more sodic margins. The calcic centres are sometimes partly replaced in a pseudoperthitic manner by sodic plagioclase. The laths are often found in groups and the margins are embayed and frequently mantled by orthoclase. The small laths are more or less clouded. The zoning is continuous and gives the following compositions: centres, maximum An_{56}, average An_{45}; margins, minimum An_{23}, average An_{24}. In some cases, the sodic rims are themselves replaced by orthoclase, resulting in an antiperthite. The original plagioclase of the gabbro had a composition of approximately An_{70}, and it is obvious that considerable alteration has taken place in this granodiorite to produce plagioclase not more basic than An_{56}. The earlier phases of alteration are obliterated in the granodiorite, but can be seen in other less altered hybrids.

The pyroxene also indicates something of the history of the hybridization. Original hypersthene is completely replaced by pale brown hornblende, and this change precedes the alteration of original augite. Up to 4 % of the augite may still be present in the hybrids of granodiorite composition. This augite is the normal gabbroic augite, and is found as corroded sub-ophitic crystals mantled by green-brown hornblende. Brown, pleochroic biotite occasionally replaces pyroxene and hornblende, but chlorite is the most universal of the late stage replacements. A groundmass of quartz and orthoclase, with a lobate to granophyric intergrowth texture, associated with a little green hornblende is developed between the gabbro minerals. Magnetite, both original and secondary sometimes reaches as much as 9 % by volume of the rock.

(ii) *Slightly assimilated gabbro.* Partially assimilated gabbros with granophyre veins occur patchily within the outcrop of the granodiorite. The earliest stage shows clouded plagioclase laths of composition An_{65-70} but with narrow margins zoned to more sodic plagioclase of composition An_{30-40}. Abundant pyroxene is full of magnetite granules and is schillerized, frequently being partly replaced by brown hornblende. It is a normal gabbroic augite. Original hypersthene is rarely seen as even at this stage it has been almost completely replaced by brown hornblende. Normal gabbroic magnetite is abundant, and the interstitial micropegmatite or quartz of the unaltered gabbro is still present, although frequently in larger proportions than normal.

(iii) *Sequence of change.* The stages of assimilation are marked by the extent of alteration of original gabbro minerals and the amount and distribution of additional minerals. The sequence is as follows:

(1) Clouding of plagioclase and zoning to more sodic margins; schillerizing of augite; replacement of hypersthene by brown hornblende; and the introduction of veins of quartz and orthoclase.

(2) Break up of the gabbro, with the introduction of abundant granitic material; further zoning of plagioclase and replacement of hypersthene; corrosion of augite and its partial replacement by hornblende.

(3) Further local spreading of fragments of basic material, breaking up into individual xenocrysts, together with continued zoning of plagioclase, replacement of pyroxene, and the start of replacement of sodic plagioclase by orthoclase.

(iv) *Chemistry*. An analysis of a granodioritic hybrid is given in table 23. A comparison of this with the analysed gabbroic rocks in table 15 and with the acid rocks of the Rhyodacite–Rhyolite series described in the Geochemistry section offers some evidence of the mode of formation of the hybrid. First, it is clear that a mixing of gabbroic rock and acid magma, as represented by the Main Granophyre or Ring Dyke Porphyry, is unlikely to have been responsible. If this were the case it would be expected that the hybrid would show chemical characters intermediate between the gabbros and the acid rocks. In fact,

TABLE 23. A CHEMICAL ANALYSIS OF A GRANODIORITE HYBRID (N 750) FROM THE NORTHERN RING COMPLEX

		C.I.P.W. *norm*		
SiO_2	53·33			
TiO_2	1·41	*Q*		12·66
Al_2O_3	14·52	*or*		10·01
Fe_2O_3	7·71	*ab*		26·72
FeO	6·16	*an*		20·29
MnO	0·25	*di*	*wo*	4·4
MgO	2·27		*en*	2·7
CaO	7·53		*fs*	1·45
Na_2O	3·13	*hy*	*en*	1·58
K_2O	1·70		*fs*	3·00
H_2O^+	0·76	*mt*		11·14
H_2O^-	0·16	*il*		2·74
P_2O_5	0·68	*ap*		1·68
CO_2	0·31	*cc*		0·7
	99·91	H_2O		0·84

Analyst: J. R. Baldwin.

the analysed hybrid contains amounts of alkalis, Al_2O_3, CaO and MgO which are typical of the rather basic varieties of rhyodacitic rock. The content of SiO_2, on the other hand, is very close to that of the quartz-hypersthene-gabbros, and the total iron content is unusually high. Hence it is clear that the analysed hybrid would not fit on to any straight-line variation diagram drawn between gabbroic and rhyodacitic or rhyolitic end-members.

A selective metasomatism of gabbroic rocks, involving the addition of alkalis and perhaps iron, and the removal of CaO, MgO and some Al_2O_3, appears to be a more likely mechanism. The calcic plagioclase would be converted progressively to sodic plagioclase and finally to orthoclase, with the freeing of CaO. The ferromagnesian minerals would change their composition, and decrease slightly in their proportion, but since hornblende is a stable phase in granite, the colour index need not drop to the lower value of a normal acid igneous rock nor even to the value required by mixing gabbro and acid magma. These changes correspond with those deduced from the mineralogy of the hybrids, and it seems likely that this method is the one by which the hybrids were produced. An increase in temperature during the metasomatism could produce partial melting of the hybrid with subsequent crystallization of the quartz and orthoclase in an igneous texture. The temperature was probably only sufficiently high to melt the quartz and orthoclase, while leaving the gabbroic minerals in their original texture. Independent evidence for heating at some stage—probably very early in the metasomatism—is offered by the clouding of the plagioclase. Partial mobilization of the hybrid produced by the rise of temperature could be responsible for producing the wispy veins of quartz and orthoclase which inject the relatively unaltered metavolcanic screens.

4. *The acid rocks*

(*a*) *The Main Granophyre*

(i) *The Red Granophyre.* The Red Granophyre is the most widespread rock-type included within the Main Granophyre in the western part of the province. In hand-specimen it is somewhat variable but is usually a fine-grained pink or red rock, occasionally slightly miarolitic, characterized by a low colour-index and the presence of small (1 to 2 mm) phenocrysts of orange or red alkali feldspar. The granophyric texture of the groundmass is visible with the hand-lens.

In thin section the typical Red Granophyre exhibits a groundmass texture which is partly granophyric and partly micrograniti c. The micropegmatite patches vary considerably in coarseness, the more finely crystallized patches tending to be micrographic and the coarser ones more irregular, lobate, intergrowths. The potash feldspar in the rock is a very turbid micro- or crypto-perthite which exists partly intergrown with quartz in the micropegmatite mentioned above, partly as discrete grains in the microgranitic parts of the groundmass and partly as a replacement of the margins of the phenocrysts. The latter are euhedral crystals, originally of albite, suffering varying degrees of replacement by microperthite. Replacement in many crystals is almost complete leaving only scattered patches of albite set in a microperthite matrix. As a result of this feature the modal proportion of albite varies considerably from as much as 20 % of the rock to less than 1 %.

The ferromagnesian minerals of the rock are probably largely secondary after an original clinopyroxene now found in small scattered remnants only. The commonest alteration product is a pale biotite, pleochroic from colourless to yellow or occasionally to green or brown. Amphibole and chlorite are also common alteration products. Iron ore is fairly abundant and is in part secondary after ferromagnesian minerals. Fluorite and epidote are the most abundant accessory minerals, followed by sphene, zircon and, occasionally, apatite. The common ore mineral appears to be magnetite.

The modal composition of the Red Granophyre is extremely variable when the whole outcrop is considered. Usually, however, in any one smaller area it is fairly uniform, only the albite-orthoclase ratio varying from specimen to specimen. Table 24 shows the modal compositions of specimens from different areas.

(ii) *The Gezani microgranite.* This is a fine-grained porphyritic equigranular microgranite containing phenocrysts of high sericitized sodic plagioclase, marginally resorbed and rimmed by potash feldspar. The ferromagnesian mineral consists of shreds and small subhedral crystals of green hornblende, heavily charged with magnetite granules. The groundmass is composed of clear quartz and red-coloured potash feldspar grains with occasional patches of micropegmatite. Granules of magnetite occur interstitially and the common accessory minerals include acicular apatites (set in the plagioclase phenocrysts), epidote, biotite, zircon and sphene. A modal analysis is given in table 24.

(iii) *The Chakumba sheet-intrusions.* These consist of variable microgranitic microporphyritic rocks somewhat more mafic than the Gezani microgranite. The microphenocrysts are subhedral tabular crystals of sodic plagioclase rimmed by potash-feldspar, and hornblende-magnetite pseudomorphs after clinopyroxene. Recognizable remnants of pyroxene are occasionally present and there may also be a little fresh, euhedral hornblende. The colour index (volume percentage of ferromagnesian and ore minerals) varied from 5 to 22 in the specimens examined. A modal analysis of the most mafic type is given in table 24.

TABLE 24

MODAL COMPOSITIONS OF SPECIMENS OF THE RED GRANOPHYRE

(volume %)

localities ...	Damabwe Pan	Masukwe and Gonakudzingwa (average of 5)	south side of Northern Ring (average of 4)	Dembe area (average of 9)
quartz	28·2	32·0	28·9	39·4
potash-feldspar	40·9	57·3	56·2	53·1
plagioclase	19·1	6·2	6·6	1·7
ferromagnesian minerals	8·6	1·8	3·1	0·4
ore minerals	3·2	1·7	2·1	4·7
accessories	—	—	—	0·7

MODAL COMPOSITIONS OF MAIN GRANOPHYRE ROCKS EXCLUDING THE RED GRANOPHYRE

	Chiwonje type	microgranite Chakumba River	microgranite Gezani Scarp	microgranite near Danje
quartz	26·6	16·6	21·5	26·0
potash feldspar	44·5	37·0	35·4	49·1
plagioclase	15·4	24·4	31·3	11·5
hornblende and augite, etc.	10·0	18·0	6·6	7·2
ore minerals	3·4	4·1	3·6	6·2
epidote	—	—	1·3	—

(iv) *The Danje sheet-intrusions*. These are composed of fine-grained microporphyritic, granophyric and microgranitic rocks. As in the Chakumba rocks, the phenocrysts consist of small, fresh, amphibole crystals, amphibole-magnetite crystals, probably pseudomorphs, and altered sodic plagioclase mantled by potash feldspar. In some of the Danje rocks, however, a glomeroporphyritic texture is found, amphibole, plagioclase and magnetite crystals being associated in clusters. The groundmass may be microgranitic or finely granophyric, frequently micrographic. Colour indices vary from less than 5, for the most leucocratic, to 10 to 15 for the normal varieties.

(v) *The Chiwonje type* (*Sabi–Lundi area*). The Chiwonje type covers a very large outcrop area but appears to be fairly uniform in mineralogy though slightly variable in colour. In the Lundi Gorge, however, a more mafic variety underlies the normal granophyre.

The latter is a fairly fine-grained porphyritic rock containing phenocrysts of sericitized plagioclase, augite and hornblende. The plagioclase phenocrysts show oscillatory zoning and have compositions in the range An_8 to An_{20}. A rim of turbid potash-feldspar is usually present. The augite phenocrysts are subhedral to anhedral, up to 3 mm in length, and are now largely replaced by green hornblende and magnetite. The groundmass is mainly granophyric but also contains micrographic patches and small, second-generation, plagioclase crystals.

An average modal analysis is given in table 24.

(vi) *The Chiwonje tonalite.* The Chiwonje tonalite is an abnormally basic variety of the Main Granophyre which crops out along the eastern margin of the Chiwonje complex. It is a coarse-grained rock with an intergranular texture which, in thin section, shows small crystals of pyroxene, hornblende, biotite and iron ore, together with micropegmatite, filling the interstices in a plexus of large (1 cm long) euhedral plagioclase crystals of composition An_{40}. The rock is thought to have resulted from the contamination of an early phase of the Main Granophyre by reaction with the basaltic country rocks. In many respects the rock is similar to the contaminated type of Causeway microgranite from the Masukwe complex.

TABLE 25. NEW CHEMICAL ANALYSES OF ROCKS FROM THE MAIN GRANOPHYRE INTRUSION

	1	2	3	4
SiO_2	66·27	67·08	72·19	73·87
TiO_2	0·95	0·66	0·45	0·32
Al_2O_3	13·28	12·25	13·07	11·78
Fe_2O_3	3·38	3·23	2·59	3·96
FeO	3·54	3·92	0·43	0·15
MnO	0·15	0·14	0·04	0·05
MgO	0·89	0·52	0·35	0·12
CaO	3·10	2·40	1·19	0·21
Na_2O	3·95	3·57	3·23	3·15
K_2O	3·86	4·19	5·36	5·18
H_2O^+	0·23	1·52	0·61	0·68
H_2O^-	0·15	0·31	0·30	0·26
P_2O_5	0·34	0·36	0·16	0·03
CO_2	n.f.	n.f.	n.f.	n.f.
F	n.d.	n.d.	0·14	n.d.
	100·09	100·15	100·11	100·10

n.f., not found; n.d., not determined.

Key to analyses

1 Chiwonje type (DW 98)—from the Main Granophyre escarpment west of the Chiwonje complex. Analyst: J. R. Baldwin.
2 Gezani microgranite (LM 215)—from the Chadutu Hill north of Gezani Dip. Analyst: M. H. Kerr.
3 Red Granophyre (C 437)—from the Hlomela's Hill, north-east Masukwe complex. Analyst: M. H. Kerr.
4 Red Granophyre (LM 87)—from Damabwe Pan, Southern Mateke Uplands. Analyst: M. H. Kerr.

(vii) *Chemistry.* New chemical and spectrographic analyses of rocks from the Main Granophyre intrusion are presented in tables 25 and 26.

(*b*) *Granitic and granophyric rocks of the ring complexes*

In the province as a whole the acid rocks exhibit considerable uniformity, and, since the many separate intrusive phases which have been distinguished differ from each other mainly in very minor textural and compositional features, it is more convenient to give a generalized account of their petrography.

(i) **General textural characters.** Those rocks in which a large proportion of the groundmass is made up of quartz-feldspar micropegmatite are designated granophyres, although many of the granites also contain small amounts of micropegmatite.

Porphyritic rocks are common, the phenocrysts almost always being perthites, little larger than the groundmass crystals in coarsely crystalline types. The phenocrysts often become distinctive only in the chilled edges of individual intrusions or in small dyke or vein offshoots. This can be of immense value in the field as a means of distinguishing phases. The Drusy granophyre and Dembe granophyre of the Dembe–Divula–Masukwe area, for example, are both leucocratic, highly granophyric, rocks, difficult to distinguish in hand-specimen. The former, however, chills to a feldspar-phyric felsite whereas the latter chills to a quartz porphyry. The groundmass of the chilled granophyric rocks is usually spherulitic to some degree, phenocrysts, if present, acting as centres for the spherulitic crystallization. It is a characteristic of many phases of both granite and granophyre, however, to become pegmatitic at intrusive contacts. Bands of pegmatite, usually consisting of large perthite and quartz crystals and often opening as miarolitic cavities, are often found alined parallel to the contact and anything from a few inches to a few feet away from it.

Table 26. New spectrographic analyses of rocks from the Main Granophyre intrusion

specimen no. ...	LM 215 (Gezani microgranite) (p.p.m.)	C 437 (Red Granophyre) (p.p.m.)	LM 87 (Red Granophyre) (p.p.m.)
Ba	> 2000	1800	> 2000
Li	< 5	10	< 5
Rb	—	~ 200	—
Sr	200	90	45
Be	< 10	< 3	< 10
Co	< 10	10	< 10
Cr	40	~ 10	20
Ga	30	15	25
La	< 100	90	< 100
Mo	8	< 10	4
Nb	120	40	100
Ni	< 10	9	< 10
Pb	25	17	18
V	19	18	< 10
Y	100	60	110
Zr	1100	500	900

Analysts: Miss J. M. Rooke and Mrs A. M. Fisher.

Amongst the granites there is no sign that grain-size is related to outcrop area. This may be partly due to the fact that many of the larger expanses of outcrop represent comparatively thin sub-horizontal sheets, e.g. possibly the Wusaka microgranite of Divula, and part of the Gombi granite in the Chiwonje complex, but is also partly due to unknown causes. The coarsest granite in the Dembe area, for example, makes up only a relatively small plug (Jevani Hill).

Textures vary considerably in the granitic rocks but in general they have a tendency to be inequigranular with quartz crystals generally smaller than feldspars. Granophyric textures are also somewhat variable as certain intrusions tend to contain regular, micrographic, intergrowths and others have more lobate, irregular, textures. The Main Granophyre and the Drusy granophyre can be distinguished in the Masukwe area partly by this criterion, the former containing the irregular type of micropegmatite.

In the granophyric rocks certain general features of the order of crystallization are worthy of mention. Feldspars, and occasionally quartz, phenocrysts crystallize first and are followed by micropegmatitic intergrowths the units of which are centred on the phenocrysts. Irregular, radiating, micropegmatite masses result, often exceptionally fine-grained in contact with the phenocrysts and becoming more coarsely intergrown further away. The later stages of crystallization frequently show a tendency towards a more granitic or microgranitic texture. Hence, in general contrast to the micropegmatite-bearing basic rocks, there is little evidence that the quartz-orthoclase intergrowth represents the final phase of crystallization.

(ii) **General mineralogical characters.** *Granites.* The majority of the granitic rocks show a considerable uniformity of mineralogy (see table 27) and are composed of a small amount of ferromagnesian minerals (usually less than 5 %), a variable but usually small amount of plagioclase, mainly oligoclase, a high proportion of microperthite, and a moderately large amount of quartz. The accessory minerals are commonly magnetite, zircon and fluorite, while epidote, allanite, apatite and sphene are somewhat less common. Fluorite, in particular, may be abundant, occasionally making up as much as 1 % of the rock.

The most common ferromagnesian mineral is biotite, occurring in brown and green varieties and frequently associated with minor amounts of green hornblende. The Mateke and Divula Granites contain hornblende as the main ferromagnesian constituents, but in the latter case there is a considerable amount of alteration to biotite. Certain granites, e.g. the Masukwe granite, contain virtually no ferromagnesian minerals.

Plagioclase is usually present as sub-hedral to euhedral crystals and in a majority of cases has a composition in the range An_{20-30}. Andesine is present in some phases, e.g. in the Divula granites (An_{30-45}) and in the Sabi granite of Mutandawhe. The amount of plagioclase is very variable even within a single type. The Masukwe granite usually contains less than 1 % while the most plagioclase rich rocks (Sabi granite) contain up to about 20 %. The majority of phases carry from 3 to 10 % of separate plagioclase crystals. The plagioclase is mainly well twinned and rarely zoned to any extent. Alteration to sericite is common as is mantling by K-feldspar. Not infrequently the mantle appears to be at least partly of replacement origin.

The common potash feldspar of the granites is a turbid, somewhat reddened, microperthite showing generally vein-like, exsolution lamellae of albite or oligoclase, occasionally of almost sub-microscopic fineness. Patch perthites are also occasionally well developed. The microperthite crystals are usually sub-hedral but are present as euhedral phenocrysts in certain phases, where they are generally little larger than groundmass crystals, e.g. Marumbe granite. In composition the host-crystals are probably mainly orthoclase ($2V_x$ in the range 60° to 80°) but it is not uncommon to find small, clear, patches within perthite crystals which have $2V_x$ in the range 40° to 50°. These may be suspected of being remnants of a high temperature feldspar (? anorthoclase), the original mineral to crystallize, now largely represented by exsolution microperthite.

Quartz crystallizes somewhat later than the feldspars in the majority of the granites. In the case of the Sabi granite, however, it is present as rounded hexagonal dipyramids which probably represent original phenocrysts.

TABLE 27. AVERAGE MODAL ANALYSES AND DISTINGUISHING FEATURES OF THE GRANITES FROM THE LATE-KARROO RING COMPLEXES

(volume %)

complex ...	Marumbe	Mateke	Dembe–Divula			Masukwe		Mutandawhe					Chiwonje		
rock type ...	Marumbe granite	Mateke granite	porphyritic biotite granite	Divula granite	Dembe granite	Masukwe granite	East Hill granite	Sabi granite	Drift porphyry	Masunji granite	Lou-pangwan granite	Monkey Hill granite	Gombi granite	Chikwaka granite	Chiwonje granite
	(1)*	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
no. of analyses averaged ...	4	3	4	20	2	6	1	5	2	5	5	5	5	5	5
quartz	35·7	30·4	37·7	33·2	37·4	34·9	30·3	37·4	26·8	18·9	22·7	29·7	33·3	33·2	31·0
perthite and orthoclase	36·7	60·3	51·9	55·1	58·9	63·1	67·7	42·5	58·8	60·2	59·3	51·5	48·4	53·1	48·5
plagioclase	24·5	2·4	6·8	7·5	1·0	0·1	—	17·4	8·7	13·1	15·6	15·2	15·1	12·6	16·8
hornblende	—	3·3	—	0·8	0·2	—	—	—	—	3·2	0·4	—	tr.	tr.	tr.
biotite	2·4	1·1	3·5	1·3	0·6	0·1	—	2·1	5·7	3·6	0·4	4·6	2·6	1·0	3·3
ore	0·5	1·7	0·9	1·3	1·8	1·7	1·3	0·1	0·1	1·0	0·3	0·1	tr.	tr.	tr.

Accessory minerals include zircon, fluorite, allanite, apatite, calcite, epidote, sericite and sphene.

* *Key to distinguishing features*

(1) Coarse-grained; xenomorphic granular texture; occasionally porphyritic or medium-grained.

(2) Medium-grained inequigranular granitic texture. Dark minerals in aggregates. Slight development of micropegmatite.

(3) Fine-grained granitic texture; feldspar phenocrysts biotite prominent.

(4) Medium-grained, micrographic in part. Occasional orthoclase phenocrysts. Rounded quartz, no chilling.

(5) Fine-grained granitic, rounded quartz (not prominent). Inequigranular quartz and feldspar intergrowth.

(6) Inequigranular granitic; very low colour index; no phenocrysts; slight development of micropegmatite; becomes pegmatitic marginally.

(7) Same as Masukwe granite.

(8) Quartz crystals occur as dihexahedra. No hornblende. Fine-grained marginally.

(9) Distinctly porphyritic phenocrysts form 25 % of the rock.

(10) Syenitic looking on account of low quartz content. Coarse to medium-grained. Inequigranular.

(11) Fine to medium-grained contains both biotite and hornblende in low proportions.

(12) Relatively high proportion of quartz. No hornblende. Coarse-grained. Pegmatite developed marginally.

(13) Coarse grained; subrounded quartz crystals. Interstitial micropegmatite.

(14) Distinctly porphyritic. Phenocrysts form 5 to 20 %. Groundmass very fine-grained.

(15) Medium-grained. Contains druses.

Table 28. Average modal analyses and distinguishing features of the granophyres and microgranites from the late-Karroo ring complexes

(volume %)

complex ...	Northern Ring			Dembe–Divula							Masukwe				
rock type ...	ring-dyke porphyry			Elephant grano-phyre	Mawanga granophyre		micro-granite dykes	Dembe grano-phyre	Divula grano-phyre	Wusaka Pan micro-granite	Cause-way micro-granite	Drusy grano-phyre	Central Hills granophyres		Tomu grano-phyre
	por-phyry	porphy-ritic micro-granite	buff micro-granite		south area	north area							marginal ring-dyke	core	
	(1)*	(2)	(3)	(4)	(5)		(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
no. of analyses averaged ...	5	3	3	2	6	3	4	5	4	5	7	2	1	2	1
quartz	24·7	24·5	34·2	43·6	47·1	36·0	40·3	41·7	39·7	41·1	28·8	37·3	30·0		37·0
perthite and orthoclase	44·5	44·2	28·8	52·7	48·9	47·1	47·0	54·6	45·1	47·2	52·5	56·5		76·0	59·5
plagioclase	13·4	16·6	17·7	1·6	1·0	13·6	8·3	1·2	7·3	8·3	12·5	3·5	64·3	12·1	2·0
hornblende	0·6	5·4	7·3	—	—	—	—	0·1	—	—		—	4·4	4·0	—
biotite	—	—	1·3	tr.	tr.	tr.	0·9	0·4	0·8	0·7	2·7	0·1	—	—	1·7
pyroxene	6·5	4·3	2·8	0·8	0·5	—	0·5	—	—	—		—	—	—	—
olivine	0·2	—	—	—	—	—	—	—	—	—	—	—	—	—	—
ore	6·9	3·4	5·1	0·7	1·0	2·0	1·3	1·4	1·5	0·9	2·5	1·1	0·5	3·6	0·6

Accessory minerals include epidote, sericite, muscovite, sphene, zircon, apatite.

* *Key to distinguishing features*

(1) Porphyritic; no quartz phenocrysts; contains fayalite, very fine-grained groundmass.

(2) Micrographic or micropegmatitic groundmass; resorbed phenocrysts; no fayalite.

(3) Porphyritic; plagioclase biotite and hornblende phenocrysts. Micropegmatitic groundmass.

(4) Medium-grained. Pink feldspar phenocrysts. Slightly drusy. Marginally chilled.

(5) Very fine-grained; partly spherulitic. Occasional feldspar phenocrysts.

(6) Microgranitic. Non-porphyritic.

(7) Medium- to fine-grained; feldspar, magnetite, and rounded quartz phenocrysts. Chilled margins.

(8) Fine-grained. Non-porphyritic; slightly drusy.

(9) Microgranitic. Euhedral feldspar phenocrysts. Rounded, glassy quartz characteristic.

(10) Porphyritic; albite phenocrysts; groundmass microgranitic or occasionally granophyric.

(11) Fine-grained; many druses; plagioclase phenocrysts but no quartz; pegmatitic marginally.

(12) Xenolithic; non-porphyritic.

(13) Very similar to the Main (Red) Granophyre.

(14) Texture variable from coarsely granitic to coarsely granophyric.

Microgranites and granophyres. These rocks are generally mineralogically similar to the granites (see table 28) except in their ferromagnesian minerals and in their occasional content of small euhedral phenocrysts of probable anorthoclase, best developed in the Drusy Granophyre. These are, as in the small remnant patches in the granites, characterized by a low $2V_x$ (approximately 40°). Stereograms show the optic orientation to be typically triclinic. In addition, it should be noted that the feldspar intergrown with quartz in the granophyres is not orthoclase but microperthite. Amongst the ferromagnesian minerals biotite is much less common than in the granites, its place being taken by pyroxene, hornblende and, occasionally, fayalite.

These minerals have been studied particularly in the Ring-Dyke Porphyry of the Northern Ring complex, the only known occurrence of fayalite-bearing rocks in the province. In this intrusion textures vary from highly to moderately porphyritic and phenocrysts, consisting of plagioclase, pyroxene and rare fayalite, are best preserved in the more chilled porphyritic varieties.

The groundmass is extremely fine-grained (0·01 to 0·02 mm) but holocrystalline, and almost entirely made up of quartz and orthoclase with occasional scattered granules of magnetite and pyroxene. Apatite is the only ubiquitous accessory mineral.

The phenocrysts all show some degree of resorption or conversion to later members of their reaction series. The plagioclase is slightly zoned and has a narrow sodic rim grading outwards into orthoclase which is frequently continuous with that of the groundmass. The pyroxene is invariably embayed and corroded, is often full of magnetite granules, and is sometimes slightly altered marginally to hornblende. Rarely this hornblende is itself replaced by chlorite. The fayalite crystals are small, much corroded, usually completely rounded, and surrounded by a mantle of iron-ore which is often slightly oxidized to hematite. Few crystals of fresh olivine remain and the mineral is usually replaced by serpentine or fibrous anthophyllite. Magnetite shows little signs of change although it is occasionally overgrown by a second generation of magnetite crystallized during the hypabyssal stage. Although occurring in small amounts, the fayalite has distinctive and constant optical characters. It is colourless, often stained slightly brown by oxidation of the iron-ore which almost invariably rims the crystals. It has a $2V_x$ of 27° and refractive index $N_Y = 1{\cdot}816 \pm 0{\cdot}004$ which coirespond with a composition of $Fa_{80}Fo_{20}$.

The common pyroxene of the intrusion is a pale green ferro-augite, which is slightly pleochroic in grain form but not noticeably so in thin-section. It has optical characters: $2V_z = (a)$ 48°, (b) 54°, $C \wedge Z$ approx. 46°; $N_Y = 1{\cdot}707 \pm 0{\cdot}002$. The optic axial angles quoted are the average from (*a*) pyroxenes from porphyritic micrograniticvarieties, and (*b*) pyroxenes from porphyries (more chilled varieties). The difference indicates a slightly variable composition in different parts of the intrusion. The compositions corresponding to these optics are (*a*) Ca 47 %, Mg 31 %, Fe 32 %; (*b*) Ca 52 %, Mg 28 %, Fe 30 %. Very little difference in refractive indices can be observed, and the compositional variation seems to be Ca, varying with respect to Mg and Fe.

Clinopyroxene has also been observed in a few specimens of the Causeway microgranite (Masukwe complex), and in the buff microgranites of the Northern Ring complex, where it is optically similar to that found in the Ring Dyke Porphyry. It also occurs in the Elephant and Mawanga granophyre dykes of the Dembe–Divula complex. In the majority

Table 29. New chemical analyses of acid intrusive rocks of the ring complexes

specimen no. ...	N 379 (%)	M 6 (%)	C 366 (%)	F 7884 (%)	C 265 (%)	753 (%)	V 325 (%)	C 104 (%)
SiO_2	66·07	69·69	71·42	72·60	73·07	73·51	75·08	75·75
TiO_2	0·82	0·40	0·48	0·34	0·31	0·22	0·22	0·14
Al_2O_3	13·74	14·60	13·36	12·89	13·12	13·05	12·33	11·69
Fe_2O_3	3·58	2·09	1·86	1·34	1·23	1·98	1·06	1·77
FeO	3·13	1·39	1·16	1·52	1·27	0·88	0·68	0·49
MnO	0·14	0·06	0·04	0·05	0·03	0·02	0·02	0·02
MgO	0·90	0·52	0·79	0·35	0·22	—	0·21	0·01
CaO	3·45	1·48	1·23	1·07	0·96	1·07	0·93	0·55
Na_2O	3·57	3·71	3·33	3·88	3·35	3·46	3·15	2·87
K_2O	3·85	5·29	5·45	5·46	5·75	5·58	5·88	5·51
H_2O^+	0·33	0·42	0·37	0·46	0·31	0·15	0·26	0·56
H_2O^-	0·17	0·24	0·20	0·07	0·25	0·13	0·16	0·42
P_2O_5	0·25	0·08	0·09	0·09	0·23	0·05	0·03	0·25
CO_2	n.f.	n.f.	n.f.	0·18	n.f.	n.f.	n.f.	n.f.
F	n.d.	n.d.	0·12	tr.	0·16	n.d.	n.d.	0·09
	100·00	99·97	100·10	100·30	100·26	100·10	100·01	100·12

n.f., not found; n.d., not determined.

Table 30. New quantitative spectrographic analyses of acid intrusive rocks of the ring complexes

specimen no. ...	N 379 (p.p.m.)	C 366 (p.p.m.)	F 7884 (p.p.m.)	C 265 (p.p.m.)	753 (p.p.m.)	V 325 (p.p.m.)
Ba	1400	1800	600	500	1000	450
Li	10	5	25	40	8	20
Rb	~ 150	130	~ 100	250	~ 300	250
Sr	250	150	65	60	60	55
Be	< 3	< 3	6	—	< 3	< 3
Cr	~ 10	30	10	55	12	< 10
Ga	16	19	35	30	20	18
La	200	85	120	~ 85	50	85
Mo	< 10	< 3	< 3	~ 3	< 10	~ 3
Nb	70	45	100	120	90	100
Ni	8	< 3	< 10	—	10	< 3
Pb	11	12	30	—	5	18
V	50	15	< 3	14	< 5	< 3
Y	80	50	70	30	85	55
Zr	550	250	300	250	250	250
Cu	—	—	—	~ 20	14	—

In all samples: Ge, 30; Cd, 30; Co, 10; Sc, 30. Analysts: Miss J. M. Rooke and Mrs A. M. Fisher.

Key to analyses presented in tables 29 and 30

specimen no.	rock type	locality	chemical analysis by
N 379	Fayalite porphyry	Northern Ring complex, Makudegwa Hill	E. Padget
M 6	Causeway microgranite (slightly contaminated)	Masukwe complex	E. Padget
C 366	Causeway microgranite (uncontaminated)	Masukwe complex	M. H. Kerr
F 7884	Biotite granite	Marumbe complex	M. H. Kerr
C 265	Divula granite	south-west Divula complex	M. H. Kerr
753	Granite	Marangudzi ring dyke	J. R. Baldwin
V 325	Biotite granite	east side of Divula complex	J. R. Baldwin
C 104	Dembe granophyre	south-west Masukwe complex	M. H. Kerr

of specimens of microgranite and granophyre, however, any original pyroxene or olivine has been replaced by irregular aggregates of chlorite, hornblende, biotite and ore. It would probably be true to say, however, that the original ferromagnesian mineral was probably pyroxene in most of the finer-grained acid rocks.

(iii) **Chemical and spectrographic analyses.** During the course of the present work several chemical and spectrographic analyses of the acid intrusive rocks have been made. These are presented in tables 29 and 30. The geochemistry of the Karroo igneous rocks as a whole is discussed in a later section.

IX. Geochemistry

1. *The basic rocks*

(*a*) *Introduction*

The geochemical study of the basic igneous rocks of the Nuanetsi Igneous Province has proved to be one of the most interesting aspects of the current work, largely because previous geochemical work on rocks of this natuie in Southern Africa has been almost confined to the Karroo dolerites of South Africa (e.g. Walker & Poldervaart 1949) and has hardly touched upon the Karroo basalts. With a larger number of analyses available it is now possible to make a preliminary study of the latter group, though, as will be seen, this tends mainly to define problems requiring further study, although certain new petrogenetic conclusions may be suggested.

In addition to the new chemical analyses which have been presented in earlier sections 14 partial analyses of basalts have been carried out to determine TiO_2, Na_2O and K_2O contents. The literature has also yielded numerous analyses of basalts and allied rocks from the Lebombo monocline, the Zoutpansberg and the Sabi–Lundi region of the Nuanetsi Igneous Province.

For purposes of geochemical study the analyses were first grouped on the basis of mineralogy and field occurrence. From the full selection of analyses of basic rocks the following groups were abstracted:

(1) Gabbros of the Nuanetsi ring-complexes.

(2) Holocrystalline picritic and olivine-monzonitic rocks from the Nuanetsi area. These have apparently no extrusive equivalents and their ultrabasic nature suggests that they do not necessarily represent original liquids. Hence their treatment initially as a separate group is justified.

(3) Nepheline-bearing rocks, including some basalts showing normative nepheline.

(4) The remaining analyses represent basalts and fine-grained dyke rocks, presumably feeders. The majority of the basalts represented lie stratigraphically below the Nuanetsi and Lebombo rhyolites. A few, however, are derived from the basalts overlying the rhyolites in the Little Lebombo or are interbedded with the rhyolites in the Nuanetsi area.

This group of analyses, 28 in number, represents what will be referred to as the Tholeiite Series and includes a variety of types ranging from the true limburgites through olivine-basalts to olivine-free basalts.

(b) The Tholeiite Series

(i) *General description.* In order to afford a means of direct comparison with the Karroo dolerites, the oxide percentages of the analysed basalts have been plotted (figure 26) against the index

$$\frac{FeO+Fe_2O_3}{FeO+Fe_2O_3+MgO}\times 100$$

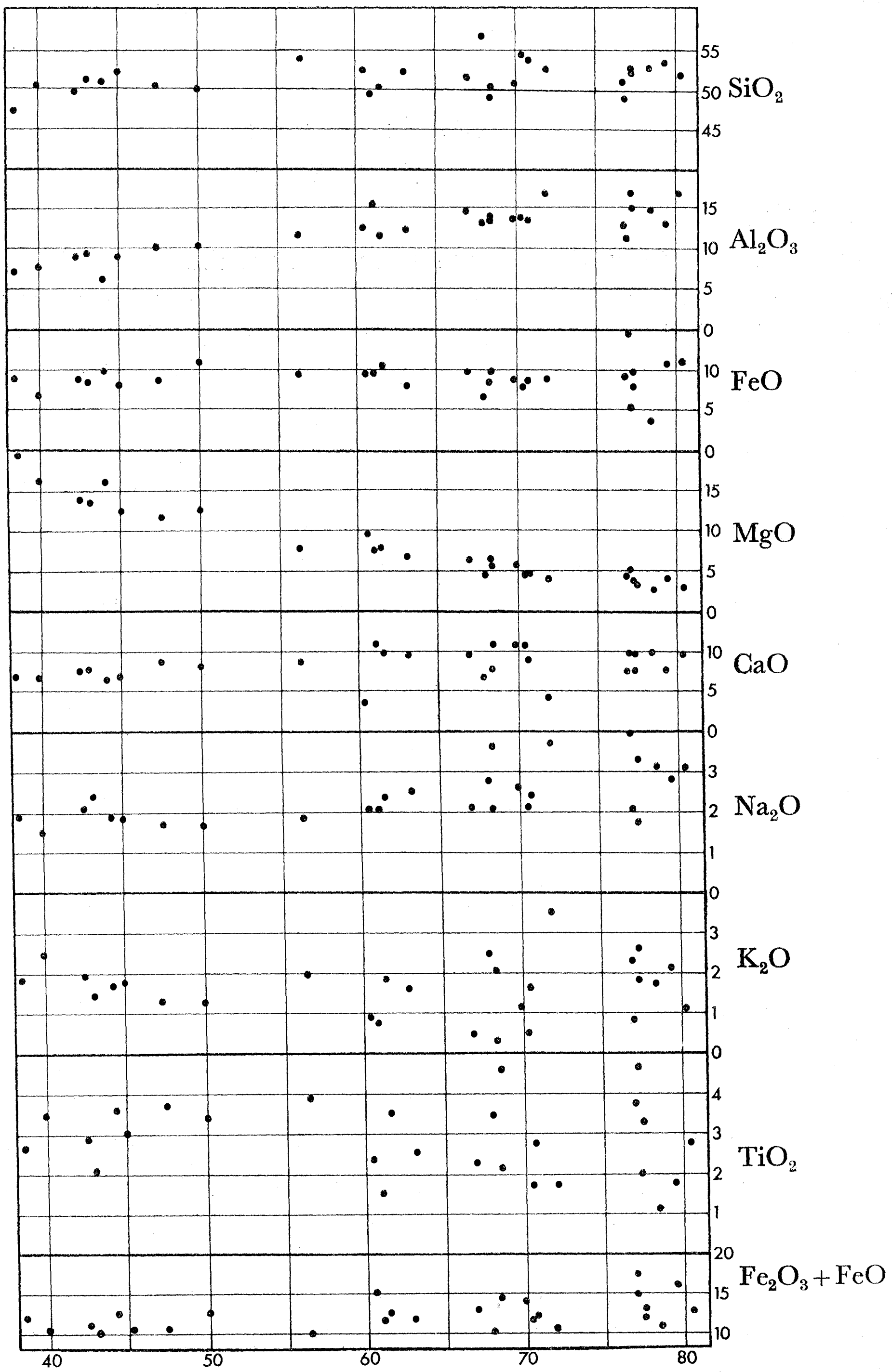

FIGURE 26. Variation diagram for the basaltic rocks of the Nuanetsi Igneous Province and the Lebombo.

as used by Walker & Poldervaart (1949). This will be referred to as the Fe/Mg index. The data used in plotting the variation diagram are given in table 31 where the available analyses have been recalculated anhydrous. The new analyses have already been given in full in table 9 and the corresponding C.I.P.W. norms in table 10. In all cases analyses are arranged in order of increasing Fe/Mg index.

The general aspect of the variation diagram shows that the basalts may be regarded, as a first approximation, as a single continuously varying series. In this respect they are very similar to the Karroo dolerites (cf. figure 26, p. 653, Walker & Poldervaart (1949)). It is clear that the distinction made in the field between the olivine-rich and olivine-free groups of basalts can only be represented by a rather arbitrary chemical division. It is convenient, however, to divide the series into high-magnesia tholeiites (Fe/Mg index less than 50) and low-magnesia tholeiites (Fe/Mg index greater than 50). Tholeiite is used only in the sense that olivine, if present, bears a reaction relation to pyroxene (e.g. see Kuno's definition in Kuno, Yamasaki, Iida & Nagashima (1957)). Generally speaking the high-magnesia tholeiites correspond with the limburgites and olivine-rich basalts and contain normative olivine though the amount of the latter is usually considerably less than the modal olivine content (see table 32). This is the justification for the use of the term tholeiite, since the reaction relationship is rarely detectable in the mineralogy of the rocks because of the high glass content. It will be seen from table 10 that hypersthene rather than olivine figures largely in the norms.

A further characteristic of the high-magnesia tholeiites is the regularity of the variation of most of the oxides when plotted against the Fe/Mg index. The low-magnesia tholeiites, in contrast, show a much more irregular behaviour.

The amount of analytical data is at present too small to justify a detailed analysis of the variation trends of particular oxides. Nevertheless, figure 26 shows certain trends which are probably significant. SiO_2 varies very little, showing perhaps a slight tendency to increase towards the low-magnesia end of the series. Al_2O_3 shows a definite gradual increase from an average value of about 8 % at the high-magnesia end of the series to an average of approximately 14 % at the low-magnesia end. FeO remains approximately constant at about 8 % throughout, whereas Fe_2O_3 is more variable. This depends on the degree of oxidation of the rocks which may be a somewhat random effect. Nevertheless, the basalts in general do show a slight tendency to be more oxidized towards the low-magnesia end of the series, e.g. $Fe_2O_3/FeO = 0{\cdot}32$ for the high-magnesia tholeiites and equals 0·45 for the series as a whole. The Karroo dolerites are considerably less oxidized and the ratio Fe_2O_3/FeO for the average rock (Walker & Poldervaart 1949, p. 649) is 0·13.

MgO decreases regularly from a little under 20 % to about 4 %. Since Fe_2O_3+FeO is approximately constant, an equally good variation diagram could be made using the MgO content by itself as an index of variation.

CaO is fairly constant at 7 to 8 % in the high-magnesia tholeiites and varies mainly between 6 and 11 % in the low-magnesia group. Na_2O shows a general increase from 2 % to 2 to 4 % but K_2O values are very scattered in the 0·5 to 3 % range. The TiO_2 content is one of the most striking features of the series, varying from 2 to 4 % in the high-magnesia group to 1 to 5 % in the low-magnesia group.

Table 31. Analyses (recalculated anhydrous) of Karroo basalt from the Nuanetsi Igneous Province, the Zoutpansberg and Lebombo areas

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SiO_2	47·44	50·59	49·84	51·19	51·05	52·15	50·79	49·93	53·98	52·40	49·14	50·16	52·14	51·53
TiO_2	2·70	3·45	2·89	3·12	3·62	3·03	3·67	3·45	3·84	2·38	1·50	3·58	2·57	2·27
Al_2O_3	7·22	8·00	9·22	9·79	6·25	9·20	10·11	10·22	11·81	12·44	15·28	11·41	12·59	14·49
Fe_2O_3	3·18	3·87	2·48	1·91	2·89	2·53	2·44	1·85	0·83	6·06	2·39	2·15	3·92	3·10
FeO	8·87	6·75	8·53	8·23	9·82	7·88	8·21	10·71	9·08	9·06	9·25	10·22	7·85	9·75
MnO	0·16	0·13	0·15	0·15	—	0·15	0·16	0·47	0·09	0·23	0·25	0·18	0·15	0·15
MgO	19·26	16·03	14·90	13·38	16·07	12·66	11·80	12·46	7·66	9·88	7·42	7·76	6·88	6·33
CaO	6·86	6·65	7·40	7·48	6·20	6·81	8·29	7·86	8·31	4·33	11·80	9·77	9·38	9·50
Na_2O	1·83	1·45	2·08	2·41	1·84	1·89	1·63	1·62	1·83	2·03	2·02	2·40	2·50	2·09
K_2O	1·91	2·52	1·99	1·48	1·73	2·79	1·35	1·26	2·02	0·89	0·76	1·85	1·61	0·48
P_2O_5	0·44	0·56	0·52	0·87	0·53	0·58	0·44	0·16	0·39	0·32	0·17	0·53	0·37	0·30
CO_2	0·10	—	—	—	—	0·03	0·97	—	—	—	—	—	—	—
	99·97	100·00	100·00	100·01	100·00	99·70	99·86	99·99	99·84	100·02	99·98	100·01	99·96	99·99
Fe/Mg index	38·5	39·8	42·5	43·1	44·2	45·1	47·4	50·0	56·4	60·5	61·1	61·5	63·1	67·0

	15	16	17	18	19	20	21	22	23	24	25	26	27	28
SiO_2	56·45	50·20	48·91	50·81	54·53	53·72	52·61	50·27	48·67	52·38	52·08	52·86	53·07	51·74
TiO_2	3·44	2·10	4·61	1·19	1·63	2·73	1·69	3·74	4·62	3·29	1·94	1·05	1·73	2·69
Al_2O_3	13·01	13·09	13·69	13·42	13·84	13·25	16·86	12·27	10·93	14·72	16·64	14·18	12·67	16·29
Fe_2O_3	3·81	4·72	4·51	5·19	3·72	3·64	1·72	5·80	2·79	3·29	4·08	7·18	5·28	1·60
FeO	6·24	9·53	8·25	8·59	7·75	8·33	8·46	8·89	14·14	9·19	7·78	3·27	10·28	10·68
MnO	0·13	0·25	0·18	—	0·22	0·14	0·10	0·17	0·23	0·13	0·14	0·17	0·24	0·24
MgO	4·72	6·60	5·92	5·94	4·79	4·92	3·96	4·41	5·03	3·66	3·46	2·84	4·03	3·00
CaO	6·68	10·98	7·66	10·78	10·68	8·82	4·05	7·45	10·11	9·73	7·40	9·76	7·47	9·29
Na_2O	2·76	2·02	3·61	2·65	2·05	2·39	3·67	3·95	2·05	1·72	3·27	3·13	2·81	3·06
K_2O	2·45	0·30	2·05	1·23	0·52	1·65	3·52	2·30	0·81	1·77	2·60	1·75	2·11	1·10
P_2O_5	0·26	0·20	0·61	0·20	0·28	0·40	1·11	0·74	0·61	0·15	0·59	0·19	0·29	0·25
CO_2	—	—	—	—	—	—	2·24	—	—	—	—	3·63	—	—
	99·95	99·79	100·00	100·00	100·01	99·99	99·99	99·99	99·99	100·03	99·98	100·01	99·98	99·94
Fe/Mg index	68·0	68·3	68·3	69·9	70·5	70·7	72·0	76·9	77·1	77·3	77·4	78·6	79·4	80·4

Key to analyses presented in table 31

number	name of rock	locality	analyst	reference
1	Limburgite	near Kloppersfontein, Kruger National Park	Geochemical Laboratories	Lombaard (1952)
2	Limburgite (LM 432)	new analysis. See table 9		
3	Limburgite (KC 37)	new analysis. See table 9		
4	Limburgite (LM 428)	new analysis. See table 9		
5	Limburgite	Zoutpansberg	H. G. Weall	Rogers (1925)
6	Olivine basalt (BR 18)	Sabi Coalfield area	P. I. Brewer	Swift *et al.* (1953)
7	Limburgite	Zoutpansberg	C. J. Liebenberg	van Eeden *et al.* (1955)
8	Limburgite	Letaba, Kruger National Park	F. Herdsman	Walker & Poldervaart (1949)
9	Basalt	Orami River, Lower Sabi, Kruger National Park	W. H. Herdsman	Lombaard (1952)
10	Dolerite basalt (62 C)	Little Lebombo, P.E.A.	—	de Assunçao *et al.* (1961)
11	Dolerite (dyke)	near Komatipoort, Eastern Transvaal	S. Parker	Lombaard (1939)
12	Limburgite (LM 434)	new analysis. See table 9		
13	Basalt (C 868)	new analysis. See table 9		
14	Basalt (DW 389)	new analysis. See table 9		
15	Olivine basalt	Limpopo River near Pafuri	E. Golding	Lightfoot (1938)
16	Dolerite basalt (I.C.)	Little Lebombo	—	de Assunçao *et al.* (1961)
17	Basalt (LM 619A)	new analysis. See table 9		
18	Dolerite (dyke)	Lebombo, Swaziland	Reinisch	J. McC. Henderson (1909)
19	Basalt (182 R)	Little Lebombo	—	de Assunçao *et al.* (1961)
20	Basalt (KC 58)	new analysis. See table 9		
21	Basalt (LM 341)	new analysis. See table 9		
22	Basalt	near Tshokane, Kruger National Park	W. H. Herdsman	Lombaard (1952)
23	Basalt (149 N)	Little Lebombo	—	de Assunçao *et al.* (1961)
24	Basalt	Chipinda Pools Lundi River	E. Golding	Lightfoot (1938)
25	Basalt (C922)	new analysis. See table 9		
26	Basalt	Cecil Mack Pass, Swaziland	Min. Res. Div. Overseas Geol. Surveys	Hunter & Urie (1958)
27	Basalt	new analysis. See table 9		
28	Glassy olivine basalt (dyke) G 676	Chiredzi River	E. P. Golding	Swift *et al.* (1953)

(ii) *Trace elements of the Tholeiitic Series.* During the present study five basalts have been analysed spectographically (see table 11). It is not proposed to discuss these analyses at present, other than to point out that the rocks in general are rather rich in Ba, Sr and Zr. If more data can be obtained in the future, the study of the variation of trace elements within the series will be possible.

TABLE 32. COMPARISON OF AMOUNTS OF MODAL AND NORMATIVE OLIVINE IN ANALYSED LIMBURGITES

specimen no.	modal olivine	normative olivine
LM 432	24·9	2·91
KC 37	24·0	13·40
LM 428	19·4	3·64
LM 434	5·7	0·97

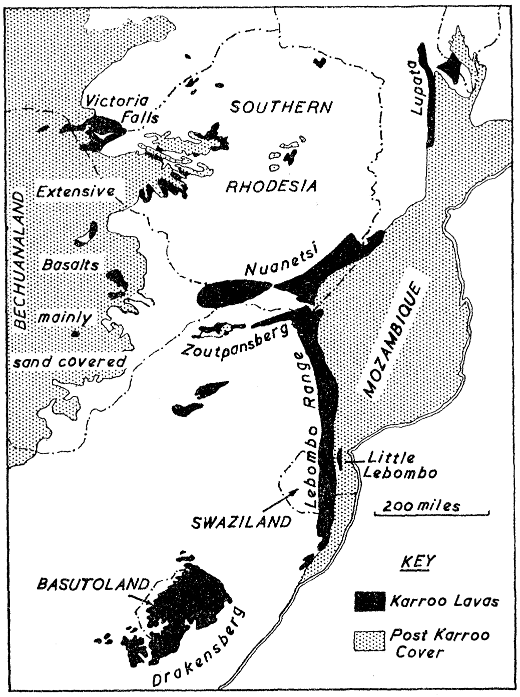

FIGURE 27. Distribution of Karroo lavas in south-eastern Africa.

(iii) *Comparison of the Tholeiite Series with Karroo basalts and dolerites from other areas* (see figure 27 for localities). For purposes of comparison the analytical data have been used as follows:

(1) Approximately equal number of analyses have been selected from the groups to be compared.

(2) As far as possible the analyses have been chosen to cover the same range of Fe/Mg index variation in each group.

The Fe/Mg index is not a completely satisfactory criterion to use but is probably as significant as any available. For any given Fe/Mg index, for example, the basalts of the Nuanetsi–Lebombo area tend to have a higher total content of Mg and Fe than the corresponding Drakensberg basalts or Karroo dolerites of South Africa. It has already been pointed out that since the total Fe content is reasonably constant, the MgO content would by itself make a good index for the plotting of variation diagrams. Comparisons of groups of analyses by the two different methods would not, therefore, give identical results. It is certain, however, that the significant differences discovered between the rocks of the main Karroo basin and those of the Nuanetsi–Lebombo area would remain substantially unchanged whichever system were used.

It has already been noted that the variation in the Tholeiite Series is broadly similar to that in the Karroo dolerites. There are, however, certain distinctive and consistent differences which can be seen by a direct comparison of the variation diagrams (figure 26 here and figure 26 in Walker & Poldervaart 1949). They can also be conveniently illustrated by a comparison of the average analyses in restricted ranges. Table 33 compares the

Table 33. Comparison of Karroo dolerites from South Africa with limburgitic lavas from the Nuanetsi area and its environs

	1	2
SiO_2	50·0	50·4
TiO_2	0·7	3·2
Al_2O_3	14·7	8·8
Fe_2O_3	1·1	2·6
FeO	9·0	8·6
MnO	0·16	0·17
MgO	12·2	14·6
CaO	9·5	7·2
Na_2O	1·9	1·8
K_2O	0·5	1·9
P_2O_5	0·1	0·5

1 Average of the 9 anhydrous analyses of Karroo dolerites with Fe/Mg indices from 39·9 to 49·4 given by Walker & Poldervaart (1949).

2 Average of the 9 anhydrous analyses of Nuanetsi Karroo basalts (limburgites) with Fe/Mg indices from 38·5 to 50·0 taken from table 31.

average of the nine analysed high-magnesia tholeiites of the Tholeiite Series with the average of the nine Karroo dolerites covering the same range of variation in Fe/Mg index (approximately 40 to 50). The differences observed between the average analyses are probably at their most significant in this range since the scatter of points is generally at a minimum here in both sets of data.

The most important differences are those of TiO_2, K_2O and P_2O_5, all of which are considerably higher in the Nuanetsi–Lebombo rocks, and Al_2O_3 which is considerably higher in the Karroo dolerites. These differences tend to disappear at the extreme low-magnesia end of the two series.

Having established that there are real differences in chemical composition between the Karroo dolerites (intrusive) of South Africa and the Karroo basalts (extrusive) of the Nuanetsi–Lebombo area the question naturally arises as to whether this is a geographical difference or whether it is due to a fundamental difference between the intrusive and the extrusive rocks. Clearly a detailed geochemical study of the Drakensberg lavas of South Africa is required to resolve this problem. The existing data, however, do tend to support the view that the difference is mainly geographical. In table 34, seven available analyses of Drakensberg lavas have been averaged after being recalculated anhydrous. These are compared with average Karroo dolerites and average Nuanetsi–Lebombo basalt analyses in the same ranges. It is clear, first, that the seven analyses are all rather similar. Secondly in almost all respects, the average composition is much more akin to an average South African Karroo dolerite than to an average Nuanetsi–northern Lebombo basalt.

TABLE 34. DRAKENSBERG BASALTS COMPARED WITH THE KARROO DOLERITES AND NUANETSI–LEBOMBO BASALTS

	1	2	3*	4	5	6	7	average of 1 to 7	9	10
SiO_2	52·09	53·38	52·42	54·67	52·35	49·80	51·05	52·25	52·94	51·56
TiO_2	0·98	0·62	0·93	0·70	0·88	0·83	1·31	0·89	1·17	2·77
Al_2O_3	13·71	16·02	16·73	15·63	15·81	16·59	15·35	15·69	15·51	12·71
Fe_2O_3	4·88	1·57	3·07	0·68	0·63	2·29	5·22	2·62	1·16	3·07
FeO	6·17	7·99	5·92	9·13	9·57	8·29	6·10	7·60	8·96	9·09
MnO	0·25	0·19	0·19	0·18	0·18	0·16	0·23	0·19	0·24	0·18
MgO	7·47	7·04	6·05	6·39	7·24	8·14	6·79	7·02	6·97	7·92
CaO	11·18	9·88	12·84	9·35	10·48	10·19	11·22	10·73	9·77	8·72
Na_2O	1·67	1·88	1·45	1·65	1·76	1·90	1·72	1·72	2·29	2·16
K_2O	1·41	0·38	0·26	1·23	0·41	1·48	0·67	0·83	0·81	1·43
P_2O_5	0·16	0·16	0·16	0·06	0·03	0·24	0·22	0·15	0·14	0·36
CO_2	—	0·89	—	0·32	0·65	—	0·01	0·27	—	—
total	99·97	100·00	100·02	99·99	99·99	99·91	99·89	99·96	99·96	99·97
Fe_2O_3 + FeO	11·05	9·56	8·99	9·81	10·20	10·58	11·32	10·22	10·12	12·16
Fe/Mg index	59·7	57·6	59·8	60·6	58·5	56·5	62·5	59·3	59·2	60·5

* Recalculated free of CO_2 because of high CO_2 content.

Key to analyses included in table 34

Analyses 1–7 recalculated anhydrous from the original references.

	locality and analyst	reference
1 basalt	Naude's Nek facing Mount Fletcher. Analyst: Geochemical Laboratories	Lombaard (1952)
2 basalt	Railway mile post 122¾. Tierkrans, Krai River, Barkly East. Analyst: W. H. Herdsman	Lombaard (1952)
3 basalt	Railway mile post 124. Tierkrans, Krai River, Barkly East. Analyst: W. H. Herdsman	Lombaard (1952)
4 basalt	Barkly East, Drakensberg. Analyst: F. Herdsman	Walker & Poldervaart (1949)
5 basalt	Roberts Gate, Drakensberg. Analyst: F. Herdsman	Walker & Poldervaart (1949)
6 basalt	Orange River above junction with Mokhotlong, Basutoland. Analyst: Deputy Master, Royal Mint, Pretoria	Stockley (1947)
7 basalt	Malibamatso River near Thakabanna's cattle post Basutoland. Analyst: Deputy Master, Royal Mint, Pretoria	Stockley (1947)

8 average of analyses 1 to 7

9 average of 7 Karroo dolerites with Fe/Mg index in the range 58·9 to 59·8. Averaged analyses taken from Walker & Poldervaart (1949, table 16).

10 average of 5 Karroo basalts from Nuanetsi–Lebombo area (nos. 9 to 13 of table 31) with Fe/Mg index in the range 56·4 to 63·1.

Hence two provinces can be approximately delimited in which the rocks of basaltic composition, irrespective of their mode of occurrence, show distinct differences.

(1) The Karroo basin, which includes the Drakensberg lavas and the majority of the Karroo dolerites so far investigated. Characteristics are high Al_2O_3, low TiO_2, K_2O and P_2O_5.

(2) The Nuanetsi–Lebombo area, characterized by high TiO_2, K_2O and P_2O_5 and by low Al_2O_3.

Many more analytical data are required before the provinces can be more accurately defined. Particularly important, relative to the relation between geochemical provinces and tectonic units, is the question of which province the basalts of the southern Lebombo in Swaziland belong to. Two analyses from this area were included in table 33 (analyses 18 and 26). Perhaps significantly, these two have the two lowest TiO_2 contents of the entire series, suggesting affinities with the Karroo basin rather than with the northern Lebombo. In contrast, however, their K_2O and Al_2O_3 contents have more affinities with the northern province. Many more analytical data are required.

TABLE 35. COMPARISON OF BASALTS FROM NUANETSI–LEBOMBO AREA WITH VICTORIA FALLS BASALTS

	1	2
SiO_2	51·63	50·53
TiO_2	2·45	2·98
Al_2O_3	13·46	13·99
Fe_2O_3	4·35	3·32
FeO	8·49	9·27
MnO	0·16	0·18
MgO	5·63	5·43
CaO	9·75	10·93
Na_2O	2·54	1·97
K_2O	1·15	0·76
P_2O_5	0·33	0·50
CO_2	—	0·06
	99·94	99·92

1 Average of 5 anhydrous analyses of Nuanetsi–northern Lebombo basalts (nos. 16 to 22 in table 31). Fe/Mg indices in range 68·3 to 70·7.
2 Average 5 basalts from the Victoria Falls area (average Fe/Mg index 69·8). Recalculated anhydrous from du Toit (1954) (analysis 43, p. 582).

As a further comparison, the general similarity, except in K_2O content, between the Nuanetsi–Lebombo tholeiites and the Karroo basalts of the Victoria Falls area should be noted (table 35). It appears from this that the Nuanetsi–Lebombo type of basalt series may have a very wide extent.

Although the Nuanetsi–Lebombo province is characterized by certain distinct chemical features there is, however, an apparent slight areal variation, involving K_2O which tends to complicate the study of the geochemical provinces. In table 35 for example it will be observed that the Nuanetsi–Lebombo average shows higher alkalis than the Victoria Falls average. This is not necessarily significant in view of the small number of analyses involved but nevertheless somewhat similar variations can be found within the Nuanetsi–Lebombo area itself. In table 36 the rocks of the Tholeiite Series are divided into those from the Nuanetsi Igneous Province and those from elsewhere in the Nuanetsi–Lebombo zone, K_2O contents being compared. It appears that the Nuanetsi rocks (both low and high magnesia tholeiites) are consistently more potassic than those of the Lebombo, though no significance can necessarily be attached to the difference observed in the average K_2O values of the high-magnesia tholeiite group, since the number of analyses is small.

(*c*) *The alkaline rocks*

Very few analytical data are at present available for the nepheline-bearing volcanic rocks of the Nuanetsi–Lebombo area and only a brief preliminary geochemical study can

TABLE 36. COMPARISON OF K_2O CONTENTS OF BASALTS FROM THE NUANETSI IGNEOUS PROVINCE WITH THOSE FROM THE LEBOMBO

Nuanetsi Igneous Province		Lebombo, etc.	
analysis no. (from table 31)	K_2O content	analysis no. (from table 31)	K_2O content
high-magnesia tholeiites		high-magnesia tholeiites	
2	2·52	1	1·91
3	1·99	5	1·73
4	1·48	7	1·35
6	2·79	8	1·26
average	2·19	average	1·55
low-magnesia tholeiites		low-magnesia tholeiites	
12	1·85	9	2·02
13	1·61	10	0·89
14	0·48	11	0·76
15	2·45	16	0·30
17	2·05	18	1·23
20	1·65	19	0·52
21	3·52	22	2·30
24	1·77	23	0·81
25	2·60	26	1·75
27	2·11		
28	1·10		
average	1·93	average	1·18

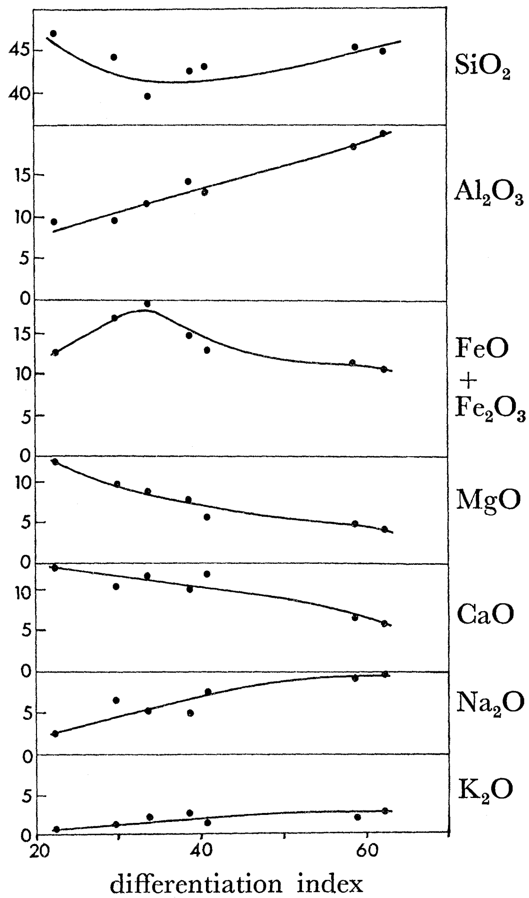

FIGURE 28. Variation diagram for the rocks of the Lower Alkaline Group.

be made. It has been found necessary to divide the group into upper and lower divisions in order to introduce an element of rationality into the oxide variations. The lower group includes the nepheline-basalts, nephelinites and ijolite from the Sabi Coalfield area, the analyses of which are given by Swift *et al.* (1953), together with a nepheline-basalt from near Kloppersfontein in the Kruger National Park (Lombaard 1952) and a nepheline-basalt from the north-eastern Zoutpansberg (Rogers 1925). The upper group consists of the

TABLE 37. ANALYSES (RECALCULATED ANHYDROUS) OF ROCKS FROM THE LOWER ALKALINE GROUP

	1	2	3	4	5	6	7
SiO_2	47·04	43·8	39·29	42·77	43·00	44·95	44·59
TiO_2	2·40	2·0	3·27	2·70	3·55	3·35	2·89
Al_2O_3	9·13	9·29	11·36	14·14	12·97	18·13	19·86
Fe_2O_3	3·92	8·98	9·11	9·97	5·74	5·92	4·47
FeO	8·79	7·8	9·11	4·50	7·05	5·15	5·59
MnO	0·17	0·16	0·25	0·21	0·17	0·36	0·37
MgO	12·25	9·2	8·65	7·58	5·10	4·52	3·88
CaO	12·50	10·2	11·39	9·94	11·89	6·07	5·32
Na_2O	2·48	6·2	5·12	4·82	7·24	8·89	9·92
K_2O	0·71	1·40	2·27	2·76	1·70	2·05	2·83
P_2O_5	0·28	0·9	0·14	0·48	1·20	0·39	0·23
total	99·67	99·93	99·96	99·87	99·61	99·78	99·95
D.I.	22·7	30·0	33·9	38·8	41·1	58·8	62·5

Key to analyses presented in table 37

	locality and analyst	reference
1 Nepheline dolerite (BR 8)	2 miles south-east of Chidumo Clinic, Chiredzi River, Sabi Coalfield. Analyst: P. I. Brewer	Swift *et al.* (1953)
2 Nepheline basalt (1667 R)	beacon E 90 north-east Zoutpansberg. Analyst: H. G. Weale	Rogers (1925)
3 Nepheline basalt (G 677)	summit of Ruwa, 1 mile north-west of Bendezi Hill, Lundi River, Sabi Coalfield. Analyst: E. P. Golding	Swift *et al.* (1953)
4 Nepheline basalt (744)	north of Kloppersfontein, Kruger National Park. Analyst: Geochemical Laboratories	Lombaard (1952)
5 Ijolite (BR 7)	3 miles south-west of Malilongwe, east bank of Chiredzi River, Sabi Coalfield. Analyst: P. I. Brewer	Swift *et al.* (1953)
6 Nephelinite (G 679)	1 mile south-east of Lipfuli, 3 miles east-north-east of Lundi River, Sabi Coalfield. Analyst: E. P. Golding	Swift *et al.* (1953)
7 Nephelinite (G 678)	Summit of Bendezi, Lundi River, Sabi Coal-field. Analyst: E. P. Golding	Swift *et al.* (1953)

basaltic, basanitic, tephritic and phonolitic rocks analysed by Assunçao, Coelho & Rocha (1961). These are all from the Little Lebombo and the eastern side of the Lebombo range itself, and lie stratigraphically above the Karroo rhyolites. A great deal of importance should be attached to the future study of this group and its counterpart in the Lupata Gorge area on the Zambezi, since compared with the sub-rhyolite lavas they are still imperfectly known.

(i) *The Lower Alkaline Group.* It has been found that a reasonably smooth variation diagram can be made if oxides are plotted against the differentiation index (D.I.) as proposed by Thornton & Tuttle (1960). This index consists of the sum of normative quartz, feldspars, excluding anorthite, and feldspathoids. A diagram almost as satisfactory is obtained by plotting against the index $(CaO \times 100)/(CaO + Na_2O)$. The Fe/Mg index proves valueless as the range of variation in this ratio is comparatively small.

The D.I. variation diagram is shown in figure 28, and the data used for its construction in table 37. With the amount of data at present available it seems reasonable to suppose that the Lower Alkaline Group may well form a continuous series and it may be expected that when additional data are obtained it will be possible to define the series more closely. At present, the variation appears to be from a basanitic type of rock (analysis 1, table 37) to a nephelinitic type (analysis 7, table 37).

In terms of normative mineralogy (see table 38) this corresponds to the gradual elimination of olivine and plagioclase feldspar and a decrease in the amount of pyroxene, coupled with a marked increase in the amount of feldspathoid, mainly nepheline.

TABLE 38. C.I.P.W. NORMS OF THE ANALYSES PRESENTED IN TABLE 37

	1	2	3	4	5	6	7
or	3·89	7·78	—	15·86	10·01	11·72	16·74
ab	16·77	1·05	—	3·30	1·57	15·78	4·21
an	11·40	—	1·16	8·54	—	3·06	1·12
ne	1·99	20·16	23·35	19·60	29·54	31·33	41·58
lc	—	—	10·50	—	—	—	—
ac	—	11·09	—	—	3·70	—	—
wo	—	—	3·62	—	3·60	—	—
di { *wo*		17·98		14·79			
di { *en*	37·87	12·50 } 34·44	34·48	12·79 } 27·58	33·69	18·21	19·54
di { *fs*		3·96		—			
fo	14·67	6·86 } 9·10	6·57	3·87 } 3·87	—	1·70	3·03 } 3·03
fa		2·24		—			—
mt	5·57	6·96	13·18	7·11	6·26	7·63	6·25
hm	—	—	—	4·76	—	0·47	—
il	4·56	3·65	6·08	4·98	6·69	6·23	5·32
ap	0·67	2·02	—	1·11	2·69	0·93	—
pr	0·40	—	—	—	—	—	—
cc	—	—	—	0·27	—	—	—
Z	—	—	—	—	—	0·36	—
H_2O	2·55	4·40	1·23	3·49	2·94	2·60	

As a further point, it should be noted that the rocks are generally much more oxidized than the basalts. The average Fe_2O_3/FeO ratio of the seven analyses given in table 37 is 1·00 as compared with the average of 0·45 for the tholeiitic series.

(ii) *The Upper Alkaline Group.* Comparatively few of these rocks have so far been analysed. Assunçao *et al.* (1961) have published six analyses of basalts, tephrites and a phonolitic tephrite, all of which may be assigned to this group. In addition the olivine-basalt analysed for Young (1920) from a borehole on the Goba railway in Mozambique may also be included. There is considerable variation in the available analyses but it is not, at the present stage, possible to attempt to define a variation series. However certain chemical features distinguish many of the rocks from those of the Lower Alkaline Group. These are:

(1) Generally higher content of SiO_2. All the analyses fall in the range of 46 to 50% SiO_2 (hydrous analysis values).

(2) Generally high content of Al_2O_3, reaching over 20% in two specimens.

Certain rocks which may perhaps be included with the Upper Alkaline Group are the rare intrusions of nepheline-syenite. A new analysis of one of these occurrences, that of the central part of the Marangudzi complex, is given in table 39. Two rocks analysed for Young (1920), one a syenite, the other a nepheline syenite porphyry, show generally similar chemistry and were collected in the vicinity of Pessene in Mozambique. Both these rocks and the nepheline-syenite from Marangudzi are presumably more equivalent in age to the Upper Alkaline Group than to the Lower.

TABLE 39. ANALYSIS OF A NEPHELINE-SYENITE FROM THE CENTRAL PART OF THE MARANGUDZI COMPLEX

	%
SiO_2	46·82
TiO_2	0·52
Al_2O_3	23·46
Fe_2O_3	2·22
FeO	4·16
MnO	0·15
MgO	1·39
CaO	5·23
Na_2O	7·56
K_2O	6·13
H_2O^+	1·22
H_2O^-	0·13
P_2O_5	0·24
CO_2	0·48
total	99·71

Analyst: M. H. Kerr.

(d) Picritic and olivine-monzonitic rocks

These have been described petrographically in an earlier section where they were included with the olivine-rich lavas and limburgitic minor intrusives. As a rock-group they are of particular interest because of their tendency to contain alkali-feldspar (probably anorthoclase) as a late crystallization product. In this they appear to be unique amongst the rocks of the province. More detailed work, however, is needed on the group before a proper assessment of their petrological significance can be made. Four chemical analyses together with their C.I.P.W. norms have been presented in table 12. Analyses 1 and 2, the picrites from Shamandali and the polygonal dyke 9 miles south-east of Nyasumi, probably represent a common rock type and are very similar chemically to the most basic types of Karroo dolerite described by Walker & Poldervaart (1949). Analyses 3 and 4 represent the more alkaline rocks of the picritic suite.

(e) Gabbroic rocks of the ring complexes

Chemical analyses of gabbros have been presented in tables 15 and 17. Compared with the tholeiitic basalts, into which they are intruded, the gabbros are rich in Al_2O_3 and CaO, and poor in TiO_2, K_2O and P_2O_5. In terms of normative mineralogy they tend to be considerably richer in feldspar, particularly the anorthite molecule, than the basaltic rocks, and poorer in ferromagnesian minerals and ore minerals.

In many respects, the high Al_2O_3 and the low TiO_2, K_2O and P_2O_5, the gabbros are more similar to the Karroo dolerites than they are to the basalts of the Nuanetsi area. They differ somewhat from the former in their higher content of CaO.

TABLE 40. ANALYSES (RECALCULATED FREE OF H_2O AND CO_2) OF ACID LAVAS AND INTRUSIVE ROCKS FROM THE NUANETSI IGNEOUS PROVINCE AND THE LEBOMBO AREA

	1	2	3	4	5	6	7	8	9	10	11	12	13
SiO_2	62·15	62·27	62·46	62·98	64·21	64·86	66·40	66·46	66·76	66·98	67·20	67·23	67·87
TiO_2	0·68	1·52	0·63	0·35	1·09	0·52	0·82	0·95	0·85	0·91	0·83	0·63	0·69
Al_2O_3	17·47	13·35	14·90	16·31	10·85	15·97	13·81	13·32	11·85	14·95	14·41	14·16	11·60
Fe_2O_3	2·00	6·03	4·17	1·53	5·50	4·27	3·60	3·39	5·93	6·20	5·07	6·18	5·96
FeO	3·74	5·06	1·81	4·50	2·51	1·25	3·15	3·55	1·35	0·45	0·77	0·15	1·62
MnO	0·12	0·18	0·06	0·15	0·09	n.d.	0·14	0·15	0·12	0·08	0·04	0·14	0·08
MgO	0·65	0·51	2·13	0·33	1·16	1·19	0·90	0·89	0·61	0·25	0·66	0·23	0·48
CaO	2·36	5·24	4·12	2·06	2·42	4·36	3·47	3·11	2·16	2·04	1·71	0·72	1·72
Na_2O	4·51	2·11	4·98	5·38	4·99	5·55	3·59	3·96	5·82	2·83	3·92	4·78	5·33
K_2O	6·17	3·20	4·68	6·28	6·93	2·02	3·87	3·87	4·33	5·19	5·20	5·63	4·52
P_2O_5	0·17	0·53	0·07	0·13	0·24	n.d.	0·25	0·34	0·21	0·12	0·18	0·15	0·12
F	—	—	—	—	—	—	—	—	—	—	—	—	—
totals	100·02	100·00	100·01	100·00	99·99	99·99	100·00	99·99	99·99	100·00	99·99	100·00	99·99

	14	15	16	17	18	19	20	21	22	23	24	25
SiO_2	68·12	68·23	68·53	68·72	68·77	69·01	69·13	69·27	69·33	69·56	70·17	70·29
TiO_2	0·63	0·67	0·66	0·53	0·62	0·60	0·61	0·59	0·56	0·48	0·40	0·43
Al_2O_3	14·82	12·46	11·18	12·96	13·10	11·03	10·73	12·86	13·48	12·21	14·70	12·81
Fe_2O_3	2·76	3·29	6·74	3·39	4·61	3·69	5·88	3·62	4·04	5·14	2·10	4·85
FeO	3·06	3·99	0·66	2·40	1·46	3·15	0·89	2·68	2·67	1·07	1·40	1·54
MnO	0·16	0·14	0·01	0·15	0·15	0·11	0·17	0·15	0·09	0·13	0·06	0·05
MgO	0·63	0·53	—	0·68	0·91	2·27	0·78	0·73	0·55	tr.	0·53	0·22
CaO	2·12	2·44	1·78	2·22	2·39	2·66	1·91	2·23	2·42	1·63	1·49	1·73
Na_2O	3·72	3·63	5·81	3·61	3·57	3·44	5·09	3·67	3·45	3·97	3·74	3·46
K_2O	3·83	4·26	4·50	4·17	4·20	3·45	4·72	4·02	3·23	5·72	5·33	4·61
P_2O_5	0·14	0·37	0·12	0·15	0·18	0·14	0·10	0·16	0·17	0·09	0·08	tr.
F	—	—	—	—	—	0·08	—	—	—	—	—	—
totals	99·99	100·01	99·99	98·98	99·96	99·63	100·01	99·98	99·99	100·00	100·00	99·99

	26	27	28	29	30	31	32	33	34	35	36	37
SiO_2	71·08	71·28	71·58	71·76	72·39	72·41	72·62	72·74	72·77	72·80	72·83	72·90
TiO_2	0·61	0·69	0·65	0·48	0·38	0·45	n.d.	0·23	0·45	0·28	0·48	0·34
Al_2O_3	12·45	16·14	11·55	13·62	13·10	12·75	12·22	12·85	13·18	12·29	11·30	12·94
Fe_2O_3	3·19	2·72	2·21	1·87	1·88	3·00	2·12	2·69	2·61	3·22	4·56	1·35
FeO	2·82	0·52	2·83	1·17	2·41	1·16	2·81	0·09	0·43	0·95	0·74	1·53
MnO	0·13	—	0·11	0·04	0·05	0·10	n.d.	0·06	0·04	0·23	0·05	0·05
MgO	0·23	0·05	tr.	0·79	0·16	0·40	0·62	0·59	0·35	0·42	0·19	0·35
CaO	5·22	1·44	2·22	1·24	0·79	1·45	2·53	2·24	1·20	1·54	1·69	1·07
Na_2O	2·19	2·46	5·18	3·35	3·82	3·42	2·54	2·20	3·26	3·28	3·07	3·90
K_2O	1·93	4·66	3·57	5·48	5·02	4·81	4·54	6·27	5·41	4·87	5·02	5·48
P_2O_5	0·13	0·03	0·09	0·09	tr.	0·06	n.d.	0·04	0·16	0·12	0·07	0·09
F	—	—	—	0·12	—	—	—	—	0·14	—	—	—
totals	99·98	99·99	99·99	100·01	100·00	100·01	100·00	100·00	100·00	100·00	100·00	100·00

	38	39	40	41	42	43	44	45	46	47	48	49
SiO_2	72·96	73·29	73·64	73·90	74·34	74·37	74·75	75·33	75·39	75·83	76·39	77·05
TiO_2	n.d.	0·31	0·22	0·36	0·01	0·30	0·32	0·35	0·22	0·29	0·14	0·35
Al_2O_3	12·95	13·16	13·07	11·69	14·51	11·74	11·92	11·55	12·38	14·30	11·79	10·38
Fe_2O_3	3·61	1·23	1·98	4·51	0·66	3·07	4·01	2·56	1·06	0·82	1·79	2·62
FeO	0·84	1·27	0·88	0·11	0·81	0·73	0·15	0·28	0·68	0·59	0·49	0·22
MnO	n.d.	0·03	0·02	0·14	0·09	0·03	0·05	—	0·02	0·04	0·02	tr.
MgO	0·48	0·22	—	0·22	0·09	0·82	0·12	—	0·21	0·06	0·01	tr.
CaO	2·00	0·96	1·07	1·06	0·65	0·53	0·21	0·81	0·93	0·94	0·56	1·04
Na_2O	2·63	3·36	3·47	2·95	3·90	2·24	3·19	2·79	3·16	2·08	2·89	3·13
K_2O	4·52	5·77	5·59	4·98	4·93	6·13	5·24	6·15	5·90	5·04	5·57	5·20
P_2O_5	n.d.	0·23	0·05	0·06	tr.	0·05	0·03	0·18	0·03	—	0·25	tr.
F	n.d.	0·16	—	—	—	—	—	—	—	—	0·09	—
totals	99·99	99·99	99·99	99·98	99·99	100·01	99·99	100·00	99·98	99·99	99·99	99·99

Key to analyses presented in table 40

index no.	rock type and specimen no.	locality and analyst	reference
1	Nordmarkite (DW 70)	Mutandawhe complex. New analysis, see table 20	—
2	Rhyolite (75M)	Mozambique	Assunçao *et al.* (1961)
3	Alkali trachyte (25)	Mozambique (near Boane)	Assunçao *et al.* (1961)
4	Nordmarkite (F 7891)	Marumbe complex. New analysis. See table 20	—
5	Hyperalkaline rhyolite (29C)	Mozambique	Assunçao *et al.* (1961)
6	Pitchstone	Impamputo River about 10 miles east of Namahacha, Mozambique. Analyst: McA. Johnston	Young (1920)
7	Ring-dyke porphyry (N 379)	Northern Ring complex. New analysis. See table 29	—
8	Main Granophyre (Chiwonje type) (DW 98)	Lower Sabi valley. New analysis. See table 25	—
9	Hyperalkaline rhyolite (37M)	Mozambique	Assunçao *et al.* (1961)
10	Rhyolite (85R)	Mozambique	Assunçao *et al.* (1961)
11	Rhyolite (65)	Mozambique	Assunçao *et al.* (1961)
12	Rhyolite porphyry (LM 242)	Nyavasikana Pools, Maose River. New analysis. See table 13	—
13	Hyperalkaline rhyolite. (44A)	Mozambique	Assunçao *et al.* (1961)
14	Rhyolite	3 miles east-south-east of Nyetane Mission, Swaziland. Analyst: Min. Res. Div., Overseas Geol. Surveys	Hunter & Urie (1958)
15	Hornblende-microgranite (LM 215)	Chadutu Hill. New analysis. See table 25	—
16	Hyperalkaline rhyolite (41)	Mozambique	Assunçao *et al.* (1961)
17	Rhyolite	$1\frac{1}{2}$ miles south-west of Nyetane Mission, Swaziland. Analyst: Min. Res. Div., Overseas Geol. Surveys	Hunter & Urie (1958)
18	Rhyolite	2 miles east of Tikuba store, Swaziland. Analyst: Min. Res. Div., Overseas Geol. Surveys	Hunter & Urie (1958)
19	Main Granophyre	Lundi Gorge. Analyst: E. Golding	Lightfoot (1938)
20	Hyperalkaline rhyolite (33)	Mozambique	Assunçao *et al.* (1961)
21	Rhyolite	$3\frac{1}{2}$ miles south-west of Buchanan beacon, Swaziland. Analyst: Min. Res. Div., Overseas Geol. Surveys	Hunter & Urie (1958)
22	Glassy rhyolite	Indulawane Hill, Lebombo, Natal	Prior (1910) taken from Hall (1938)
23	Rhyolite (17)	Mozambique	Assunçao *et al.* (1961)
24	Microgranite (Causeway Phase) (M 6)	Masukwe complex. New analysis. See table 29	—
25	Rhyolite	Railway milepost $55\frac{3}{4}$, Komatipoort. Analyst: W. H. Herdsman	Lombaard (1952)
26	Rhyolite (127C)	Mozambique	Assunçao *et al.* (1961)
27	Rhyolite (9N)	Mozambique	Assunçao *et al.* (1961)
28	Hyperalkaline rhyolite (19C)	Mozambique	Assunçao *et al.* (1961)
29	Microgranite (Causeway Phase) (C 366)	Masukwe complex. New analysis. See table 29	—
30	Granophyre	Muntshes Hill, near Sabi River. Kruger National Park. Analyst: W. H. Herdsman	Lombaard (1952)
31	Granophyre	4 miles north-west of Stegi, Swaziland. Analyst: Min. Res. Div., Overseas Geol. Surveys	Hunter & Urie (1958)
32	Pitchstone	Road from Ischlesche to du Toits, east slopes of Lebombos, Mozambique. Analyst: Reinisch	McC. Henderson (1909)
33	Massive rhyolite tuff, (LM 466)	Nuanetsi River. New analysis. See table 13	—
34	Main Granophyre (Red Granophyre type) (C 437)	Masukwe complex. New analysis. See table 25	—
35	Rhyolite	2 miles south-east of Groenpan, Swaziland. Analyst: Min. Res. Div., Overseas Geol. Surveys	Hunter & Urie (1958)
36	Ignimbrite (LM 389)	Tchovi Ridge, Maose River. New analysis. See table 13	—
37	Biotite granite. (F 7884)	Marumbe complex. New analysis. See table 29	—
38	Rhyolite (quartz-porphyry)	Between Manzinyama River. and Lebombo summit at 2200 ft., Mozambique. Analyst: Reinisch	McC. Henderson (1909)
39	Divula Granite (C 265)	Dembe–Divula complex. New analysis. See table 29	—
40	Granite (753)	New analysis. See table 29	—
41	Rhyolite (174R)	Mozambique	Assunçao *et al.* (1961)
42	Rhyolite	Manuan Creek, Lebombos, Natal	Prior (1910)
43	Rhyolite	Buffalo Bend, Nuanetsi River. Analyst: E. Golding	Lightfoot (1938)
44	Main Granophyre (Red Granophyre type) (LM 87)	Damabwe Pan. New analysis. See table 25	—
45	Rhyolite (56R)	Mozambique	Assunçao *et al.* (1961)
46	Biotite-granite (V 325)	Dembe–Divula complex. New analysis. See table 29	—
47	Rhyolite (193R)	Mozambique	Assunçao *et al.* (1961)
48	Granophyre (Dembe Phase) (C 104)	Masukwe complex. New analysis. See table 29	—
49	Rhyolite (188R)	Mozambique	Assunçao *et al.* (1961)

Spectrographic determination of the trace elements in the four analysed gabbros from the Northern Ring complex have been given in table 16. It is not proposed to discuss the analyses in detail but certain points are worth special mention. First, compared with the basalts (see table 11) the gabbros are distinctly poor in Ba, Sr and Zr, the low values of Ba and Sr being probably connected with the low K content. Secondly, the gabbros appear

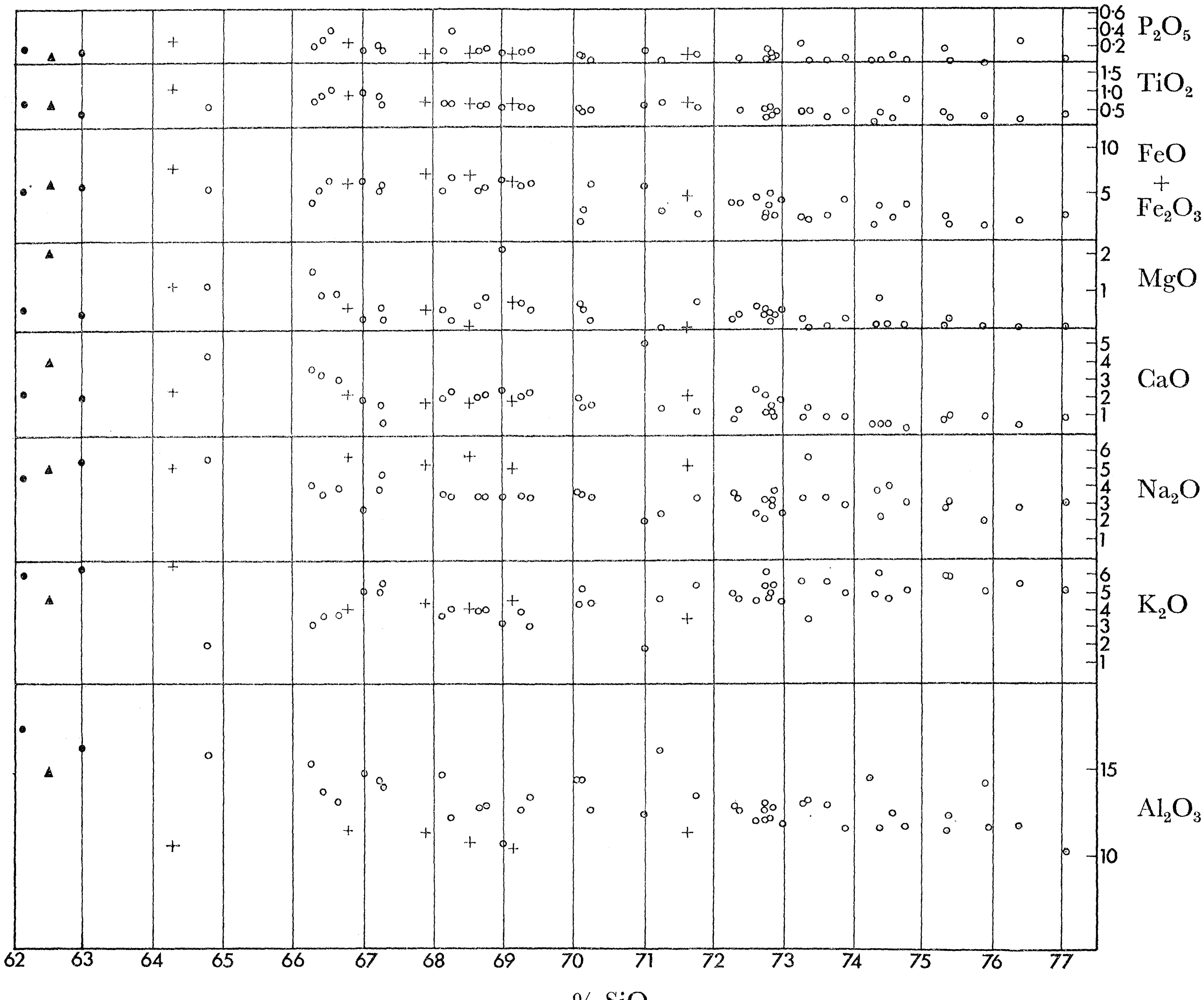

FIGURE 29. Variation diagram for the Rhyodacite–Rhyolite Series.

to be moderately rich in Cu, a point of interest in view of the copper mineralization in the Limpopo area. Cu contents have so far not been determined for the basalts except for the one sample listed in table 11.

2. *The acid rocks*

The total number of analyses of acid rocks from the Lebombo–Nuanetsi area is now approximately 50 and it is possible to study their chemical variation and to attempt a significant classification. The recent invaluable contribution of Assunçao *et al.* (1961) in which 17 new analyses of Lebombo rhyolites were included, made clear the existence of hyperalkaline rhyolites, a previously unsuspected type in the area. Eighteen new analyses of nordmarkite, granophyres, granites and rhyolites have already been presented (see

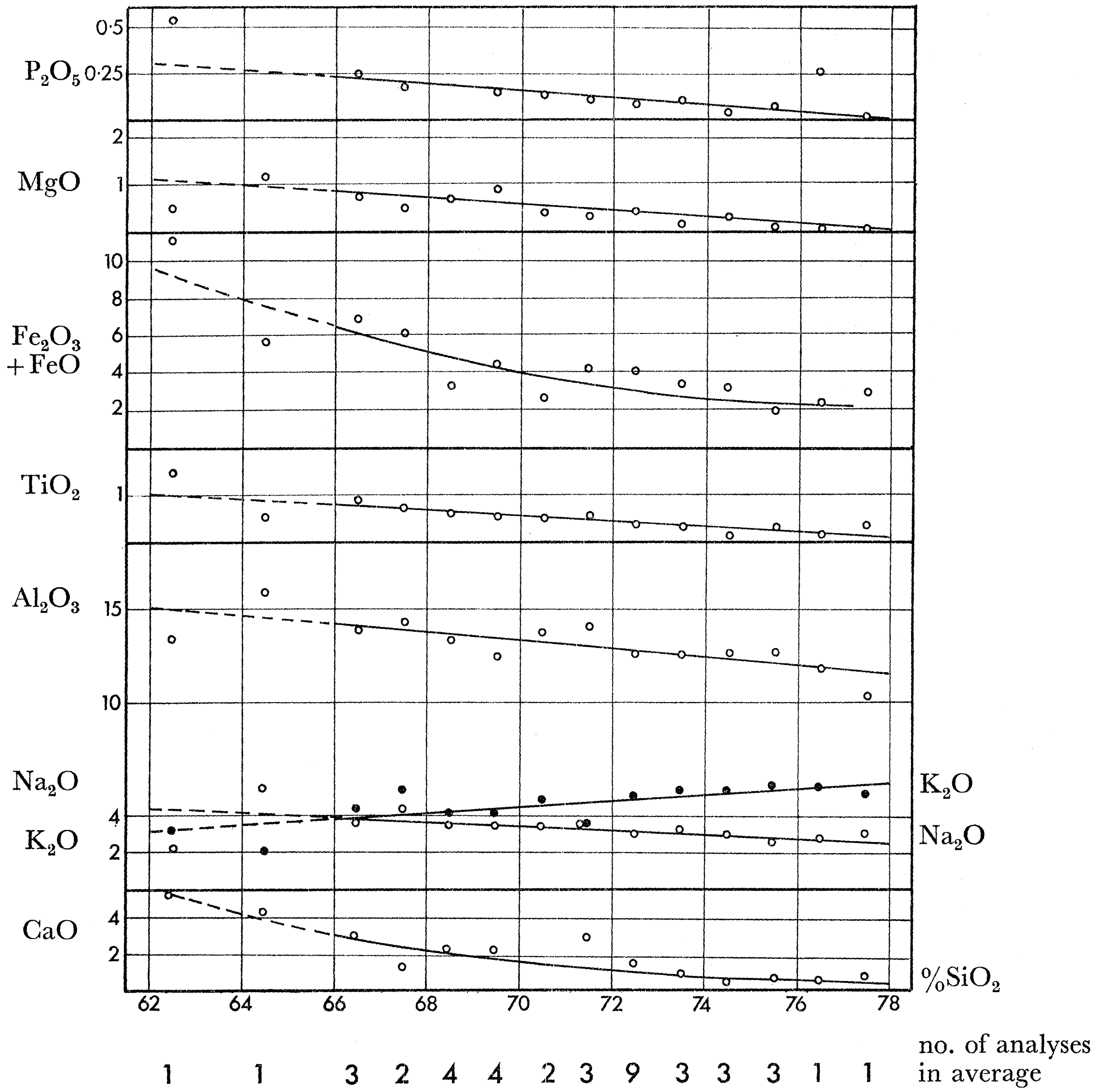

FIGURE 30. Smoothed variation diagram for the Rhyodacite–Rhyolite Series.

tables 13, 20, 25 and 29) and a further 15 analyses are available in the literature. The following grouping can now be adopted:

The Rhyodacite–Rhyolite Series. This is a continuous variation series and includes the majority of the analysed rhyolites. Included in the series are the intrusive granites and granophyres since these are chemically indistinguishable from the rhyolites.

The hyperalkaline rhyolites as defined by Assunçao. These rocks are characterized by low Al_2O_3 and high Na_2O with resultant normative acmite.

The nordmarkites and similar rocks. Two nordmarkites from the Nuanetsi Igneous Province have been analysed and tend to be chemically distinct from the granitic and rhyolitic rocks. An alkali trachyte analysed by Assunçao *et al.* (1961) appears to be the nearest extrusive equivalent.

The new and already existing analyses (recalculated free of H_2O and CO_2) are given in table 40. The data in the latter table were used to plot the variation diagram of oxides against SiO_2 (figure 29). The diagram demonstrates the reality of the Rhyodacite–Rhyolite Series and also that the granites and granophyres are chemically indistinguishable from the extrusives. The hyperalkaline rhyolites fall in a fairly distinct field on both the Al_2O_3 and Na_2O curves. The nordmarkite rocks, in their high K_2O content, also show a lack of correspondence with the Rhyodacite–Rhyolite Series.

TABLE 41. COMPARISON OF K_2O CONTENTS OF ACID ROCKS FROM THE NUANETSI IGNEOUS PROVINCE WITH THOSE FROM THE LEBOMBO

Nuanetsi Igneous Province		Lebombo	
analysis no. (table 40)	K_2O content	analysis no. (table 40)	K_2O content
33	6·27	30	5·02
34	5·41	31	4·81
36	5·02	32	4·54
37	5·48	35	4·87
39	5·77	38	4·52
40	5·59	41	4·98
43	6·13	42	4·93
44	5·24	45	6·15
46	5·90	47	5·04
48	5·57	49	5·20
average	5·64	average	5·01

Note: Only rocks with more than 72 % SiO_2 are included since in the lower SiO_2 range only one Nuanetsi rhyolite has been analysed. Hence the comparison in the lower range would be mainly between Nuanetsi intrusive rocks and Lebombo extrusive rocks. It would not therefore necessarily form a good basis for comparison.

A smoothed variation diagram of the series is given in figure 30 to illustrate the essential chemical characters. The diagram was constructed by taking the average value of each oxide percentage in each 1 % SiO_2 division. Average values were then plotted at the centre of the 1 % SiO_2 division. The number of values averaged in each case is noted at the foot of the figure, giving some guide to reliability of each point. The rocks of the series may be divided into rhyodacites, with less than 70 % of SiO_2 and rhyolites with more than 70 % SiO_2. Reference to table 29 shows that the majority of the acid intrusive rocks belong to the rhyolitic group.

Within the Rhyodacite–Rhyolite Series itself there is less opportunity to study areal chemical variation than is the case with the Karroo basalts. Nevertheless, although the acid rocks are practically confined to the Lebombo and Mateke–Sabi monoclines it is of extreme interest to note that those of the Nuanetsi Igneous Province are somewhat more potassic than those from the Lebombo (see table 41). In the study of the basalts it was established that within the Tholeiite Series there was a distinctly higher content of K_2O in the Nuanetsi rocks than in those from elsewhere. Evidently the more potassic nature of the volcanics in this area is a feature not only of the basalts but of the rhyolites and their associated intrusives as well.

There was also some suggestion in the basalt analyses that the lavas from Swaziland were comparatively low in TiO_2. This cannot be amplified by a study of the acid rocks. The TiO_2 curve in figure 30 is remarkably smooth and no significant areal variations can be detected.

Thirteen new spectrographic analyses of acid rocks from the Nuanetsi Province have been presented in tables 14, 20, 26 and 30. Discussion is deferred until more data become available.

X. Petrogenesis

1. *Introduction*

At the present time there exists no comprehensive account of the petrogenesis of the Karroo igneous rocks of southern Africa. Even now with a considerably larger amount of field evidence, petrological, and geochemical information available the synthesis presented here must be regarded as speculative and no more than a working hypothesis. There are, however, sufficient data to justify a critical consideration of some existing petrogenetical hypotheses and to explore further possibilities.

2. *Tectonics and volcanism*

A useful starting point in the discussion of Karroo petrogenesis is the question of the relationship between tectonism and volcanism. Southern Africa is in many respects an ideal terrain for this type of study since the lavas are found in a variety of tectonic settings, and, either as a result of warping or erosion, are exposed in full stratigraphic sequences in numerous localities over a wide area.

Broadly, the possible relations between tectonism and volcanism may be summarized as follows:

(1) Volcanism is the parental element, tectonic processes being secondary effects. Volcanism here is used in a narrow sense referring to the extrusion and intrusion of igneous rocks but excluding any possible deep seated thermal disturbances which may give rise to them.

(2) Tectonic processes are parental to volcanism.

(3) Tectonic and volcanic processes both result from a third process.

This may be called the 'fraternal' hypothesis, following the usage of van Bemmelen (1956).

None of these hypotheses, it is clear, can be rejected outright, and the question is mainly one of assessing their relative importance.

The first hypothesis, that of 'parental volcanism', finds little support in Southern Africa, because of the age-relations between the volcanic and the tectonic processes. In a large number of cases it can be demonstrated that the main tectonic movements during the Karroo period were initiated long before any igneous rocks appeared. The subsequent volcanic activity may have intensified such movements but, clearly, volcanism, in the narrow sense, cannot originally have caused them.

The Nuanetsi syncline, which, as has been mentioned in an earlier section, is regarded as a possible volcano-tectonic structure, may be exceptional. This supposition is based on the apparent lack of dependence on Basement structure of the location of the syncline, a feature in which it is unique amongst the neighbouring late-Karroo structures.

The second hypothesis, that of 'parental tectonism' has long been a most popular view. Tectonic depression of the crust, for example, may transport potentially fusible crustal layers into regions of sufficiently high temperature to cause magma formation. Additionally, tension may reduce confining pressure and so cause melting.

This hypothesis would seem ideally suited to explain the volcanic features of the Lebombo–Nuanetsi zone, since tensional stresses were much in evidence during the extrusion of the lavas. There was, moreover, a considerable depression of the Mozambique Block and the base of the Nuanetsi syncline. These features, tensions coupled with depression of parts of the crust, might well account for the production, for example, of the Lebombo rhyolites, by remelting of the granitic crustal-layer. There are several reasons, however, why this hypothesis cannot be regarded as a complete answer to the problems of Karroo magma generation.

First, although during the Karroo period the Lebombo–Nuanetsi zone was subjected to the tectonic effects mentioned above, the tectonic environment of much of Southern Africa where lavas were also produced, though in less quantity and variety, was quite different. Considerable thicknesses of basalt were erupted in the Karroo and Kalahari basins, areas which were not subjected to the violent tensions and warpings of the Lebombo–Nuanetsi zone. It is difficult to see a tectonic cause behind this aspect of the Karroo volcanicity. The floor of the Karroo basin, it is true, was considerably depressed during the pre-volcanic sedimentation, possibly by as much as 35000 ft. (du Toit 1954). Nevertheless, many non-volcanic sedimentary basins contain this thickness of deposits, and it seems unlikely that the basining could have been the sole cause of magma generation. As an alternative it appears more likely that the basalts of the central, relatively undeformed, part of southern Africa were produced as a result of a period of abnormally high heat-flow from depth.

If this is so, the volcanic activity of the Lebombo–Nuanetsi zone similarly need not be related directly to tectonic processes. An interesting question is raised here, namely the distribution and intensity of the postulated heat-flow. One possibility is that it was essentially uniform over a large area, in which case tectonic deformation may be regarded as an *additional* factor, directly responsible for determining the intensity of the volcanicity at any point.

On the other hand, the heat-flow may have been much greater along such lines as the Lebombo–Nuanetsi zone than it was elsewhere. In this case the intensity of the volcanism is not related to tectonic *processes* but is directly related to the disposition of tectonic *units*, in this case, the block-structure of the crust. In this view, the relationship between tectonic processes and igneous activity is distinctly fraternal, since there is coincidence in time and space between essentially vertical earth-movement and an excessive heat-flow from depth. Igneous activity is then controlled tectonically in its locale, but not in its intensity.

3. *Petrogenetical aspects of the major variations in Karroo igneous rocks*

General accounts of Karroo volcanic activity have been given by du Toit (1954) and, more briefly, by Walker & Poldervaart (1949).

One of the most important points made by the latter authors (p. 687) is their division of Southern Africa into three zones (western, eastern and central) on the basis of the composition of the Karroo lavas. The *western zone* includes the igneous areas of South-west

Africa; the *eastern zone* comprises the Lebombo, Nuanetsi and Lupata areas. These two zones are similar in containing a great variety of lavas ranging from basalts to rhyolites and alkaline rocks. The *central zone* includes the Karroo basin, the isolated basalt areas of Springbok Flats, and the area of eastern Bechuanaland and western Southern Rhodesia where the Karroo basalts are found extensively round the edge of the Kalahari basin. The central zone differs markedly from the western and eastern zones in containing only basaltic lavas. The lavas are also generally rather thinner in this zone than in the east.

Walker & Poldervaart use the term 'highly differentiated' to describe the variable volcanic rocks of the western and eastern zones; the term 'undifferentiated' is applied to the rocks of the central zone.

The differentiation in question, however, stems from du Toit (1929) who visualized a basaltic 'magmatic wedge' along the Lebombo, which became differentiated, 'partly through assimilation and partly through gravitative influences', to give the acid magma of the rhyolitic lavas. This speculation, as du Toit himself remarked, was in essential agreement with the facts. Nevertheless, the process must remain as an hypothesis which is justified largely by analogy with the processes of differentiation proved to have been operative in numerous, well-studied, basic intrusive bodies.

In the previous section an attempt has been made to group the volcanic rocks according to their chemical characters. The distribution of the various groups in the central and eastern zones of southern Africa must now be considered in more detail. First, the common element in all the volcanic areas is the low-magnesia type of tholeiitic basalt. As far as the evidence goes, the more basic, magnesian, tholeiites have a more restricted occurrence and are found mainly in the Nuanetsi area, the Zoutpansberg, and in the northern part of the Lebombo. They tend to occur towards the base of the volcanic succession. Similar rocks are found amongst the Karroo dolerites of South Africa and in a few other places, but they are not quantitatively important. Secondly, the rhyolites are entirely confined to the immediate area of the Lebombo monocline and its continuation northwards. Intrusive rocks of a similar composition are only found in large quantities in the Nuanetsi area. In addition, it must be noted that the alkaline lavas are similarly restricted in occurrence. A characteristic of the Lower Alkaline Group is its generally low position in the stratigraphic sequence. Indeed, in numerous localities in the Lundi–Sabi region and the northern end of the Kruger National Park, nephelinites and nepheline-bearing rocks are found at or near the base of the volcanic succession. The picritic rocks too, are apparently somewhat restricted since they represent a comparatively rare type of Karroo dolerite in South Africa but a comparatively common type in the Nuanetsi Igneous Province.

Thus, the great diversity of rock types is found very closely confined to the line along which late-Karroo deformation has been most intense. In contrast, the uniformly basaltic, relatively thin, successions are found in the comparatively undeformed central zone comprising the Karroo basin and the area to the north. An hypothesis seeking to interpret the major features of the variation in the deformed zones in terms of differentiation of a basaltic magma has the difficult task of explaining how it was that differentiation took place only in these zones and not elsewhere. These difficulties are avoided if it is postulated that several primary magmas were generated in the deformed zones whereas only one was generated in the undeformed central area. This implies some form of tectonic control of magma generation, general aspects of which have been discussed in the preceding section.

In southern Africa during the Karroo volcanic episode there is evidence of the existence of primary basaltic magma and primary granitic magma. The existence of the former has been generally recognized and the magma has been thought of (e.g. see Turner & Verhoogen 1960) as typically tholeiitic, in that it gave rise to slightly oversaturated basalts. Magmas are generally considered as being primary if they are of widespread occurrence, and are not obviously descended from another magma in the same area. It is because of the last point that basaltic magmas have frequently been recognized as primary, and acid magmas have frequently not. In southern Africa, instances of the ability of tholeiitic magmas to produce an acid residuum are not uncommon (e.g. see Walker & Poldervaart 1949, and above in this work) and as a result there has been a tendency to regard the Lebombo rhyolites, similarly, as differentiates of basaltic magma. The present authors consider this to be unlikely in view of the tectonic setting of the Lebombo.

The differentiation theory fails to explain the existence of enormous amounts of acid lava only in certain tectonically distinct zones, when the allegedly parental basaltic magma had a much more widespread occurrence. It seems more likely that the acid magma was formed by the melting of granitic crustal rocks in areas where heat flow from depth was greatest, or where tectonic relief of confining pressure was most marked.

In addition to primary basaltic and rhyolitic magmas, it is also possible that primary ultrabasic (picritic) magma existed in the Nuanetsi region during the Karroo period. Further work is needed on this topic, particularly the detailed examination of the bodies of fine-grained picrite, such as the Bezi dyke, which are found in the Mateke area. These rocks are exceptionally fine-grained and look as if they may have crystallized from liquids of ultrabasic composition.

4. *Petrogenesis of the basalts*

In considering the petrogenesis of the Lebombo–Nuanetsi basalts it is convenient to take the variation diagram of oxide percentages against the Fe/Mg index (figure 26) as a starting point.

Reference to the diagram will show that the variation in most oxides is approximately linear between values of the Fe/Mg index of 40 and 65. Above 65 a considerable scatter of points appears and it will, therefore, be convenient to consider these analyses separately.

The scattered analyses indicate that the variation in the least magnesian of the tholeiitic rocks is no longer adequately represented by the Fe/Mg index. Attempts have been made to replot these analyses against other indices, but no significant improvements have resulted. Hence several independent factors must influence the variation in these rocks.

One of these is obviously a differentiation controlled by the separation or concentration of basic plagioclase crystals. Feldspar-phyric basalts are common in the upper part of the basalt sequence in the Nuanetsi Igneous Province and several cases of inhomogeneity have been found. A flow, for example, was found to have a very irregular distribution of phenocrysts and several dykes have non-porphyritic margins grading into porphyritic centres. There is little doubt in these cases that the phenocrysts are of intratelluric origin and inhomogeneities of this type clearly indicate that some differentiation involving the phenocrysts has occurred.

Glomeroporphyritic pyroxene-phyric basalts are also common amongst the low-magnesia tholeiites and these suggest a further possible mechanism involving separation or concentration of pyroxene crystals, which, however, has not been demonstrated in the field.

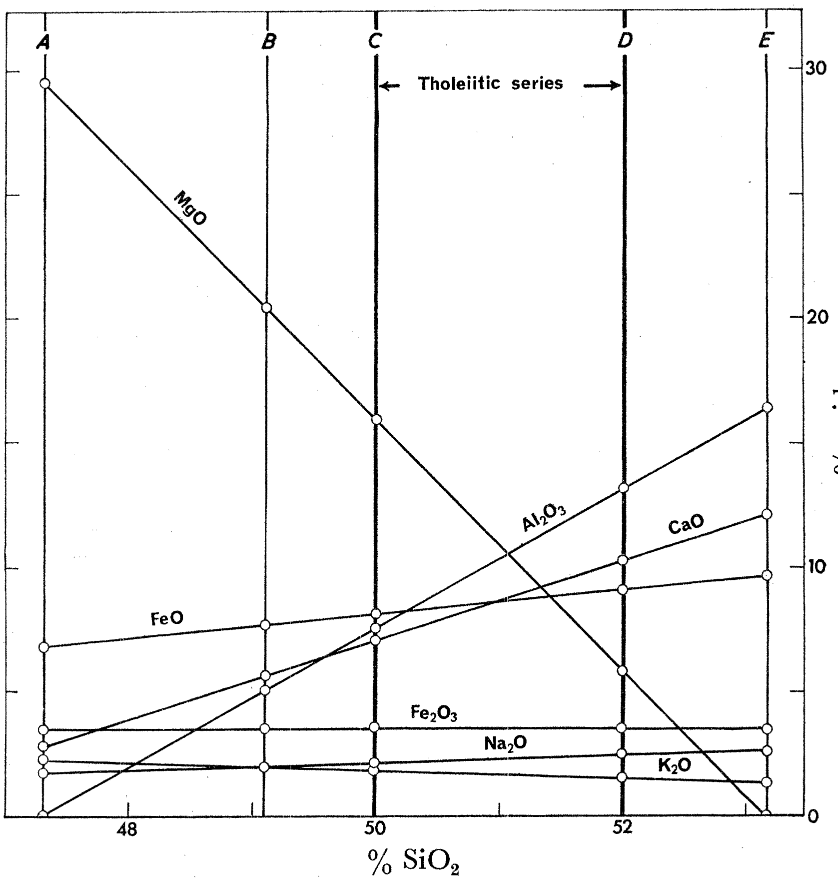

FIGURE 31. Addition and subtraction diagram for the Tholeiite Series.

For the linear range (Fe/Mg index = 40 to 65), an addition and subtraction diagram (figure 31) of the type used by Bowen (1928) has been constructed in order to explore possible mechanisms of differentiation. The Tholeiite Series is represented by the vertical lines *C* and *D* with their connecting oxide-lines. *C* represents an average high-magnesia tholeiite (Fe/Mg index = 40) and *D* represents an average low-magnesia tholeiite of Fe/Mg index = 65).

The figure shows that it is possible to convert the magnesium-rich magma, *C*, into the magnesium-poor magma, *D*, by the removal of any composition represented by a vertical line falling between *A* and *C*. *A* is the limiting case where Al_2O_3 falls to zero. If volumes are considered, it may be noted that 43% of composition *A* must be removed and, for example, 69% of composition *B*. The normative mineralogy of compositions *A* and *B* are given in table 42 with the norm of magma *C*. A separating composition lying between *B* and *C* is inherently less likely than one between *A* and *B* because of the larger volume which it would be necessary to remove. The table shows that whatever the separating composition is, it must be extremely rich in MgO and must contain approximately 4% of total alkalis. An alkaline picrite, such as that analysed in table 12 is the nearest approach to a possible composition which is actually represented by rocks occurring in the area.

In view of the alkaline nature of the necessary separating composition it is difficult to interpret the differentiation in terms of the actual minerals of the rocks. The high-magnesia tholeiites characteristically contain phenocrysts of olivine and clino-pyroxene. Hypersthene is very rare, and plagioclase, found mainly in varieties of the low-magnesia tholeiite, is not present as phenocrysts in the more magnesian rocks. With olivine and pyroxene to choose from as possible separating phases, the removal of considerable amounts of alkalis from the magma, by crystal settling, seems unlikely. A further difficulty lies in the fact that olivine phenocrysts are the earliest crystallization products, but the postulated separating mixtures contain considerably more pyroxene than they do olivine.

TABLE 42. ANALYSES AND NORMS OF POSSIBLE SEPARATING MIXTURES COMPARED WITH THE AVERAGE HIGH-MAGNESIA THOLEIITE (C)

approximate chemical compositions

	A	*B*	*C*
SiO_2	47·3	49·1	50
TiO_2	3·7	3·2	3
Al_2O_3	—	5·0	7·5
Fe_2O_3	3·5	3·5	3·5
FeO	6·8	7·6	8
MgO	29·5	20·5	16
CaO	2·8	5·1	7
Na_2O	1·5	1·9	2
K_2O	2·3	2·0	1·8

approximate norms

	A	*B*	*C*
or	—	12	11
ab	—	16	17
an	—	—	6
ac	11	—	—
ks	2	—	—
di	10	20	22
hy	43	19	22
ol	23	20	11
mt	—	5	5
il	7	6	6

The same difficulties are encountered if the possibility of a parental magma of low-magnesia tholeiitic composition is considered (*D* or *E* in figure 31). In this case the high magnesia tholeiites would have to be considered as accumulative differentiates and, apart from the objections on mineralogical grounds, the hypothesis would be at variance with the known age relations between the high and low magnesia types.

It must be concluded that whatever the Tholeiitic Series represents, it does not represent a crystallization-differentiation trend caused entirely by the separation or concentration of the minerals actually present in the lavas. It might be argued that this conclusion is based largely on the high potash content of the magnesian tholeiites, a character possibly due to accidental contamination by sialic matter. If, however, a comparison of the high-magnesia tholeiites is made with Karroo dolerites of the same Fe/Mg index it is found that, although the former are distinctly richer in potash, there is no significant difference in SiO_2. Incorporation of granitic material by the low-potash magma would certainly affect the SiO_2 content considerably. Recent experimental work at high pressures by Yoder & Tilley (1961) and by Boyd & England (1961) has suggested several possible mechanisms by which variation can be effected in basalts at considerable depth. Since differentiation under these conditions involves mainly eclogitic rather than basaltic minerals, it follows that a variation series so produced will not necessarily make sense in terms of the low pressure minerals crystallizing in the erupted lavas. This appears to give a promising line of approach to the Lebombo–Nuanetsi basalts. In this connection, however, numerous alternative possibilities arise. It is important to distinguish between crystallization-differentiation and partial melting as causes of variation. In addition a lava-sequence may represent the re-working of an already differentiated layered substructure. The latter may be referred to as *primary differentiation*, that which has affected the source rocks prior to the volcanic episode in question. It will be evident that the present authors consider the variation from basalts to rhyolite, in the Lebombo–Nuanetsi zone, as an example of this type of differentiation. Secondary differentiation will be used to refer to changes affecting a magma after its production during the volcanic episode.

Before attempting to assess the relative merits of these possibilities it is necessary to take a broader view of the Karroo volcanism and, in particular, to discuss its cyclical nature.

TABLE 43. THE KARROO VOLCANIC CYCLE IN THE LUPATA–NUANETSI–LEBOMBO ZONE

	Nuanetsi–Lebombo area		Lupata area after Dixey (1929)
stages of cycle	extrusives	intrusives	extrusives
waning phase	lavas of Upper Alkaline Group (phonolites, tephrites, basanites, etc.) with tholeiites	Nepheline-syenites, etc.	Lupata alkaline volcanics
culmination	rhyolites and basalts interbedded	granites and granophyres, nordmarkites, gabbros	Lupata rhyolite, basalt, Karroo rhyolite
waxing phase	low-magnesia tholeiite dominant	dolerites	Karroo basalts
	high-magnesia tholeiite dominant	picrites	
initiation	Lower Alkaline Group (nephelinite, tephrite, etc.)	Ijolites, nepheline-dolerites, etc.	

5. *The Karroo volcanic cycle*

If the broad outline of the Karroo lava sequence in the Lupata–Nuanetsi–Lebombo zone is considered, it is apparent that a strong element of symmetry is present which justifies the use of the term volcanic cycle. This may be illustrated by a brief comparison of the Lupata succession (Dixey 1929) with a generalized Nuanetsi–Lebombo succession (table 43). The alkaline rocks of the Lupata area, phonolites and trachytes being the dominant types according to Coelho (1959), are of post-Karroo age and are separated by an unconformity from the Karroo lavas. Hence, what is termed here, the Karroo volcanic cycle, does not coincide with existing stratigraphic time divisions.

The cycle defined above has a purely empirical basis and is derived from a consideration of the time-sequence of the eruptive rocks. If it is accepted that the Karroo volcanicity was caused essentially by a period of abnormally high heat-flow from depth, it follows that a cyclic process of magma generation is involved, since geo-isotherms must first have risen and subsequently have fallen. The period of rising geo-isotherms may be referred to as the waxing phase of the volcanic cycle, and the period of falling geo-isotherms as the waning phase. The culmination of the cycle corresponds with the period at which geo-isotherms were at their highest level.

The most likely type of secondary differentiation, involving the separation of early formed mineral phases, demands an environment of falling temperature. During the waxing phase of the cycle such conditions could be realized only during the period when a magma was moving towards the surface. The minerals formed in the basalts at this stage, however, were probably the olivine, pyroxene and plagioclase phenocrysts, which, as has been shown, appear to have caused little differentiation. At the level of magma generation, separation of garnet and pyroxene might perhaps, as far as chemical characters go, account for the observed peculiarities (e.g. high K_2O) in the Tholeiite Series. In view of the improbability that a falling-temperature environment would exist at this level, however, the hypothesis is difficult to assess and a variant of this process involving zone-refining (Harris 1957) might seem more promising. The possibility also exists that the variation in the basalts is due either to varying degrees of partial fusion of a uniform host-rock, or to the re-working of a variable rock-series, itself a product of previous (primary) differentiation processes.

An explanation of the major rock-variations in terms of partial fusion of an ultrabasic source rock has the advantage of ready applicability to the whole area of Karroo volcanic activity. In this hypothesis the low-magnesia tholeiite, since it is so voluminous and widespread, might be considered as the normal product of partial fusion. The high-magnesia tholeiites and their picritic associates may then be regarded as products of more complete fusion in restricted areas in response to a local build up of heat at or soon after the initiation of the thermal cycle (Harris 1962).

6. *Picritic rocks and alkaline lavas*

It will be evident from the foregoing discussion of the basalts that it is difficult to envisage all the picritic rocks, in view of the alkaline nature of many of them, as accumulative differentiates of basaltic magma. There is, moreover, some suggestion that a primary picritic magma may have existed in the Nuanetsi area.

It may be significant that the rocks of the Lower Alkaline Group, nephelinites, tephrites, etc., were erupted very early in the Karroo volcanic episode and have a 'highly differentiated' aspect. It is these rocks, however, which should be most suspected of being partial fusion products, particularly since large amounts of somewhat alkaline, basic and ultrabasic rock, perhaps representing a closer approach to the composition of the source-rock, were intruded and erupted shortly afterwards. It is probably significant that it is possible to construct a reasonably smooth variation diagram for the Lower Alkaline Group, suggesting that a single fractionation process has had a predominating influence. The Upper Alkaline Group, in contrast, is much more variable, a feature to be expected if the volcanic cycle is considered. It is possible, for example, that the rocks of this group are derived from magmas produced at an early stage and held at a relatively high temperature throughout the duration of the cycle. The long time interval implied, admits the possibility that numerous different differentiation processes, such as diffusion and fractional crystallization, could be operative. Moreover, during the waning phase of the cycle, conditions for differentiation by crystallization processes would be at an optimum, since it is probable that the fall of geo-isotherms would be a slow process compared with the rate of rising during the waxing phase.

7. *The acid rocks*

It is not intended to discuss the acid rocks of the Nuanetsi–Lebombo zone in detail because, compared with the basalts, there are few data available. Virtually all the acid rocks are confined to a single tectonic setting so that comparison between different areas is not possible. Further, although the existence of a continuous series, varying from rhyodacite to rhyolite can be demonstrated, the lack of precise knowledge of time relations within the series is a handicap which only future research can overcome. It has already been stated, however, that the present authors regard the rhyolitic and granitic rocks as products of the re-melting of the granitic crust, a conclusion based on considerations of regional tectonics. A study of the ring complexes of the Mateke region tends to support this view.

The Marangudzi–Masukwe line of complexes runs east of north-east along the centre line of the Basement Limpopo orogenic belt structure. For reasons which are not apparent but undoubtedly connected with the structure of at least the upper part of the crust, the line had a marked effect on localizing intrusive activity during the late-Karroo period.

The time relations of the intrusive types show a considerable uniformity in the various complexes. Gabbros when present always pre-date the granites and granophyres of the same area. In a unique instance, the gabbro-granite association of Marangudzi was followed by nepheline syenites. Rocks intermediate in composition between gabbro and granite are rare in all the complexes.

The mechanism of intrusion of many of the acid rocks was very probably one of cauldron subsidence. This is perhaps most convincingly demonstrated by the structure of the granite of the Marumbe complex, but also appears reasonably certain for the granites of Divula and Mutandawhe. Similarly, the polygonal intrusions of the western and north-western part of the Masukwe complex, probably represent the foundering of angular crustal blocks. Thus, the existence of magma chambers at a fairly high level in the crust can be assumed.

The main map shows the pattern and age relations of the fracturing associated with granitic intrusion in the Dembe–Divula–Masukwe area. The steady migration and considerable overlap of the fractures suggests that one elongated magma chamber was present. Hence, the Marungudzi–Masukwe line can be envisaged as underlain by an elongated, though probably discontinuous, magma chamber reaching a high level in the crust. In order to accommodate the subsiding blocks, the chamber must have been at least 2 miles wide in the vicinity of the Marumbe complex, and 4 to 5 miles wide in the Divula area.

It is evident that a body of magma of these dimensions could not have been forcibly intruded into position without causing a considerable deformation of the country rocks. This could take the form of folding, or pronounced linear fracturing with consequent dyke intrusion. The latter effect may possibly be represented by the swarm of acid dykes near Marumbe, but the total amount of crustal extension affected by the swarm is probably negligible compared with the dimensions of the magma chamber. In addition, folding parallel to the chamber is demonstrably absent.

Thus, it must be assumed that the acid magma occupying the high level line of chambers did not force its way into position but must either have formed *in situ* or reached a high level by a stoping process. This does not exclude the possibility of a certain excess of pressure in the chamber, owing possibly to superheating of the magma. Such pressure seems likely to have caused the doming centred on the Masukwe complex and the possible doming around Dembe. In addition, intrusions such as the causeway dyke-swarm of Masukwe may have been forcibly intruded as a result of a high magma-pressure rather than permissively intruded following foundering of the country rocks. The actual physical condition of the 'magma' during the intrusive process must be a matter of speculation pending further detailed work. Certainly the process of fluidization as outlined by Reynolds (1954) must be considered—especially because of the close association of the acid intrusive rocks with the ignimbrites, the latter essentially representing fluidized extrusive systems.

In any discussion of the acid rocks some attention must be given to the problem of the nordmarkites found in the Mutandawhe, Marumbe, and Vangambi complex. Only one of these, the Vangambi complex, contains gabbros, although a large, poorly exposed gabbro body is found adjacent to the Marumbe complex, and a basalt ring-dyke occurs at Mutandawhe, cutting the nordmarkite but pre-dating most of the granitic intrusions. In both Marumbe and Mutandawhe the nordmarkite is older than the granitic rocks. In Vangambi the nordmarkite is younger than the gabbro. Hence in general the nordmarkites were probably intruded after the gabbros but before the granites.

Chemically the nordmarkites differ from the rhyodacites mainly in having a higher content of K_2O and Al_2O_3 and rather low CaO, MgO and FeO. In addition, few of the rhyodacites have such a low content of SiO_2. Since the nordmarkites are only of local extent it is possible to invoke some special process to account for their formation, such as the intermingling, at the base of the granitic crust, of rhyodacite magma and a trachytic differentiate of the basaltic magma which had accumulated locally in small quantities. No sign of the pure trachyte has, however, so far been discovered in the complexes, although Swift *et al.* (1953) and Assunçao *et al.* (1961) report small amounts of trachyte from the lavas.

8. *Carbonatite associations and the Karroo volcanic cycle*

It has been demonstrated above, that the generation of the magmas of the Nuanetsi Igneous Province, including those of an alkaline composition, can be explained in terms of a cyclical rise, culmination, and fall of geo-isotherms through a layered earth structure. Since several of the alkaline magmas present in the province correspond to types which various workers have regarded as parental to carbonatite associations, it is of interest to consider the origin of these associations in the light of the Karroo volcanic cycle.

In the Nuanetsi Igneous Province the earliest rocks to be erupted included the nephelinites of the Lower Alkaline Group, and it has been suggested above that these rocks may represent magmas produced at depth, by partial fusion of an ultrabasic layer when the geo-isotherms began to rise. At Shawa and Dorowa, 200 miles north of the province, a typical nephelinite-carbonatite association was developed (Johnson 1961) and has been dated (Nicolaysen, Burger & Johnson 1962) at 209 ± 16 My. At these localities nephelinite magma, believed to represent the parent magma of the association, was available over a wide area, and as at other carbonatite localities, no rocks intermediate between nephelinite and basalt are in evidence. It seems probable, therefore, that the nephelinites at Shawa and Dorowa, like those in the Nuanetsi Province originated by some process other than the fractional crystallization of basalt.

Since the age determination has indicated that Shawa and Dorowa can be considered as features of Karroo volcanicity, it is suggested that the process of partial fusion of an ultrabasic layer, which has been argued for the origin of the nephelinite at Nuanetsi, was also responsible for the generation of the parental magma at Dorowa and Shawa. At the latter localities, however, the rise of the geo-isotherms apparently culminated at a relatively lower level, before they had risen to a sufficient height to produce basalt.

The low-level culmination of the cycle at Dorowa and Shawa may be related to the fact that the two complexes are situated within the Archeaen shield area of Southern Rhodesia which behaved as a stable positive area during Karroo times, contrasting with the Limpopo–Lebombo–Lupata mobile belts, where a major cycle was developed.

The concept of the Karroo volcanic cycle can be further extended in an attempt to explain the puzzling contrast, even allowing for differences in erosion level, between Dorowa and Shawa on the one hand and the Chilwa Alkaline Province (Garson 1961) on the other. In the latter area large intrusions of quartz syenite, syenite and nepheline syenite are associated with the carbonatite centres, and a much greater variety of rocks is developed than at Dorowa and Shawa, where the associated igneous intrusions are restricted to nephelinites and ijolites. Bloomfield (1961), however, has quoted an age of 138 ± 14 My. for the Chilwa Province and Garson (1961) has equated it with the Lupata alkaline volcanics. Thus, the earlier Dorowa and Shawa carbonatite complexes are equivalent to the waxing stage of the complete cycle, as developed in Nuanetsi, or perhaps to the culmination of the thermal cycle at a much lower level. The Chilwa province, on the other hand, is clearly equivalent in both age and general variety and types of rocks to the waning phase of the complete Karroo volcanic cycle, fully developed in the neighbouring Lupata area.

It is possible, in the same connexion, that the distinction between the nephelinite-carbonatite and olivine-basalt-trachyte-phonolite associations emphasized by King & Sutherland (1960), may also be understood in terms of thermal cycles, as exemplified by the Karroo volcanic cycle. Thus, the former association may imply partial melting at the beginning of a major cycle, or during the low-level culmination of a minor one. The latter, in contrast, indicates differentiation during the waning phase of a cycle which culminated at a relatively higher level.

The hypotheses discussed in this section are of a tentative nature, and more field and experimental data will undoubtedly lead to their modification. Nevertheless, the present authors feel that the attempt which has been made to demonstrate the relationship between carbonatite associations and the more normal basaltic volcanic associations, in terms of a simple cyclic process, is a useful one, especially since carbonatites have tended in the past to occupy a rather isolated position in petrogenetical thought.

On this basis, any general study of carbonatites should take into account the possible fundamental differences between parental alkaline magmas produced at different stages of a volcanic cycle.

9. *Conclusion*

It has been considered worth while to put forward the speculative views here mainly because no attempt has been made in the past towards a general petrogenetical synthesis to account for the Karroo igneous rocks. Accent has been placed on the volcanic cycle and on melting processes as a means of explaining variation. It will be noted that no attempt has been made, for reasons of brevity, to compare Karroo rocks with igneous rocks in other parts of the world, though valuable comparisons could be made, especially with the Deccan Traps of India and with the Thulean Igneous Province.

Few problems can be said to have been solved so far, though it is hoped that the present work will serve to stress the importance of Basement structure in the evolution of Karroo rocks. Of outstanding interest in the future will be the study of geochemical provinces in southern Africa, particularly their relation to the fundamental tectonic units. The widespread Karroo igneous rocks will be an invaluable source of data.

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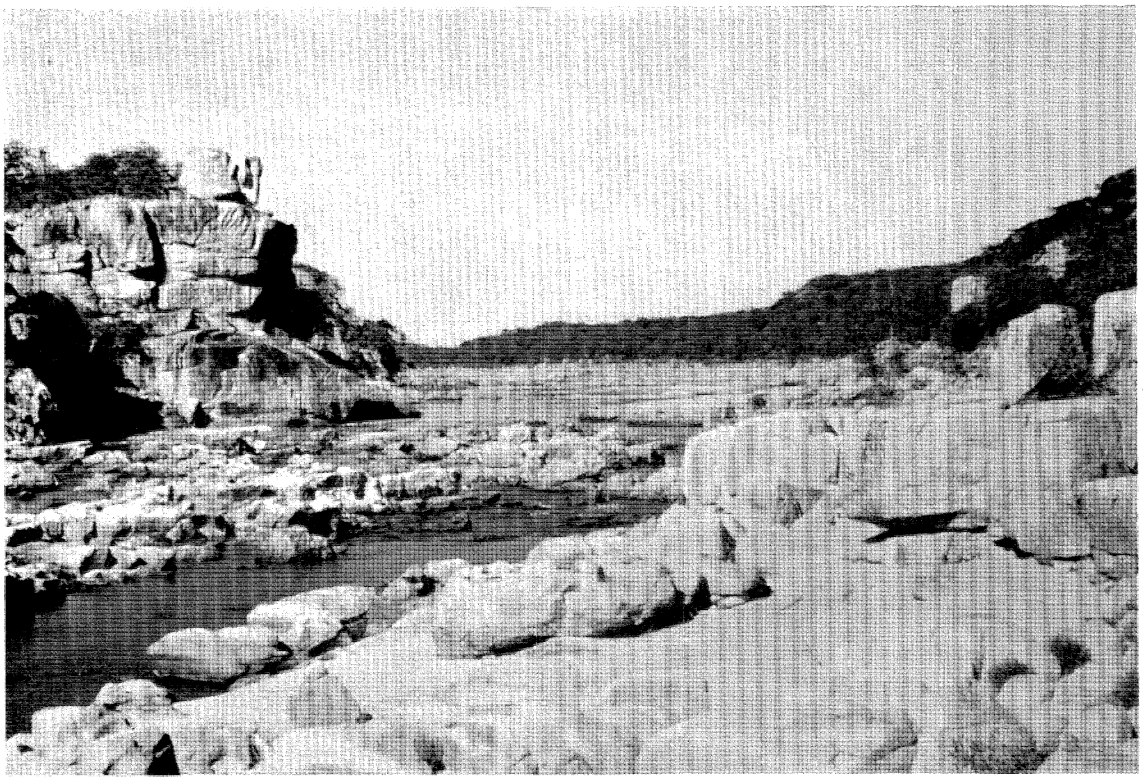

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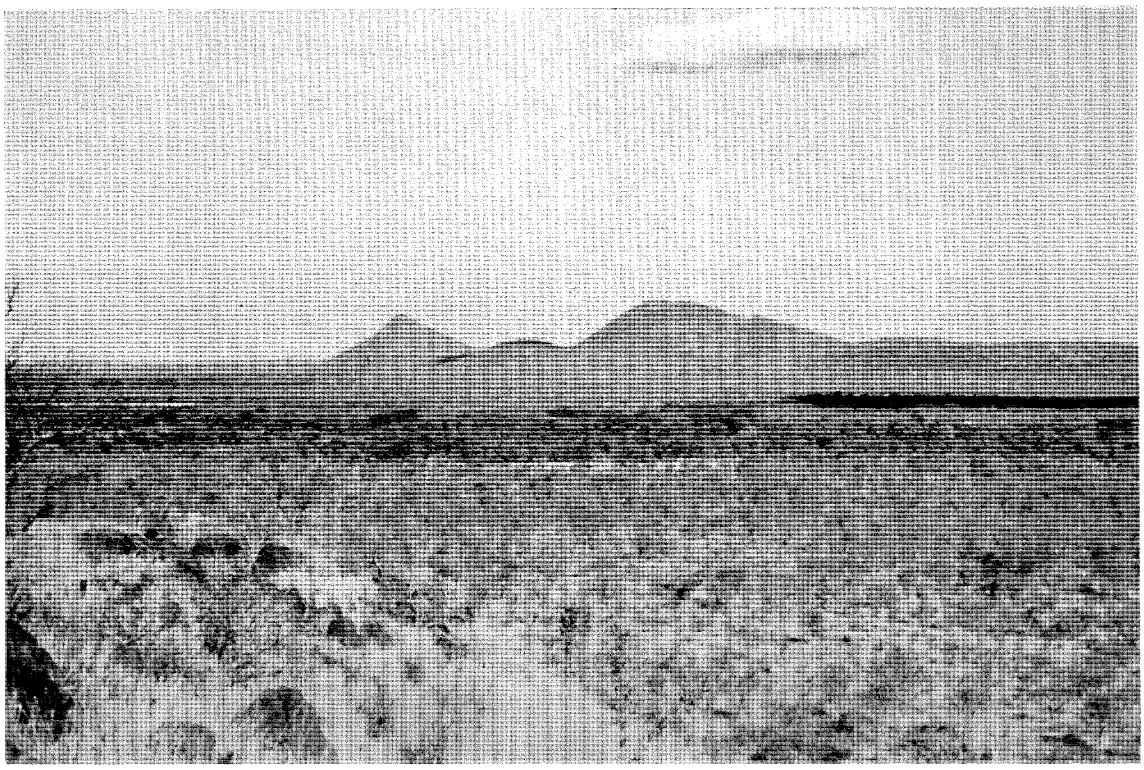
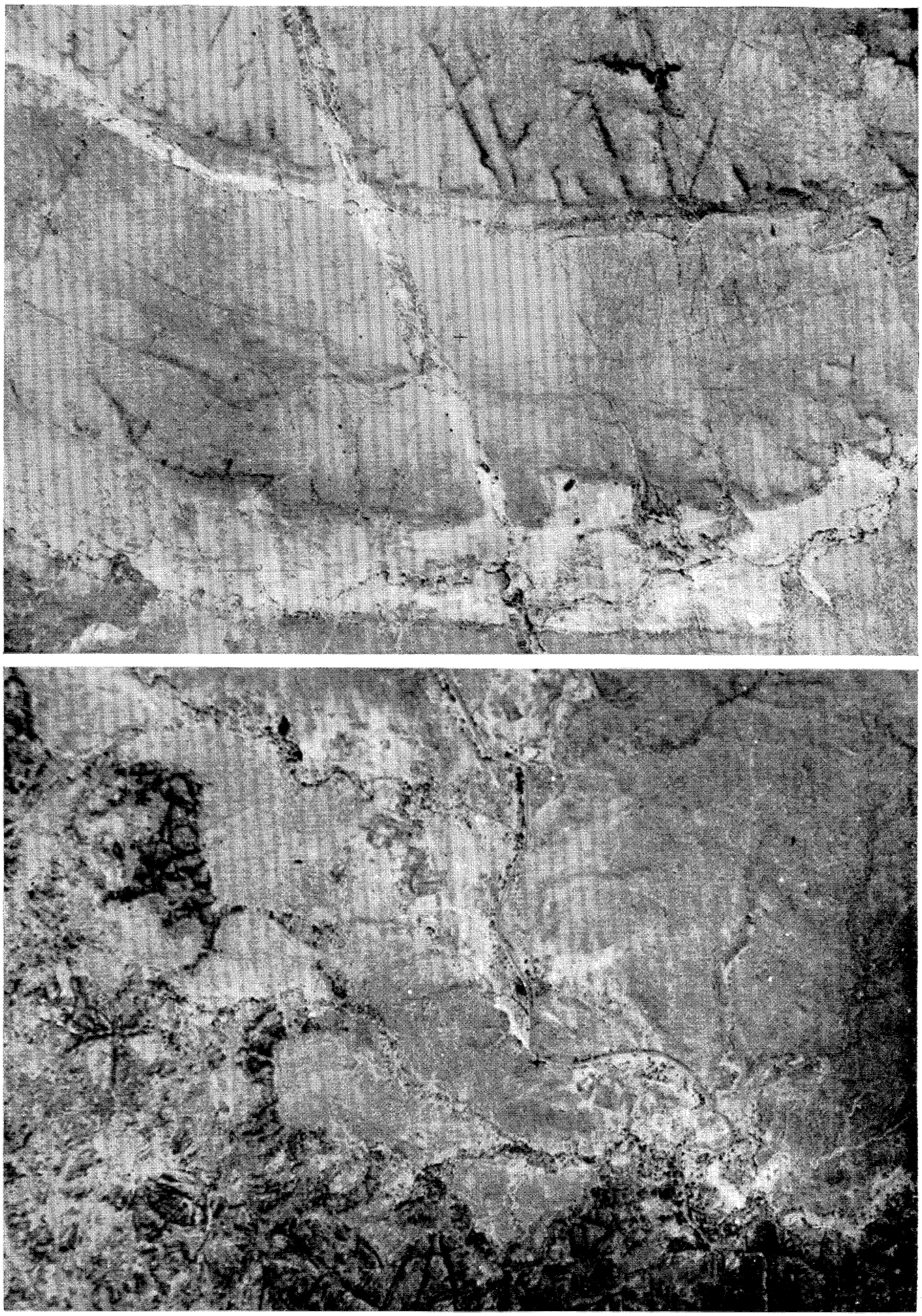


b

FIGURE 32. (*a*) The Chiribira Gorge where the Sabi River cuts through the granites of the Chiwonje complex. (*b*) Hills of the Northern Ring complex viewed from the north-west with basalts in the foreground. Madzenwene Hill (left) and Gurutangu (right) are the topographic expression of the marginal ring-dyke.

(*Facing p.* 218)



a

b

FIGURE 33. (*a*) Aerial photograph of the Maose crush zone (running top to bottom) cutting basalts and rhyolites striking east–west on the southern limb of the Nuanetsi syncline. The two east–west valleys are cut in basalt and are those of the Hlangalungwe (upper) and Umvumvu (lower) rivers. Area is approximately 5 by 3 miles, situated at 31° 11′ E., 21° 55′ S. (*b*) Aerial photograph of the contact between the Cave Sandstone (bottom, left) and the overlying basalts (top, right) in the vicinity of the Pesu River. The irregularity of the contact suggests that dunes may have been present at the top of the sandstone sequence. Area is $3\frac{1}{2}$ by $2\frac{1}{2}$ miles, situated at 31° 11′ E., 22° 16′ S. Both photographs published by permission of the Federal Department of Trigonometrical and Topographical Surveys, Salisbury, Southern Rhodesia.

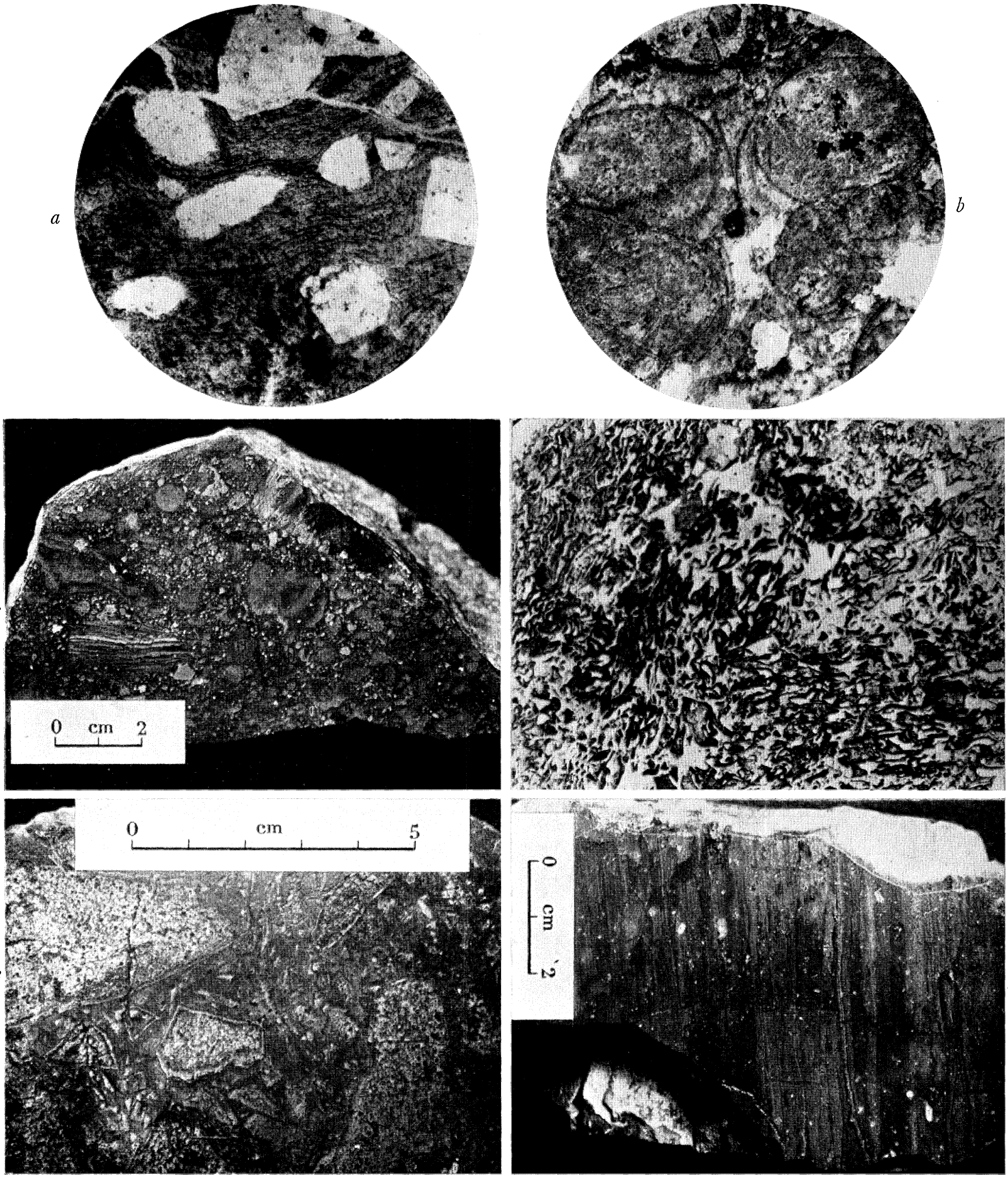


FIGURE 34. (*a*) Micro-eutaxitic structure in an ignimbrite. Photomicrograph in plane polarized light (× 20). (*b*) Perlitic cracks in devitrified vitrophyre. Photomicrograph in plane polarized light (× 20). (*c*) Breccia, base of Uche ignimbrite. (*d*) Vitric tuff showing typical vitroclastic texture, Tchovi ignimbrite. Photomicrograph (× 8). (*e*) Breccia, Tchovi ignimbrite. (*f*) Eutaxitic banding, Tchovi ignimbrite.

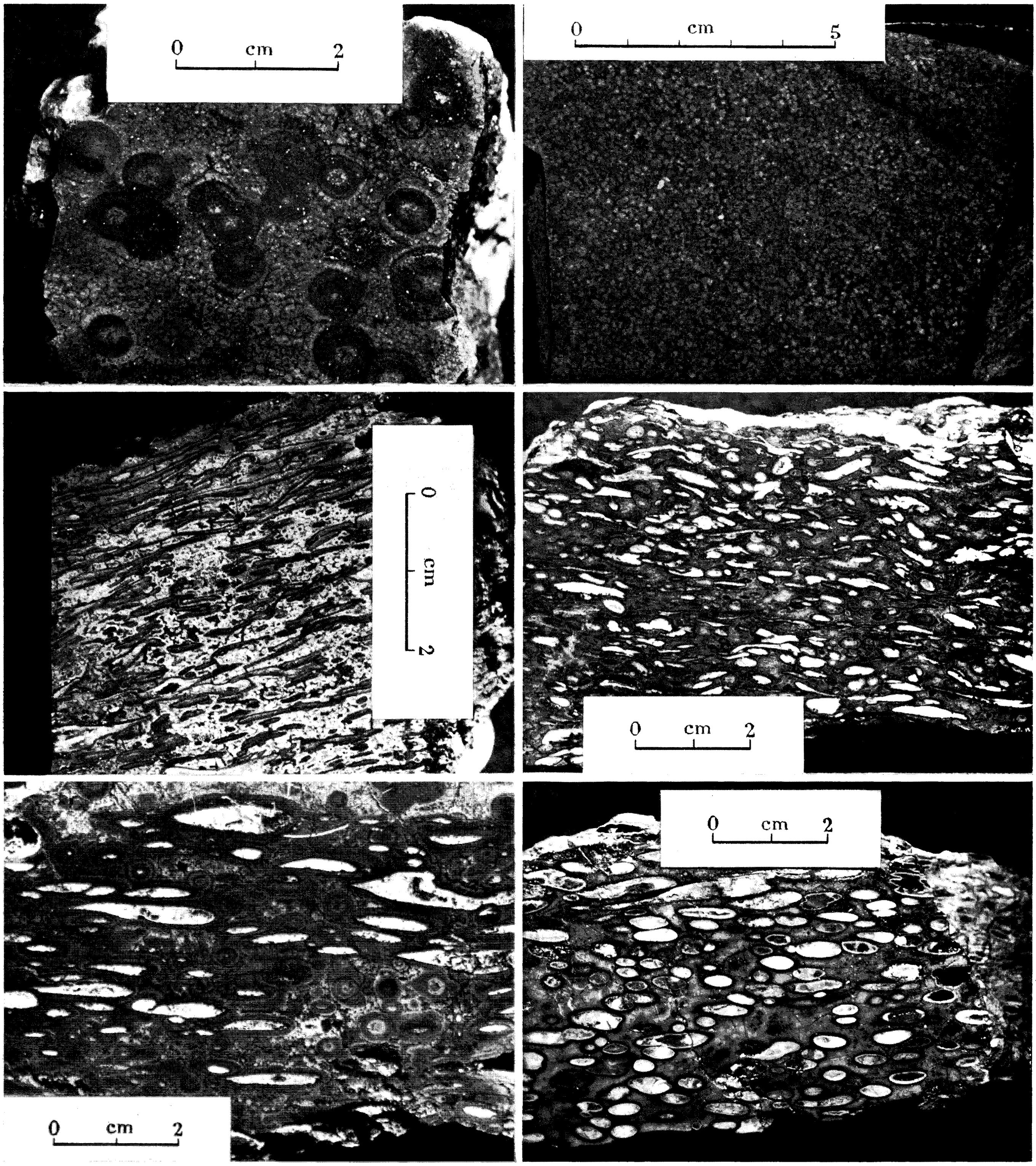


FIGURE 35. (*a*) Spherulitic structures, Tchovi ignimbrite. (*b*) Felsitic texture, Tchovi ignimbrite. (*c*) Compaction structures, Chasitchi ignimbrite. (*d*) Compaction structures, Chasitchi ignimbrite. (*e*) and (*f*) Specimens from the Malipanda ignimbrite, showing spherulites and lithophysal structures somewhat flattened by compaction.

a b
c d

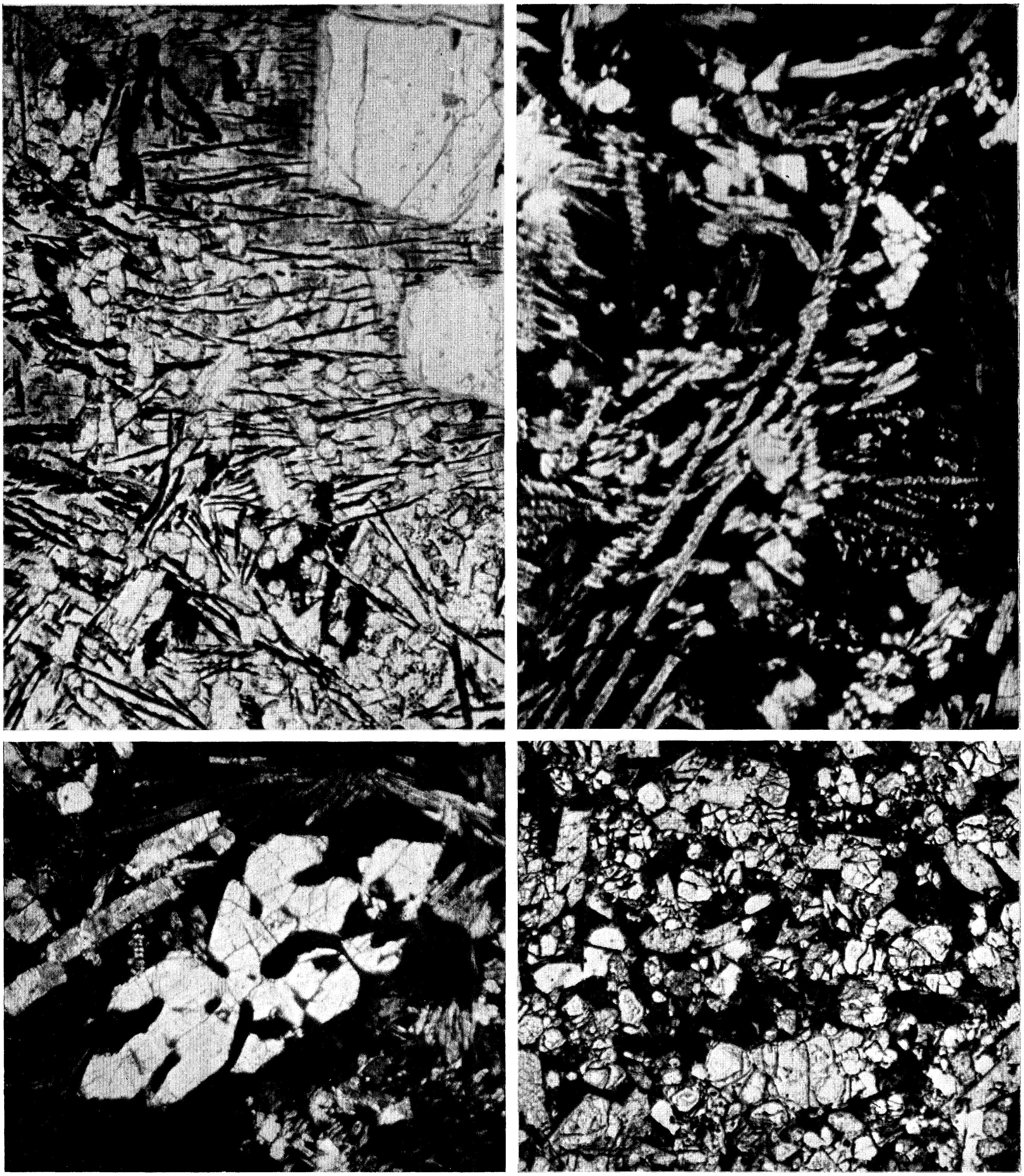
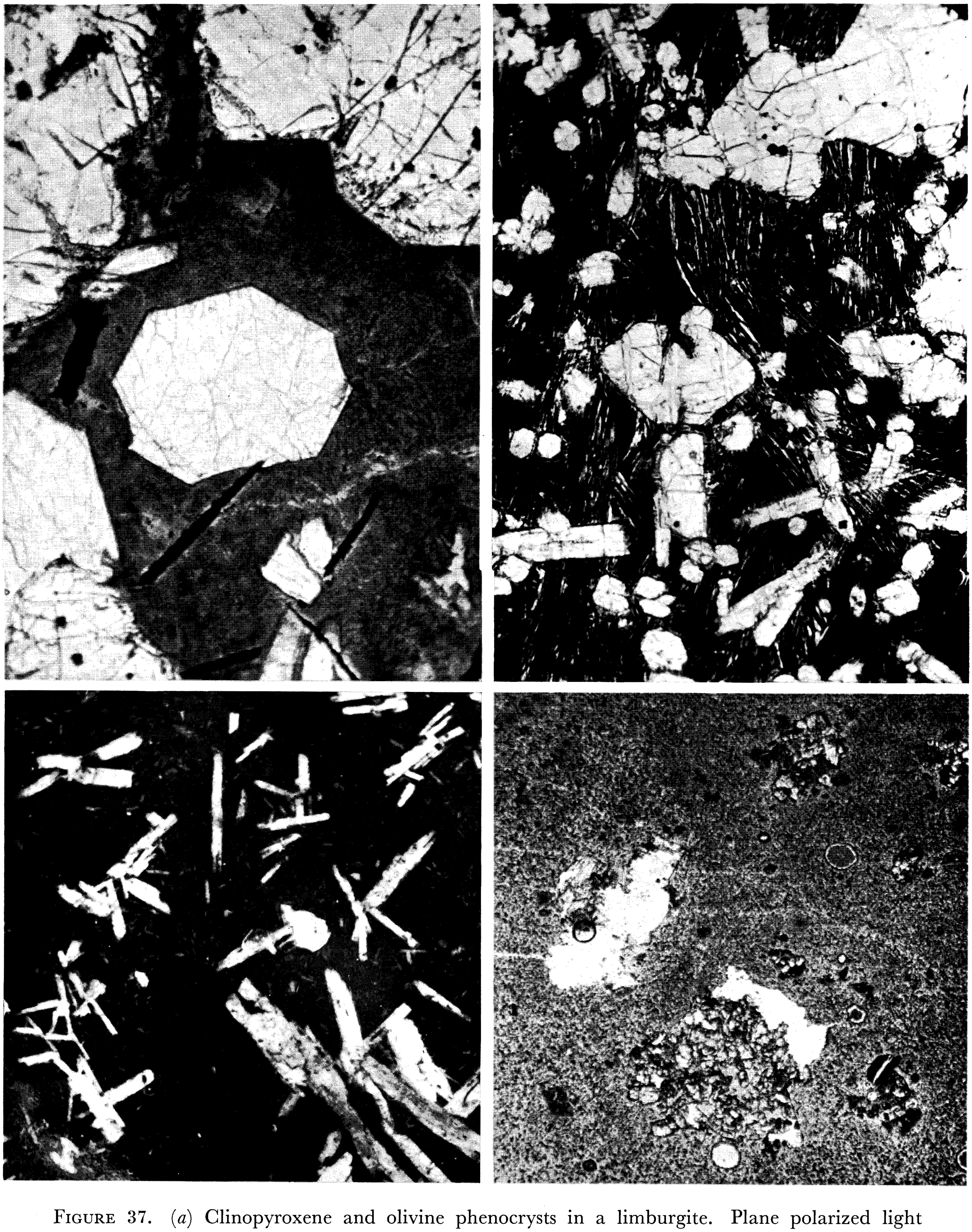


FIGURE 36. (*a*) A limburgite showing the characteristic arrangements of combs of ore. Plane polarized light (× 30). (*b*) Dendritic crystals of clinopyroxene set in a glassy ground-mass in a limburgite. Crossed nicols (× 60). (*c*) Skeletal olivine phenocryst in a limburgite. Crossed nicols (× 30). (*d*) Texture of the limburgites. Olivine and clinopyroxene microphenocrysts set in a ground-mass of dark glass. Ordinary light (× 10).

a

b

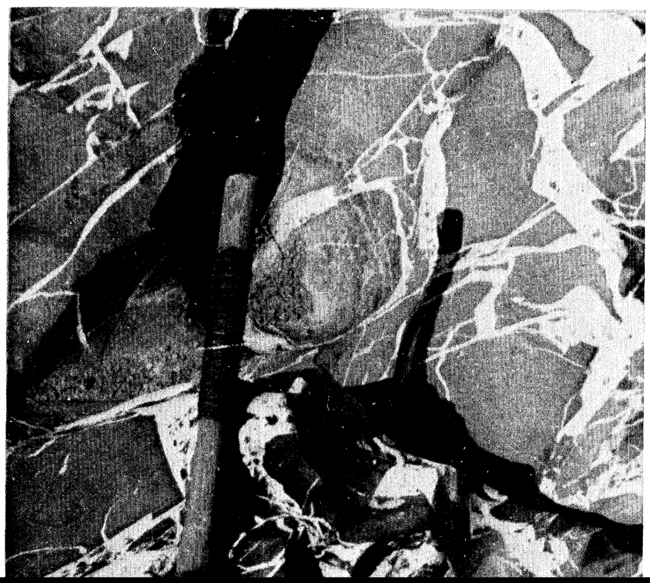


c

d

FIGURE 37. (*a*) Clinopyroxene and olivine phenocrysts in a limburgite. Plane polarized light ($\times$ 50). (*b*) Texture of an olivine basalt showing olivine, pyroxene and plagioclase laths set in glass. Plane polarized light ($\times$ 30). (*c*) Feldspar-phyric basalt from Upper Basalts of Chikombedzi area. Ordinary light ($\times$ 6). (*d*) Glomeroporphyritic pyroxene-phyric basalt from Upper Basalts of Chikombedzi area. Ordinary light ($\times$ 6).

a



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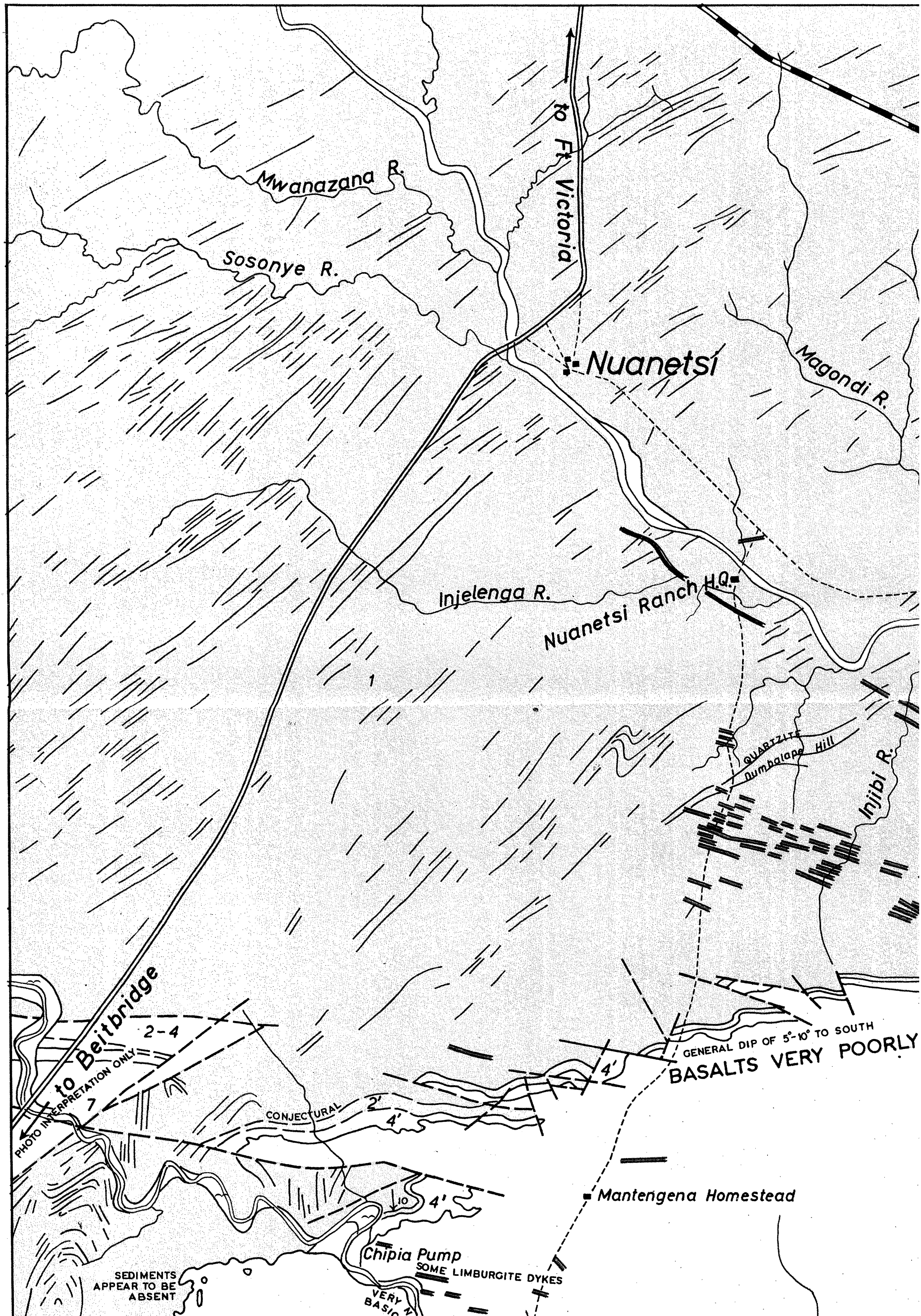
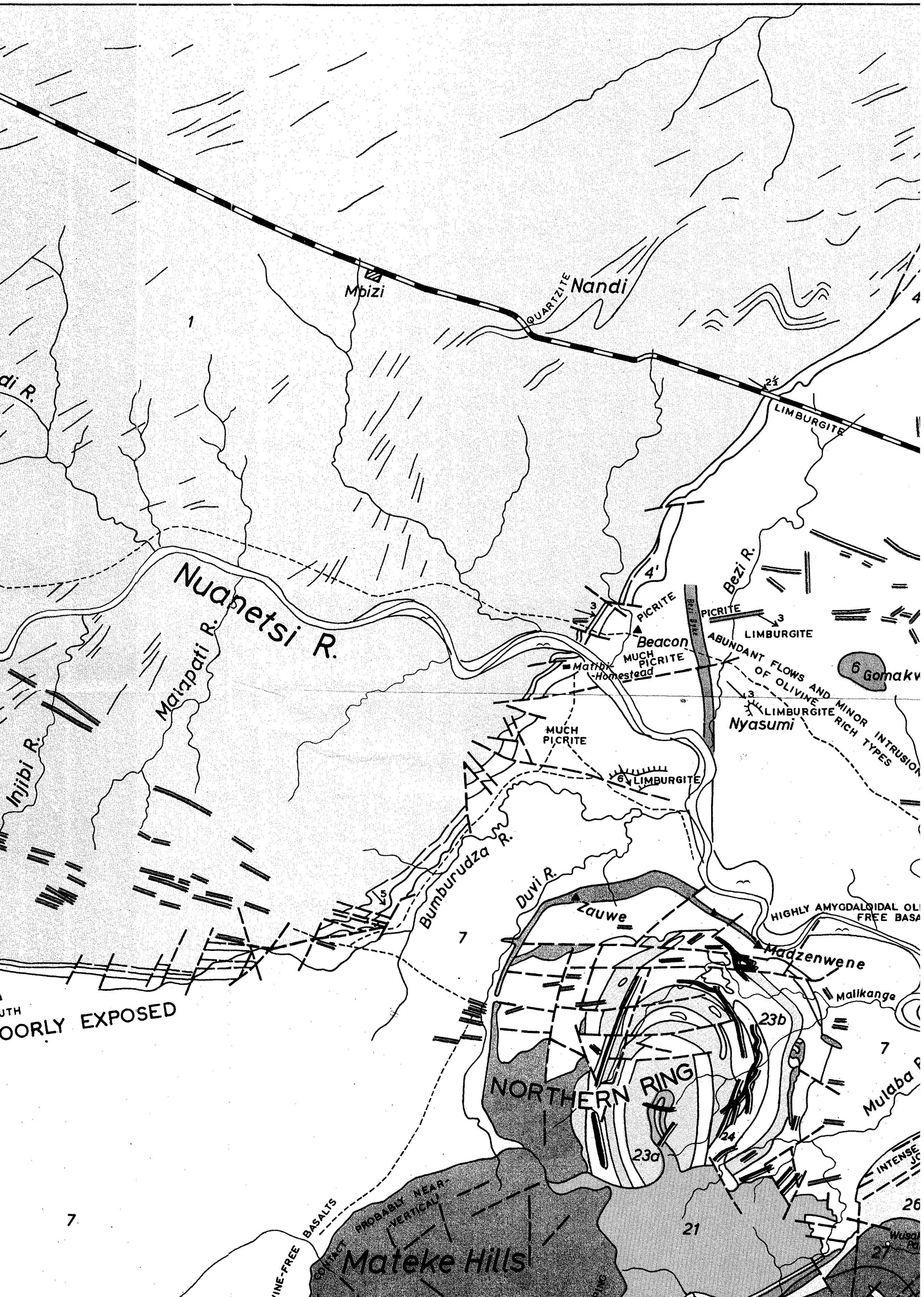
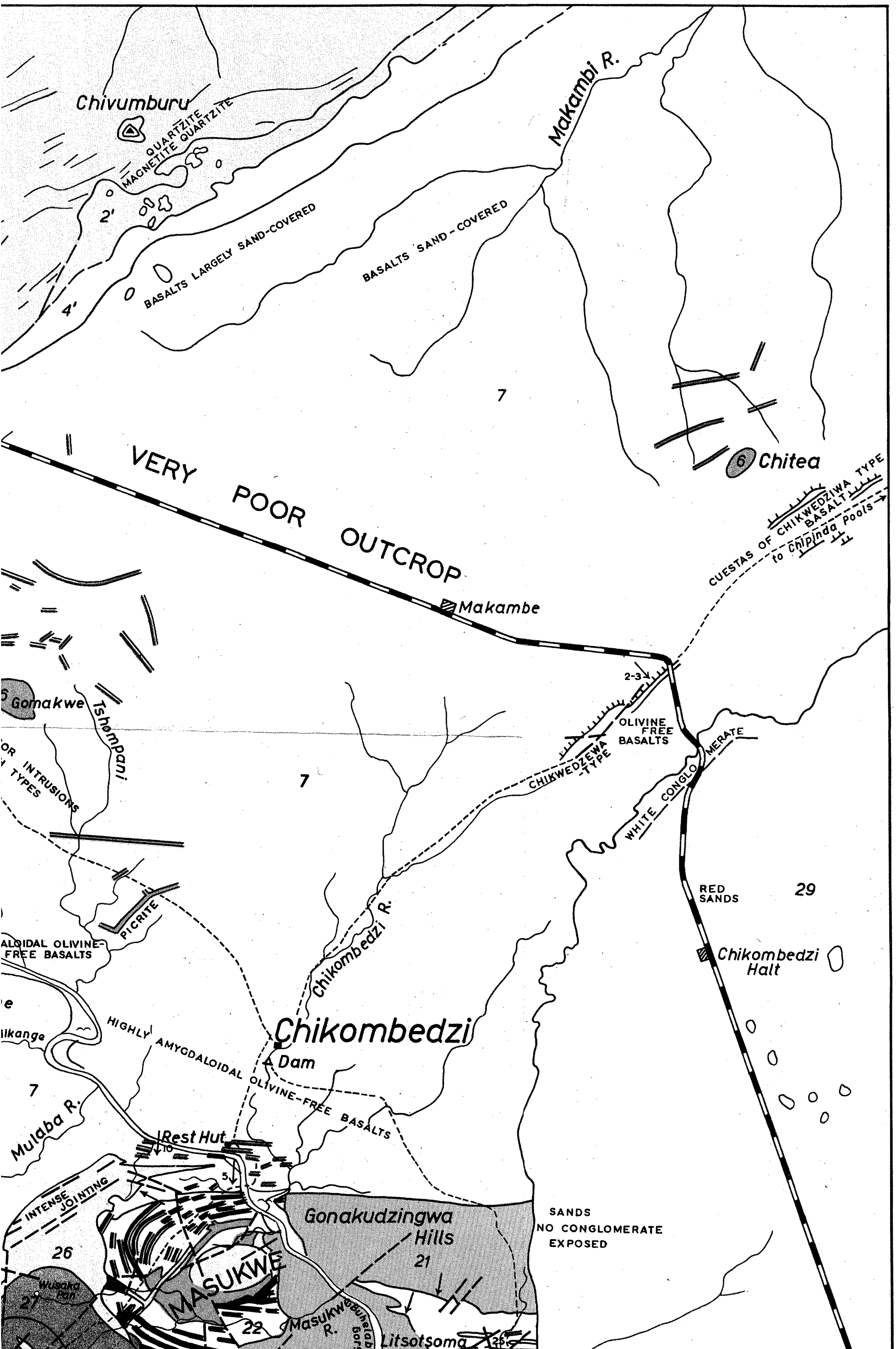


to Ft Victoria
Mwanazana R.
Sosonye R.
Nuanetsi
Magondi R.
Injelenga R.
Nuanetsi Ranch H.Q.
1
QUARTZITE
Dumbalape Hill
Injibi R.
to Beitbridge
PHOTO INTERPRETATION ONLY
2-4
7
CONJECTURAL
2'
4'
GENERAL DIP OF 5°-10° TO SOUTH
BASALTS VERY POORLY
Mantengena Homestead
10
Chipia Pump
SOME LIMBURGITE DYKES
SEDIMENTS APPEAR TO BE ABSENT


Mbizi
QUARTZITE
Nandi
1
di R.
2½
LIMBURGITE
Nuanetsi R.
Bezi R.
4'
3
PICRITE
PICRITE
3
LIMBURGITE
Beacon
MUCH PICRITE
Matibi Homestead
ABUNDANT FLOWS AND MINOR INTRUSION
OF OLIVINE RICH TYPES
6 Gomakw
3
LIMBURGITE
Nyasumi
Malapati R.
Injibi R.
MUCH PICRITE
6 LIMBURGITE
Bumburudza R.
5
Duvi R.
Zauwe
7
HIGHLY AMYGDALOIDAL OL
FREE BASA
Madzenwene
Malikange
23b
7
Mulaba R
POORLY EXPOSED
NORTHERN RING
24
23a
21
7
PROBABLY NEAR-VERTICAL
CONTACT
BASALTS
Mateke Hills
INTENSE
26
27



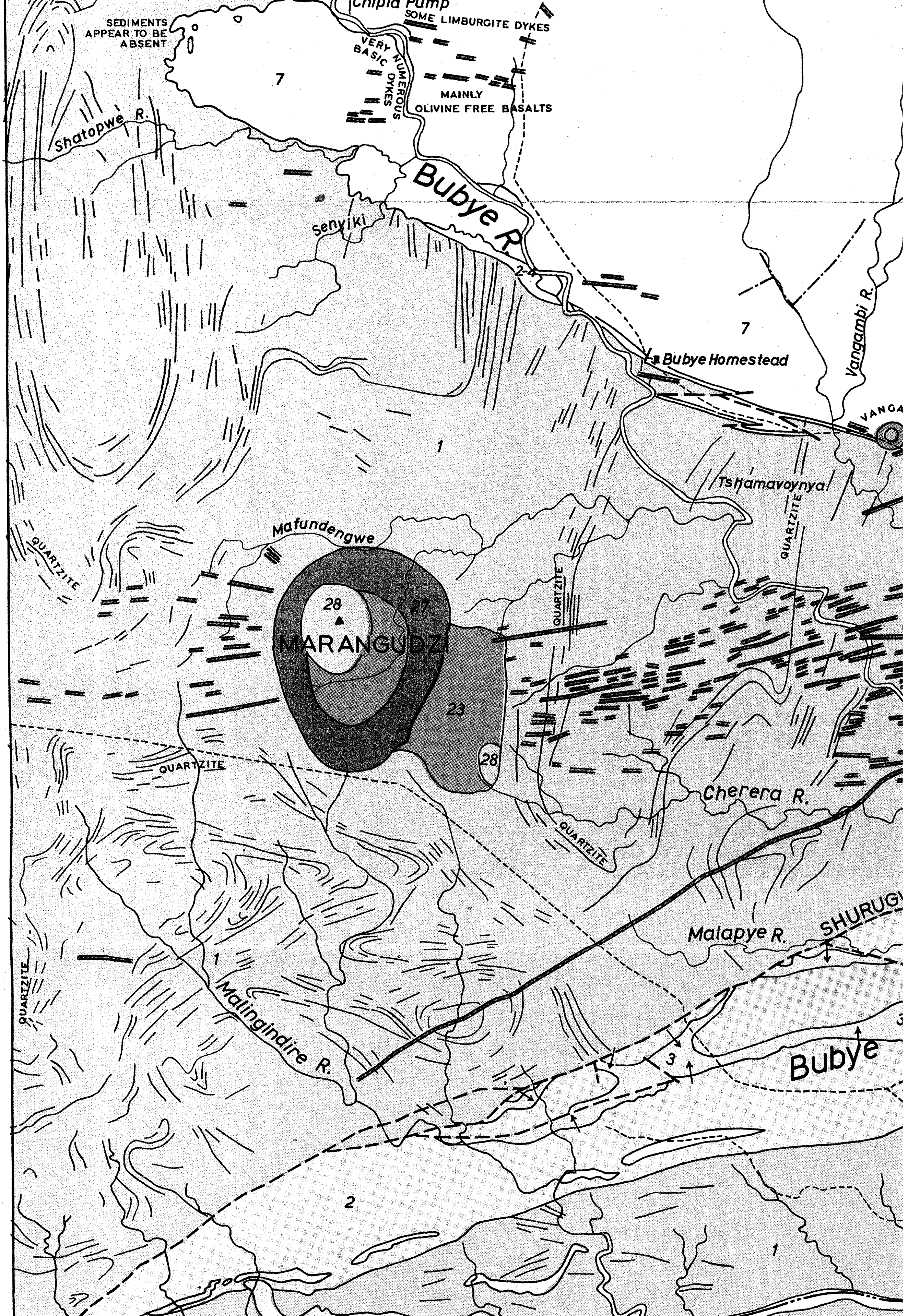
Chivumburu
QUARTZITE
MAGNETITE QUARTZITE
2'
4'
BASALTS LARGELY SAND-COVERED
BASALTS SAND-COVERED
Makambi R.
7
Chitea
VERY POOR OUTCROP
CUESTAS OF CHIKWEDZIWA TYPE BASALT
to Chipinda Pools
Makambe
2-3
OLIVINE FREE BASALTS
CHIKWEDZEWA -TYPE
WHITE CONGLOMERATE
Gomakwe
Tshompani
INTRUSIONS
TYPES
PICRITE
RED SANDS
29
Chikombedzi R.
Chikombedzi Halt
FREE BASALTS
Chikombedzi
Dam
HIGHLY AMYGDALOIDAL OLIVINE-FREE BASALTS
Mulaba R.
Rest Hut
INTENSE JOINTING
26
Wusaka Pan
27
MASUKWE
22
Gonakudzingwa Hills
21
SANDS
NO CONGLOMERATE EXPOSED
Masukwe R.
Litsotsoma

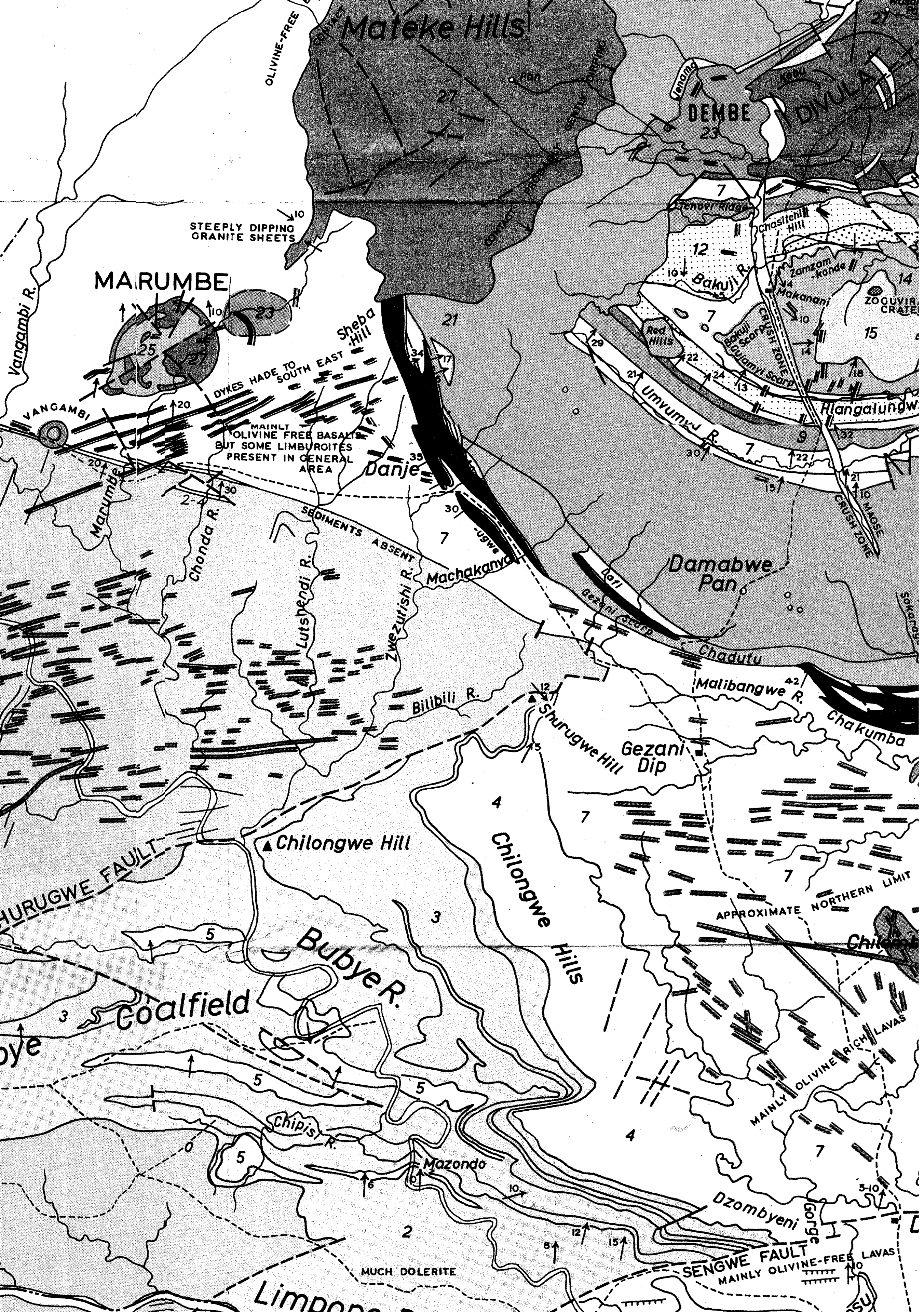
GEOLOGICAL MAP
OF THE
NUANETSI IGNEOUS PROVINCE
(SOUTH WESTERN SECTION)

0 1 2 3 4 5 6 7 8 9 10 11 12 MILES

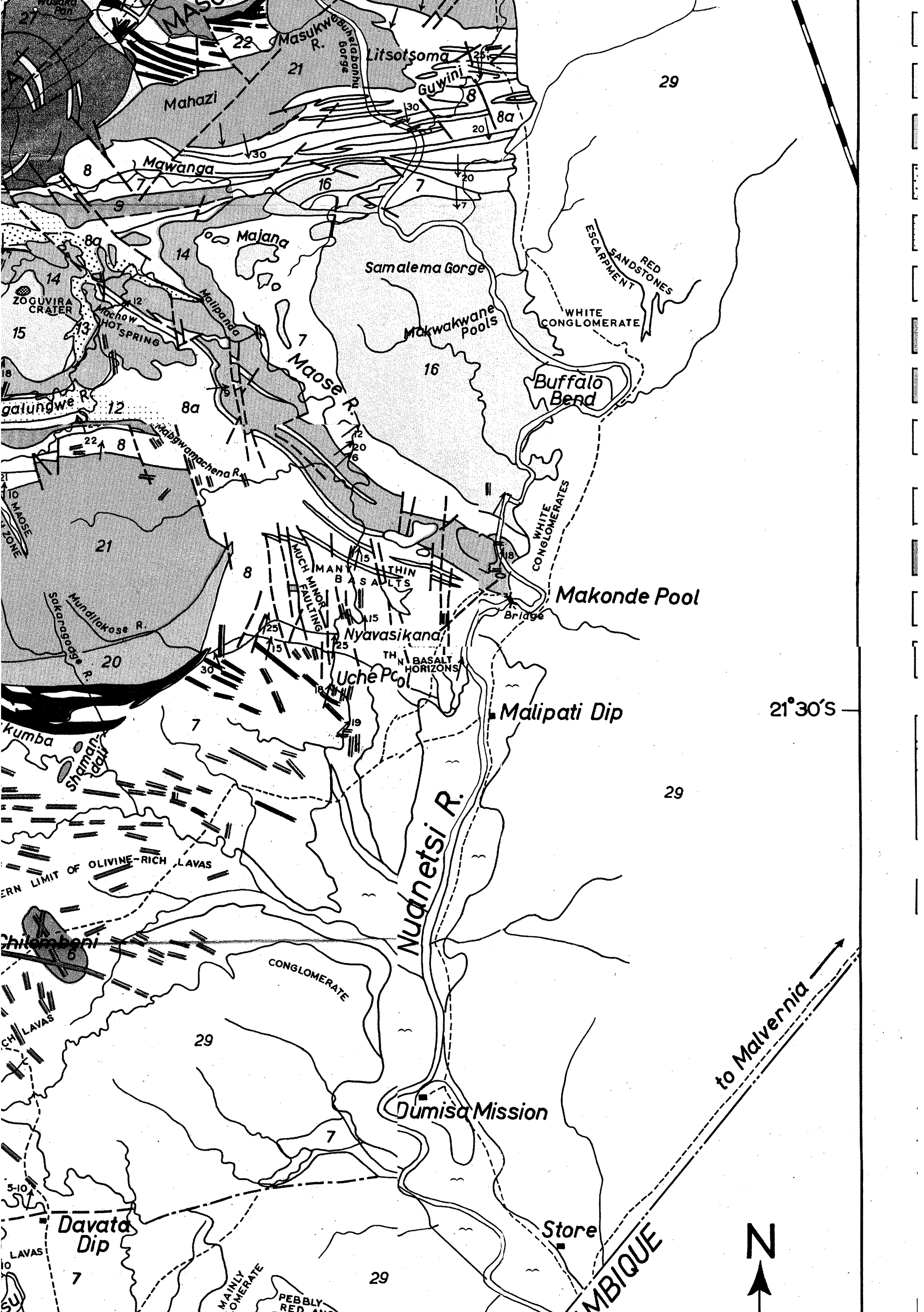
LEGEND

~	ALLUVIUM		RECENT
29	MALVERNIA BEDS		CRETACEOUS
28	NEPHELINE SYENITE ETC.		INTRUSIVE ROCKS OF THE LATE-KARROO RING-COMPLEXES
27	GRANITE & MICROGRANITE		
26	GRANOPHYRE		
25	NORDMARKITE		
24	HYBRID ROCKS (GRANODIORITE ETC.)		
23	GABBRO (UNDIFFERENTIATED)	23 a OLIVINE GABBRO; 23 b QUARTZ GABBRO — NORTHERN RING-COMPLEX	
22	MICROGABBRO		
21	RED GRANOPHYRE	MAIN GRANOPHYRE (NOTE—POST-DATES BASIC ROCKS OF THE RING-COMPLEXES)	OTHER INTRUSIVES
20	HORNBLENDE MICROGRANITE OF GEZANI SCARP		
(black)	MICROGRANITE & GRANOPHYRE OF DANJE & CHAKUMBA SHEETS		
18	ACID DYKES — MICROGRANITE, GRANOPHYRE, FELSITE	IN PART ASSOCIATED WITH THE RING-COMPLEXES	
17	VENT AGGLOMERATE		
16	SAMALEMA FLOWS		


Chipia Pump
SEDIMENTS APPEAR TO BE ABSENT
SOME LIMBURGITE DYKES
VERY NUMEROUS BASIC DYKES
MAINLY OLIVINE FREE BASALTS
7
Shatopwe R.
Bubye R.
Senyiki
2-4
7
Bubye Homestead
Vangambi R.
VANGA
1
Tshamavoynya
QUARTZITE
Mafundengwe
QUARTZITE
QUARTZITE
28
27
MARANGUDZI
23
28
QUARTZITE
QUARTZITE
Cherera R.
QUARTZITE
Malapye R.
SHURUG
QUARTZITE
1
Malingindire R.
3
Bubye
2
1



Mateke Hills
OLIVINE-FREE
CONTACT
Pan
GENTLY DIPPING
PROBABLY CONTACT
27
Venama
Kaeu
DEMBE
23
DIVULA
21
STEEPLY DIPPING GRANITE SHEETS
MARUMBE
25
27
23
Vangambi R.
Sheba Hill
DYKES HADE TO SOUTH EAST
VANGAMBI
MAINLY OLIVINE FREE BASALTS BUT SOME LIMBURGITES PRESENT IN GENERAL AREA
Danje
Marumbe
Chonda R.
SEDIMENTS ABSENT
Lutshendi R.
Zwezutshi R.
Machakanya
Ugwe
7
Tchovi Ridge
Chasitchi Hill
12
Bakuji R.
Zamzam-konde
Makanani
14
ZOGUVIR CRATER
Red Hills
Bakuji Scarp
Gulamyi Scarp
CRUSH ZONE
15
Umvumvu R.
Hlangalungwe
9
MAOSE CRUSH ZONE
Damabwe Pan
Lari
Gezani Scarp
Chadutu
Malibangwe R.
Chakumba
Bilibili R.
Shurugwe Hill
Gezani Dip
4
Chilongwe Hill
Chilongwe Hills
SHURUGWE FAULT
APPROXIMATE NORTHERN LIMIT
3
5
Bubye R.
Coalfield
MAINLY OLIVINE RICH LAVAS
Chipisi R.
Mazondo
2
Dzombyeni Gorge
SENGWE FAULT
MAINLY OLIVINE-FREE LAVAS
MUCH DOLERITE
Limpopo



Masukwe R.
Wusaka Pan
Litsotsoma
Guwini
Mahazi
Mawanga
Majana
Samalema Gorge
Makwakwane Pools
RED SANDSTONES ESCARPMENT
WHITE CONGLOMERATE
ZOGUVIRA CRATER
Machow HOT SPRING
Malipanda
Maose R.
Buffalo Bend
Mabgwamachena R.
MAOSE ZONE
MUCH MINOR FAULTING
MANY THIN BASALTS
WHITE CONGLOMERATES
Makonde Pool
Bridge
Mundilakose R.
Sakaragoda R.
Nyavasikana
THIN BASALT HORIZONS
Uche Pool
Malipati Dip
21°30'S
Shamandali
LIMIT OF OLIVINE-RICH LAVAS
Chilombeni
CONGLOMERATE
Nuanetsi R.
LAVAS
Dumisa Mission
to Malvernia
Store
Davata Dip
MAINLY CONGLOMERATE
PEBBLY RED
MBIQUE
N
29
21
22
8
8a
7
9
14
15
13
12
16
20

16	SAMALEMA FLOWS	RHYOLITE GROUP (KARROO VOLCANICS)
15	ZOGUVIRA FLOWS	
14	MALIPANDA FLOWS (≡ ZAMZAMKONDE)	
13	BAKUJI FLOW	
12	CHASITCHI FLOW	
11	TOMBWANANI FLOW	
10	SHAVANI FLOW	
9	TCHOVI FLOW	
8	LOWER PORPHYRIES & IGNIMBRITES & OTHER RHYOLITES (UNDIFFERENTIATED) (8a)	
7	BASALT, INCLUDING LIMBURGITE ETC. IN PART INTERBEDDED WITH THE RHYOLITES	BASIC LAVAS AND ASSOCIATED MINOR INTRUSIVES (KARROO VOLCANICS)
6	PICRITE ETC. (WHERE DISTINGUISHED)	
	BASIC DYKES (OF VARIOUS AGES)	
5	DOLERITE SILLS (MAINLY IN BUBYE COALFIELD)	

KARROO SEDIMENTS

AREA OF BUBYE COALFIELD

4	CAVE SANDSTONE
3	SHURUGWE GRITS
2	RED BEDS & BEAUFORT
	CHIPISI SANDSTONE
2	COAL MEASURES

(DIAGRAMMATIC ONLY)

SHELF AREA NORTH OF COALFIELD

4′	CAVE SANDSTONE
2′	LOWER SEDIMENTS (VARIABLE MUDSTONES, SHALES, SANDSTONES)
2–4	SEDIMENTS NOT DIFFERENTIATED

BASEMENT COMPLEX, TRENDS MARKED WHERE KNOWN — ARCHAEAN

SIGNS & SYMBOLS

GEOLOGICAL BOUNDARY, REASONABLY ACCURATE OR ACCURATE

GEOLOGICAL BOUNDARY, CONJECTURAL OR APPROXIMATE

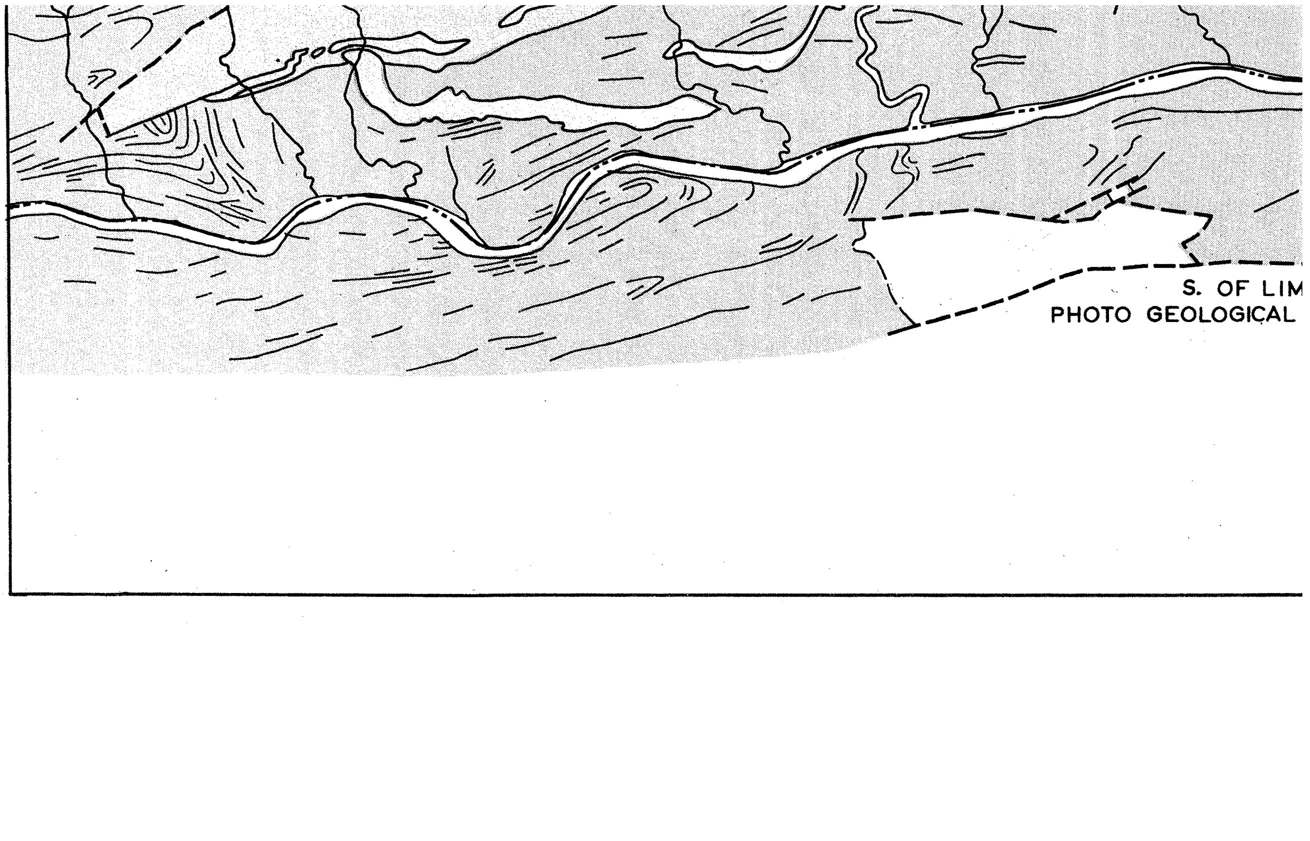
FAULT

CONJECTURAL FAULT OR MAJOR JOINT

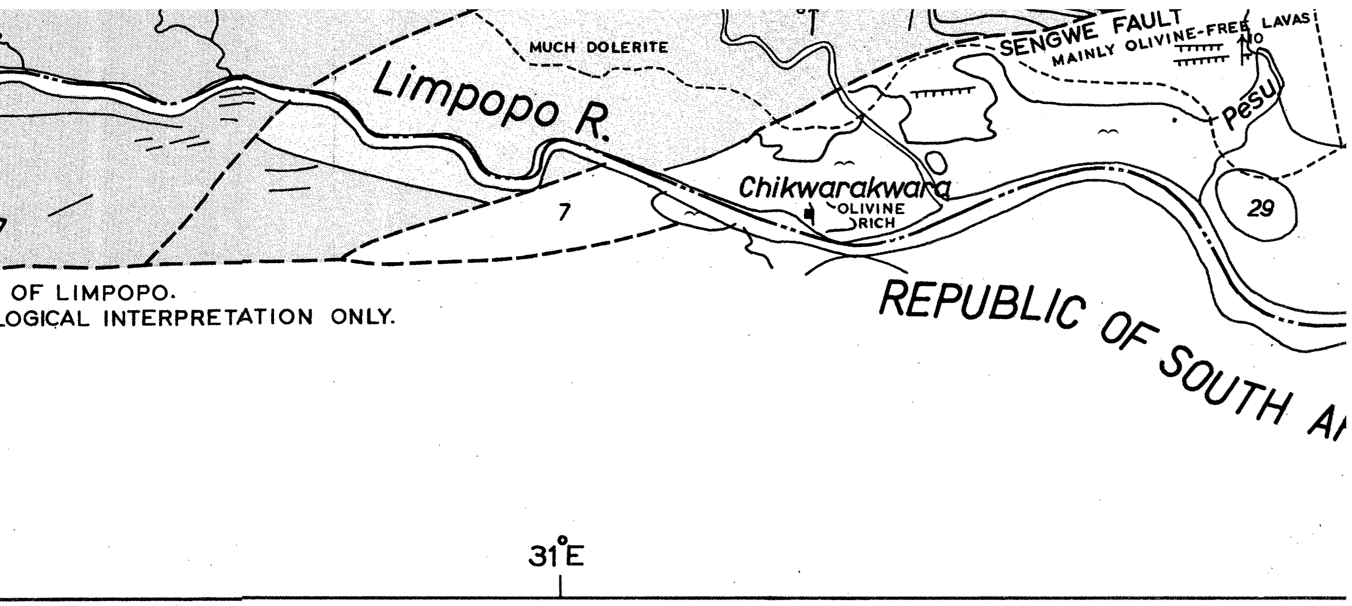
10 DIP OF BEDDING, LAVA FLOW OR IGNEOUS CONTACT

SMALL SCARPS & CUESTAS FORMED BY INDIVIDUAL BASALT FLOWS

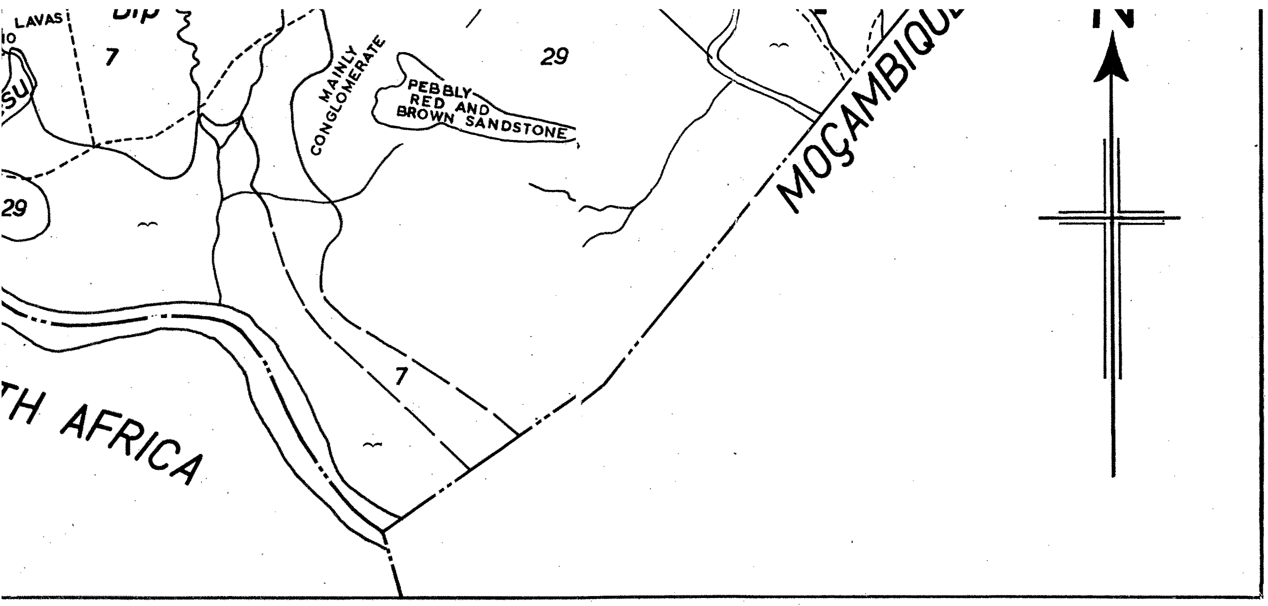
DEMBE etc. NAMES OF INDIVIDUAL RING-COMPLEXES



S. OF LIM
PHOTO GEOLOGICAL



MUCH DOLERITE
Limpopo R.
SENGWE FAULT
MAINLY OLIVINE-FREE LAVAS
10
Pesu
29
7
Chikwarakwara
OLIVINE RICH
REPUBLIC OF SOUTH A
OF LIMPOPO.
LOGICAL INTERPRETATION ONLY.
31°E



LAVAS
7
29
MAINLY CONGLOMERATE
PEBBLY RED AND BROWN SANDSTONE
29
7
TH AFRICA
MOÇAMBIQU
N

10 DIP OF BEDDING, LAVA FLOW OR IGNEOUS CONTACT

SMALL SCARPS & CUESTAS FORMED BY INDIVIDUAL BASALT FLOWS

DEMBE etc. NAMES OF INDIVIDUAL RING-COMPLEXES

▲ PROMINENT HILL

■ BUILDINGS, DIP TANKS ETC. WHERE LABELLED

RIVER

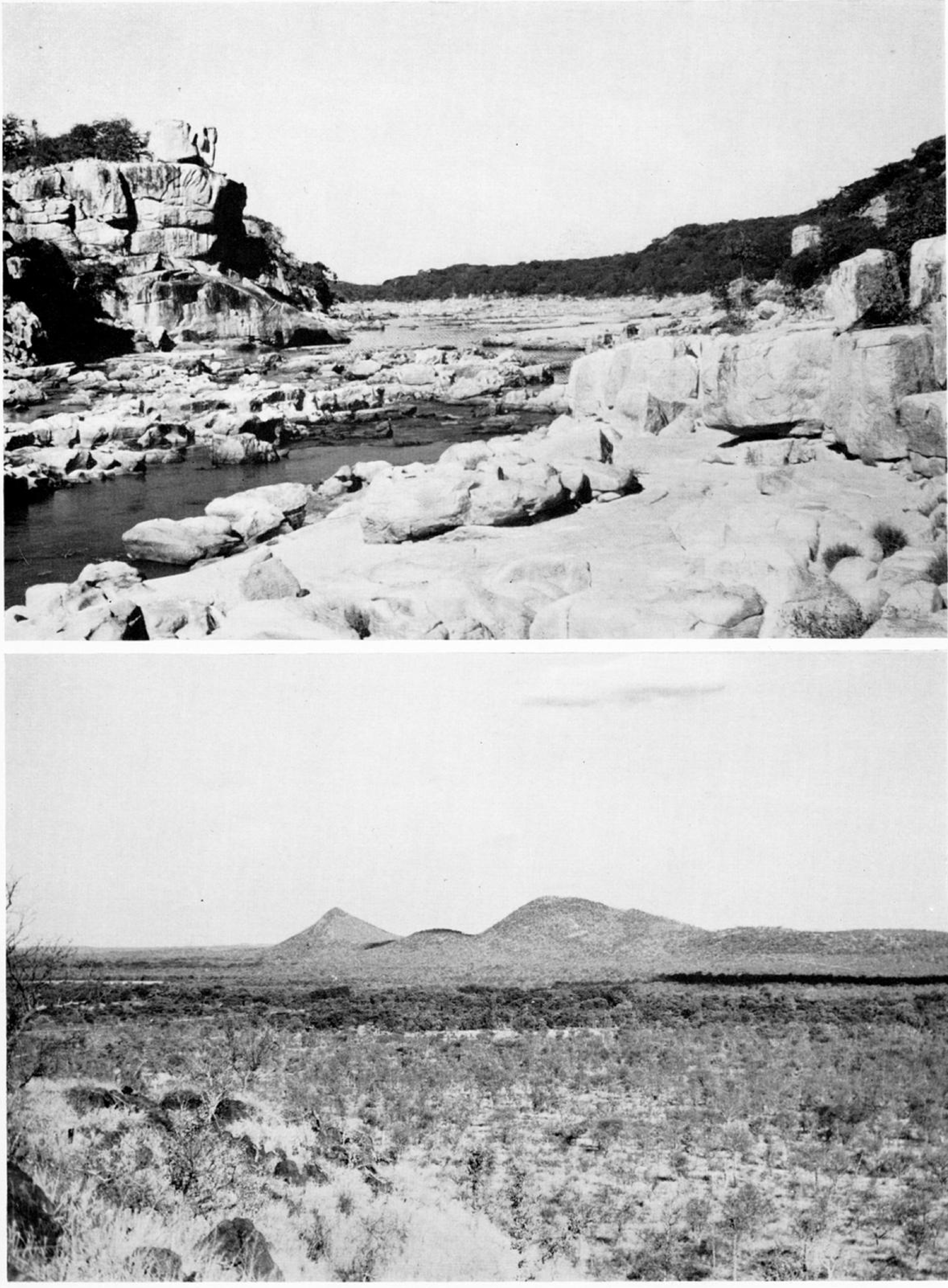
PAN

MAIN ROAD

MOTORABLE TRACK

RAILWAY

INTERNATIONAL BOUNDARY

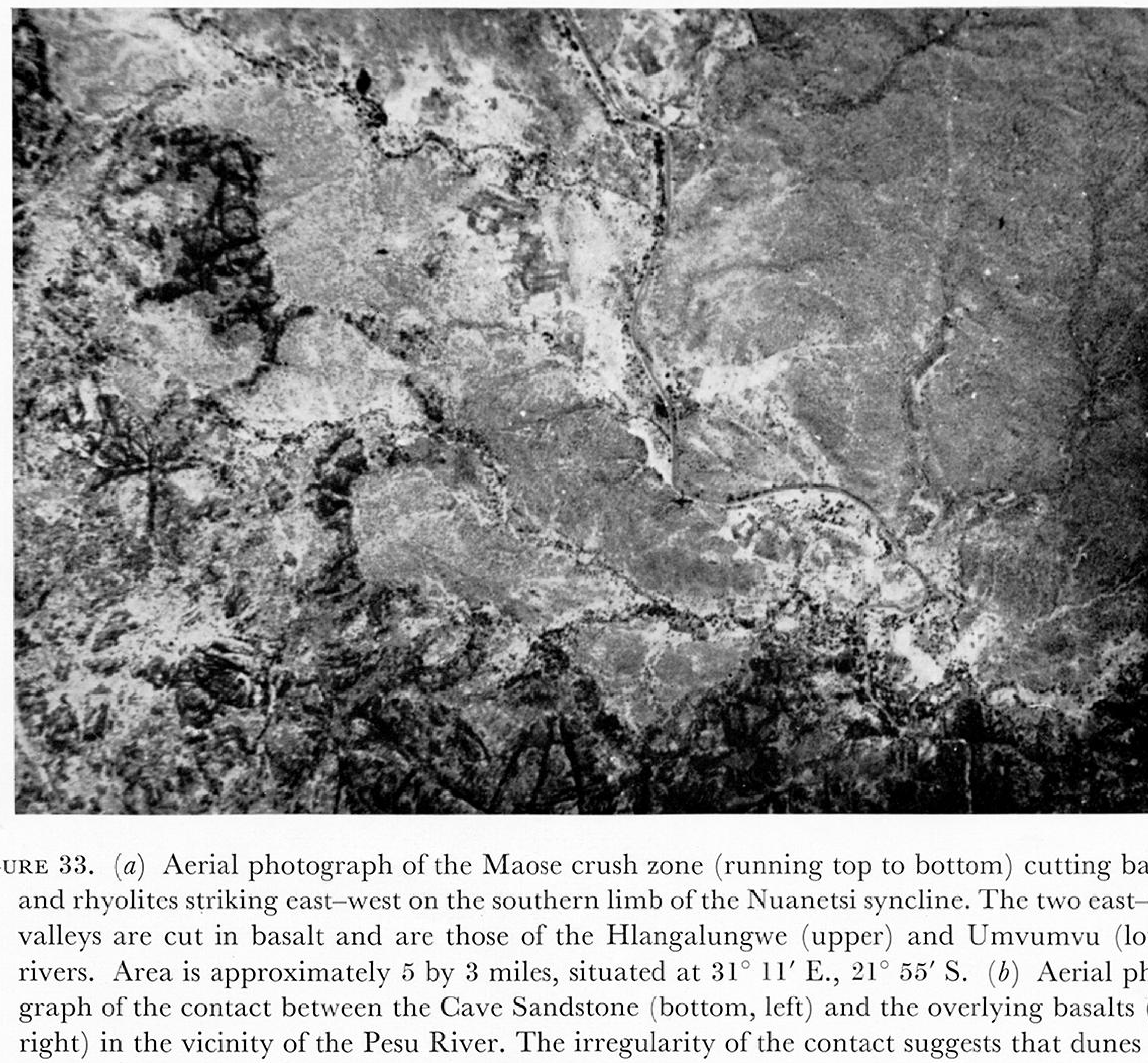


a

b

FIGURE 32. (*a*) The Chiribira Gorge where the Sabi River cuts through the granites of the Chiwonje complex. (*b*) Hills of the Northern Ring complex viewed from the north-west with basalts in the foreground. Madzenwene Hill (left) and Gurutangu (right) are the topographic expression of the marginal ring-dyke.

a



b

FIGURE 33. (*a*) Aerial photograph of the Maose crush zone (running top to bottom) cutting basalts and rhyolites striking east–west on the southern limb of the Nuanetsi syncline. The two east–west valleys are cut in basalt and are those of the Hlangalungwe (upper) and Umvumvu (lower) rivers. Area is approximately 5 by 3 miles, situated at 31° 11′ E., 21° 55′ S. (*b*) Aerial photograph of the contact between the Cave Sandstone (bottom, left) and the overlying basalts (top, right) in the vicinity of the Pesu River. The irregularity of the contact suggests that dunes may have been present at the top of the sandstone sequence. Area is $3\frac{1}{2}$ by $2\frac{1}{2}$ miles, situated at 31° 11′ E., 22° 16′ S. Both photographs published by permission of the Federal Department of Trigonometrical and Topographical Surveys, Salisbury, Southern Rhodesia.

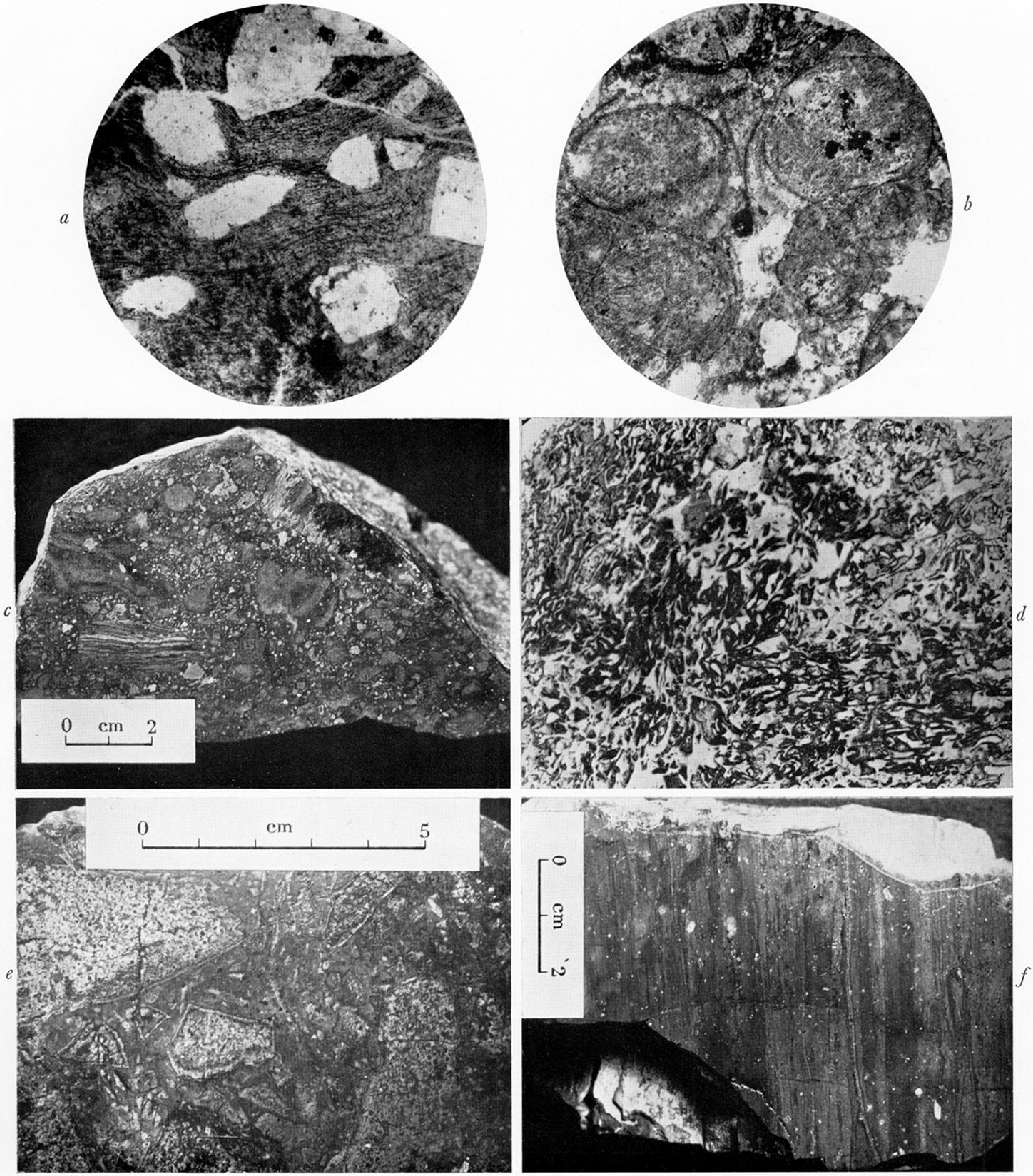


FIGURE 34. (*a*) Micro-eutaxitic structure in an ignimbrite. Photomicrograph in plane polarized light (× 20). (*b*) Perlitic cracks in devitrified vitrophyre. Photomicrograph in plane polarized light (× 20). (*c*) Breccia, base of Uche ignimbrite. (*d*) Vitric tuff showing typical vitroclastic texture, Tchovi ignimbrite. Photomicrograph (× 8). (*e*) Breccia, Tchovi ignimbrite. (*f*) Eutaxitic banding, Tchovi ignimbrite.

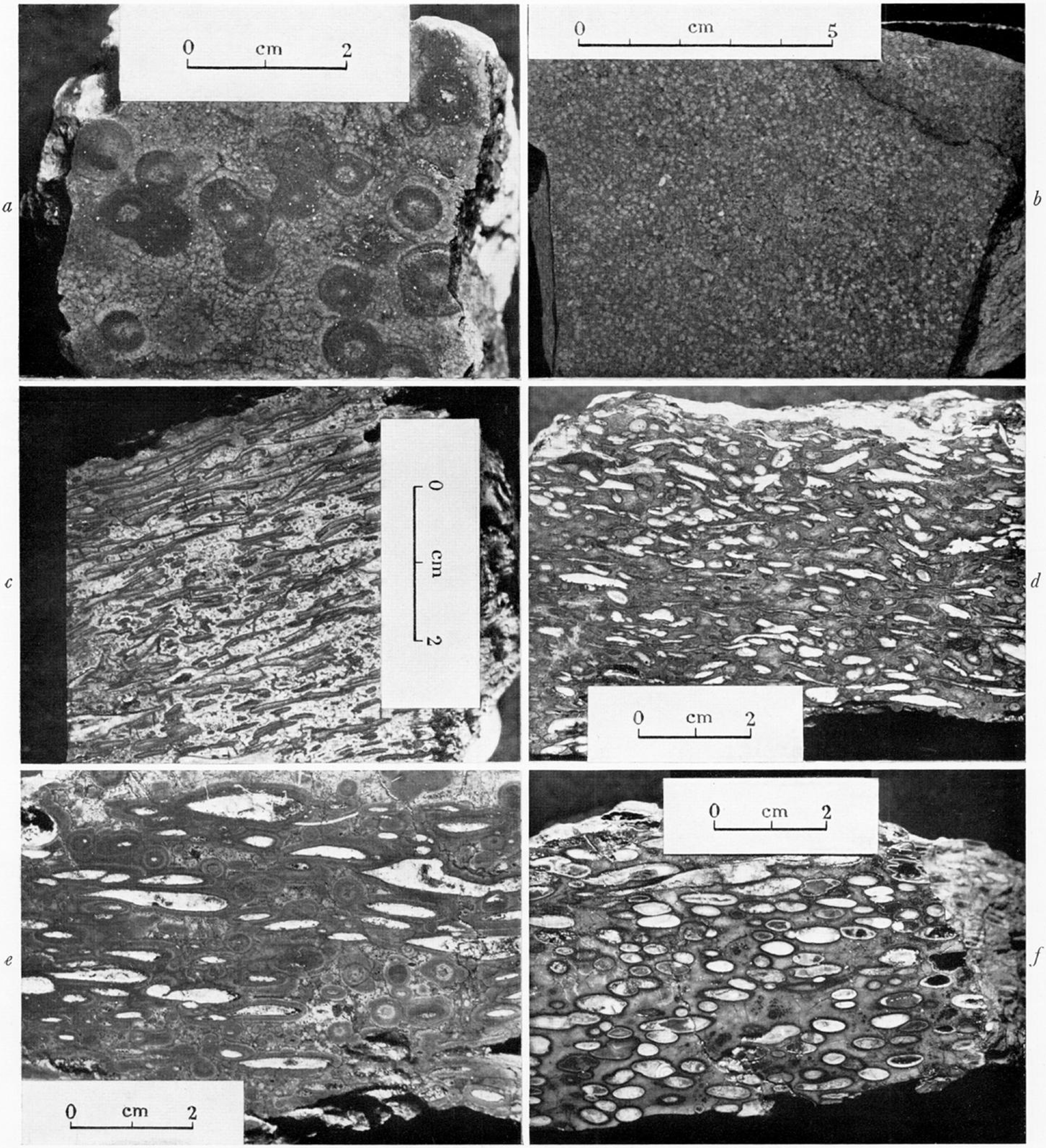
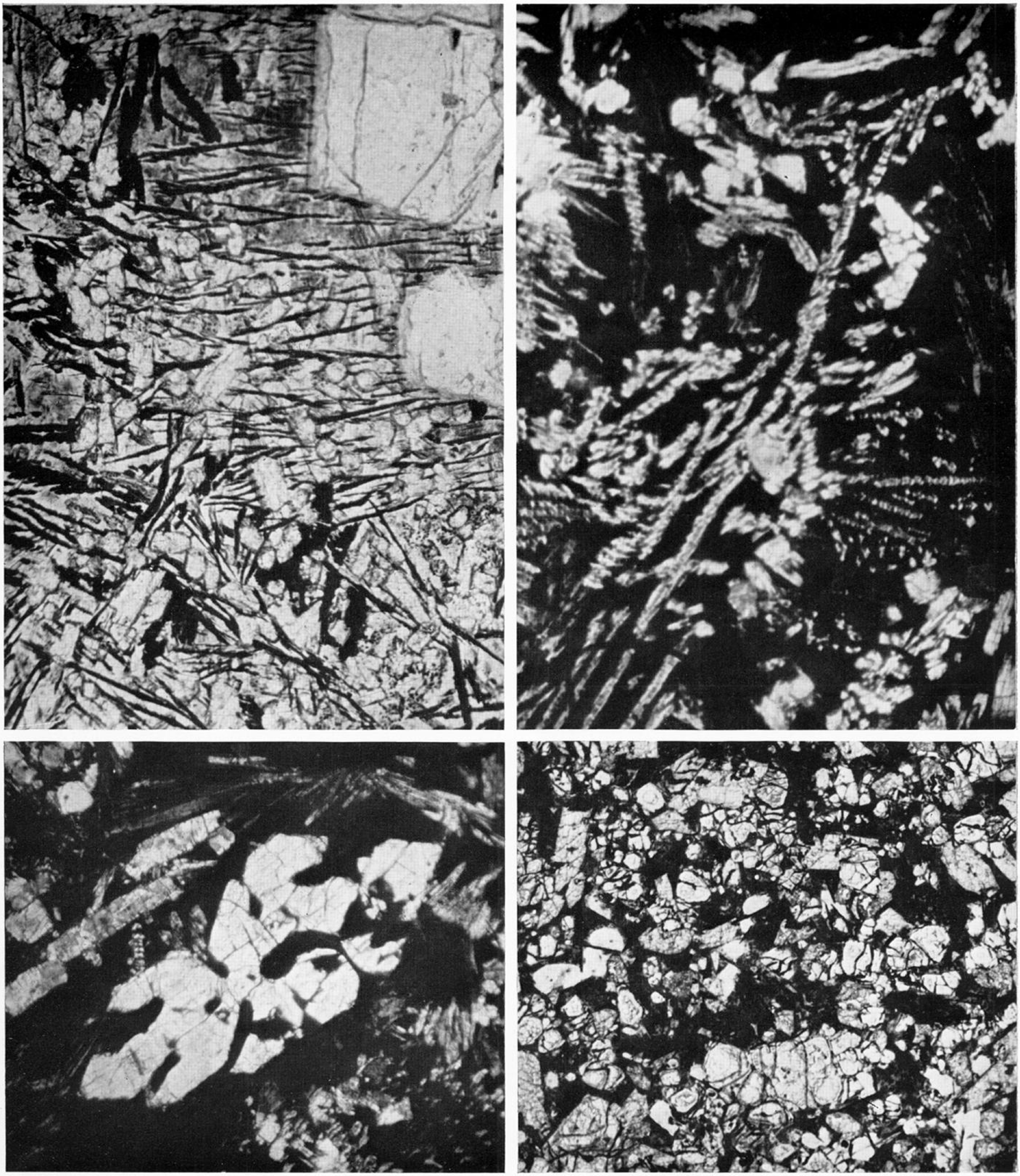
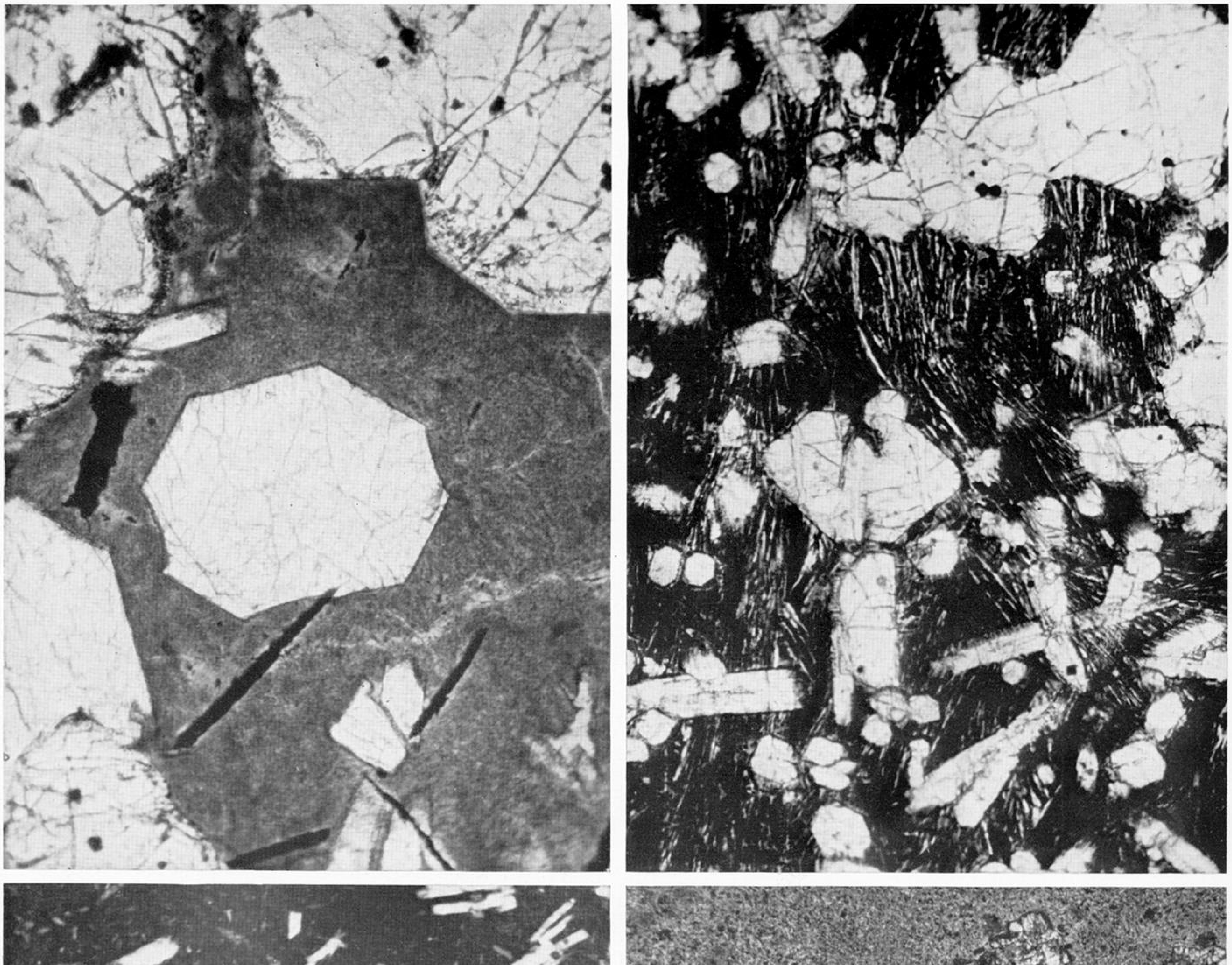


FIGURE 35. (*a*) Spherulitic structures, Tchovi ignimbrite. (*b*) Felsitic texture, Tchovi ignimbrite. (*c*) Compaction structures, Chasitchi ignimbrite. (*d*) Compaction structures, Chasitchi ignimbrite. (*e*) and (*f*) Specimens from the Malipanda ignimbrite, showing spherulites and lithophysal structures somewhat flattened by compaction.



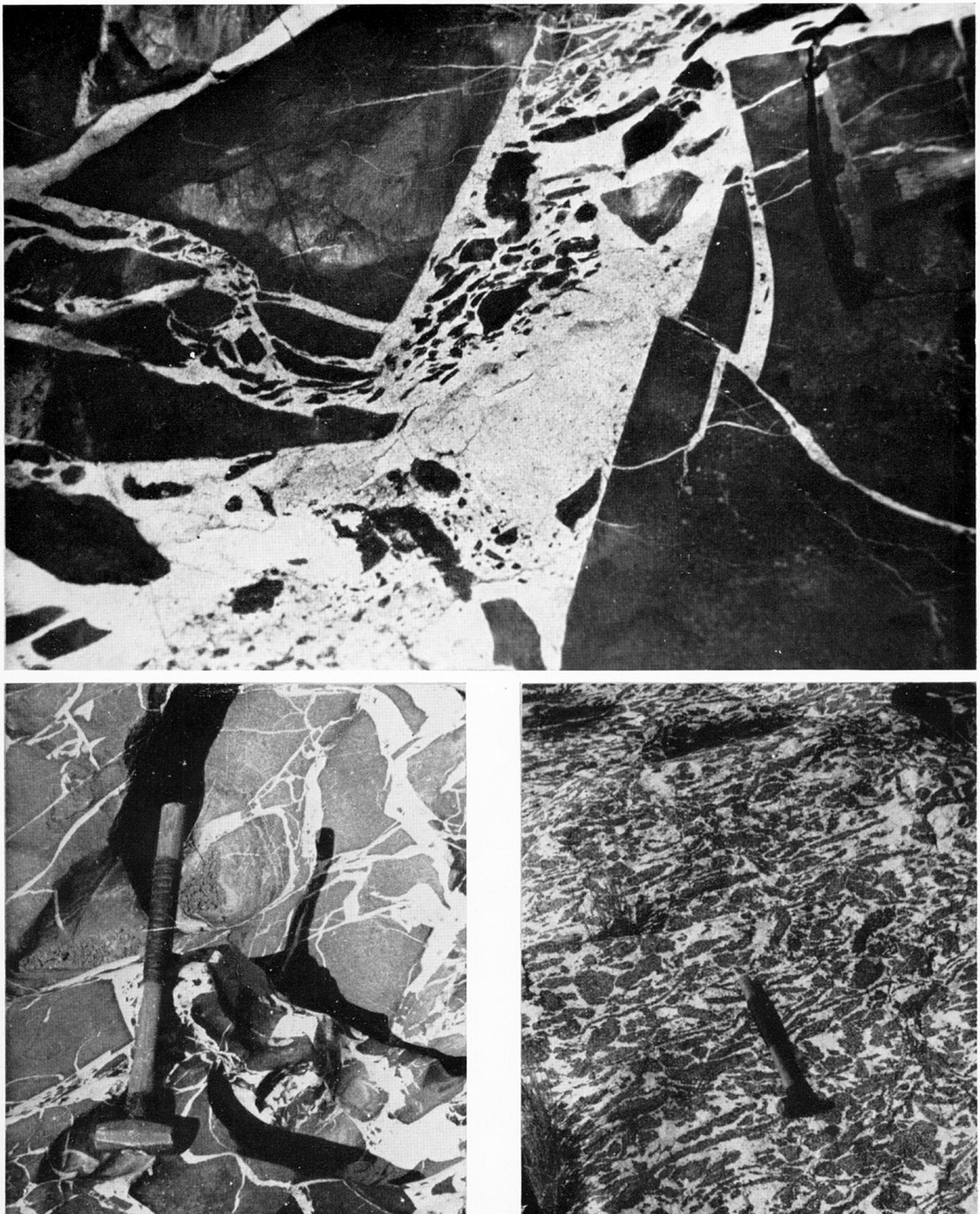
a b c d

FIGURE 36. (*a*) A limburgite showing the characteristic arrangements of combs of ore. Plane polarized light (× 30). (*b*) Dendritic crystals of clinopyroxene set in a glassy ground-mass in a limburgite. Crossed nicols (× 60). (*c*) Skeletal olivine phenocryst in a limburgite. Crossed nicols (× 30). (*d*) Texture of the limburgites. Olivine and clinopyroxene microphenocrysts set in a ground-mass of dark glass. Ordinary light (× 10).



a b c d

FIGURE 37. (*a*) Clinopyroxene and olivine phenocrysts in a limburgite. Plane polarized light (× 50). (*b*) Texture of an olivine basalt showing olivine, pyroxene and plagioclase laths set in glass. Plane polarized light (× 30). (*c*) Feldspar-phyric basalt from Upper Basalts of Chikombedzi area. Ordinary light (× 6). (*d*) Glomeroporphyritic pyroxene-phyric basalt from Upper Basalts of Chikombedzi area. Ordinary light (× 6).

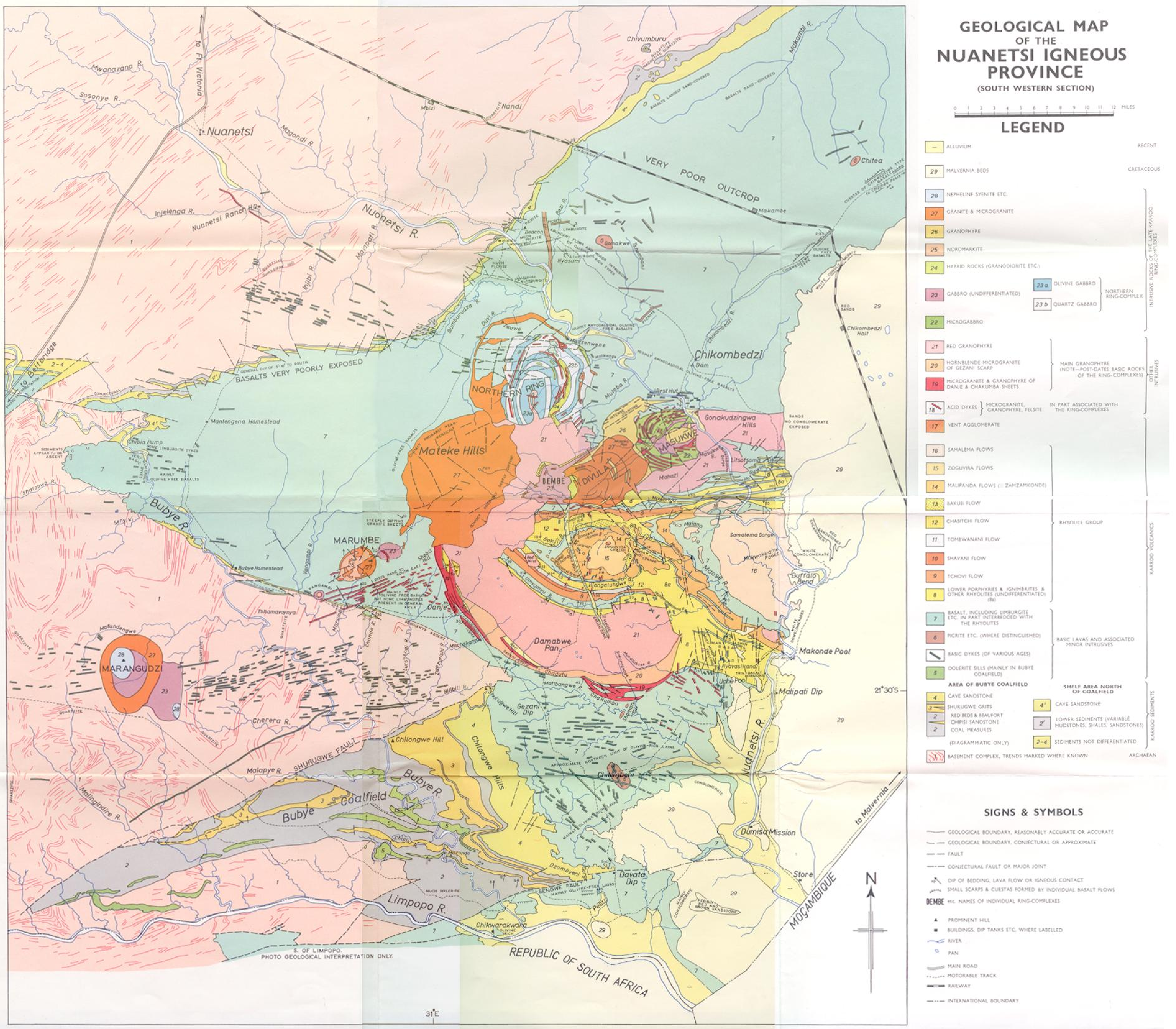


a

b

c

FIGURE 38. Intrusion breccias from the Mutandawhe complex. (*a*) and (*b*) Loupangwan granite with basalt fragments. (*c*) Mutandawhe nordmarkite with rounded and partially digested basalt fragments.



GEOLOGICAL MAP OF THE NUANETSI IGNEOUS PROVINCE
(SOUTH WESTERN SECTION)
0 1 2 3 4 5 6 7 8 9 10 11 12 MILES
LEGEND
ALLUVIUM
RECENT
29 MALVERNIA BEDS
CRETACEOUS
28 NEPHELINE SYENITE ETC.
27 GRANITE & MICROGRANITE
26 GRANOPHYRE
25 NORDMARKITE
24 HYBRID ROCKS (GRANODIORITE ETC.)
23 GABBRO (UNDIFFERENTIATED)
23 a OLIVINE GABBRO
23 b QUARTZ GABBRO
NORTHERN RING-COMPLEX
22 MICROGABBRO
INTRUSIVE ROCKS OF THE LATE-KARROO RING-COMPLEXES
21 RED GRANOPHYRE
20 HORNBLENDE MICROGRANITE OF GEZANI SCARP
19 MICROGRANITE & GRANOPHYRE OF DANJE & CHAKUMBA SHEETS
MAIN GRANOPHYRE (NOTE—POST-DATES BASIC ROCKS OF THE RING-COMPLEXES)
18 ACID DYKES
MICROGRANITE, GRANOPHYRE, FELSITE
IN PART ASSOCIATED WITH THE RING-COMPLEXES
OTHER INTRUSIVES
17 VENT AGGLOMERATE
16 SAMALEMA FLOWS
15 ZOGUVIRA FLOWS
14 MALIPANDA FLOWS (= ZAMZAMKONDE)
13 BAKUJI FLOW
12 CHASITCHI FLOW
11 TOMBWANANI FLOW
10 SHAVANI FLOW
9 TCHOVI FLOW
8 LOWER PORPHYRIES & IGNIMBRITES & OTHER RHYOLITES (UNDIFFERENTIATED) (8a)
RHYOLITE GROUP
7 BASALT, INCLUDING LIMBURGITE ETC. IN PART INTERBEDDED WITH THE RHYOLITES
6 PICRITE ETC. (WHERE DISTINGUISHED)
BASIC DYKES (OF VARIOUS AGES)
5 DOLERITE SILLS (MAINLY IN BUBYE COALFIELD)
BASIC LAVAS AND ASSOCIATED MINOR INTRUSIVES
KARROO VOLCANICS
AREA OF BUBYE COALFIELD
4 CAVE SANDSTONE
3 SHURUGWE GRITS
2 RED BEDS & BEAUFORT
CHIPISI SANDSTONE
2 COAL MEASURES
(DIAGRAMMATIC ONLY)
SHELF AREA NORTH OF COALFIELD
4' CAVE SANDSTONE
2' LOWER SEDIMENTS (VARIABLE MUDSTONES, SHALES, SANDSTONES)
2-4 SEDIMENTS NOT DIFFERENTIATED
KARROO SEDIMENTS
BASEMENT COMPLEX, TRENDS MARKED WHERE KNOWN
ARCHAEAN
SIGNS & SYMBOLS
GEOLOGICAL BOUNDARY, REASONABLY ACCURATE OR ACCURATE
GEOLOGICAL BOUNDARY, CONJECTURAL OR APPROXIMATE
FAULT
CONJECTURAL FAULT OR MAJOR JOINT
DIP OF BEDDING, LAVA FLOW OR IGNEOUS CONTACT
SMALL SCARPS & CUESTAS FORMED BY INDIVIDUAL BASALT FLOWS
DEMBE ETC. NAMES OF INDIVIDUAL RING-COMPLEXES
PROMINENT HILL
BUILDINGS, DIP TANKS ETC. WHERE LABELLED
RIVER
PAN
MAIN ROAD
MOTORABLE TRACK
RAILWAY
INTERNATIONAL BOUNDARY
N
Nuanetsi
Nuanetsi R.
Mwanazana R.
Sosonye R.
to Ft. Victoria
to Beitbridge
Nuanetsi Ranch HQ
Injelenga R.
VERY POOR OUTCROP
BASALTS VERY POORLY EXPOSED
NORTHERN RING
Mateke Hills
DEMBE
DIVULA
MASUKWE
MARUMBE
MARANGUDZI
Chikombedzi
Gonakudzingwa Hills
Bubye R.
Bubye Coalfield
Limpopo R.
Damabwe Pan
Chilongwe Hill
Chilongwe Hills
Gezani Dip
Makonde Pool
Malipati Dip
Buffalo Bend
Dumisa Mission
Davata Dip
Chikwarakwara
Chitea
Chivumburu
Makambe
Mbizi
Nandi
Shurugwe Fault
Sengwe Fault
Nuanetsi R.
MOÇAMBIQUE
to Malvernia
REPUBLIC OF SOUTH AFRICA
S. OF LIMPOPO. PHOTO GEOLOGICAL INTERPRETATION ONLY.
21°30'S
31°E


to Ft. Victoria
Mwanazana R.
Sosonye R.
Nuanetsi
Magondi R.
Injelenga R.
Nuanetsi Ranch H.Q.
1
QUARTZITE
Dumbalape Hill
Injibi R.
to Beitbridge
PHOTO INTERPRETATION ONLY
2-4
7
CONJECTURAL
2'
4'
4'
4'
GENERAL DIP OF 5°-10° TO SOUTH
BASALTS VERY POORLY
10
Mantengena Homestead
Chipia Pump
SOME LIMBURGITE DYKES
SEDIMENTS APPEAR TO BE ABSENT

Mbizi
QUARTZITE
Nandi
1
LIMBURGITE
Nuanetsi R.
Malapati R.
Injibi R.
4'
Bezi R.
PICRITE
3
Beacon
PICRITE
3
LIMBURGITE
ABUNDANT FLOWS AND MINOR INTRUSIONS OF OLIVINE RICH TYPES
MUCH PICRITE
Matibi Homestead
Nyasumi
3
LIMBURGITE
MUCH PICRITE
6
LIMBURGITE
Bumburudza R.
Duvi R.
5
Zauwe
7
Madzenwene
Malikange
23b
7
POORLY EXPOSED
NORTHERN RING
Mulaba R.
23a
24
26
21
7
CONTACT PROBABLY NEAR-VERTICAL
Mateke Hills
27

Chivumburu
QUARTZITE
MAGNETITE QUARTZITE
2'
4'
BASALTS LARGELY SAND-COVERED
BASALTS SAND-COVERED
Makambi R.
7
6 Chitea
VERY POOR OUTCROP
Makambe
CUESTAS OF CHIKWEDZIWA TYPE BASALT
to Chipinda Pools
2-3
OLIVINE FREE BASALTS
CHIKWEDZEWA TYPE
WHITE CONGLOMERATE
6 Gomakwe
Tshompani
OR INTRUSIONS
TYPES
7
PICRITE
ALOIDAL OLIVINE-FREE BASALTS
Chikombedzi R.
RED SANDS
29
Chikombedzi Halt
Chikombedzi
Dam
HIGHLY AMYGDALOIDAL OLIVINE-FREE BASALTS
7
Mulaba R.
Rest Hut
10
5
INTENSE JOINTING
Gonakudzingwa Hills
21
SANDS NO CONGLOMERATE EXPOSED
26
Wusaka Pan
27
MASUKWE
22
Masukwe R.
21
Litsotsoma
25

GEOLOGICAL MAP
OF THE
NUANETSI IGNEOUS PROVINCE
(SOUTH WESTERN SECTION)

0 1 2 3 4 5 6 7 8 9 10 11 12 MILES

LEGEND

~	ALLUVIUM		RECENT
29	MALVERNIA BEDS		CRETACEOUS
28	NEPHELINE SYENITE ETC.		INTRUSIVE ROCKS OF THE LATE-KARROO RING-COMPLEXES
27	GRANITE & MICROGRANITE		
26	GRANOPHYRE		
25	NORDMARKITE		
24	HYBRID ROCKS (GRANODIORITE ETC.)		
23	GABBRO (UNDIFFERENTIATED)	23 a OLIVINE GABBRO; 23 b QUARTZ GABBRO — NORTHERN RING-COMPLEX	
22	MICROGABBRO		
21	RED GRANOPHYRE	MAIN GRANOPHYRE (NOTE—POST-DATES BASIC ROCKS OF THE RING-COMPLEXES)	OTHER INTRUSIVES
20	HORNBLENDE MICROGRANITE OF GEZANI SCARP		
19	MICROGRANITE & GRANOPHYRE OF DANJE & CHAKUMBA SHEETS		
18	ACID DYKES — MICROGRANITE, GRANOPHYRE, FELSITE	IN PART ASSOCIATED WITH THE RING-COMPLEXES	
17	VENT AGGLOMERATE		
16	SAMALEMA FLOWS		


SEDIMENTS
APPEAR TO BE
ABSENT
SOME LIMBURGITE DYKES
VERY NUMEROUS BASIC DYKES
7
MAINLY
OLIVINE FREE BASALTS
Shatopwe R.
Bubye R.
Senyiki
2-4
7
Vangambi R.
Bubye Homestead
VANGA
1
Tshamavoynya
QUARTZITE
Mafundengwe
QUARTZITE
QUARTZITE
28
27
MARANGUDZI
23
28
QUARTZITE
Cherera R.
QUARTZITE
Malapye R.
SHURUGW
QUARTZITE
1
Malingindire R.
3
3
Bubye
2
1

Mateke Hills
OLIVINE-FREE
CONTACT
Pan
27
CONTACT PROBABLY GENTLY DIPPING
Jenama
DEMBE
23
Kobu
DIVULA
STEEPLY DIPPING GRANITE SHEETS
MARUMBE
Vangambi R.
25
Sheba Hill
21
DYKES HADE TO SOUTH EAST
VANGAMBI
MAINLY OLIVINE FREE BASALTS BUT SOME LIMBURGITES PRESENT IN GENERAL AREA
19
Danje
Chikala-ugwe
Marumbe R.
Chonda R.
SEDIMENTS ABSENT
Machakanya
Lutshendi R.
Zwezutishi R.
Bilibili R.
Chovi Ridge
Chasitchi Hill
12
Bakuji R.
Zamzam-konde
Makanani
14
ZOGUVIRA CRATER
15
Red Hills
Bakuji Scarp
Gujamyi Scarp
CRUSH ZONE
Umvumvu R.
Hlangalungwi
9
MAOSE
Damabwe Pan
Dari
Gezani Scarp
Chadutu
Malibangwe R.
Chakumba
Shurugwe Hill
Gezani Dip
Chilongwe Hill
Chilongwe Hills
SHURUGWE FAULT
APPROXIMATE NORTHERN LIMIT
Chilembe
Bubye R.
Coalfield
Bubye
MAINLY OLIVINE RICH LAVAS
Chipisi R.
Mazondo
Dzombyeni Gorge
MUCH DOLERITE
SENGWE FAULT
MAINLY OLIVINE-FREE LAVAS
Limpopo R.
Pesu


Masukwe R.
Buhalabahnu Gorge
Litsotsoma
Guwini
Mahazi
Mawanga
Majana
Samalema Gorge
RED SANDSTONES ESCARPMENT
WHITE CONGLOMERATE
Makwakwane Pools
ZOGUVIRA CRATER
Machow HOT SPRING
Malipanda
Maose R.
Buffalo Bend
galungwe R.
Mabgwamachena R.
MAOSE ZONE
WHITE CONGLOMERATES
MUCH MINOR FAULTING
MANY THIN BASALTS
Makonde Pool
Bridge
Mundilakose R.
Sakaragoage R.
Nyavasikana
THIN BASALT HORIZONS
Uche Pool
Malipati Dip
21°30'S
kumba
Shamandali
Nuanetsi R.
RN LIMIT OF OLIVINE-RICH LAVAS
Chilembeni
CONGLOMERATE
LAVAS
Dumisa Mission
to Malvernia
Store
Davata Dip
LAVAS
MAINLY GLOMERATE
PEBBLY RED AND BROWN SAN
SAMBIQUE
N

16	SAMALEMA FLOWS	RHYOLITE GROUP	KARROO VOLCANICS
15	ZOGUVIRA FLOWS		
14	MALIPANDA FLOWS (≡ ZAMZAMKONDE)		
13	BAKUJI FLOW		
12	CHASITCHI FLOW		
11	TOMBWANANI FLOW		
10	SHAVANI FLOW		
9	TCHOVI FLOW		
8	LOWER PORPHYRIES & IGNIMBRITES & OTHER RHYOLITES (UNDIFFERENTIATED) (8a)		
7	BASALT, INCLUDING LIMBURGITE ETC. IN PART INTERBEDDED WITH THE RHYOLITES	BASIC LAVAS AND ASSOCIATED MINOR INTRUSIVES	
6	PICRITE ETC. (WHERE DISTINGUISHED)		
	BASIC DYKES (OF VARIOUS AGES)		
5	DOLERITE SILLS (MAINLY IN BUBYE COALFIELD)		

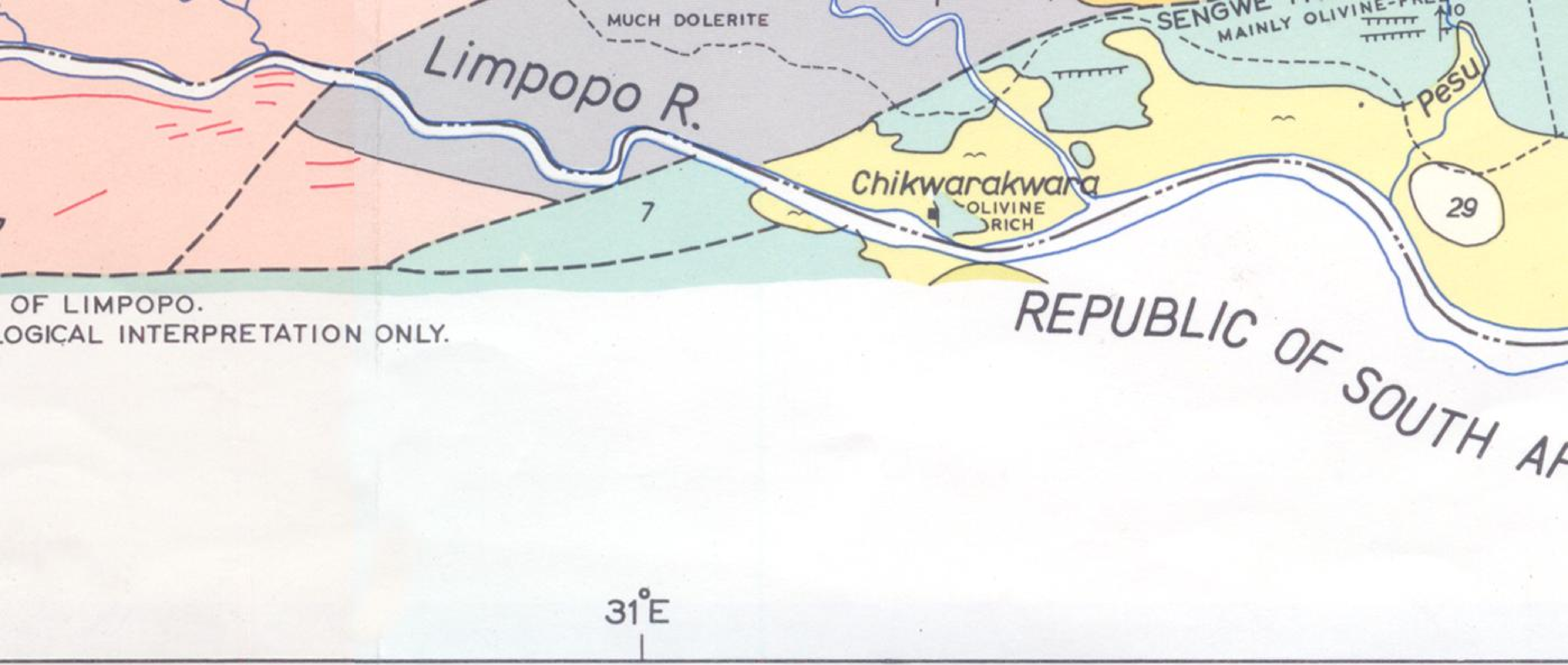
AREA OF BUBYE COALFIELD		SHELF AREA NORTH OF COALFIELD		
4	CAVE SANDSTONE	4′	CAVE SANDSTONE	KARROO SEDIMENTS
3	SHURUGWE GRITS	2′	LOWER SEDIMENTS (VARIABLE MUDSTONES, SHALES, SANDSTONES)	
2	RED BEDS & BEAUFORT	2–4	SEDIMENTS NOT DIFFERENTIATED	
	CHIPISI SANDSTONE			
2	COAL MEASURES			
	(DIAGRAMMATIC ONLY)			

1	BASEMENT COMPLEX, TRENDS MARKED WHERE KNOWN	ARCHAEAN

SIGNS & SYMBOLS

- GEOLOGICAL BOUNDARY, REASONABLY ACCURATE OR ACCURATE
- GEOLOGICAL BOUNDARY, CONJECTURAL OR APPROXIMATE
- FAULT
- CONJECTURAL FAULT OR MAJOR JOINT
- 10 DIP OF BEDDING, LAVA FLOW OR IGNEOUS CONTACT
- SMALL SCARPS & CUESTAS FORMED BY INDIVIDUAL BASALT FLOWS
- DEMBE etc. NAMES OF INDIVIDUAL RING-COMPLEXES


S. OF LIM
PHOTO GEOLOGICAL



OF LIMPOPO.
LOGICAL INTERPRETATION ONLY.

7
29
MAINLY CONGLOMERATE
PEBBLY RED AND BROWN SANDSTONE
29
7
H AFRICA
MOÇAMBIQ

	SMALL SCARPS & CUESTAS FORMED BY INDIVIDUAL BASALT FLOWS
DEMBE	etc. NAMES OF INDIVIDUAL RING-COMPLEXES
▲	PROMINENT HILL
■	BUILDINGS, DIP TANKS ETC. WHERE LABELLED
	RIVER
	PAN
	MAIN ROAD
	MOTORABLE TRACK
	RAILWAY
	INTERNATIONAL BOUNDARY