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REGIONAL GEOCHEMISTRY OF THE KAROO IGNEOUS PROVINCE

by

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ABSTRACT

The extrusive and intrusive rocks of the Karoo Igneous Province are dominantly of basaltic or rhyolitic (*sensu lato*) composition. There are, however, a considerable variety of other rock types within the province including picritic basalts, nephelinites, shoshonites, latites, andesites and dacites.

Detailed geochemical comparisons of basic rocks in different geographic areas show that there are three "clans" of basic magma types in the Karoo Igneous Province. These clans have their type areas in the Nuanetsi–Lebombo area, the Central Karoo area and the Etendeka area of SWA/Namibia. There is little or no relationship between the composition of Karoo basic magmas and the age or character of the major crustal tectonic units on which they were erupted. Detailed studies have shown that most differences in incompatible element ratios and in Sr- and Nd-isotope ratios between Karoo basic magmas are not due to crustal contamination, partial melting or fractional crystallization processes. They are therefore considered to indicate mantle heterogeneity on a variety of scales. Many or all of the mantle source regions for Karoo basalts must be enriched in incompatible elements and comparison with mantle nodules included as xenoliths in kimberlite suggests that "mantle metasomatism" may be the enrichment process.

Rhyolites and quartz latites in the Karoo Igneous Province are located only near the contental margin of southern Africa. They are thought to have been produced by anatexis at or near the base of the crust during crustal thinning which immediately preceded the disruption of Gondwanaland. The Karoo basalts are not concentrated near the continental margins and the acme of Karoo volcanism pre-dates the disruption of Gondwanaland. The distribution, age and inferred lithospheric source of Karoo magmas is consistent with a model which relates the generation of Jurassic–Cretaceous Gondwana flood basalts to a major convective roll in the mantle induced by subduction beneath the Pacific margin of Gondwanaland.

CONTENTS

I. INTRODUCTION

The extrusive and intrusive rocks of the Karoo Igneous Province exhibit a strongly bimodal distribution of SiO_2 with silica maxima corresponding to basalts and rhyolites (*sensu lato*) as is illustrated in Fig. 1. There are, however, a considerable variety of rock types within the province covering the range from the abundant basalts and their intrusive equivalents to high-MgO picritic basalts and the more alkaline nephelinites and shoshonites; together with a spectrum of intermediate and acid rocks which range from andesitic to rhyolitic in character. The overall geological character of the province and the detailed stratigraphy, petrology and geochemistry of various sections of it are covered in other chapters of this volume. It is the aim of the present paper to view the geochemistry of the province as a whole and to attempt to synthesize the available data, much of it new, in order to investigate whether or not there are systematic variations in the chemistry of the Karoo igneous rocks which can be related to geographic area or tectonic regime. Any possible relationships between geochemical characteristics and tectonic regime are of critical importance in trying to define the possible relationships between Karoo volcanicity and geodynamic processes.

There have been many papers which have contributed geochemical data on Karoo igneous rocks and many of the authors have drawn attention to local or regional variations in composition. There are relatively few papers, however, which have previously attempted to synthesize the data available for the Karoo basic igneous rocks as a whole (Cox *et al.*, 1967; MacDonald, 1967; Cox, 1972; Rhodes and

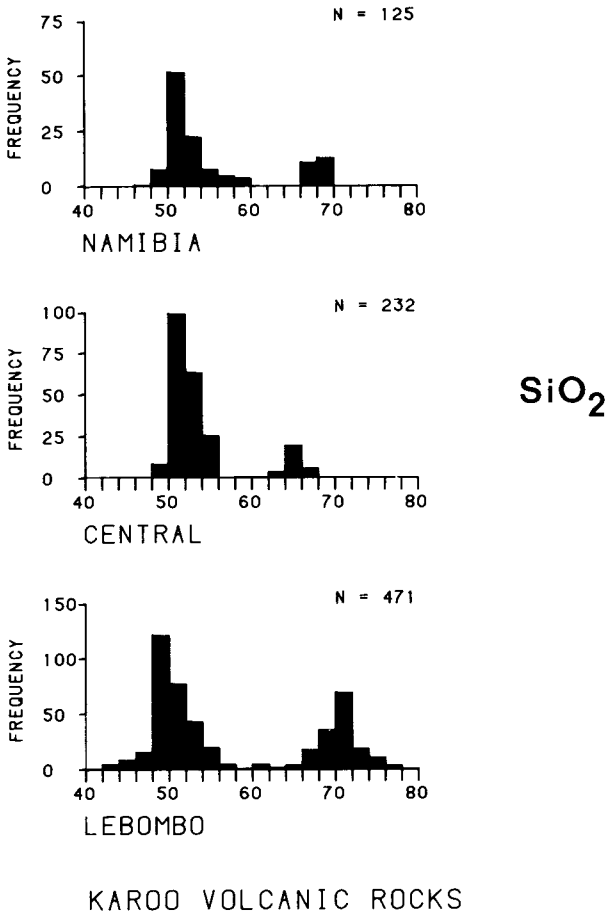

Figure 1
Histogram of SiO_2 abundances in the volcanic rocks of three geographic regions of the Karoo Igneous Province. It should be noted that the relative sample frequencies do not reflect the relative areas of volcanics with a particular SiO_2 content.

Krohn, 1972) and only one (Cox, 1972) which has discussed both basic and acid rocks.

There have been two fundamentally different conclusions reached. Cox and his co-workers recognized "northern" and "southern" geochemical "provinces" within the Karoo basic igneous rocks but pointed out that their "province" boundaries did not correspond in any simple way with tectonic environment. Thus Cox (1972) commented that the Lebombo zone was found to change character along its length and that all the Rhodesian (Zimbabwean) basalts appeared to be more or less K-rich regardless of whether they occurred in the deformed zones of Tuli and Nuanetsi or on the cratonic areas such as at Bulawayo and Livingstone. Rhodes and Krohn (1972), on the other hand, argued for a close relationship between the geochemistry of Karoo basalts and dolerites and the regional tectonics of the Karoo basin.

Within the Karoo Province there is often a strong correspondence between the compositional characteristics of the volcanics and their stratigraphic position. This is best exemplified perhaps by the section through the Karoo volcanics in the northern portion of the Lebombo monocline and in the Nuanetsi area of south-eastern Zimbabwe which has been described by various authors (e.g. Cox *et al.*, 1965; Cox, 1972; Bristow, 1984a, b; Cleverly and Bristow, 1979; Cleverly *et al.*, 1984; Eales *et al.*, 1984). The lower half of this section has the Mashikiri Formation at the base which consists of nephelinite and related rock types, overlain by the Letaba Basalt Formation which dominantly consists of tholeiitic picrite basalts and which is in turn overlain by the Sabie River Formation which consists largely of basalts and tholeiitic andesites (Bristow and Cox, 1984) with subordinate shoshonite and absarokite. The upper half of the section consists of the Jozini Rhyolite Formation in the northern Lebombo and the Nuanetsi rhyolite, with some interbedded basalts, in the Nuanetsi area.

In the Central Karoo area the base of the stratigraphic succession consists of several basalt formations which are petrographically and compositionally distinct from each other and from the overlying Lesotho Formation basalts (Marsh and Eales, 1984). Associated with the lower basalt formations are small volumes of intermediate composition ("dacite" and "andesite") lavas and intrusives. The overall succession in the Central area is thus one of compositional diversity at the base, succeeded by large volumes of compositionally uniform basalts comprising the Lesotho Formation.

The Etendeka Formation of SWA/Namibia contrasts strongly with the Lebombo–Nuanetsi and Central Karoo areas since there is no clear correspondence between lava composition and stratigraphic position. The Etendeka Formation consists of basalts and evolved basalts which are *interbedded* with latites and quartz latites. However, two specific basalt types (designated Albin and Tafelberg types by Erlank *et al.*, 1984) do show a consistent stratigraphic superposition with only minor interbedding.

II. GEOCHEMICAL CLASSIFICATION PROCEDURES

A. Conventional Classification Techniques

In discussing geochemical variation in the Karoo Igneous Province it is convenient to distinguish between relatively gross variations in composition, such as those which would give rise to different names for the rock types, and more subtle variations which are typically shown by the minor and trace constituents in the rocks. It is also important to make use of the stratigraphic information which is available so that geochemical variations can be studied in both areal and temporal contexts.

As has been the case in studies of many suites of igneous rocks, SiO_2 has been chosen as the variable on which to make the most fundamental division of the Karoo igneous rocks. The classification adopted is one in which rocks with less that 56 % SiO_2 (weight % on a volatile-free basis) are termed "basic", those with 56–63 % are termed "intermediate" and those with more than 63 % are termed "acid". Thus rock types such as tholeiitic or basaltic andesites are included in the "basic" rocks, whereas dacites are included in the "acid" rock group. These divisions are convenient ones for the discussion of Karoo igneous rocks since the overwhelming majority of analysed rocks from the Karoo Igneous Province fall into either the "basic" or "acid" groups if this classification is utilized.

Details of the classification procedure adopted for the mafic rocks of the Lebombo–Nuanetsi–Sabi area are given by Bristow and Cox (1984). We have made use of many aspects of their classification when considering the *basic* rocks of the Karoo as a whole but have adopted a lower maximum SiO_2 content (56 %) than that proposed by them (60 %) as an upper limit for *mafic* rocks.

The level of silica saturation in the basic rocks of the Karoo Igneous Province has been used to separate the small proportion of alkaline nephelinites which occur at the base of the stratigraphic section in the northern Lebombo and Sabi areas from the dominant group of tholeiitic basaltic volcanics which occur throughout the province. The majority of the nephelinites have more than 20 % nepheline in the CIPW norm, whereas all the remaining basic rocks range from quartz normative through olivine–hypersthene normative. A few of the picritic basalts of the Letaba Basalt Formation contain very small amounts of nepheline in the norm and the dividing line between nephelinites and all the basaltic rock types has therefore been chosen as 5 % normative nepheline.

As noted by Bristow and Cox (1984), there is a natural division within the basic volcanics into those of >9 % MgO, termed high-MgO or picritic basalts, and those of <9 % MgO, termed basalts (see Figs. 2 and 3). Their additional subdivision at 5 % MgO (with mafic rocks with <5 % MgO termed "evolved") has not proved necessary for the purposes of the present paper.

The acid rocks of the Lebombo and Nuanetsi areas have been subdivided on the basis of their SiO_2 content into rhyolites, rhyodacites, dacites and trachyandesites by Cleverly *et al.* (1984). However, these authors have advocated the continued usage of "rhyolite" (*sensu lato*) as a general term for all the acid volcanics of the Lebombo and Nuanetsi areas and we have followed that convention in the present paper. Erlank *et al.* (1984) have subdivided the acid rocks of the Etendeka Formation in northern SWA/Namibia into quartz latites, latites and dacites according to their SiO_2 and K_2O contents. It should be noted that the "rhyolites" of the Lebombo and Nuanetsi areas and the "quartz latites" of the Etendeka Formation are similar in major element composition in spite of the different names given to them by the authors cited above.

B. Statistical Comparison Techniques

In order to discuss any regional variations in the geochemistry of the volcanics and their associated intrusives it is necessary to look in some detail for compositional differences between generally similar rock types (frequently from the same formation) in adjacent geographic areas. Rhodes and Krohn (1972) performed this type of comparison using the Mann-Whitney U-test which is the non-parametric analogue to the two-sample t-test. Since the test can only be performed on a variable-by-variable basis for all possible pairs of rock suites it was considered impractical for general application in the present study. Rhodes and Krohn were able to apply this test because they considered Karoo igneous rocks as belonging to only four "groups" with each sample being allocated either to the "central basin" or "basin margin" and according to whether it was north or south of latitude 26°S.

In the present study it was considered desirable to examine the possible differences between rocks of essentially similar composition in different areas. For instance, to investigate the compositional variability of the basalts of the Sabie River Formation in different areas of the Lebombo (Fig. 4, localities 4, 5, 7), and to compare them with basalts of the Lesotho Formation in the Drakensberg and eastern Cape Province (see Fig. 4, localities 2, 3). In order to allow effective use of the large database now available for the Karoo igneous rocks (see Microfiche Cards 1 and 2 in this volume) and to permit the comparison of many possible groups of samples it was considered essential that a multivariate technique should be used. The technique chosen was discriminant function analysis since it provides an effective way of recognizing multivariate differences between groups of samples and in the present application it also indicates which elements are the most effective discriminants.

In order to explain the technique of discriminant function analysis it is convenient to discuss a specific example. Consider the case of two groups of samples both of which were taken from the Letaba Basalt Formation, but one group of samples was collected from the northern portion of the Lebombo monocline and the other from the Nuanetsi area in south-eastern Zimbabwe (Fig. 4, locality 8). The major oxides and the trace elements Rb, Sr, Zr, Nb, Cr, V, Ni, Co, Zn, Cu and Y have been determined in 17 Lebombo samples and 12 Nuanetsi samples. The purpose of the discriminant function analysis is to find a function which is a linear combination of some or all of the original variables (the element and oxide abundances) such that values of this

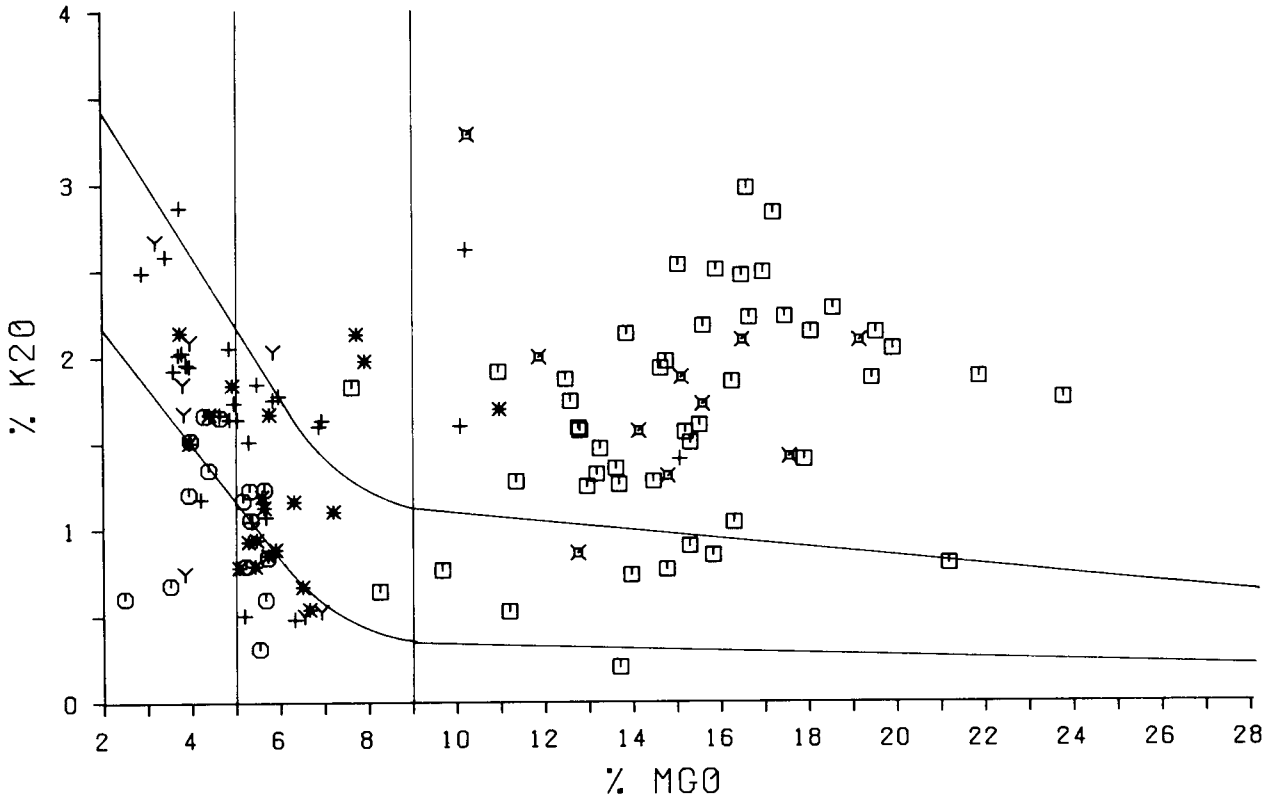

Figure 2

Diagram of MgO *vs* K_2O for the Karoo basic volcanics of Zimbabwe. The lines on the diagram represent the boundaries of the various compositional fields suggested by Bristow and Cox (1984), some of which are discussed in the text.
Symbols are: □ Nuanetsi, Letaba Fm.; + Nuanetsi, Sabie River Fm.; Y Nuanetsi, interbedded basalts; ⊡ Tuli, Letaba Fm.; ⊙ Tuli, Sabie River Fm.; * Wankie, Nyamandhlovu and Featherstone basalts.

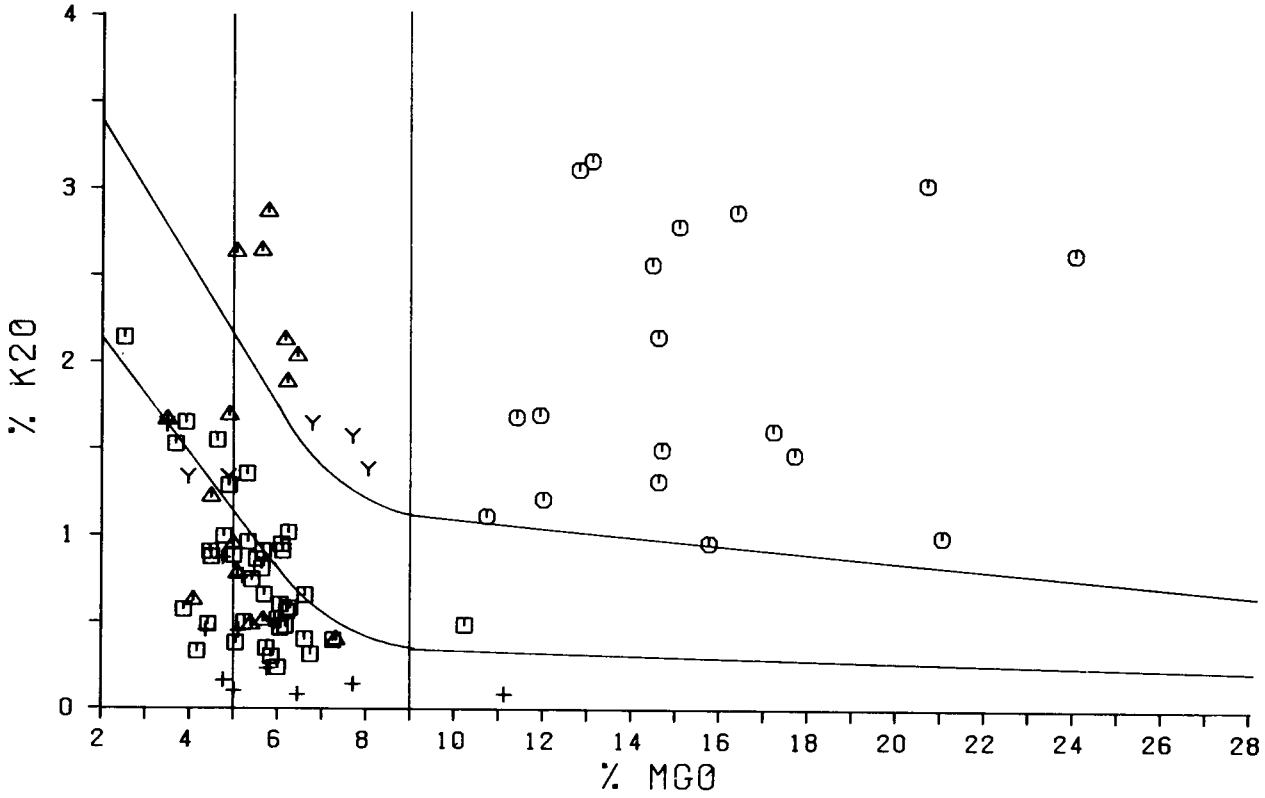

Figure 3

Diagram of MgO *vs* K_2O for the Karoo basic volcanics of the Lebombo monocline. The lines on the diagram are the same as those described for Fig. 2.

Symbols are: ⊡ southern Lebombo, SRBF (Zululand); + southern Lebombo, SRBF (Swaziland); △ central Lebombo, SRBF; ⊙ northern Lebombo, Letaba Fm.; Y northern Lebombo, SRBF.

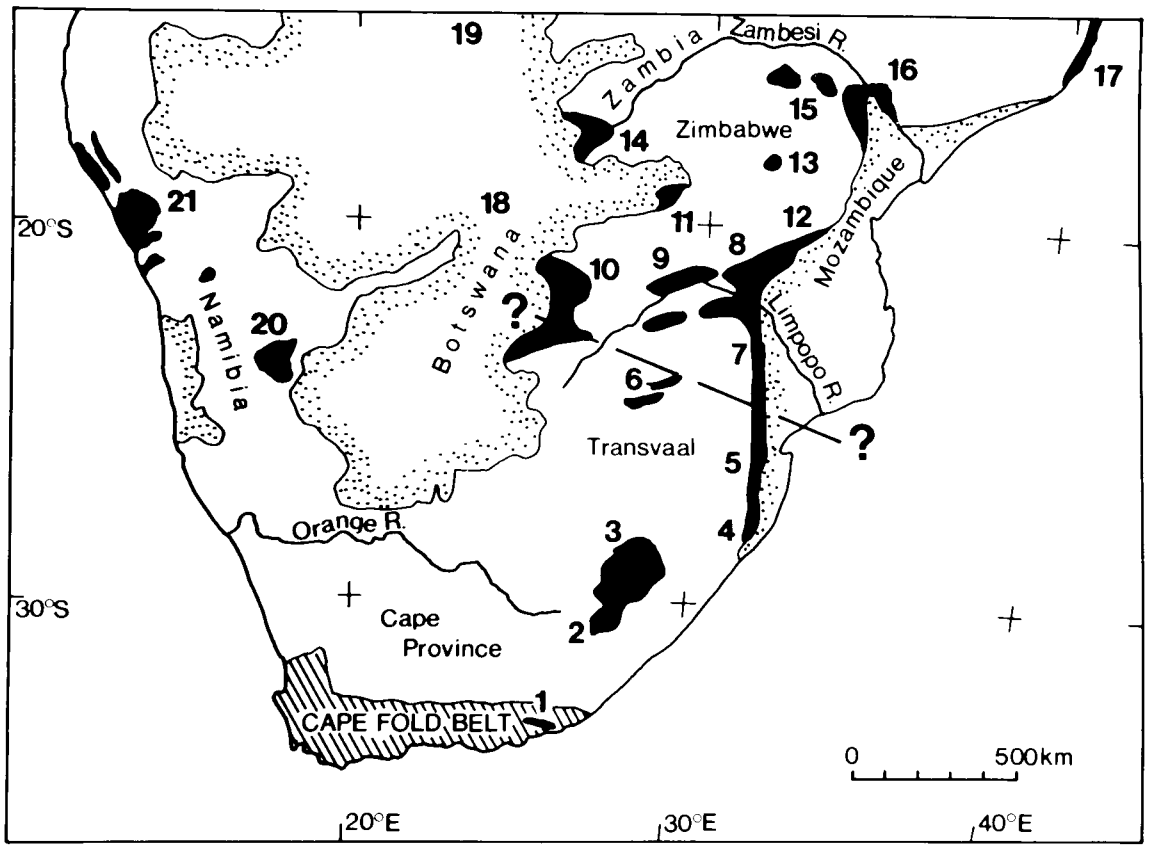

Figure 4

Locality map for the Karoo Igneous Province. Karoo lavas: black, younger cover: stippled. Localities are: 1–Suurberg, 2–Barkly East (E. Cape), 3–Lesotho, 4–Zululand, 5–Swaziland, 6–Springbok Flats, 7–Northern Lebombo (the Lebombo monocline runs from 4 to 8), 8–Nuanetsi, 9–Tuli, 10–Serowe, 11–Nyamandhlovu, 12–Sabi, 13–Featherstone, 14–Victoria Falls, 15–Southern Malawi, 16–Lupata, 17–Mozambique Island, 18–Okavango Swamps, 19–Barotseland, 20–Mariental (Kalkrand basalts), 21–Etendeka. Dashed line represents current best estimate of the southern limit for outcrops of Zimbabwe clan basic magma types. Modified after Cox (1983).

function produce the maximum differences between the defined groups of samples. If such a function can show significant differences between the two groups of samples then that in itself is valuable information. If significant differences between the two groups are found then the discriminant function can also be used to allocate additional samples of unknown origin to one of the two groups.

It is important to note that discriminant function analysis is not a primary classification tool since the groups of samples must have been pre-defined before the analysis can take place. It should also be noted that the process of allocating unknown samples to one of the two groups cannot take into account the possibility that one or more of the unknown samples might really be quite unlike either of the two defined groups.

The computational procedures used in this work were those embodied in the program P7M which is part of the BMDP package of statistical programs (Dixon *et al.*, 1981). In order to optimize the choice of variables for the discriminant function this program follows a stepwise procedure for variable selection. Before any variables have been selected (step 0) the F-to-enter for each variable is calculated where this corresponds to the F-statistic computed from a one-way analysis of *variance* on that variable for all groups of samples used in the analysis. The variable with the highest value of F-to-enter is entered into the discriminant function as this is the variable which discriminates best between the groups. For each subsequent step in the procedure the F-to-enter values for those variables not yet in the discriminant function are re-computed and the variable with the highest F-to-enter value is added to the discriminant function provided its value exceeds a specific threshold (an F-to-enter threshold of 4.0 was used in the present study). F-to-enter values at step 1 and subsequent steps are computed from a one-way analysis of *covariance* where the covariates are the previously entered variables. This means that variables which are strongly correlated with variables already entered into the discriminant function will not themselves be added to it since they can contribute little extra to the function's discriminating ability. At each step an F-to-remove value is also computed for each variable which has previously been entered into the discriminant function and any variable whose F-to-remove value is below an F-to-remove threshold (3.996 in the present study) is removed from the discriminant function. The stepping procedure finishes when none of the variables *excluded* from the discriminant function have F-to-enter values in excess of the F-to-enter threshold and none of the variables *included* in the discriminant function have F-to-remove values below the F-to-remove threshold.

In the present example the element Cr entered the discriminant function at step 1, Al_2O_3 at step 2 and Y at step 3. The stepwise selection procedure was then terminated as the highest value of F-to-enter was 3.796 (for Zn) and the lowest value of F-to-remove for variables already in the discriminant function was 10.544 (for Y). The program P7M expresses the discriminant function as a "canonical variable" and in this case there is only one such variable as only two groups are present in the analysis. Where more than two groups are present in the discriminant function analysis then a set of canonical variables are computed where the second canonical variable is the next best linear combination of the discriminant variables which is orthogonal to the first one, and so on. The values of the canonical variable(s) can be calculated for all samples in the groups and these are shown in Fig. 5 as a histogram of "scores" on the first canonical variable for the two groups in our example. Examination of Fig. 5 shows that the discriminant function analysis is reasonably effective in differentiating between the two groups of samples from the Letaba Basalt Formation with only three samples being

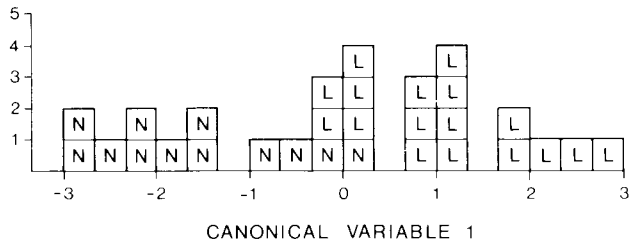

Figure 5

Histogram of scores on the first canonical variable derived by discriminant function analysis of Letaba Formation picritic basalts from the Nuanetsi (N) and northern Lebombo (L) areas. CV1 = $-(1.67224*Al_2O_3) - (0.00994*Cr) + (0.32613*Y) + 13.70176$. In this equation for the canonical variable, and in all such equations given subsequently in this paper, the concentrations of major oxides are in weight % and the concentrations of trace elements are in ppm.

"misclassified". The misclassification is indicated visually by a sample falling on the "wrong" side of the dividing line (canonical variable value of zero) between the two groups shown in Fig. 5. Throughout this paper the success of a discriminant function analysis has been judged by the degree of misclassification apparent both visually and in terms of the computed allocation of each sample to a particular group. It is possible to express the "success" of the procedure in statistical terms but this involves assumptions of normality in the distributions of each element/oxide and equality of variances between groups of samples together with a number of other statistical constraints. As there are often doubts about the validity of such assumptions with geochemical data we have chosen not to evaluate the success of a particular analysis in a rigorous statistical fashion.

Discriminant function analysis (DFA) has thus been used to evaluate possible differences between groups of rocks which would be classified together on the basis of conventional classification procedures. It has not been, and could not be, used as a "primary" classification tool. In the sections that follow DFA for the basic rocks and the Central area dacites and andesites has been performed using a variable set containing the major element oxides and the trace elements Rb, Sr, Zr, Nb, Cr, V, Ni, Co, Zn, Cu and Y. The variable set for the Lebombo and Etendeka silicic rocks contains the major element oxides and Rb, Sr, Zr, Nb, and Y. In view of the fact that full variable sets are not available for all analysed samples the numbers of samples used for DFA are not the same as those used to calculate the averages in Table I. All data used for calculating these averages are contained in Microfiche Card 2 attached to this volume.

C. Rock Types and Magma Types

The previous two sections have discussed the subdivision and classification of the Karoo igneous rocks on a geochemical basis. If one is to interpret variations in rock type within and between suites of volcanic rocks then inevitably one must consider which of the various rock types actually represent magma types, rather than rocks which may be cumulates or have undergone cumulus enrichment in one or more mineral phases.

In this paper, magma types and rock types have been considered equivalent where the rock type is geochemically coherent (i.e. it has limited variability) and where there are at least some samples of the rock type which are essentially aphyric (<5 % phenocrysts in total). This means that some of the average "magma type" compositions reported in this paper are likely to include some rocks which are partial cumulates but it is considered that the compositional bias introduced by such rocks will be small.

The use of the term "magma type" is not meant to imply that any such magma is a "primary" magma. Some explicit discussion of the possible relationships between magma types is given in later sections of this paper.

III. BASIC MAGMA TYPES

A. Nephelinites

Karoo nephelinites are geographically restricted to the northern portions of the Lebombo monocline and to the Sabi area of south-eastern Zimbabwe (Fig. 4, locality 12. Do not confuse with the Sabie River in the central Lebombo). They constitute the Mashikiri Nephelinite Formation and represent the base of the Karoo volcanic stratigraphy in their areas of outcrop. Average analyses of the two geographic groups of nephelinites are given in Table I (all data tables referred to in this paper will be found in Appendix A). The two groups of nephelinites (Lebombo and Sabi areas) are similar in their major element composition but can be clearly distinguished from each other by minor and trace element compositional data. This is reflected in the DFA diagram presented in Fig. 6 in which the single canonical variable is defined on the basis of Nb and Zn. From Table I it can be seen that the nephelinites from the Sabi area are markedly higher in abundances of the incompatible elements (e.g. Rb, Ba, Sr, Zr, Nb, TiO_2, Na_2O and K_2O) and somewhat lower in SiO_2, MgO and CaO.

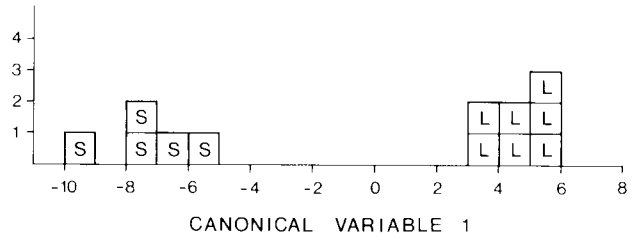

Figure 6

Histogram of scores on the first canonical variable derived by discriminant function analysis of Mashikiri Formation nephelinites from the Sabi area (S) of south-east Zimbabwe and the northern Lebombo area (L).

CV1 = (−0.13451*Nb) + (0.11944*Zn) + 1.98556

These differences between the nephelinite suites from the two areas could be ascribed to differences in the source composition, degree of partial melting or degree of fractionation at either high or low pressures. Bristow (1984a) has argued that the differences arise from markedly different degrees of high-pressure fractionation but followed by rather similar amounts of low-pressure fractionation to produce the similar trends that both suites show on many variation diagrams. Both suites are inferred by Bristow (1984a) to be derived from the same mantle source type, but the compositional characteristics of this source are considered to be different from that for the overlying picritic basalts and basalts. These conclusions are based on the distinctive relative abundances of incompatible elements in the nephelinites, particularly the Zr/Nb ratio which is not only remarkably constant in both nephelinite suites but is also very much lower (Zr/Nb ~1.7) than in any other Karoo basic rock type (see Appendix A).

B. Picritic Basalts and Intrusive Picrites

Voluminous high-MgO picritic basalts and their intrusive equivalents are geographically restricted to the northern portion of the Lebombo monocline and to the Nuanetsi and Tuli (Fig. 4, locality 9) areas of south-eastern Zimbabwe. A few picritic intrusives have also been reported from the Central Karoo area but Eales and Marsh (1979) consider these to be enriched in cumulus olivine and not to be a true magma type. The picritic basalts of the Lebombo and south-eastern Zimbabwe constitute the Letaba Basalt Formation which stratigraphically overlies the Mashikiri nephelinites.

The picrite basalts of the Letaba Basalt Formation are a very unusual group of rocks in terms of their minor and trace element composition. They have previously been documented and discussed by Cox *et al.* (1965), Jamieson (1969), and Cox and Jamieson (1974). In the present volume additional data are presented by Bristow (1984b) and the petrogenesis of these rocks is discussed by Cox *et al.* (1984).

The Karoo picritic basalts are unusually K_2O-rich (see Figs. 2 and 3) and are remarkably enriched in incompatible trace elements (see Table II) and the rare earth elements (REE) with strongly light-REE enriched chondrite normalized rare earth patterns (Cox *et al.*, 1984). However, they also have high contents of MgO, Ni and Cr and all the authors noted above have argued that there are some rocks (with 13–18 % MgO) from this suite of Karoo picrites which represent primary magmas.

DFA techniques have been used to compare the Letaba Formation picrite basalts with the Nuanetsi and northern Lebombo areas and the DFA diagram obtained is shown in Fig. 5. Its derivation has been discussed in some detail in a previous section as it was chosen to illustrate the DFA technique. Fig. 5 shows that the picrite basalts from these two areas can be partially separated on the basis of their compositional differences but the overlap on the DFA diagram indicates that this compositional difference is not particularly marked. Study of the data presented in Table II shows that the picrite basalts from these two areas are indeed very similar in composition and in turn are very similar to picrite basalts from the Tuli area, for which there was too little trace element data for them to be included in the discriminant function analysis.

The compositional similarity between these picrite basalt magmas over quite a wide geographic area is most important considering the very unusual compositional characteristics of this magma type and the implications for its petrogenesis. Cox *et al.* (1984) have suggested that this picrite basalt magma type is produced by rather small degrees of partial melting (~5 %) of a two-component mantle source; one component of which is relatively "normal" mantle while the other is basalt-depleted but enriched in incompatible minor and trace elements, and the constituents of clinopyroxene and phlogopite, by metasomatic processes in the mantle.

C. Basaltic Lavas and Intrusives

1. Zimbabwe and the Lebombo monocline

The majority of the Karoo basalts of Zimbabwe and the Lebombo monocline form a stratigraphic unit termed the Sabie River Basalt Formation (Cleverly and Bristow, 1979) which immediately overlies the Letaba Basalt Formation of picritic basalts in the Tuli, Nuanetsi and northern Lebombo areas but which rests directly on pre-volcanic rocks (mainly Karoo sediments) in the central and southern portions of the Lebombo monocline. The stratigraphic relationships, petrography and petrogenesis of the basalts comprising this formation are discussed by Cox and Bristow (1984) and some additional petrogenetic interpretation is given by Cox *et al.* (1984). Due to the geographic extent of this formation and to facilitate the recognition of compositional change as a function of locality, the available data for basalts of the Sabie River Basalt Formation (SRBF) have been subdivided in Table III to indicate average compositions for the following areas: Zululand, Swaziland, south-central Lebombo (between Swaziland and the Komati River), north-central Lebombo (from the Crocodile to the Olifants rivers), northern Lebombo (north of the Olifants River), Nuanetsi and Tuli.

An overall compositional comparison between different geographic areas of the SRBF has been made using discriminant function analysis and the resulting DFA diagram is shown in Fig. 7. There is a relatively clear division between the northern and southern areas of SRBF outcrop with the northern areas (northwards from the Sabie River) showing negative scores for canonical variable 1 (CV1) and the southern areas positive scores for CV1. In terms of the variables utilized by the DFA this reflects higher values of TiO_2, Nb, Co and Y and lower values of Ni, Zn and Cu in samples from the northern areas. Inspection of the data in Table III shows a clear difference between samples of the SRBF from the two areas, with the northern variant of the SRBF being markedly richer in the incompatible minor and trace elements (e.g. TiO_2, K_2O, P_2O_5, Ba, Sr, Zr, Nb, etc.).

The recognition of a rather abrupt change in the compositional character of the SRBF in the vicinity of the Komati River (see also Cox and Bristow, 1984) is an important result of the Karoo Geodynamics Project. It could be explained by magma derivation from mantle source areas which have markedly different degrees of enrichment in incompatible elements or by derivation from similar source areas but by grossly different degrees of partial melting. These possibilities are discussed further by Cox *et al.* (1984).

There is an intriguing possibility that the change of compositional character in the SRBF is in fact a stratigraphic feature, and that the stratigraphic pattern of successive offlap in the sequence of nephelinites, picrite basalts and basaltic rocks in the northern Lebombo area (see Cox and Bristow, 1984, Fig. 11) continues upwards through the stratigraphic section. This would imply that the low-K_2O (and also low incompatible element) southern variant of the SRBF is also present in the area north of the Komati River at the top of the stratigraphic section, but that it is largely covered by the Jozini Rhyolite which unconformably oversteps the basalt formations in the northern Lebombo. This possibility is supported by the very few occurrences of low-K_2O basalts north of the Komati River, since they occur only at the very top of the stratigraphic section through the basalts. Additional field work, sampling and analytical work would be required to investigate this possibility more thoroughly.

Within the northern variant of the SRBF magma type it is possible to distinguish compositionally lavas from the Nuanetsi area. Their low scores on CV2 in Fig. 7 are indicative of relatively lower TiO_2, Zn, Cu and Ni contents relative to SRBF basalts from the northern Lebombo and Tuli areas. With the present limited sampling of SRBF lavas in the area between Zululand and the Komati River it is not possible to state whether any such compositional distinctions could be made within the southern variant of the SRBF.

The basalts which crop out in the Featherstone, Nyamandhlovu and Wankie districts of Zimbabwe (Fig. 4, localities 13, 11, 14) were described by Cox *et al.* (1967) and the trace elements in their samples have been re-analysed during the present project. These new data show that they are very similar in character to the SRBF basalts of the northern Lebombo, Tuli, and Nuanetsi areas. The basalts in the upper portion of the stratigraphic succession in the Nuanetsi syncline, which are interbedded with the rhyolites (Cox *et al.*, 1965), are unlike any other Karoo basalt so far

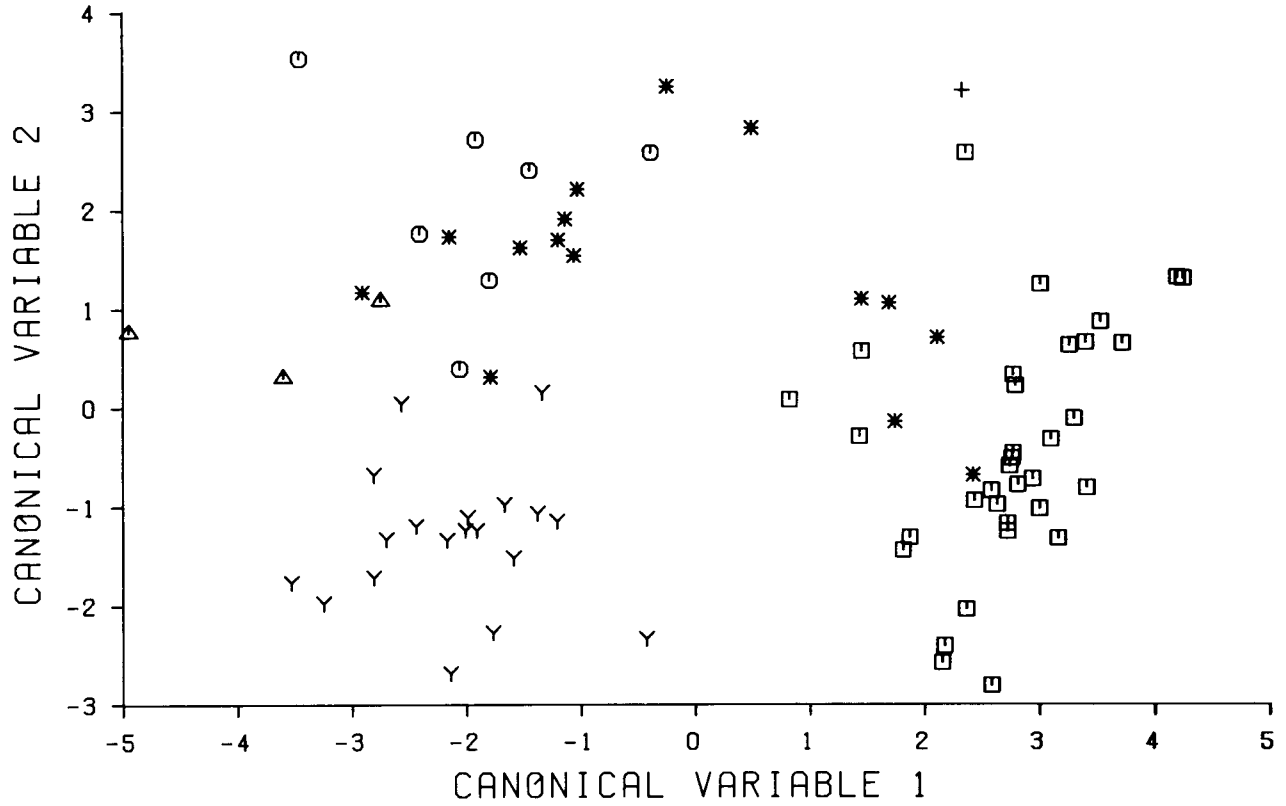

Figure 7

Discriminant function analysis (DFA) diagram for basalts of the Sabie River Basalt Formation.

CV1 = $-(2.49801*TiO_2) + (0.73531*Fe_2O_3) + (1.27571*P_2O_5) - (0.08133*Nb) + (0.00489*Cr) - (0.00305*Ni) - (0.14664*Co) + 3.74573$

CV2 = $-(0.97064*TiO_2) - (0.56729*Fe_2O_3) + (8.42001*P_2O_5) - (0.08515*Nb) + (0.00158*Cr) - (0.00787*Ni) + (0.02407*Co) + 7.21490$

Symbols are: □ southern Lebombo (Zululand), + southern Lebombo (Swaziland), * central Lebombo, ⓘ northern Lebombo, Y Nuanetsi, △ Tuli.

analysed (they are termed "Nuanetsi I.B.B." in Table III). These interbedded basalts are relatively high in K_2O and P_2O_5 like the evolved shoshonitic varieties of the SRBF, but are markedly lower in TiO_2 and some incompatible elements such as Sr and Zr.

Most of the basaltic intrusive rocks in the northern portion of the SRBF are compositionally similar to the lavas with which they are spatially associated. However, the Rooi Rand dyke swarm (Fig. 4, locality 4) of the southern Lebombo area (see Armstrong *et al.*, 1984), which is by far the most extensive and voluminous dyke swarm associated with the Lebombo monocline, is compositionally different from the southern variant of the SRBF which it intrudes. This can be seen by the lower SiO_2, Al_2O_3 and Na_2O values and higher TiO_2 and Fe_2O_3 values in Rooi Rand rocks (Table V) when compared to the southern SRBF lavas from Zululand and Swaziland (Table III). In the next section the Rooi Rand magma type is compared with both the SRBF and with the magma types of the Central Karoo area utilizing the DFA technique.

2. Central Karoo area

All the basalt magma types in the Central area of the Karoo Igneous Province are of moderate MgO content. Picritic basalts and nephelinites have not been reported. The vast majority of samples from the Central Karoo area are from the Lesotho Formation but these are stratigraphically preceded by a number of volcanic units which are distinctive in terms of their composition and petrography. These basal units are the Moshesh's Ford, Omega, Vaalkop, Kraai River and Pronksberg High-K basalt formations (Marsh and Eales, 1984. All are from locality 2 in Fig. 4). Average compositions for all the volcanic units in the Central Karoo area are given in Table IV.

The two most striking things about the Lesotho Formation magma type are its compositional coherence, as shown by the small standard deviations for many elements in Table IV, and its extremely widespread geographic occurrence. The Lesotho Formation comprises the top of the stratigraphic sequence in the Central Karoo area and volumetrically dominates the major exposures of Karoo basalt in southern Africa which form the Stormberg and Drakensberg mountain ranges. By far the majority of the dykes and sills which form a dense subvolcanic intrusive complex in the Central Karoo are also representatives of this magma type.

We have used discriminant function analysis to compare the overall composition of the different basaltic magma types in the Central area of the Karoo Igneous Province and the resulting DFA diagram is shown in Fig. 8. Using the DFA technique it is possible to show that all six of the magma types corresponding to the formations noted above are compositionally distinctive. In addition, there is a seventh recognizable magma type from the Springbok Flats area of the northern Transvaal (Fig. 4, locality 6) which shows greater compositional resemblance to the other basaltic magma types of the Central area than to the geographically closer SRBF in the northern Lebombo and Tuli areas (see also Marsh and Eales, 1984). When utilizing the DFA technique for all seven magma types simultaneously some of the compositional distinctions are obscured but conversely the compositional similarities between specific sets of these magma types are illustrated.

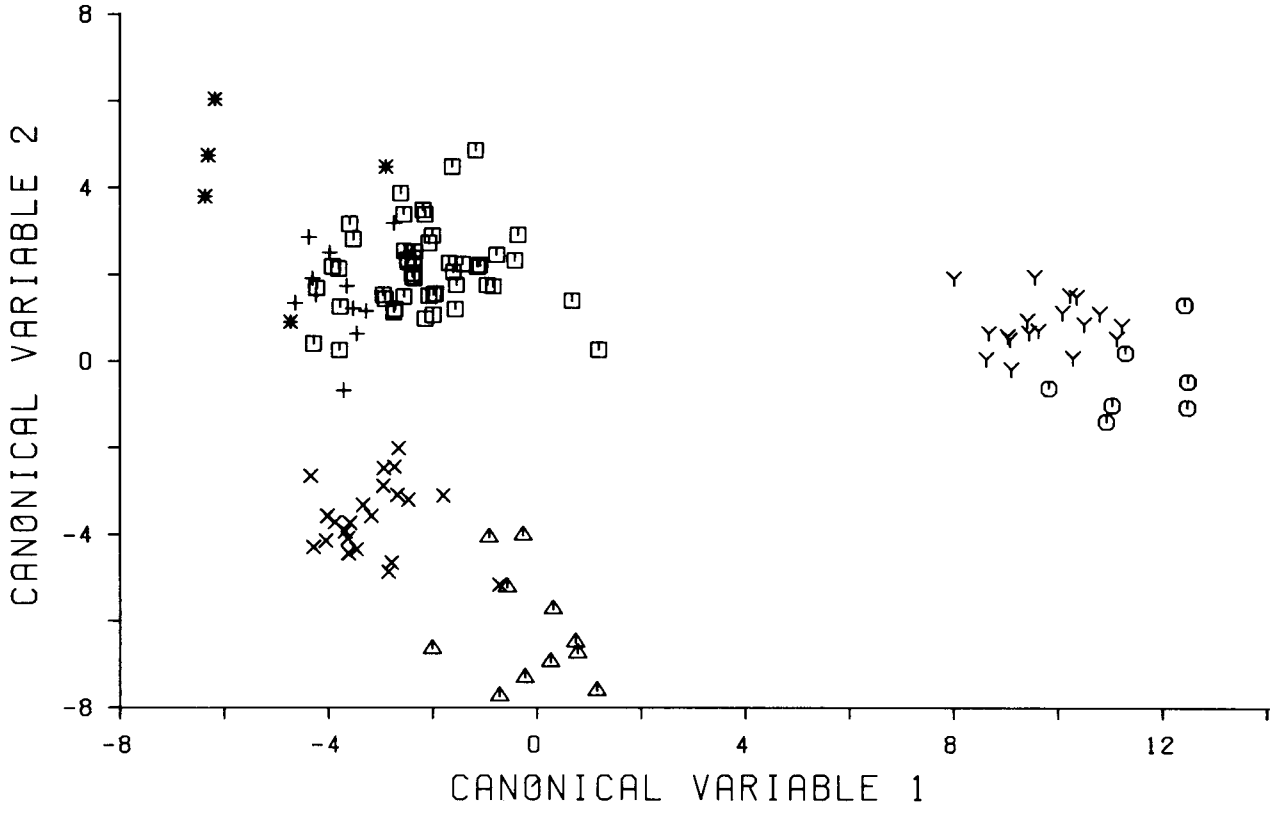

Figure 8

DFA diagram for basalt magma types of the Central Karoo.

CV1 = + (1.17633*TiO_2) + (6.62942*MnO) + (0.46443*CaO) + (1.07646*Na_2O) + (1.51120*K_2O) + (10.29664*P_2O_5) + (0.00681*Sr) + (0.06093*Zr) + (0.65640*Nb) + (0.00550*Cr) + (0.01315*Ni) − (0.06638*Co) + (0.00906*Cu) − (0.51329*Y) − 12.45877

CV2 = + (5.08668*TiO_2) − (10.40098*MnO) + (0.81252*CaO) + (1.08935*Na_2O) + (0.99413*K_2O) − (4.03409*P_2O_5) − (0.00257*Sr) − (0.03961*Zr) + (0.21604*Nb) − (0.01053*Cr) + (0.06997*Ni) − (0.08437*Co) + (0.05305*Cu) + (0.01098*Y) − 13.39369

Symbols are: ⓘ Pronksberg high-K basalts, Y Moshesh's Ford Fm., + Omega Fm., × Kraai River Fm., △ Vaalkop Fm., ⊡ Lesotho Fm., ✻ Springbok Flats basalts.

Thus it can be seen from Fig. 8 that the Lesotho, Omega and Springbok Flats magma types are similar to each other; that the Kraai River and Vaalkop magma types are similar to each other; and that the Moshesh's Ford and the Pronksberg high-K basalt magma types are similar to each other. It should be noted that the Moshesh's Ford and Pronksberg high-K basalt magma types are particularly distinctive and this can be clearly seen from the data in Table IV where these two magma types show notably higher K_2O and Nb values and lower V and Zr/Nb values than other Central area magma types.

We have also used DFA to compare the composition of the SRBF magma type from Zululand and Swaziland with the compositions of the Central area magma types (Fig. 9) since these areas are geographically adjacent. The SRBF magma type is clearly different from the Lesotho Formation and from the other Central area magma types by virtue of its lower scores on CV1 in Fig. 9, which reflect its higher content of TiO_2, Fe_2O_3, Zr and Y, and lower content of Al_2O_3 and K_2O. However, it is no more different from the Lesotho magma type than are the other magma types in the Central Karoo area. It is perhaps worth re-emphasizing that in the various DFA diagrams shown in this paper the data sets included in the DFA analysis are generally different. This implies that the geochemical variables chosen by the stepwise discriminant procedure will generally be different and that the coefficients of these variables in the equations defining the canonical variables will also be different (note that these equations are given in figure captions). This can be seen quite clearly by comparing Figs. 8 and 9 which both show the same data for the basalts of the Central area, but where the addition of the SRBF data in Fig. 9 has resulted in rather different definitions of the canonical variables.

In Fig. 10 the DFA results for the basaltic intrusives of the Central Karoo, together with the dykes of the Rooi Rand swarm in the southern Lebombo, are compared with the basalts of the Central Karoo and the SRBF in the southern Lebombo. Most of the subvolcanic intrusions in the Central area are compositionally similar to the Lesotho magma type as noted above. There are a few intrusives with composition equivalent to that of the Kraai River and Vaalkop magma types and one which is compositionally equivalent to the Moshesh's Ford magma type. There is a general tendency for the intrusive rocks to have slightly higher scores on CV2 in Fig. 10 than their equivalent lavas. It would be tempting to attribute this to a tendency for greater degrees of low-pressure fractionation to occur in the intrusives but there is no clear evidence for this in the compositional data since the intrusives and lavas show very similar concentrations of Cr, Ni, K_2O and incompatible elements.

There are three goups of intrusives which do not appear to have compositional analogues in the Karoo extrusive rocks. One is a suite of rocks from the Hangnest sill in the Calvinia district (Le Roex and Reid, 1978), the second is the high-TiO_2 members of the Rooi Rand dyke swarm, and the third is the Horingbaai minor intrusives which will be discussed in the next section. Average compositions for the first two of these suites of dolerites are given in Table V.

A suite of dykes which cut the top of the Lesotho Formation lava succession in the Witsieshoek area appear

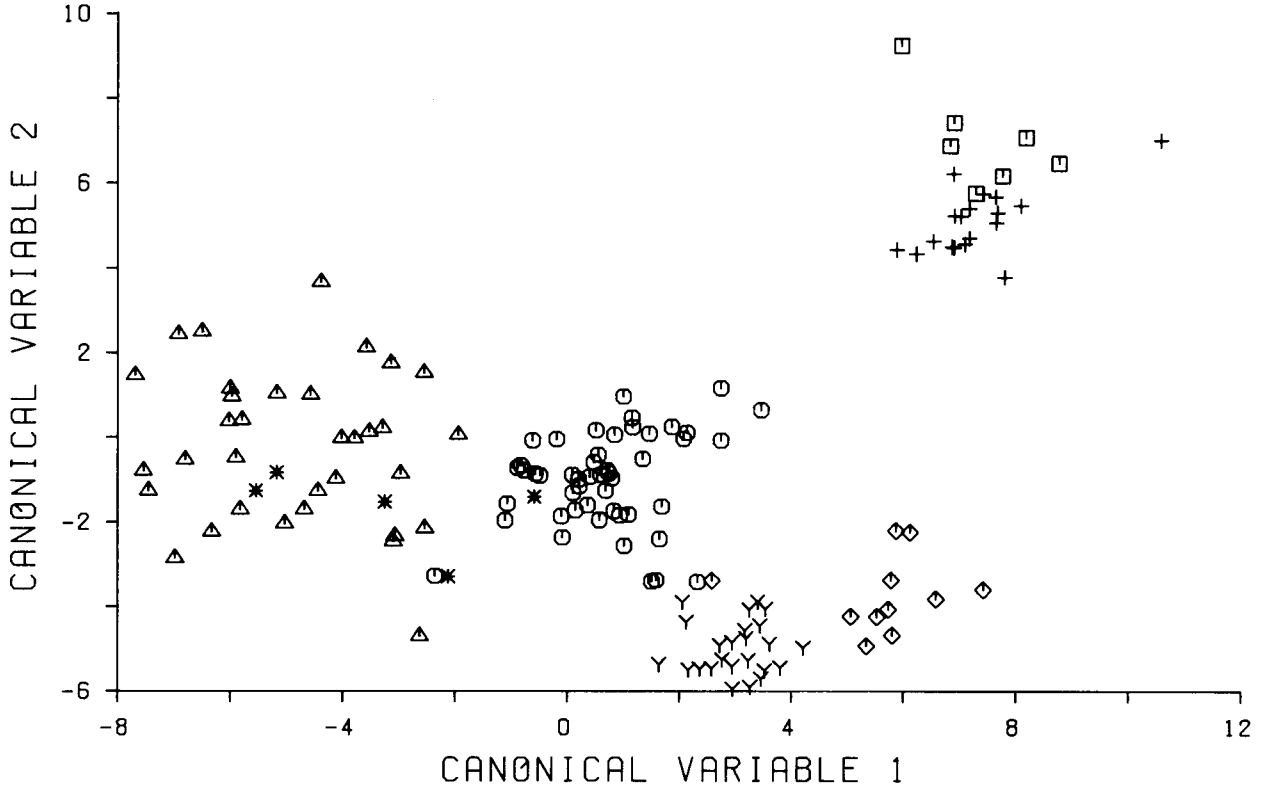

Figure 9

DFA diagram for basalt magma types of the Central Karoo and southern Lebombo areas.

CV1 = $-(0.44566*SiO_2) - (1.91316*TiO_2) + (0.45346*Al_2O_3) - (1.01872*Fe_2O_3) + (9.72194*MnO) + (0.84872*MgO) - (0.23289*CaO) - (9.79201*P_2O_5) - (0.00261*Sr) + (0.56623*Nb) + (0.01334*Cr) - (0.04696*Ni) - (0.02116*Co) + (0.15118*Y) + 21.71522$

CV2 = $-(1.41235*SiO_2) - (1.35648*TiO_2) - (1.19256*Al_2O_3) - (0.03147*Fe_2O_3) + (0.27876*MnO) - (1.52993*MgO) - (0.89845*CaO) - (9.64193*P_2O_5) + (0.00508*Sr) + (0.63773*Nb) - (0.00436*Cr) + (0.04103*Ni) - (0.00440*Co) - (0.18340*Y) + 111.89531$

Symbols are: □ Pronksberg high-K basalt, + Moshesh's Ford Fm., Y Kraai River Fm., ◇ Vaalkop Fm., ⊙ Lesotho Fm., * Springbok Flats basalts, △ SRBF (southern Lebombo).

to have compositions very similar to the basalt lavas from the Springbok Flats area of the northern Transvaal. This is the only indication that we currently have of the relative age of the Lesotho Formation and the Springbok Flats lavas and it is obviously very tentative in view of the very small sample set (five) from the Springbok Flats lavas.

3. Namibia

Two sequences of Karoo basic lavas of different ages crop out in SWA/Namibia. These are the Jurassic Kalkrand Basalt Formation in the Mariental area (Fig. 4, locality 20) in the southern portion of the country (see Eales *et al.*, 1984) and the Cretaceous basalts of the Etendeka Formation in the Kaokoveld area (Fig. 4, locality 21) of north-western Namibia (see Erlank *et al.*, 1984).

The Kalkrand basalts (Table VI) are compositionally identical and of a similar age (Fitch and Miller, 1984) to the Lesotho magma type of the Central area. There are also numerous dolerites of presumed Karoo age found throughout Namibia and some of these which have been analysed, such as the Tandjiesberg sill in southern Namibia (Richardson, 1979, 1984) and some dolerites cutting basement rocks and Karoo sediments in the Etendeka area (Erlank *et al.*, 1984), are also compositionally equivalent to the Lesotho magma type. On the basis of geochemical correlation we can therefore state that the Lesotho magma type is represented by dolerite dykes and sills throughout much of Namibia and by a locally preserved lava field (the Kalkrand Basalt Formation) in southern Namibia.

The basic *lavas* of the 121 m.y. Etendeka Formation (Allsopp *et al.*, 1983a), comprising the Tafelberg and Albin lava types (referred to as Etendeka Fm. (T) and (A) respectively in Table VI), are a diverse suite with SiO_2 contents between 50 and 57 %. This range in composition is greater than that shown by the basalts of the Central area but is matched by the SRBF basalts of the Lebombo which include strongly evolved types such as tholeiitic andesites (as defined by Bristow and Cox, 1984) and shoshonites. The basic lavas of the Etendeka Formation are generally more evolved compositionally and thus have higher contents of TiO_2, K_2O and incompatible trace elements such as Rb, Ba and Zr than any of the Central area magma types except for the Pronksberg high-K basalts. They contain higher K_2O, Rb, Ba and Zr abundances than the southern variant of the SRBF, but they do not show as much relative enrichment in these elements as the northern variant of the SRBF. Erlank *et al.* (1984) discuss their petrogenesis in some detail and suggest their derivation from a heterogeneous and enriched mantle source region, followed by fairly extensive low pressure fractional crystallization.

The basic *intrusives* within the Etendeka Formation include those mentioned above with a Lesotho magma type chemistry (which do not cut the lavas), dolerite dykes which are compositionally equivalent to the Tafelberg-type lavas and which have been averaged together with the lavas in Table VI, and a suite of dolerites which are petrographically identical to the Albin-type lavas but which have not yet been analysed. In addition to these intrusive types there is also a fourth variety, termed the Horingbaai minor intrusives (designated Etendeka Fm. (H) in Table VI), which has no known extrusive equivalent.

The Horingbaai minor intrusives are found only in the Albin section, which is near the coast of Namibia just north of Cape Cross (Erlank *et al.*, 1984), and are distinct from all other Karoo magma types described in this study. Specifically, they are the most "primitive" rock type encountered during this project (even more so than the Rooi Rand dolerites on the eastern continental margin), as

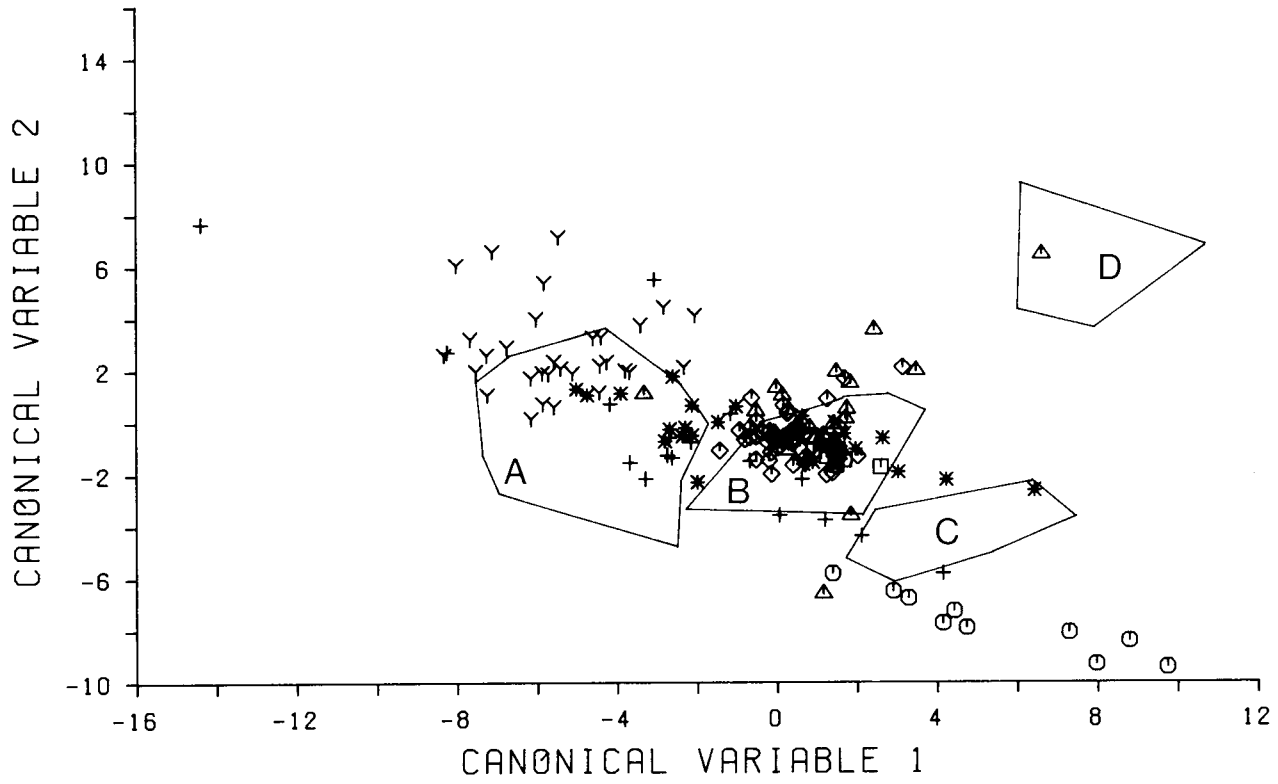

Figure 10

DFA diagram for dolerite types of the Central Karoo and southern Lebombo areas compared to basalt magma types shown as fields A (SRBF, southern Lebombo), B (Lesotho Fm.), C (Kraai River Fm. and Vaalkop Fm.) and D (Moshesh's Ford Fm. and Pronksberg high-K basalts). Equations for the canonical variables are the same as those given for Fig. 8.

Symbols are: ◇ dolerites from southern Namibia, ◫ Blaauwkrantz dolerites (Le Roex and Reid, 1978), ⓘ Hangnest dolerites, ✻ dolerites from central and southern Karoo, △ dolerites from eastern Cape, + dolerites from Transvaal and Natal, Y Rooi Rand dyke swarm (southern Lebombo).

demonstrated by their low incompatible element abundances and $^{87}Sr/^{86}Sr$ ratios and high $^{143}Nd/^{144}Nd$ ratios (Erlank *et al.*, 1984). These authors speculate that the Horingbaai intrusives are derived from a deeper mantle source (asthenosphere?) during the initial separation of the South American and African plates, which could account for their narrow geographical distribution.

4. Botswana

Only seven samples of Karoo basalt and dolerite from Botswana have been analysed as a reconnaissance survey during the present project. These samples have been classified using discriminant function analysis and three samples from Serowe (Fig. 4, locality 10) are compositionally very similar to the SRBF magma type in the Tuli area of south-western Zimbabwe. The other four samples, which are from the Mashoro and Kolokome districts, are compositionally equivalent to the Lesotho magma type, once again extending the geographic area over which this magma type is recognized.

All these samples come from a relatively restricted area in south-eastern Botswana and this area would be well worth additional study since it might provide an indication of the stratigraphic relationship between the lavas of the SRBF magma type and those of the Central area, a relationship which is presently unknown.

IV. INTERMEDIATE MAGMA TYPES

Volcanic or intrusive rocks of intermediate composition or dacitic composition (as defined earlier) are extremely rare in the Karoo Igneous Province. Marsh and Eales (1984) have described "dacites" (63–68 % SiO_2) from the Pronksberg, Dikkop and Roodehoek localities, and "andesites" (61–63 % SiO_2) and dacites from the Belmore locality, all of which are in the eastern Cape Province (Fig. 4, locality 2). The lava suite from the Etendeka Formation in SWA/Namibia (Erlank *et al.*, 1984) includes a few rocks classified as "latites" (58–60 % SiO_2, 4–5 % K_2O). Average analyses of samples from all of these localities are given in Table VII and the individual samples are plotted on a SiO_2 *vs* K_2O diagram in Fig. 11.

The andesitic and dacitic rocks from the eastern Cape all have rather similar compositions but the individual localities are compositionally distinct on a DFA diagram (Fig. 12) and they are clearly separated from the Etendeka latites which have markedly higher TiO_2, K_2O, P_2O_5, Rb, Ba, Zr and Nb values, but lower SiO_2, MgO, Cr and Ni values.

All the intermediate rock types in the Karoo have relatively high initial $^{87}Sr/^{86}Sr$ isotope ratios (0.7095–0.7154) and this, together with a variety of other petrogenetic arguments, has led Marsh and Eales (1984) and Erlank *et al.* (1984) to propose that they originated as partial melts of crustal material. It is also possible that some of the intermediate rocks could have been derived from basic magmas by very extensive crustal contamination followed by fractional crystallization but this is considered to be less likely.

V. ACID MAGMA TYPES

A. Lebombo and Nuanetsi areas

By far the largest volume of acidic volcanics in the Karoo Igneous Province is exposed in the Lebombo monocline and the Nuanetsi area. The acid volcanics in these areas reach an estimated thickness of 5000 m and have a total volume of approximately 35,000 km^3 (Cleverly *et al.*, 1984). The bulk of the samples have been classified by these authors as rhyolitic in composition with a number of samples being lower in SiO_2 content and termed rhyodacites, dacites and trachyandesites (see Fig. 13). For convenience, and in line with the previous descriptions of these rocks, Cleverly *et al.* (1984) have referred to all of them as rhyolites (*sensu lato*) and this convention has been followed here.

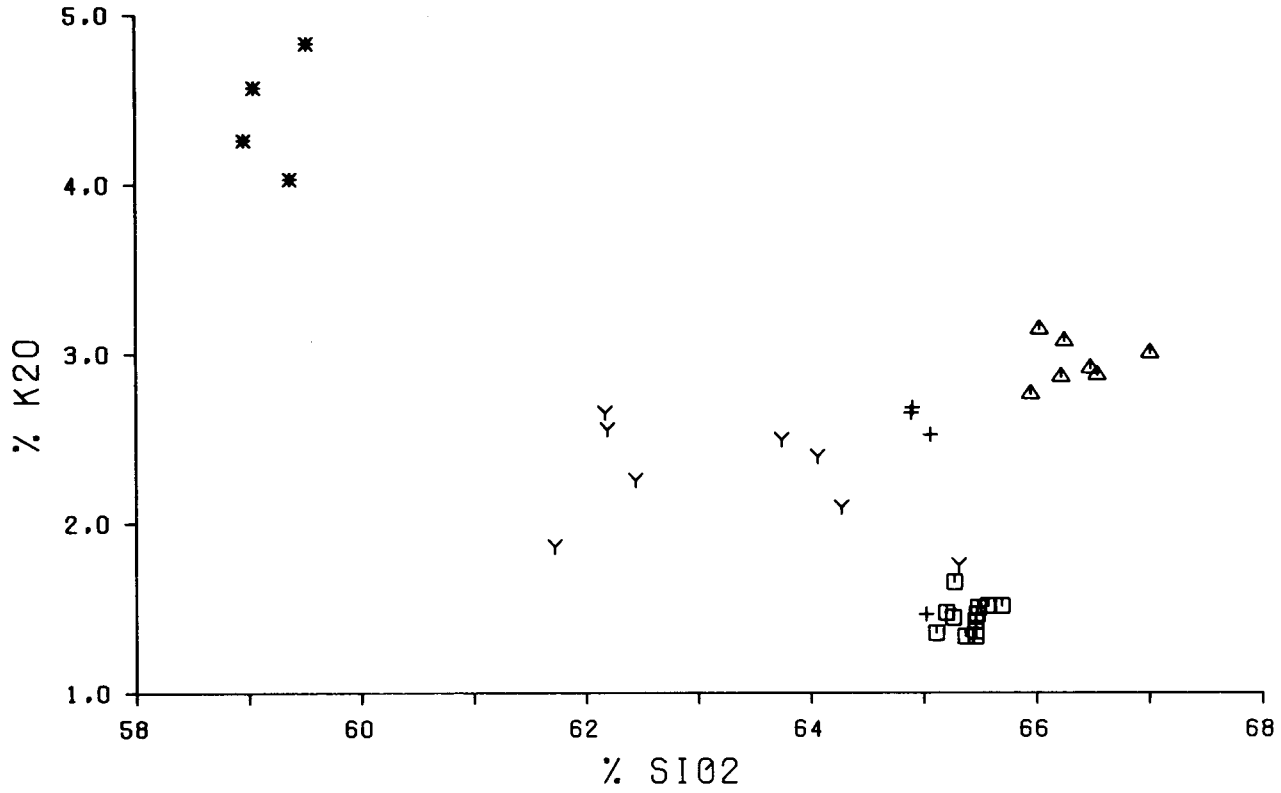

Figure 11

Diagram of SiO_2 *vs* K_2O for Karoo lavas and intrusives of intermediate composition.
Symbols are: □ Pronksberg dacite, + Dikkop dacite, △ Roodehoek dacite, Y Belmore andesite and dacite, * Etendeka latite.

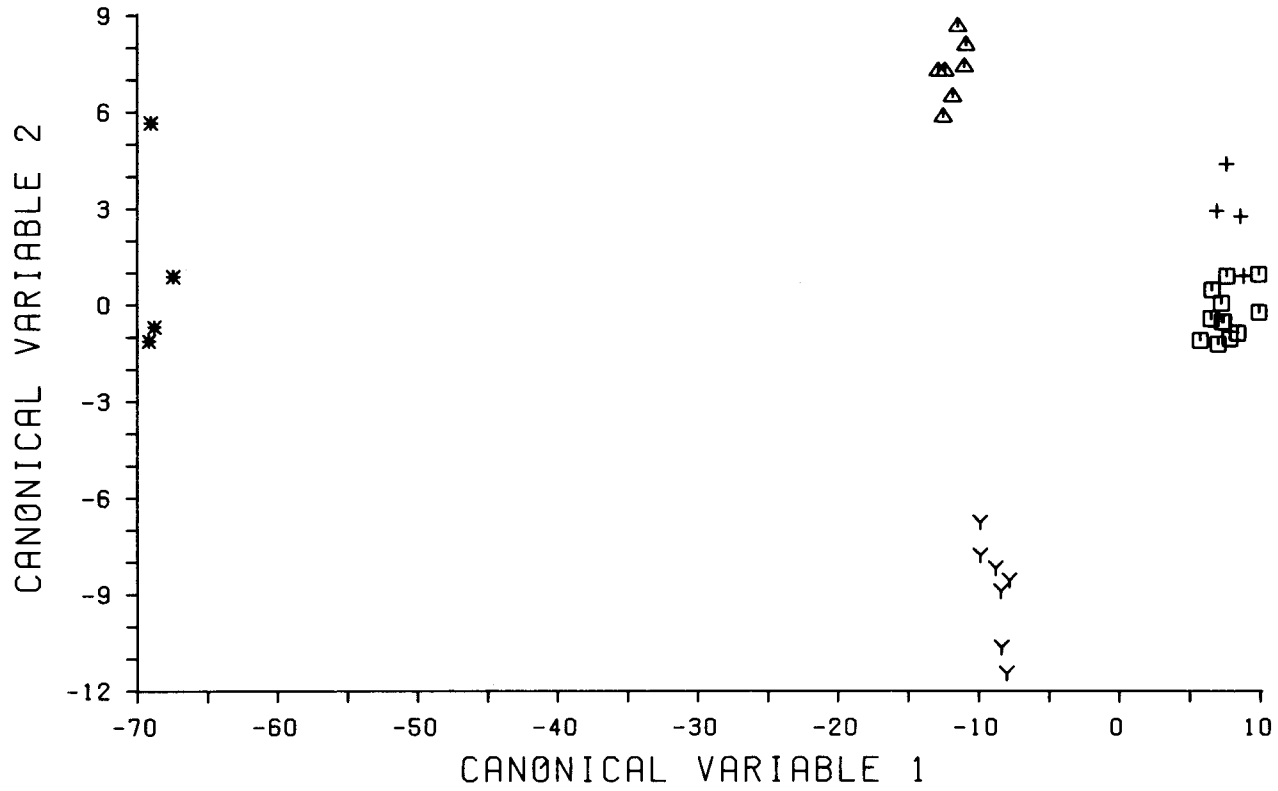

Figure 12

DFA diagram for Karoo lavas and intrusives of intermediate composition.

CV1 = + (6.84453*Al_2O_3) − (1.28061*CaO) + (1.96220*Na_2O) − (0.23105*Zr) − (0.07674*Cr) + 0.13236*Zn) + (0.17554*Cu) − 79.31202

CV2 = − (0.80113*Al_2O_3) − (3.71293*CaO) − (3.50552*Na_2O) − (0.04842*Zr) + (0.13195*Cr) + (0.30318*Zn) − (0.57910*Cu) + 24.54581

Symbols are: ⊡ Pronksberg dacite, + Dikkop dacite, △ Roodehoek dacite, Y Belmore andesite and dacite, ✻ Etendeka latite.

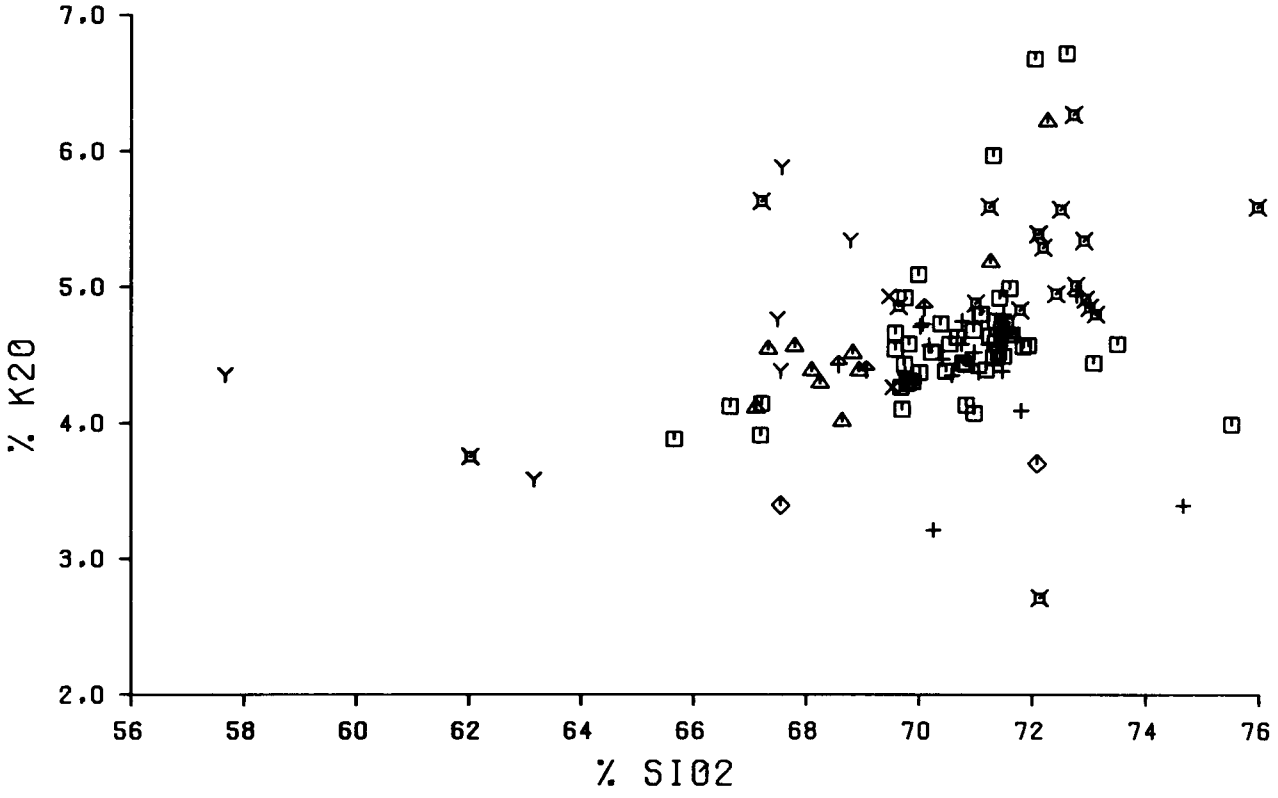

Figure 13

Diagram of SiO_2 *vs* K_2O for Karoo acid volcanics in the Lebombo and Nuanetsi areas.

Symbols are: ⊡ Jozini Fm., Zululand; ⍋ Jozini Fm., Swaziland; × Jozini Fm., central Lebombo; △ Jozini Fm., northern Lebombo; + Mbuluzi Fm.; ◇ Mkutshane Beds; Y Twin Ridge Beds; ⊡ Nuanetsi rhyolites.

The major stratigraphic unit in the Lebombo rhyolites is the Jozini Formation which crops out along the entire length of the Lebombo monocline (approx. 700 km). The Jozini Formation overlies the Sabie River Basalt Formation unconformably and there is evidence that its base is transgressive. It is in turn overlain by the Mbuluzi Rhyolite Formation in Swaziland (Fig. 4, locality 5), by the younger volcanic units of the Bumbeni Complex and Mpilo Andesite in Zululand and by the Movene Basalt Formation north of Komatipoort (Cleverly and Bristow, 1979). It is also overlain in a number of different areas by post-Karoo sedimentary rocks of Cretaceous age. Compositional data for the Jozini Formation rhyolites are given in Table VIII and their most striking characteristic is the relatively high content of incompatible trace elements such as Rb, Ba, Sr, Zr, Nb and Y. Although the Jozini Formation is very similar in composition throughout its outcrop length (see Table VIII) there are some indications of a systematic change in composition in the DFA diagram shown in Fig. 14 (cf. Cleverly *et al.*, 1984). The elements contributing to CV1 in Fig. 14 are MnO, Sr, Zr and Nb. Of these, Sr does indeed show a systematic change with geographic area in Table VIII and the other three elements do show differences, but not serial variation. Other elements which appear to vary in a serial fashion (but noting the very few analysed samples from Swaziland and the central Lebombo) are TiO_2, Al_2O_3, CaO and Y.

The second major rhyolite unit in the Lebombo is the Mbuluzi Formation which was distinguished by Cleverly and Bristow (1979) and Cleverly *et al.* (1984) primarily on petrographic grounds as it is quartz-phyric in contrast to the underlying Jozini Formation. It is compositionally similar to the Jozini Formation (see Table VIII and Fig. 13) but on average it is slightly more siliceous and has lower values of Fe_2O_3, Ba, Sr and Zr.

There are two minor rhyolitic units which are interbedded with the basalts of the Sabie River Formation in Swaziland. The upper unit, termed the Twin Ridge Beds (Cleverly and Bristow, 1979), is compositionally similar to the Jozini Formation but contains some rock types which are dacitic or trachyandesitic in composition (see Table VIII and Fig. 13). The lower unit, termed the Mkutshane Beds (Cleverly and Bristow, 1979), is markedly lower in incompatible trace element content (e.g. Rb, Ba, Sr, Zr, Nb and Y) than other rhyolitic rocks from the Lebombo monocline.

Rhyolites in the Nuanetsi area also overlie the basalts of the Sabie River Formation but differ from the rhyolite formations in the Lebombo monocline in having a suite of basalts intercalated with them (the Nuanetsi "interbedded basalts" discussed in a previous section). The Nuanetsi rhyolites are compositionally distinct from the Jozini Formation in the Lebombo monocline (see Table VIII) and Cleverly *et al.* (1984) have termed them "more evolved" in view of their relatively higher K_2O, Rb, Ba and Nb, and lower Zr and Y contents.

The combination of high concentrations of incompatible trace elements in most of the Lebombo–Nuanetsi rhyolites with low $^{87}Sr/^{86}Sr$ initial ratios (0.704–0.708), which are similar to the lowest ratios observed from basalts and dolerites in the Lebombo, led Cleverly *et al.* (1984) to propose that most of the rhyolites are derived by partial melting of basalt. Specifically, they envisage that basaltic sills emplaced in the lower crust during the phase of Sabie River Basalt eruption are subsequently re-melted (approximately 10 % partial melting) to give rise to the bulk of the Lebombo and Nuanetsi rhyolites (but not the Mkutshane rhyolites as discussed above). However, the Nd isotopic data presented by Hawkesworth *et al.* (1984) show differences between the initial $^{143}Nd/^{144}Nd$ ratios of the

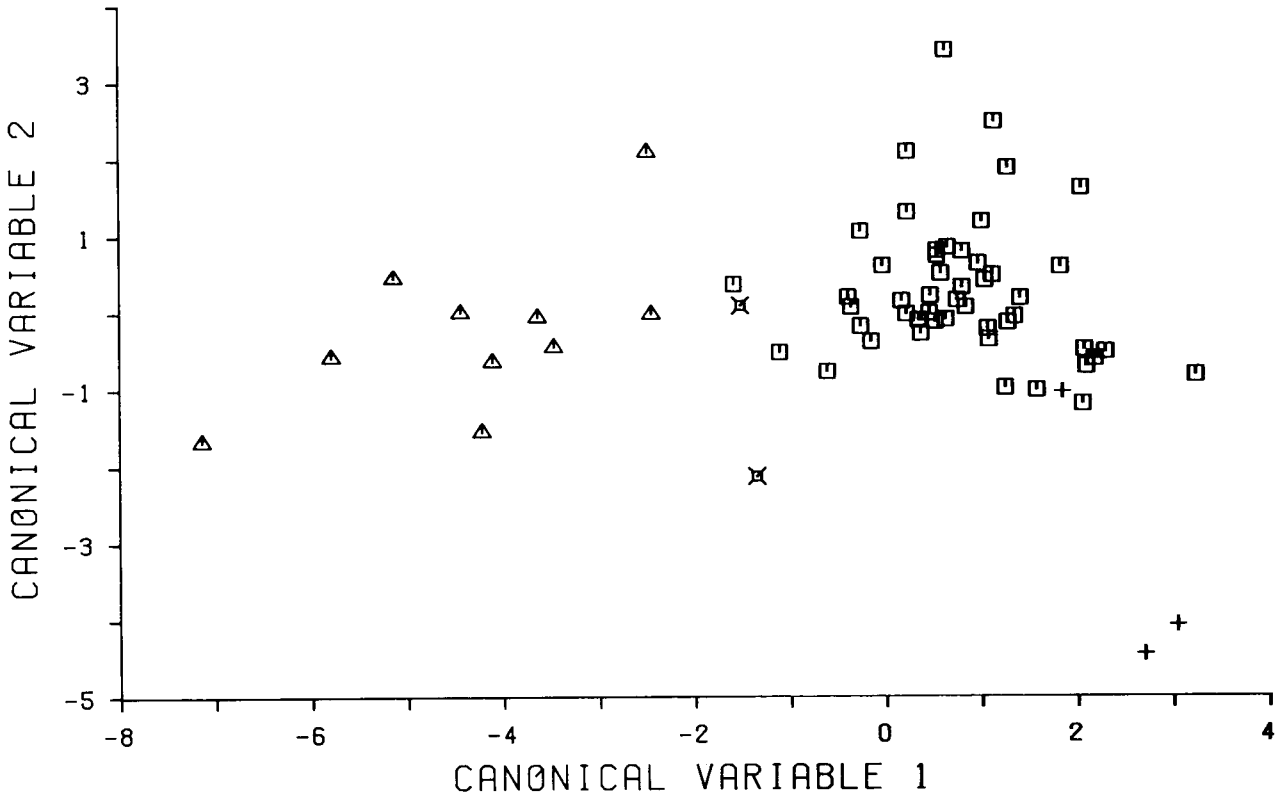

Figure 14
DFA diagram for rhyolites of the Jozini Formation.
CV1 = −(21.84489*MnO) − (0.02140*Sr) + (0.01087*Zr) − (0.17022*Nb) + 8.83790
CV2 = −(5.31868*MnO) − (0.00911*Sr) − (0.01442*Zr) + (0.01947*Nb) + 16.22778
Symbols are: □ Jozini Fm., Zululand; + Jozini Fm., Swaziland; ⊡ Jozini Fm., central Lebombo; △ Jozini Fm., northern Lebombo.

rhyolitic and basaltic rocks of the Lebombo which is not in accord with the model advanced by Cleverly *et al.* (1984).

It was noted above that the Mkutshane Beds are distinguished from the bulk of Lebombo–Nuanetsi rhyolites by their much lower content of incompatible elements. This characteristic, together with high initial $^{87}Sr/^{86}Sr$ ratios of 0.715–0.741 and relatively radiogenic Pb isotope ratios, led Cleverly *et al.* (1984) to suggest that the Mkutshane rhyolites are either partial melts of crustal material or derived by extreme crustal contamination and crystal fractionation of basalts.

B. Namibia

At least two acid volcanic units occur within the lavas of the Etendeka Formation of north-western Namibia. These acid volcanics are termed dacites and quartz latites by Erlank *et al.* (1984) and their composition is shown in Fig. 15 and Table IX. In spite of the different names given to these rock types it should be noted that they are very similar in their SiO_2 and K_2O contents to the "rhyolites" of the Lebombo and Nuanetsi areas which were discussed above (compare Figs. 13 and 15). The Etendeka quartz latites and dacites are interbedded with the basic lavas and latites (which have been discussed in previous sections) as part of the total lava pile.

The acid volcanics of the Etendeka Formation are compositionally different from the bulk of Lebombo–Nuanetsi rhyolites as they contain higher TiO_2, MgO and CaO contents but markedly lower Ba, Zr, Nb and Y concentrations. These are the same criteria which compositionally distinguish the Mkutshane Beds from the rest of the Lebombo–Nuanetsi rhyolites and for this reason the Mkutshane rhyolites and Etendeka quartz latites plot together on a DFA diagram (Fig. 16). Etendeka quartz latites also show relatively high initial $^{87}Sr/^{86}Sr$ ratios and Erlank *et al.* (1984) have suggested that they were most probably formed by crustal anatexis of Pan-African Damaran granitic rocks.

VI. GEOGRAPHIC DISTRIBUTION OF MAGMA TYPES

One of the stated aims of this paper was to investigate whether there were systematic variations in the composition of Karoo igneous rocks which could be related to geographic area. Consideration of the data discussed in the preceding sections, together with the wealth of additional information presented in the other papers in this volume and in the microfiche data tables, now allows us to do this.

Probably the most striking feature of the geographic distribution of Karoo igneous rocks is the localization of acid volcanism around the margins of the volcanic province. Acid volcanics constitute approximately 30 % of the total volcanic pile exposed in the Lebombo and Nuanetsi areas and about 10–20 % of the volcanics in the Etendeka Formation. Karoo volcanic rocks with more than 67 % SiO_2 are completely absent from the whole of the Central Karoo area and the few "dacites" and "andesites" which are present have trivial volumes. The generation of acidic volcanics only in those areas where the Karoo Igneous Province impinges on the sites of intercontinental warping and rifting must surely be of considerable significance.

The compositional distinction between the magma types of southern Zimbabwe and the northern Lebombo areas versus all other basic magma types in the Karoo Igneous Province which was made by Cox *et al.* (1967) is still valid. The nephelinites of the Mashikiri Formation, the picrite basalts of the Letaba Formation and the incompatible element enriched northern variant of the Sabie River Basalt Formation can still be viewed as rock types unique to this area. What has changed, however, is the recognition of magma types typical of the Central area in the same geographic area as the "northern" magma types (Botswana). Wooley *et al.* (1979) have also shown that dolerites whose composition is similar to Central area magma types occur in Malawi (Fig. 4, locality 15) to the north of the Cox *et al.* (1967) "northern province".

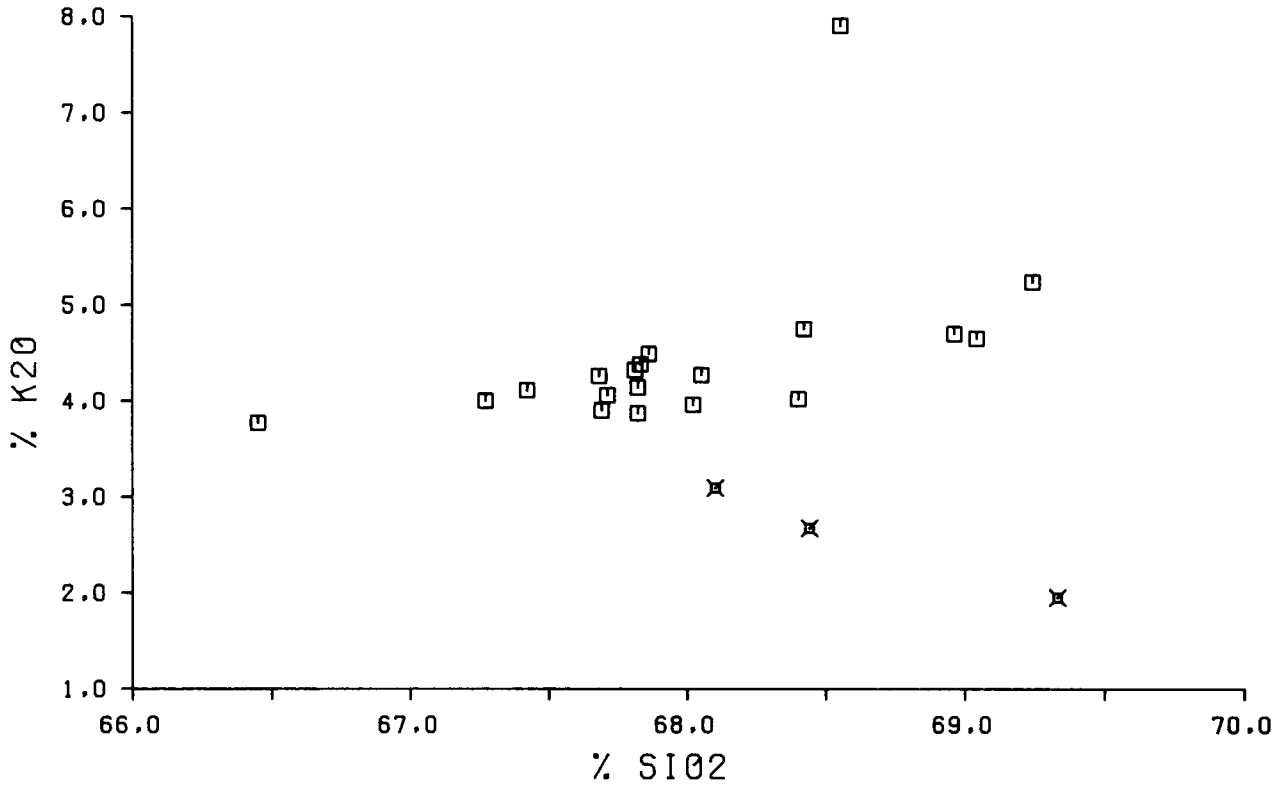

Figure 15

Diagram of SiO_2 *vs* K_2O for acid volcanics in the Etendeka Formation of Namibia.
Symbols are: ⊡ Etendeka quartz latites, ⊡ Etendeka dacites.

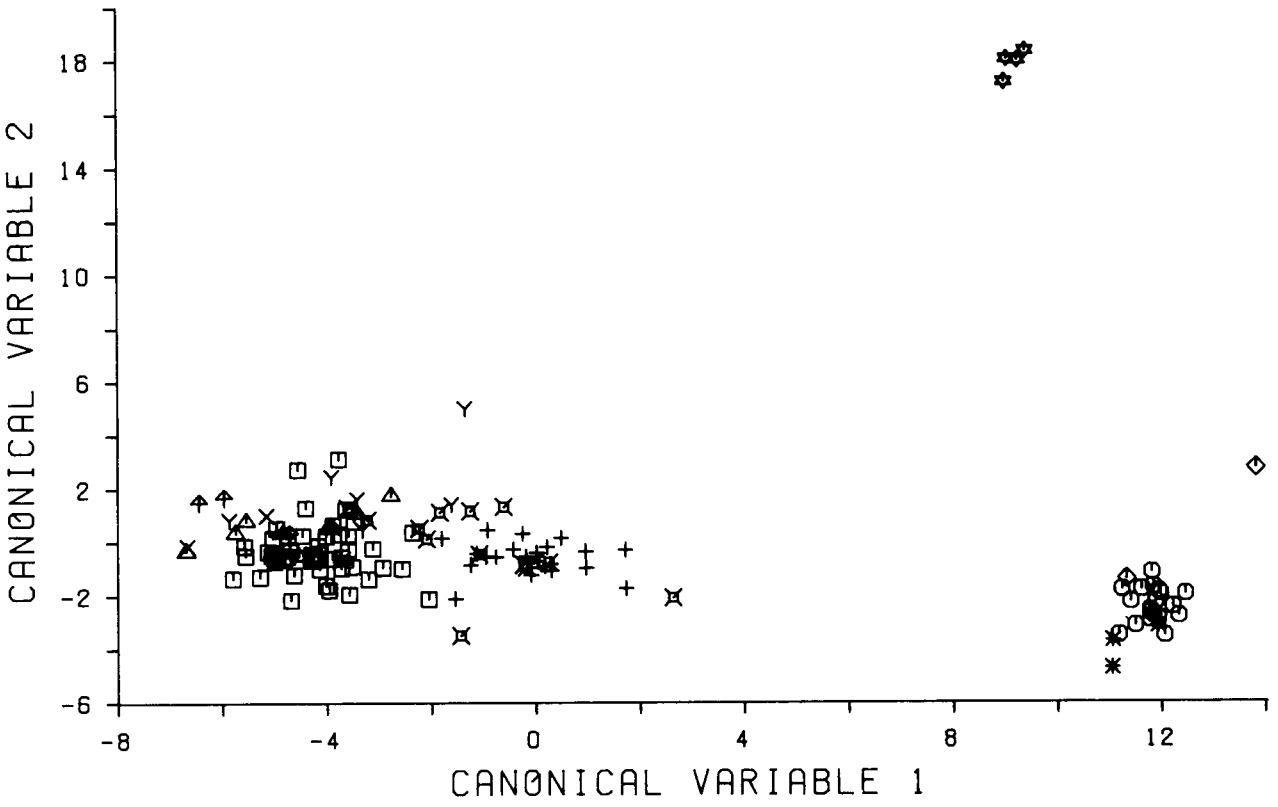

Figure 16

DFA diagram for all Karoo acid volcanics.

CV1 = $-(0.32183*SiO_2) - (0.83053*TiO_2) + (0.15836*MgO) - (0.21476*K_2O) - (8.85530*P_2O_5) - (0.00513*Sr) - (0.01278*Zr) - (0.10105*Nb) + 44.26748$

CV2 = $+(0.29455*SiO_2) + (20.46586*TiO_2) - (0.21367*MgO) + (0.72229*K_2O) - (35.67437*P_2O_5) - (0.00116*Sr) + (0.00403*Zr) + (0.02326*Nb) - 35.97166$

Symbols are: □ Jozini Fm., Zululand; ⍋Jozini Fm., Swaziland; × Jozini Fm., central Lebombo; △ Jozini Fm., northern Lebombo; + Mbuluzi Fm.; ◇ Mkutshane Beds; Y Twin Ridge Beds; ⌼ Nuanetsi rhyolites; ☆ Etendeka latites; ⓘ Etendeka quartz latites; ✻ Etendeka dacites.

It therefore seems appropriate to propose that the word "clan" should be used to describe a compositionally associated group of Karoo magma types whose typical area of occurrence can be defined, but which is not geographically limited *solely* to that area. Conversely, any geographic area may contain representatives of more than one magma clan, but typically one such clan will be dominant in any particular area. What was the "northern geochemical province" of the Karoo basic lavas as defined by Cox *et al.* (1967) would now become the type area for the "Zimbabwe clan" of magma types (which would include the Mashikiri nephelinites, the Letaba picritic basalts and the basalts of the Sabie River Formation).

The relationship between the Zimbabwe clan of magma types and those typical of the Central Karoo area is not yet known. There are indications from the central Lebombo that the southern variant of the SRBF (which is compositionally more akin to the Central area magma clan) may stratigraphically overlie the northern variant of the SRBF. Both Central area clan and Zimbabwe clan magma types have been sampled from the same geographic area of Botswana (Fig. 4, locality 10) but the stratigraphic relationships are unknown and areas which might well contain both clans of magma types (such as the Soutpansberg and Springbok Flats areas) are either unstudied or were studied only in a reconnaissance fashion during the present project.

The type area for the Central area clan of magmas would be in the eastern Cape area, which was studied in detail by Marsh and Eales (1984) and their co-workers. The only magma type in that clan which is currently known outside the type area is the Lesotho magma type which is now known to occur over an enormous area of southern Africa (throughout the Central area, throughout Namibia, and at least in southern Botswana).

Two other magma types, the southern variant of the SRBF and the Springbok Flats lavas collected in the present project, are rather similar to each other in composition and are somewhat different from both the Zimbabwe clan and the Central area clan. However, until the Springbok flats lava and magma types are better studied we believe it would be premature to propose another clan to group these all together. We have therefore made use of the DFA diagrams shown in Figs. 7, 8 and 9 which suggest that they should be compositionally classified with the Central area clan rather than the Zimbabwe clan, at least for the moment.

The Etendeka clan of basic magmas, which would include the Tafelberg, Albin and Horingbaai magma types, is only known from the outcrop area of the Etendeka Formation in north-western Namibia, which would thus be its type area. There are other major areas of Karoo volcanics in northern Namibia which have not been studied during the present project and for which detailed geochemical data has not been published. These include the Erongo mountains, the top of the Brandberg massif, the Messum lava field, and suboutcrops below Kalahari sand to the north-east of Grootfontein and in the Caprivi area.

Rhodes and Krohn (1972) have argued that the Cox *et al.* (1967) proposal of northern and southern "geochemical provinces" for Karoo basic rocks is not valid and that the compositional differences are rather between rocks of the central Karoo *basin* and the areas marginal to it. The present project has shown that the Lesotho magma type can

be recognized well beyond the margins of the central Karoo sedimentary basin, which is not consistent with the Rhodes and Krohn model. Equally, the additional data for central and southern Karoo dolerites collected during the Karoo Geodynamics Project does not support these authors' contention that the magmas from this area are significantly higher in K_2O, TiO_2 and P_2O_5 content than those from nearer the centre of the basin (e.g. eastern Cape magma types).

In the northern portion of the Karoo Igneous Province there is a close spatial relationship between the tectonic environment, which governed Karoo sedimentation, and the localities in which relatively thick sequences of lavas are preserved. Thus the Tuli–Nuanetsi and Wankie–Victoria Falls regions of Zimbabwe are sites of thick accumulations of both Karoo sediments and the succeeding Karoo lavas. Cox (1970) has noted that these areas were sites of Karoo-age rifting and graben formation, and very probably were also sites of eruption. However, not all Karoo sedimentary troughs in Zimbabwe were the sites of subsequent eruptions as is indicated by the lack of Karoo volcanics throughout much of the Zambezi valley (Cox, 1970).

Further south in the province there is the coincidence of a major Karoo eruptive zone with the Lebombo monocline, where flexuring and related faulting predate, coincide with and postdate the eruption of basic and acid volcanics (Bristow, 1976). In the Central Karoo area and in southern SWA/Namibia the relationships between sites of eruption and Karoo tectonics are not readily apparent (Eales *et al.*, 1984; Marsh and Eales, 1984). The sparse preservation of lavas other than in the Drakensberg–Stormberg and Mariental areas, together with the abundance of Karoo-age dolerite intrusions throughout much of central-southern Africa, does not allow us to identify specific sites of eruption (as distinct from sites of preservation).

The systematic variations of Karoo basic magma types as a function of geographic area show some correlation between the occurrence of a particular magma type and the Karoo-age tectonic regime. Thus the Zimbabwe clan of magma types is generally associated with graben development as described above. This is not always the case, as shown by the Nyamandhlovu and Featherstone lavas which are not associated with Karoo rifting. These specific lavas might have travelled some distance from their eruption sites, as suggested by Worst (1962), but this is considered unlikely by Cox (1970).

It is clear, however, that there is no correlation between the occurrence of a particular magma type and its presence on or within *major* crustal tectonic *units*. This may be shown by the close compositional similarity of basalts in the SRBF from the Wankie, Nyamandhlovu and Featherstone areas on the Archaean Zimbabwe craton, SRBF basalts from the Tuli and Nuanetsi areas on the Limpopo mobile belt and SRBF basalts from the northern Lebombo monocline (cf. Cox, 1972). Similarly, the Lesotho magma type shows extraordinarily little variability throughout its outcrop areas on the Kaapvaal craton, Namaqua–Natal mobile belt, and in various Damaran tectonic provinces in SWA/Namibia (cf. Eales *et al.*, 1984).

VII. SOURCE AREA CHARACTERIZATION OF BASIC MAGMA TYPES

The systematic variations of Karoo basic magma types as a function of geographic area were discussed in the previous section. These differences, together with differences observed in the *same* geographic area (e.g. between the members of the Central Karoo magma clan), may be due to differences in source composition, the nature and extent of partial melting, fractional crystallization *en route* to the surface and contamination by crustal materials.

It is particularly important to evaluate the role of crustal contamination (possibly accompanied by fractional crystallization) since this process has been suggested as the dominant control of compositional variability in many continental flood basalt provinces (e.g. Carlson *et al.*, 1981; Mahoney *et al.*, 1982). A number of arguments can be advanced to suggest that although some contamination of Karoo basic magmas by crustal material has occurred, it is not a dominant process in their petrogenesis. Erlank *et al.* (1984) have shown that crustal contamination, with or without accompanying fractional crystallization, cannot explain the compositional trends shown *within* the basic volcanics in the Etendeka area. It is thus unlikely to be the process systematically responsible for compositional differences *between* the Etendeka Basalts and other Karoo basaltic magma types. Cox *et al.* (1984) draw attention to the strong correlation between Sr abundances and those of strongly incompatible elements such as Rb, Ba and Zr in basaltic magma types from the northern Lebombo and Nuanetsi areas and point out that incompatible element enrichment in these magmas is unlikely to be due to crustal contamination since plagioclase (with a high K_d value for Sr) would almost certainly be residual in such a process. Similar arguments have been made for magma types in the Central Karoo clan by Marsh and Eales (1984) who noted that any attempt to explain the differences between magma types in this clan by crustal contamination would require a material of geologically implausible composition.

Samples from the SRBF in the southern Lebombo area are the one group of basic lavas in the Karoo Igneous Province which possibly show evidence for significant crustal contamination. Samples of this magma type, for which Sr isotope data are available, show a significant positive correlation between initial $^{87}Sr/^{86}Sr$ ratios and SiO_2, and all samples show a negative correlation between SiO_2 and Fe_2O_3* (total Fe), TiO_2 and V (Cox and Bristow, 1984). These data are consistent with a model of contamination by old crustal granitic materials (the sample with highest initial $^{87}Sr/^{86}Sr$ ratio contains what appears to be a partially digested granitic xenolith; Cox and Bristow, 1984) but such a model is difficult to reconcile with the positive correlation between initial $^{87}Sr/^{86}Sr$ ratios and total Sr and other aspects of element *vs* $^{87}Sr/^{86}Sr$ relationships also shown by this group of lavas (Bristow *et al.*, 1984). The petrogenesis of this magma type remains problematic, but it is probably the best candidate for a Karoo magma whose compositional characteristics may be significantly controlled by crustal contamination.

Nd- and Sr-isotopic studies (Hawkesworth *et al.*, 1984) have also provided support for suggesting that crustal contamination plays only a limited role in the petrogenesis of Karoo basic magmas. The *relative* positions of the groups of data points for magmas of the Zimbabwe, Central area and Etendeka clans on an Sm/Nd–Rb/Sr diagram are similar to those on an ϵ_{Nd}–ϵ_{Sr} diagram (Figs. 4 and 5 in Hawkesworth *et al.*, 1984). Thus the majority of isotope and parent/daughter trace element ratios are mutually consistent in Karoo basic magmas. In contrast, the SRBF lavas from the southern Lebombo, which have high initial $^{87}Sr/^{86}Sr$ ratios (and high ϵ_{Sr} values), do not plot in the same relative positions on these two diagrams; their isotope and trace element ratios are "decoupled". The negative slope of the trend defined by the high ϵ_{Sr} southern Lebombo SRBF lavas on a Nd isochron diagram (Fig. 7 in Hawkesworth *et al.*, 1984) could be due to interaction with Archaean crustal material. If the positive-slope trend shown by the majority of Karoo basic rocks on a Nd isochron diagram was also due to crustal contamination, then the slope of the trend implies that the contaminant was upper Proterozoic in age (i.e. it would plot on or above a 1.4 b.y. reference isochron). The Karoo lavas crop out on terranes of Archaean to Pan-African in age and it is difficult to envisage why there should be no correlation between basement age and the isotopic character of a putative contaminant. It is particularly

difficult to understand how upper Proterozoic crust could be responsible for the contamination of those Karoo magmas erupted onto Archaean cratons (Hawkesworth *et al.*, 1984).

In summary, crustal contamination may have strongly affected the composition of some SRBF lavas from the southern Lebombo but its effects cannot be recognized with certainty in other Karoo basic magmas and it is most unlikely to be a major facet of their petrogenetic history. Thus, while we concede that individual samples may have had their geochemical characteristics altered by crustal contamination, we do not believe that the overall trends *within* the various basic lava clans nor the differences *between* clans can be ascribed to this process.

In order to evaluate the relative importance of fractional crystallization, partial melting and variations in source composition in the petrogenesis of Karoo basic magmas we have chosen to look mainly at incompatible and relatively incompatible elements, including the REE (see Figs. 17, 18 and 19). This suite of elements will vary substantially in *absolute* abundance with varying degrees of partial melting and fractional crystallization but the *relative* abundances of the various elements must reflect differences in source composition except where it may be argued that a particular element is not incompatible with respect to the restite or fractionating mineral assemblages.

The data values chosen to represent the different Karoo basic magma types in Figs. 17, 18, and 19 are taken from averages of selected samples with relatively "primitive" compositions in each magma type (sample numbers are given in the figure caption for Fig. 17). The averages given in Appendix A were not used for this purpose as they include some "evolved" rocks and the combination of average data for elements analysed in only a few samples (e.g. REE, Th, U, Hf) with elements analysed in all samples could bias interelement ratios.

The nature of fractional crystallization processes affecting Karoo magmas is comparatively well known (Cox, 1980, 1983; Cox and Bristow, 1984; Cox *et al.*, 1984; Marsh and Eales, 1984; Erlank *et al.*, 1984). Fractionation of gabbroic assemblages is well established for the Rooi Rand dolerites, some of the SRBF lavas in the southern Lebombo and for the less K-rich SRBF lavas of the northern Lebombo and south-east Zimbabwe (Cox and Bristow, 1984). It may also have contributed to the evolution of Lesotho-type magmas of the Central Karoo clan (Cox, 1980). The picritic magmas of the Letaba Formation have undergone olivine and orthopyroxene fractionation (Cox and Jamieson, 1974; Cox *et al.*, 1984) and the K-rich members of the SRBF have evolved by fractionation of an assemblage dominated by clinopyroxene (Cox and Bristow, 1984). The enrichment factors for incompatible trace elements in Karoo basaltic magmas relative to a picritic parent would be in the range 1.3–4 as predicted by the authors cited above in a number of specific calculated fractionation models. An enrichment factor of greater than

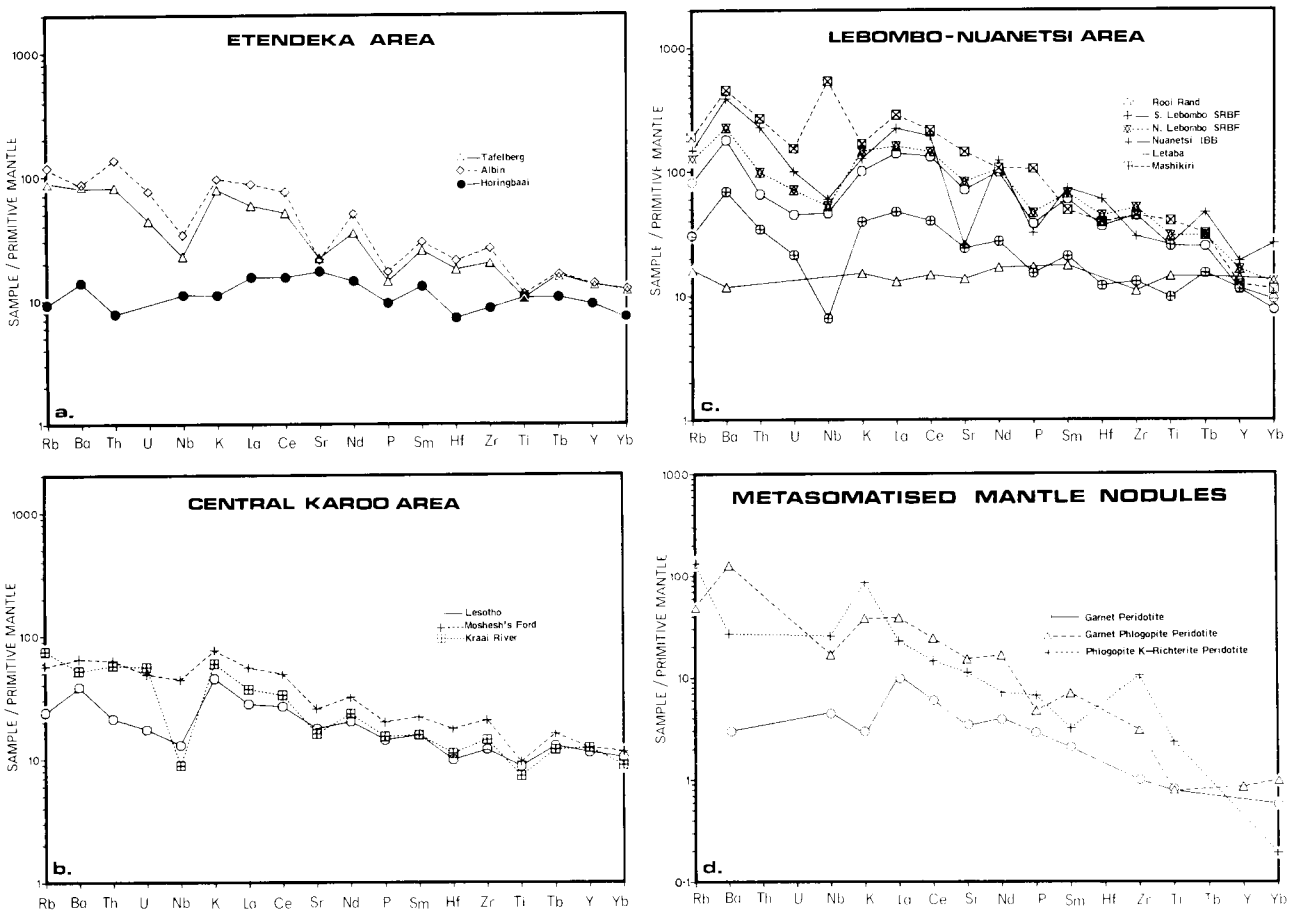

Figure 17

Incompatible minor and trace elements for Karoo magma types and metasomatized mantle nodules normalized to "primitive mantle" concentrations. Normalization values are taken from Rogers (1979). Samples chosen as representative of different Karoo magma types are as follows: Etendeka Fm. (Tafelberg): KLS-24, KLS-26; Etendeka Fm. (Albin): KLS-144; Etendeka Fm. (Horingbaai): KLS-122, KLS-145; Lesotho Fm.: JP-22, JP-27; Moshesh's Ford Fm.: CLA-01, KL-38; Kraai River Fm.: KF-2, KF-11; Rooi Rand: A-129; S. Lebombo SRBF: L-18, L-32; N. Lebombo SRBF: CL-100, CL-115, CL-120, N-175; Nuanetsi IBB: NTS-56; Letaba Fm: N-133, N-149; Mashikiri Fm.: NTS-7, NTS-12. Data for these samples may be found in the microfiche tables attached to this volume. Data for metasomatized mantle nodules are from Erlank (unpublished data).

4 could result if the fractionation process were to be modelled as one of periodic replenishment in long-lived continuously fractionating magma chambers (O'Hara, 1977; O'Hara and Mathews, 1981). However, it seems most improbable that fractionation processes could account for the large range in incompatible element abundances shown by Karoo basic magma types (a factor of 20 is shown in Figs. 17 and 18), particularly when it is recalled that the values plotted in these figures represent "primitive" members of each magma type.

Variations in the degree of partial melting could be responsible for very large abundance differences in incompatible trace elements provided that the most incompatible-enriched magma types represent very low degrees of partial melting. Large variations in incompatible element abundances with little variation in major element composition can be readily explained by variable (but low) degrees of partial melting and melting modes such that mineral proportions in the restite are changing relatively slowly. The general range of incompatible element abundances in the Karoo basic magma suite could be a consequence of the degree of partial melting varying from, say, 2 % to 30 %, accompanied by slight differences in the amount of fractional crystallization which occurs subsequent to melt segregation.

It is clear, however, from detailed studies of specific Karoo magma types (e.g. Cox *et al.*, 1984; Marsh and Eales, 1984) together with Sr- and Nd-isotopic studies (Hawkesworth *et al.*, 1984) that many of the compositional differences between Karoo basic magma types *cannot* be due to variations in the degree of partial melting and fractional crystallization involved in their genesis. Thus there is evidence for at least local heterogeneity with respect to major and trace elements in the source of Karoo magmas and isotopic evidence for the possibility of larger scale heterogeneities.

We turn now to a more specific appraisal of absolute and relative incompatible element abundances in the Karoo basic magma types. These are shown as values normalized to "primitive mantle" abundances (Wood *et al.*, 1979; Rogers, 1979) in Fig. 17 and to "average" MORB (Pearce, 1982) in Fig. 18. These incompatible element distribution plots show that many Karoo basic magma types have characteristics in common. In Fig. 17 where the elements are plotted with increasing bulk distribution coefficients for typical mantle mineral assemblages from left to right (after Wood *et al.*, 1979), it is clear that most magma types are relatively enriched in the more strongly incompatible elements. This infers that the Karoo magmas were derived by relatively modest degrees of partial melting (<15 %) and/or that their mantle source areas were enriched in incompatible elements relative to the "primitive mantle" composition used for normalization.

One of the most striking features of Karoo basic magmas is their general relative depletion in Nb, Sr, P and Ti which is illustrated by the "negative anomalies" for these elements in the distribution patterns of Figs. 17 and 18. Depletion of Nb, P and Ti in these magmas cannot be due to fractional crystallization processes since minerals with large distribution coefficients for these elements (e.g. apatite, ilmenite, magnetite) do not crystallize early enough in Karoo magmas to be a significant part of the fractionating mineral assemblage. Relative Sr depletion could in principal be ascribed to plagioclase fractionation but this is not consistent with the absence of significant Eu anomalies in these magma types (Fig. 19) and the very late crystallization of plagioclase in the high-K magmas of the Letaba formation and the SRBF in the northern Lebombo. Relative depletion of Nb, P and Sr would be equally difficult to generate during partial melting processes but relative Ti depletion could possibly be ascribed to the presence of ilmenite in the restite mineral assemblage.

It follows that the negative anomalies for Nb, P, Sr and probably for Ti, which are shown in Figs. 17 and 18, represent compositional characteristics of the mantle source for these magmas. Variations in the magnitude of these anomalies which do not correlate with total abundance variations of incompatible elements must be a reflection of compositional differences between the mantle source areas for some of the magma types. The gross variations in Nb, Sr and Ti relative to another incompatible element such as Zr for the Lesotho, Kraai River and Moshesh's Ford magma types (Fig. 17b) is strong evidence for mantle inhomogeneity in the source area for these magmas (Marsh and Eales, 1984). Differences in various ratios involving these elements (e.g. Zr/Nb) are shown in Table IV and histograms of Zr/Nb and Ti/Zr ratios for these magma types shown by Marsh and Eales (1984) indicate that such differences are *general* for these magma types and are not an artefact of sample selection in Figs. 17 and 18.

The most strikingly different incompatible element distribution patterns shown in Figs. 17 and 18 are for the Horingbaai and Rooi Rand magma types. Both these magma types have relatively primitive "flat" incompatible element distribution patterns and the differences between their patterns and those for other Karoo magma types in the same geographic areas (e.g. the Tafelberg and Albin types in the Etendeka area) preclude their derivation from the same source merely by a greater degree of partial melting. Both the Horingbaai and Rooi Rand magma types are very similar in incompatible element abundance patterns to average MORB (Fig. 18) and show almost flat REE patterns with slight LREE enrichment in Horingbaai and slight LREE depletion in Rooi Rand types (Fig. 19). These compositional characteristics suggest that these magma types have been derived from a MORB-type mantle source region, although Cox (1983) has suggested that the source region for the Rooi Rand magmas may be somewhat enriched in K, Rb and Ba relative to typical MORB sources. Both magma types have depleted isotopic characteristics with negative ϵ_{Sr} and positive ϵ_{Nd} values in the same range as shown by some ocean island basalts and MORB (Hawkesworth *et al.*, 1984). The geodynamic significance of these two magma types will be discussed in the following section of this paper.

A number of differences can be observed between incompatible element distribution patterns for basic magma types from the Nuanetsi and Lesotho areas (Fig. 17c). The Mashikiri nephelinites are characterized by a strong positive Nb anomaly (also shown by an extremely low average Zr/Nb ratio of 1.7 in Table I) which is a common feature of strongly alkaline rocks (Pearce and Norry, 1979; Sun, 1980). This anomaly must indicate a feature of the source composition or the direct incorporation of metasomatic fluids into the nephelinite magma (Bailey, 1982). The Nuanetsi interbedded basalts show a particularly pronounced negative Sr anomaly (see Fig. 17c and K/Sr ratios in Table III) for which there is no corresponding Eu anomaly (Fig. 19) thus implying that this is a source characteristic for this magma type. The more pronounced negative Nb anomaly for SRBF basalts from the southern Lebombo area cannot be ascribed to source characteristics with any certainty in view of the evidence for crustal contamination of this magma type.

There seems little doubt that the variability of incompatible element ratios and Sr- and Nd-isotope ratios indicates mantle heterogeneity on both a local scale (e.g. within the Central Karoo area) and on a regional scale (e.g.between the northern Lebombo and Central Karoo areas). Absolute levels of incompatible element abundances in the source areas for Karoo basalts and any variations in such abundances are more difficult to determine as they are model dependent. However, Cox (1983) and Cox *et al.* (1984) have shown that even if an

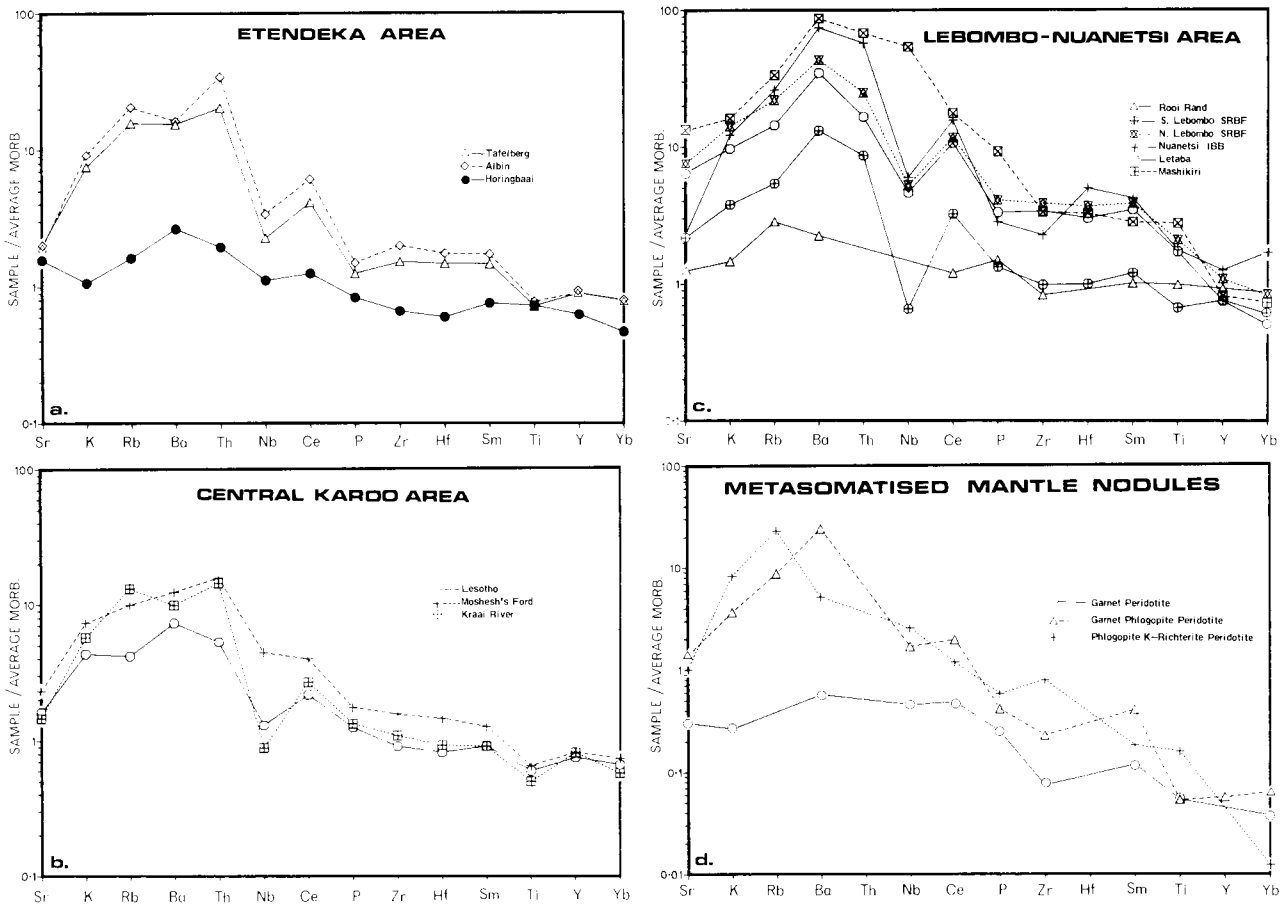

Figure 18

Incompatible minor and trace elements for Karoo magma types and metasomatized mantle nodules normalized to "average MOR basalt" concentrations. Normalization values are from Pearce (1982). Sources of data are the same as those for Fig. 17.

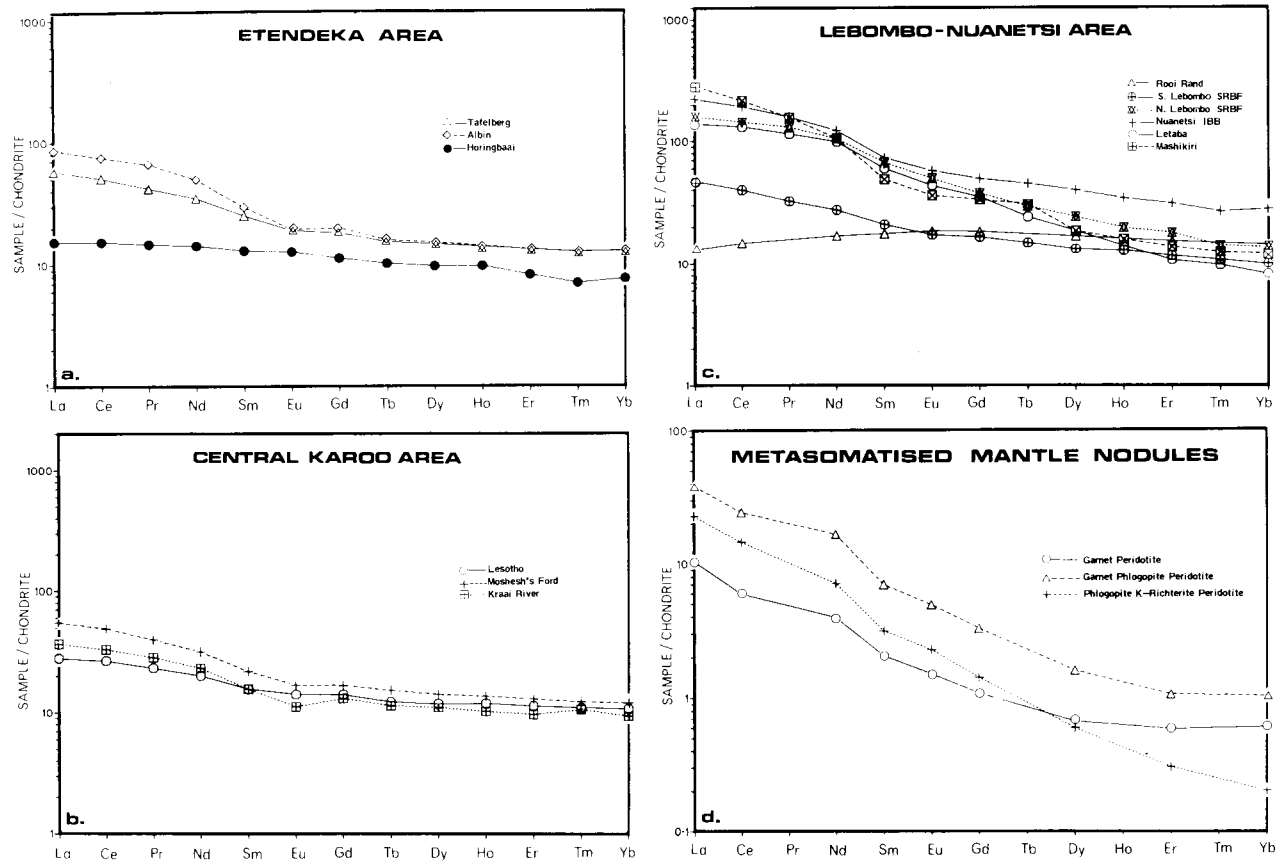

Figure 19

Rare earth elements for Karoo magma types and metasomatized mantle nodules. Chondrite normalization values are from Taylor and Gordon (1977). Sources of data are the same as those for Fig. 17.

improbably small degree of partial melting (<1%) is assumed, then the source for the Letaba picrites must be enriched in the more incompatible elements by a factor of 5–10 relative to "primitive mantle" values. *Provided* that all the mantle source regions for Karoo basalt magmas are similarly enriched then the variations in absolute incompatible element abundances between different magma types could be due to a large range in degree of partial melting (as noted earlier in this section). Alternatively, the heterogeneous nature of *relative* incompatible element abundances in the Karoo source areas could also apply to *absolute* levels of these elements. Intuitively, it seems to us that the latter possibility is more likely.

As many or all of the mantle source areas for the Karoo basalts must be enriched in incompatible trace elements, it is appropriate to examine the suite of mantle xenoliths brought to the surface by kimberlite pipes in southern Africa for evidence of a process by which this enrichment might have occurred. Mantle xenoliths showing a history of metasomatism appear to have many of the compositional characteristics expected of the Karoo source materials.

Erlank *et al.* (1982) recognize four different types of peridotite xenolith in the Kimberley area which can be characterized mineralogically as: garnet peridotite (GP) which contains no texturally equilibrated or "primary" phlogopite, garnet phlogopite peridotite (GPP), phlogopite peridotite (PP) and phlogopite K-richterite peridotite (PKP). The latter two groups contain no garnet while diopside may or may not be present in all four groups. Clear textural evidence for mantle metasomatic replacement processes exists in the three phlogopite bearing groups, especially in the PKP peridotites (Erlank and Rickard, 1977; Erlank *et al.*, 1980, 1982; Haggerty *et al.*, 1983). The garnet-bearing (GP and GPP) and garnet-free (PP and PKP) peridotites exhibit different patterns of incompatible element enrichment relative to primitive mantle values. Both groups of peridotites are similarly enriched in LREE and have similar Sm/Nd ratios, although the garnet-bearing types predictably have higher HREE abundances (see Fig. 19). Presently available data show substantial variations in enrichment ratios for many incompatible elements (Figs. 17d and 18d) but the PP and PKP rocks are characterized by higher Rb (and K) contents and higher Rb/Sr and Rb/Ba ratios (Erlank *et al.*, 1982). The two enrichment styles can be distinguished on a plot of Ba *vs* Rb (Erlank *et al.*, 1982) and the differences in Rb/Sr ratios at similar Sm/Nd ratios gives rise to trends of quite different slopes on an ϵ_{Nd}–ϵ_{Sr} diagram with time. The one style of enrichment (PP and PKP), with high Rb/Ba, high Rb/Sr and consequently high $^{87}Sr/^{86}Sr$ ratios, could produce a suitable source area for the Kraai River and Etendeka magma types. The second enrichment style (GP and GPP), with lower Rb/Ba and Rb/Sr ratios, could have produced source area characteristics consistent with the Central area, Nuanetsi and northern Lebombo magma types which plot close to the "mantle array" in an ϵ diagram and which have consistently lower Rb/Ba ratios than those shown by the Kraai River and Etendeka magma types.

More detailed appraisal of the incompatible element distribution patterns shown by the metasomatized mantle xenoliths is difficult since many incompatible elements included in Figs. 17 and 18 are not yet analysed in the xenolith suite. The GPP incompatible element pattern is perhaps the closest match to Karoo basic magmas as it shows negative anomalies for Nb, Sr, P and Ti, although the Sr and Ti anomalies are smaller than those typical of many Karoo magma types. The PKP (and PP) enrichment pattern which was suggested for the source of the Kraai River and Etendeka magma types on the basis of Rb/Ba and Rb/Sr ratios does not show the strong negative Sr and Ti anomalies characteristic of those Karoo magma types. It seems unlikely that the two "enrichment styles" currently recognized in mantle xenoliths are unique, and they are perhaps more likely to be merely two samples of a continuum of such styles. The overall character of incompatible element enrichment processes shown by metasomatized mantle xenoliths and Karoo magmas suggest that mantle metasomatism is indeed one suitable process for creating many or all of the incompatible element characteristics inferred for the source regions of these magmas. On the other hand, we do not wish to imply that mantle metasomatism (*sensu stricto*) is the only process capable of causing incompatible element enrichment in the mantle. Such enrichment could, for example, also be due to entrapment of small volume melts which might have quite different geochemical characteristics from mantle metasomatic fluids.

We have used the character of metasomatized xenoliths as an indication of processes that may have affected the mantle source areas for Karoo basalts. It should be noted, however, that many of the xenoliths themselves could not be samples of the source material since the maximum age of Rb (and K) metasomatism in the PP and PKP xenoliths is 150 m.y., coeval with or younger than the Karoo Central area volcanism (Erlank *et al.*, 1980, 1982).

Hawkesworth *et al.* (1984) and Cox (1983) have pointed out that some aspects of the incompatible element enrichment patterns for Karoo basic magma types are similar to those observed in island arc rocks. In particular, the low Nb/Ba ratios shown by all Karoo basic magmas and the low Ti/Y ratio shown by southern Lebombo and Central Karoo magmas are often considered diagnostic of island arc or active continental margin environments. This might be due to the contribution of a "subduction component" to the subcontinental lithosphere during its growth (Hawkesworth *et al.*, 1984). Alternatively this similarity in compositional characteristics might be an indication of a similar process controlling certain compositional features, but in different tectonic environments. For instance, it is suggested above that most (or all) of the source regions for Karoo basalts have been compositionally modified by metasomatic processes. It is quite feasible that these processes could be very similar to those taking place in the mantle wedge overlying a subduction zone during de-watering of the subducted slab.

A model for generating Karoo basalts by a subduction-related convection cell is discussed in the next section. However, it seems most unlikely that a post-Devonian subduction system (Cox, 1978) is responsible for adding the required "subduction component" to the source areas for Karoo magmas in view of the Proterozoic age suggested for incompatible element enrichment in these areas (Hawkesworth *et al.*, 1984). Any "subduction component" added to the lithosphere must therefore relate to an earlier subduction event. In this regard there is geophysical data defining the "Southern Cape Conductive Belt" which has been interpreted by De Beer *et al.* (1982) as evidence of a Proterozoic subduction zone beneath southern Africa.

In summary, we conclude that variation in the degree of partial melting, fractional crystallization and crustal contamination processes have all played their part in generating the compositional diversity we observe in Karoo basaltic rocks. However, we believe that the major compositional differences between clans of basic rocks in the Karoo Igneous Province reflect compositional differences between their mantle source regions. Mantle inhomogeneity also seems the most probable explanation of some compositional differences between magma types in a single clan, such as those between the Lesotho, Kraai River and Moshesh's Ford magma types of the Central Karoo clan.

It is clear that the source regions for most Karoo basaltic rocks were relatively enriched in incompatible minor and

trace elements, but that the pattern and the total degree of enrichment were variable. The isotopic and trace element characteristics of metasomatized mantle xenoliths are similar to those inferred for the source regions of Karoo basalts. It is therefore possible that "mantle metasomatism" may be the process by which incompatible element enrichment took place and that most of the Karoo basalt source regions lie within the subcontinental lithosphere.

VIII. GEODYNAMIC CONTROL OF MAGMA GENERATION

The most fundamental question regarding geodynamic control of Karoo volcanism is the relationship between the disruption of Gondwanaland and the generation of the Karoo magmas. Various aspects of this question include the relative ages of Karoo volcanism and the disruption of Gondwanaland; the location of Karoo volcanism with respect to the continental margins of southern Africa and those of Gondwanaland; and the variability in magma composition as a function of proximity to either the western or eastern margins of southern Africa at the time of plate separation.

Sea-floor spreading magnetic anomalies oriented roughly east–west have been identified in the Mozambique and Somali basins off East Africa (Segoufin, 1978; Simpson *et al.*, 1979; Segoufin and Patriat, 1980; Parson *et al.*, 1981; Rabinowitz *et al.*, 1983). There is, however, still some controversy about the exact anomaly identifications. The identifications of Segoufin (1978) and Simpson *et al.* (1979) in the Mozambique basin are compatible with each other and are consistent with those of Segoufin and Patriat (1980) in the Somali Basin. According to these authors sea-floor spreading began near-synchronously in both basins at anomaly M21 to M22 time (an age of approximately 140 m.y.). However, Rabinowitz *et al.* (1983) have claimed that Somali Basin sea-floor spreading began in the Jurassic Quiet Normal Interval prior to M25 time, implying an age of approximately 165 m.y. Their argument involves the further hypothesis that the "quiet zone" crust in the northernmost and southernmost Somali Basin is truly oceanic. This viewpoint is explicitly rejected by Segoufin and Patriat (1980) who regard the sea-floor south of the Comores Islands as being underlain by stretched and thinned continental crust (see also Scrutton *et al.*, 1980).

It seems almost certain, then, that the onset of sea-floor spreading between West and East Gondwanaland significantly postdates the major phase of Karoo basaltic volcanism in the adjacent areas of southern Africa (Nuanetsi, Lebombo, Central Karoo) at about 185–195 m.y. (MacDougall, 1963; Manton, 1968; Fitch and Miller, 1984; Allsopp *et al.*, 1984a). It also postdates the rhyolitic eruptions of the Jozini and Mbuluzi formations in the Lebombo (Cleverly *et al.*, 1984) at 177 m.y. (Allsopp *et. al.*, 1984b). Some younger and relatively minor Karoo volcanic episodes either postdate or coincide with the opening of the Somali and Mozambique basins. These are the eruption of the Kuleni and Bumbeni rhyolite complexes in the southern Lebombo (146 and 133 m.y.; Allsopp *et. al.*, 1984b) and the alkaline Lupata volcanics in north-west Mozambique (approx. 110 m.y.; see discussion following Cox, 1972).

Earlier ideas held that the oldest sea-floor spreading magnetic anomaly recognized in the Cape Basin off the west coast of southern Africa is either M12 (Larson and Ladd, 1973) or M13 (Rabinowitz and LaBrecque, 1979). However, there is currently considerable controversy regarding both the identification, and the geochronological calibration, of the M-anomaly sequence in this area. The recent work of Austin and Uchupi (1982) suggests that rift propagation in the South Atlantic proceeded from south to north with the ocean–continent boundary becoming progressively younger northward. They suggest that the oldest ocean floor in the south Atlantic at the latitude of Cape Town is not older than anomaly M9 and that the oldest sea-floor spreading anomaly that can be recognized with any certainty off the coast of SWA/Namibia is anomaly M4. This would correspond to an age of 127 m.y. (Cox in Harland *et al.*, 1982) or 123 m.y. (Lowrie, 1982). The Lesotho magma type forms the 180 m.y. Kalkrand basalts of southern SWA/Namibia and, together with numerous dolerite sills and dykes throughout Namibia with ages of 134–196 m.y. (Siedner and Mitchell, 1976; Erlank *et al.*, 1984), demonstrates that the onset of Karoo volcanicity in this area predates the opening of the South Atlantic. The main phase of Karoo volcanism near the present-day Atlantic coast of southern Africa is the Etendeka Formation, for which Siedner and Mitchell (1976) have suggested an age of 121 m.y. based on a $^{40}Ar/^{36}Ar$–$^{40}K/^{36}Ar$ isochron. However, ^{40}Ar-^{39}Ar step heating ages on plagioclase from dykes cutting the Etendeka lavas yield ages of 125–130 m.y. (Erlank *et al.*, 1984) while Allsopp *et al.* (1984a) obtained an Rb-Sr isochron age of 132 m.y. for the Messum Complex which is believed to intrude the Etendeka lavas. All in all, there is still a margin of doubt regarding the relative ages of the Etendeka Formation lavas and the onset of sea-floor spreading in adjacent parts of the South Atlantic. On balance, it seems probable that nearly all the Karoo volcanism on this western margin of southern Africa also predates the onset of sea-floor spreading in that area.

The location of Karoo volcanism as a whole is clearly not a *direct* consequence of Gondwana intercontinental rifting since the basaltic products of the Karoo magmatic event are distributed over the entire subcontinent of southern Africa and are not preferentially located near the sites of plate separation. However, as discussed in previous sections, the Karoo acid volcanics are only found adjacent to the continental margin in Namibia, along the Lebombo monocline, and in the Nuanetsi area. The northern portion of the Lebombo monocline and the Nuanetsi area are up to 400 km from the present continental margin but recent plate tectonic reconstructions (Martin and Hartnady, 1983) suggest that the Dronning Maud Land area of Antarctica was adjacent to the Lebombo monocline. This implies that the eastern margin of the present Lebombo monocline either coincides with or is parallel to a sheared continental margin produced by spreading in the Mozambique Basin about a ridge orientated nearly at right angles to the monoclinal axis. Development of the Lebombo monocline began during eruption of the Sabie River Basalt Formation (Bristow, 1976) and could well have been complete shortly after eruption of the Jozini rhyolites. Its period of deformation would thus predate spreading in the Mozambique Basin by approximately 10–35 m.y.

The origin of the Karoo acid volcanics might be either by crustal anatexis, as suggested by Cox (1972) for rhyolites of the Nuanetsi–Lebombo region and by Erlank *et al.* (1984) for the quartz latites of the Etendeka Formation, or by partial melting of underplated basalt as suggested by Cleverly *et al.* (1984) for the Lebombo and Nuanetsi rhyolites. Both models specifically require elevated temperatures at or near the base of the crust, but in the case of the Etendeka quartz latites melting may have occurred at higher levels on the basis of Sr- and Nd-isotopic data (Erlank *et al.*, 1984). Evidence for possible crustal contamination of the Sabie River basalts in the southern Lebombo (see previous section and Cox and Bristow, 1984) could also be an indication of elevated crustal temperatures. These aspects of the distribution of Karoo magma types thus imply that crustal temperatures were significantly elevated along the loci of the developing plate boundaries around southern Africa. This could have been associated with a process of crustal thinning in which hot asthenosphere penetrated and heated the lithosphere. This

would correspond to a model of "active" rather than "passive" rifting (Turcotte and Emerman, 1983).

Elevated crustal temperatures in Karoo times cannot be simply a product of basaltic intrusion since the development of acid volcanics does not coincide with the outcrop area of Karoo basaltic rocks, but is confined to those areas where basalts were produced in close proximity to the developing plate boundaries.

The geographic distribution of compositionally distinctive *basic* magma types in the Karoo Igneous Province does not generally appear to reflect any control by the age or character of the major crustal tectonic units (discussed in previous sections and by Cox, 1972) or by proximity to the plate boundaries around southern Africa. Cox has, however, suggested that the confinement of the picritic basalts of the Letaba Formation to the Tuli, Nuanetsi and northern Lebombo areas could be a consequence of the greater ease with which these high-density magmas could erupt in areas of crustal thinning.

Petrogenetic arguments which were summarized in the previous section suggest that the mantle source regions for some of the Karoo basic magmas have undergone previous episodes of basalt depletion (Cox *et al.*, 1984) and that the source regions for most Karoo basic magmas have undergone episodes of metasomatism during the period 1000–1400 m.y. (Hawkesworth *et al.*, 1984). The data are consistent with a model which derives most Karoo basaltic magmas from a subcontinental lithospheric "keel", such as that proposed by Brooks *et al.* (1976), which has existed below southern Africa at least since the Proterozoic. The only Karoo magmas which could possibly be derived directly from melting in the asthenosphere, assuming that such a magma would have many characteristics in common with present-day mid-ocean-ridge basalts, are the Horingbaai and Rooi Rand magma types which were discussed in the previous section. The proximity of these two magma types to the original plate margins of southern Africa is consistent with their derivation from sources below or adjacent to the continental lithosphere during the final stages of crustal thinning prior to the onset of sea-floor spreading and the disruption of Gondwanaland. In both areas of outcrop these magmas form dykes which are clearly younger than basaltic lavas from the same areas which have inferred sources in the continental lithosphere. However, the precise age relationships of the dykes are not yet known.

Two geodynamic mechanisms have been proposed for Karoo magma genesis and either could contribute to, or cause, the disruption of Gondwanaland. Morgan (1981) has attributed the Karoo volcanics in the Central Karoo area and the Lebombo to the action of the Crozet (Prince Edward) hotspot and the younger Parana (and Etendeka) volcanics to the action of the Tristan hotspot. On the other hand, Elliot (1975), Cox (1978) and Froidevaux and Nataf (1981) have all proposed a relationship between subduction under the Pacific margin of Gondwanaland and the generation of Jurassic–Cretaceous Gondwana flood basalts.

Morgan (1981, 1983) has suggested that hotspots heat the subcontinental lithosphere for periods of 10–30 m.y. and that flood basalts are generated in the area heated as the hotspot track leaves its margin. This model fits the geometry and ages of the Parana and the Etendeka volcanics, but is less satisfactory for the bulk of Karoo volcanics in southern Africa. The Crozet hotspot is constrained to the Nuanetsi–northern Lebombo area in the 200–180 m.y. timeframe and then moves *north-east* relative to this area. The bulk of the Karoo basalts are generated over southern Africa to the *south-west* of Nuanetsi at much the same time as the volcanism in the Nuanetsi and northern Lebombo areas.

It should be noted that there is a striking coincidence between the location of the Crozet hotspot, at the onset of Karoo volcanism in the Nuanetsi and northern Lebombo areas, and the mantle region for which we have inferred the maximum degree of incompatible-element enrichment (see previous section). We have interpreted this enrichment process to be of Proterozoic age (see previous section and Hawkesworth *et al.*, 1984) and thus unrelated to any younger hotspots (or "mantle plumes"). However, if the isotopic, Rb/Sr and LREE characteristics of the lithosphere were "swamped" by material introduced from a plume, and if the "age" preserved by this plume material was Proterozoic, then the metasomatic event may have taken place at 200 m.y. (not in Proterozoic time as we have inferred) and be plume-related.

Elliot (1975), Cox (1978) and Froidevaux and Nataf (1981) all point out that the distribution of the Parana, Karoo and Kirkpatrick (Antarctic) basalts forms a band which parallels the Pacific margin of a reconstructed Gondwanaland, along which subduction has occurred at least since the Devonian. Elliot and Cox suggested that these flood basalts formed in a tectonic environment analogous to marginal basin or back-arc spreading environments in the western Pacific. However, as Cox (1978) has pointed out, many models of back-arc spreading (e.g. Sleep and Toksoz, 1971; Toksoz and Bird, 1977) can provide an explanation for spreading phenomena no more than a few hundred kilometres from the subducted margin. Froidevaux and Nataf (1981) have recently shown that fluid dynamics experiments provide evidence for large-scale convective "rolls" developing on the continental side of subduction zones. These large-scale convective rolls would have their upwelling limb some 3000–4000 km from the subduction zone itself and would take some 200 m.y. to develop. The Parana, Karoo and Kirkpatrick basalts lie some 2000–4000 km behind the Pacific margin of Gondwanaland and were generated approximately 200–300 m.y. after subduction is known to have been active. Marginal basins close to the subduction zone are compatible with such a model but would be generated by "trench suction" as proposed by Chase (1978).

A mechanism such as that suggested by Froidevaux and Nataf (1981) is a very appropriate one for large-scale heating of the subcontinental lithosphere over a large area broadly parallel to the Pacific margin of Gondwanaland. We thus believe it to be a more appropriate mechanism for generating the Karoo magmatism than the hotspot-heating model proposed by Morgan (1981, 1983).

IX. SUMMARY

1. Comprehensive geochemical comparisons of basic rocks in different geographic areas show that there are three clans of basic magma types in the Karoo Igneous Province. Neither the distribution of the clans themselves, nor of most magma types within the clans, shows any evidence of regional tectonic control.
2. Detailed studies have shown that most differences in incompatible element ratios, and in Sr- and Nd-isotopic ratios (Bristow *et al.*, 1984; Hawkesworth *et al.*, 1984), between Karoo basic magma types are unlikely to be a result of crustal contamination, partial melting, or fractional crystallization processes. They are therefore believed to reflect mantle heterogeneity on a variety of scales.
3. Relative and absolute abundances of incompatible elements in Karoo basic magmas suggest that many (or all) of their source regions are relatively enriched in incompatible minor and trace elements. Isotopic data are consistent with such an enrichment being Proterozoic in age. These incompatible element enriched source regions are believed to lie within the subcontinental lithosphere.

4. Suites of metasomatized mantle xenoliths from kimberlite pipes have isotopic and trace element characteristics similar to those inferred from the source regions of Karoo basalts. Mantle metasomatism would therefore appear to be a suitable mechanism for generating these characteristics in the subcontinental mantle on a relatively large scale.
5. Rhyolite and quartz latite magmas are only found near the original plate margins of southern Africa. It is argued that they are produced by partial melting at or near the base of the crust and are a thermal consequence of crustal thinning and rifting preceding the disruption of Gondwanaland.
6. Two suites of basaltic intrusives (Horingbaai and Rooi Rand) have compositional and isotopic characteristics similar to those of MORB. They occur in the Etendeka and southern Lebombo areas close to the continental margins and may indicate magma derivation from asthenospheric MORB-type source regions during the initial stages of sea-floor spreading.
7. The Karoo basalts themselves are not concentrated near the initial plate margins and the acme of Karoo volcanism predates the disruption of Gondwanaland. Thus the Karoo basalts do not appear to be a direct *consequence* of Gondwana disruption but a common process could be responsible for both Karoo magmatism and the breakup of Gondwanaland.
8. Basaltic magmas were generated throughout a broad region parallel to the Pacific margin of Gondwanaland shortly before (Central Karoo, Lebombo, Kirkpatrick basalts), or coincident with (Parana, Etendeka basalts), its disruption. This could reasonably be related to the thermal consequences of a large convective roll in the mantle induced by subduction under the Pacific margin of Gondwanaland since the Devonian (or earlier). Basaltic magma generation over such a large area in a relatively short time seems to us to be less likely to be related to the palaeoposition of the Crozet and Tristan hotspots.

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APPENDIX A

Tables of compositional data for the Karoo Volcanics

These tables contain the arithmetic mean and standard deviation for the major oxides, trace elements and a selected set of interelement ratios in each of the units of the Karoo Volcanics, or for a unit in a specific geographic area. The number of samples for which data were available in any particular unit is indicated in the column marked "N". The values designated "Fe_2O_3*" are total Fe expressed as Fe_2O_3. The values designated "Mg#" are the atomic ratio of $Mg/Mg + Fe^*$ where Fe^* is the Fe^{2+} content of the rock based on an assumed $FeO/(FeO + Fe_2O_3)$ ratio of 0.85.

Data values given for trace elements have been rounded to indicate the approximate precision of the data. Ratios and standard deviations have not been rounded and were calculated prior to rounding the elemental data. Mean ratios reflect only those cases where both elements analysed were above analytical detection limits in the same sample and are not the ratio of individual element mean values.

The original data used for the compilation of these tables was calculated on a volatile free basis so that major oxides totalled 100%. The factor required to correct major oxide totals to 100% on this basis was also applied to trace elements for the same sample. All data used for calculating these averages are contained in Microfiche Card 2 attached to this volume.

TABLE I
Mashikiri Nephelinite Formation

	Northern Lebombo			Sabi		
Variable	Mean	S.D.	N	Mean	S.D.	N
SiO_2	44.86	0.64	8	43.94	1.81	13
TiO_2	2.87	0.34	8	3.55	0.62	13
Al_2O_3	11.45	2.26	8	14.04	3.03	13
Fe_2O_3*	14.52	1.22	8	13.46	2.04	13
MnO	0.19	0.02	8	0.23	0.06	13
MgO	7.51	0.54	8	5.83	2.35	13
CaO	10.20	1.33	8	8.35	2.56	13
Na_2O	5.86	0.99	8	7.43	2.44	13
K_2O	1.60	0.47	8	2.25	0.62	13
P_2O_5	0.93	0.16	8	0.92	0.41	13
Cs	1.19	0.00	1	0.96	0.535	2
Rb	49	12.9	7	68	14.7	9
Ba	1365	622	7	2020	466	9
Sr	1080	277	7	1645	454	9
Th	5.5	0.0	1	13.5	0.14	2
U	0.50	0.0	1	2.31	0.98	2
Zr	166	27	7	268	62	9
Hf	5.09	0.00	1	8.05	0.99	2
Nb	96	10.1	7	175	17	5
Cr	93	29.6	7	70	44.2	9
V	311	77	7	355	51	5
Sc	18	3.7	7	0.0	0.0	0
Ni	70	15.3	7	43	22.1	8
Co	54	5.2	7	53	2.7	5
Ga	14.2	5.5	2	0.0	0.0	0
Pb	152	0	1	29	1.6	2
Zn	127	13	7	126	16	6
Cu	241	21	7	345	110	7
Y	23	5.1	7	25	1.6	5
Zr/Nb	1.73	0.21	7	1.63	0.16	5
Zr/Y	7.74	2.41	7	11.4	1.0	5
Zr/Hf	39.8	0.0	1	38.3	1.0	2
K/Rb	265	48	7	307	57	9
K/Ba	10.4	3.1	7	10.4	2.6	9
K/Sr	12.3	3.6	7	13.3	4.5	9
K/Zr	80.7	30.0	7	79.5	23.8	9
K/Nb	139	53	7	115	12	5
K/Y	591	181	7	807	111	5
Ba/Rb	28.0	10.4	7	30.8	9.2	9
Ba/Sr	1.36	0.86	7	1.40	0.89	9
Ba/Zr	8.49	4.02	7	8.06	3.18	9
Rb/Sr	0.047	0.015	7	0.043	0.011	9
Ni/Co	1.32	0.36	7	1.00	0.38	5
Cr/Ni	1.37	0.44	7	2.39	2.89	8
Ti/P	4.30	0.63	8	6.90	4.20	13
Th/U	11.0	0.0	1	6.43	2.68	2
Mg#	54.3	1.2	8	49.9	7.3	13

TABLE II
Letaba Basalt Formation (Picrite Basalts)

	Northern Lebombo			Nuanetsi			Tuli		
Variable	Mean	S.D.	N	Mean	S.D.	N	Mean	S.D.	N
SiO_2	49.97	1.25	19	49.49	1.02	48	49.25	1.07	10
TiO_2	3.07	0.41	19	2.70	0.48	48	3.02	0.29	10
Al_2O_3	8.22	1.27	19	8.82	1.76	48	8.57	1.07	10
Fe_2O_3*	12.02	0.75	19	12.33	0.90	48	13.62	1.45	10
MnO	0.16	0.02	19	0.15	0.02	48	0.15	0.02	10
MgO	15.52	3.51	19	15.20	3.25	48	14.78	2.66	10
CaO	7.07	1.08	19	7.55	1.22	48	6.76	0.69	10
Na_2O	1.43	0.53	19	1.63	0.42	48	1.65	0.53	10
K_2O	2.10	0.91	19	1.70	0.73	48	1.82	0.65	10
P_2O_5	0.45	0.09	19	0.43	0.11	48	0.38	0.09	10
Cs	1.96	0.94	2	0.308	0.096	2	0.0	0.0	0
Rb	55	22.8	17	34	16.5	44	41	19.6	10
Ba	917	351	17	794	321	44	915	202	10
Sr	1000	272	17	857	246	44	1025	192	10
Th	3.17	0.47	2	3.31	0.55	2	0.0	0.0	0
U	0.76	0.09	2	0.68	0.11	2	0.0	0.0	0
Zr	402	84	17	308	89	44	436	70	10
Hf	8.48	0.70	2	7.32	1.58	2	0.0	0.0	0
Nb	19	7.4	17	19	6.0	20	22	6.0	6
Cr	804	140	17	941	231	43	0.0	0.0	0
V	204	31	17	191	35	16	0.0	0.0	0
Sc	21	3.0	16	21	0.0	1	0.0	0.0	0
Ni	827	299	17	761	246	44	0.0	0.0	0
Co	81	15.5	17	88	14.8	12	63	10.3	9
Ga	16.0	2.5	6	15.8	2.00	4	0.0	0.0	0
Pb	54	55.3	2	7.6	2.04	2	0.0	0.0	0
Zn	110	7	17	103	7	21	115	10	10
Cu	83	12.2	17	72	21.4	20	0.0	0.0	0
Y	28	3.4	17	25	3.5	12	0.0	0.0	0
Zr/Nb	23.2	6.8	17	18.8	6.1	20	21.3	4.9	6
Zr/Y	14.6	2.9	17	13.5	3.8	12	0.0	0.0	0
Zr/Hf	43.6	4.2	2	42.1	1.3	2	0.0	0.0	0
K/Rb	353	112	17	424	120	44	486	353	10
K/Ba	20.9	6.8	17	17.5	3.7	44	17.2	7.0	10
K/Sr	18.6	7.0	17	15.8	4.4	44	15.2	5.0	10
K/Zr	45.3	14.2	17	43.6	10.7	44	35.2	11.1	10
K/Nb	1028	356	17	793	381	20	843	313	6
K/Y	673	285	17	602	342	12	0.0	0.0	0
Ba/Rb	17.7	6.6	17	25.0	8.8	44	29.6	21.8	10
Ba/Sr	0.899	0.179	17	0.901	0.158	44	0.918	0.232	10
Ba/Zr	2.23	0.50	17	2.54	0.61	44	2.15	0.56	10
Rb/Sr	0.056	0.021	17	0.039	0.012	44	0.039	0.015	10
Ni/Co	10.1	2.4	17	9.34	2.09	12	0.0	0.0	0
Cr/Ni	1.04	0.24	17	1.29	0.34	43	0.0	0.0	0
Ti/P	9.60	2.00	19	8.79	1.22	48	11.4	3.0	10
Th/U	4.19	0.12	2	4.90	0.04	2	0.0	0.0	0
Mg#	74.8	4.6	19	73.9	5.3	48	71.4	5.5	10

TABLE III
Lebombo–Zimbabwe low-MgO Basalts

	Zululand SRBF			Swaziland SRBF			S.C. Lebombo SRBF		
Variable	Mean	S.D.	N	Mean	S.D.	N	Mean	S.D.	N
SiO_2	52.84	2.49	37	51.66	2.16	11	50.98	2.22	5
TiO_2	1.44	0.46	37	1.76	0.46	11	2.15	0.38	5
Al_2O_3	14.87	1.40	37	14.49	1.47	11	14.11	1.62	5
Fe_2O_3*	12.32	1.69	37	13.01	1.11	11	13.98	1.68	5
MnO	0.17	0.03	37	0.17	0.02	11	0.19	0.04	5
MgO	5.51	1.27	37	5.85	1.86	11	5.49	1.18	5
CaO	9.27	1.28	37	9.69	1.68	11	9.93	1.11	5
Na_2O	2.55	0.56	37	2.82	0.73	11	2.32	0.43	5
K_2O	0.78	0.43	37	0.38	0.27	11	0.59	0.21	5
P_2O_5	0.25	0.10	37	0.17	0.05	11	0.26	0.12	5
Cs	0.573	0.812	3	1.06	1.27	2	0.0	0.0	0
Rb	19	15.5	37	11.0	6.9	4	13	6.4	5
Ba	295	169	37	171	117	4	207	37	5
Sr	316	155	37	280	23	4	324	81	5
Th	2.13	0.72	3	1.70	1.29	2	0.0	0.0	0
U	0.42	0.19	3	0.32	0.18	2	0.0	0.0	0

TABLE III (cont.)

	Zululand SRBF			Swaziland SRBF			S.C. Lebombo SRBF		
Variable	Mean	S.D.	N	Mean	S.D.	N	Mean	S.D.	N
Zr	134	49	37	145	33	4	148	22	5
Hf	2.65	0.39	3	3.92	1.15	2	0.0	0.0	0
Nb	5.3	2.96	34	7.2	3.20	4	9.1	2.2	5
Cr	136	81	37	458	491	2	96	40.6	5
V	261	69	37	242	71	2	307	62	5
Sc	30	7.4	9	20	2.5	2	31	10.9	5
Ni	76	63.6	37	267	239	2	94	21.2	5
Co	48	8.2	37	53	11.7	4	54	2.9	5
Ga	19.9	1.5	19	18.3	0.0	1	25	2.9	5
Pb	5.4	0.91	3	65	35.6	2	0.0	0.0	0
Zn	96	13.8	37	120	11	4	111	10	5
Cu	130	113	37	196	197	4	228	154	5
Y	29	7.8	37	36	7.2	4	33	8.5	5
Zr/Nb	29.5	9.3	34	24.8	8.5	7	17.0	4.1	5
Zr/Y	4.60	0.84	37	4.36	0.47	7	4.63	0.59	5
Zr/Hf	38.0	3.6	3	34.8	3.1	2	0.0	0.0	0
K/Rb	421	159	37	333	28	4	436	210	5
K/Ba	25.8	14.3	37	24.2	11.0	4	24.4	10.8	5
K/Sr	23.8	15.2	37	13.1	8.6	4	15.9	6.6	5
K/Zr	49.3	20.9	37	23.3	12.3	4	33.2	11.2	5
K/Nb	1432	687	34	509	357	4	585	302	5
K/Y	230	109	37	96.0	55.5	4	158	72	5
Ba/Rb	22.8	17.9	37	16.1	7.3	4	20.8	14.4	5
Ba/Sr	0.957	0.391	37	0.623	0.460	4	0.700	0.345	5
Ba/Zr	2.26	1.16	37	1.10	0.68	4	1.40	0.18	5
Rb/Sr	0.069	0.060	37	0.046	0.020	7	0.044	0.024	5
Ni/Co	1.50	0.92	37	4.64	3.67	2	1.74	0.40	5
Cr/Ni	2.04	1.16	37	1.49	0.50	2	1.01	0.26	5
Ti/P	8.91	3.31	37	14.8	3.3	11	12.2	2.6	5
Th/U	5.20	0.66	3	4.96	1.20	2	0.0	0.0	0
Mg#	50.7	6.5	37	50.8	7.0	11	47.4	4.1	5

	N.C. Lebombo SRBF			N. Lebombo SRBF			Nuanetsi SRBF		
Variable	Mean	S.D.	N	Mean	S.D.	N	Mean	S.D.	N
SiO_2	51.92	1.48	9	51.00	1.44	7	52.41	1.56	27
TiO_2	3.23	0.29	9	3.42	0.43	7	2.77	0.53	27
Al_2O_3	13.13	0.45	9	13.84	2.52	7	13.65	1.75	27
Fe_2O_3*	13.28	1.87	9	12.44	1.88	7	12.10	0.81	27
MnO	0.17	0.03	9	0.15	0.03	7	0.15	0.02	27
MgO	5.34	0.95	9	5.47	1.98	7	5.64	2.57	27
CaO	7.98	0.59	9	8.94	1.44	7	8.79	0.99	27
Na_2O	2.34	0.42	9	2.17	0.62	7	2.28	0.35	27
K_2O	2.08	0.54	9	2.01	1.39	7	1.72	0.56	27
P_2O_5	0.53	0.14	9	0.57	0.13	7	0.49	0.16	27
Cs	0.357	0.163	3	0.614	0.000	1	0.318	0.153	2
Rb	45	11.7	9	39	35.2	7	33	13.1	22
Ba	853	266	9	911	716	7	692	210	22
Sr	856	245	9	936	204	7	795	275	22
Th	5.03	0.32	3	3.1	0.0	1	6.05	1.91	2
U	1.12	0.02	3	0.68	0.0	1	1.28	0.50	2
Zr	349	49	9	364	62	7	332	75	22
Hf	9.08	0.58	3	11.5	0.0	1	8.87	0.52	2
Nb	20	8.7	9	23	12.8	7	24	17.0	22
Cr	85	51.4	9	152	183	7	192	339	22
V	246	57	9	253	57	7	228	66	22
Sc	24	1.8	9	24	4.4	4	24	1.8	18
Ni	84	37.7	9	124	69	7	95	96.0	22
Co	49	4.7	9	48	9.1	7	53	14.0	22
Ga	25	2.3	9	21	2.1	3	20	4.9	4
Pb	13	4.8	3	8.1	0.00	1	12	0.8	2
Zn	120	11	9	118	16	7	99	7.9	22
Cu	113	97	9	152	89	7	75	71.9	22
Y	36	6.0	9	37	4.8	7	33	4.2	22
Zr/Nb	20.9	8.2	9	18.8	7.6	7	17.0	6.1	22
Zr/Y	9.94	2.06	9	9.95	1.73	7	9.99	1.64	22
Zr/Hf	39.1	1.9	3	36.1	0.0	1	42.4	3.4	2
K/Rb	387	40	9	489	137	7	471	144	22
K/Ba	21.3	6.2	9	19.6	4.5	7	21.4	4.0	22
K/Sr	20.7	3.8	9	17.1	8.0	7	19.2	5.7	22
K/Zr	49.9	12.5	9	44.9	25.8	7	44.1	10.7	22
K/Nb	1093	602	9	917	861	7	720	284	22

(*continued*)

TABLE III (cont.)

Variable	N.C. Lebombo SRBF Mean	S.D.	N	N. Lebombo SRBF Mean	S.D.	N	Nuanetsi SRBF Mean	S.D.	N
K/Y	501	180	9	434	225	7	444	134	22
Ba/Rb	19.3	4.8	9	25.9	8.4	7	23.9	14.5	22
Ba/Sr	1.03	0.29	9	0.935	0.534	7	0.893	0.201	22
Ba/Zr	2.45	0.67	9	2.49	1.69	7	2.11	0.63	22
Rb/Sr	0.054	0.011	9	0.039	0.026	7	0.044	0.016	22
Ni/Co	1.65	0.69	9	2.56	1.19	7	1.62	1.18	22
Cr/Ni	1.05	0.62	9	1.00	0.71	7	1.47	0.77	22
Ti/P	8.69	1.53	9	8.43	1.40	7	8.43	2.30	27
Th/U	4.49	0.25	3	4.56	0.0	1	4.83	0.40	2
Mg#	48.0	7.4	9	50.2	9.5	7	51.7	9.0	27

Variable	Nuanetsi I.B.B. Mean	S.D.	N	Tuli SRBF Mean	S.D.	N	Zimbabwe Mean	S.D.	N
SiO_2	52.00	1.88	8	49.72	0.72	17	51.57	1.16	20
TiO_2	2.04	1.21	8	2.93	0.77	17	3.00	0.38	20
Al_2O_3	13.36	0.57	8	14.77	1.18	17	12.72	1.17	20
Fe_2O_3*	14.84	1.57	8	13.99	1.99	17	13.41	1.33	20
MnO	0.21	0.03	8	0.15	0.03	17	0.17	0.02	20
MgO	4.76	1.45	8	4.61	0.95	17	6.02	1.61	20
CaO	8.34	1.85	8	9.16	1.17	17	9.07	0.78	20
Na_2O	2.51	0.49	8	2.75	0.41	17	2.33	0.21	20
K_2O	1.51	0.82	8	1.44	1.14	17	1.28	0.51	20
P_2O_5	0.32	0.15	8	0.47	0.12	17	0.44	0.14	19
Cs	1.78	0.00	1	0.0	0.0	0	0.0	0.0	0
Rb	42	19.6	6	104	297	16	27	14.3	12
Ba	579	486	6	765	540	17	817	465	12
Sr	271	159	6	721	292	17	711	269	12
Th	11.4	0.0	1	0.0	0.0	0	0.0	0.0	0
U	1.50	0.0	1	0.0	0.0	0	0.0	0.0	0
Zr	177	90	6	321	64	17	343	126	12
Hf	12.0	0.0	1	0.0	0.0	0	0.0	0.0	0
Nb	18	8.2	6	34	26.9	17	17	7.1	12
Cr	41	15.9	6	98	99.4	3	199	242	12
V	262	57	6	279	59	3	257	76	12
Sc	40	4.8	4	0.0	0.0	0	0.0	0.0	0
Ni	36	20.4	6	75	40.0	3	112	81	12
Co	59	15.0	6	49	14.5	17	55	12.0	12
Ga	19.1	5.9	2	24	0.0	1	23	4.6	11
Pb	13	0.0	1	0.0	0.0	0	0.0	0.0	0
Zn	101	25	6	107	16	17	107	10	12
Cu	79	44.3	6	205	62	3	149	54	12
Y	33	9.7	6	36	1.6	3	38	7.9	12
Zr/Nb	9.55	0.81	6	11.7	4.3	17	21.7	4.4	12
Zr/Y	4.99	1.46	6	9.50	0.37	3	9.09	2.97	12
Zr/Hf	17.1	0.0	1	0.0	0.0	0	0.0	0.0	0
K/Rb	265	94	6	425	203	16	442	129	12
K/Ba	22.0	8.8	6	15.9	7.0	17	15.2	6.5	12
K/Sr	39.3	15.7	6	15.7	6.8	17	15.4	2.8	12
K/Zr	61.0	16.8	6	36.4	28.0	17	31.7	5.7	12
K/Nb	583	177	6	433	522	17	687	191	12
K/Y	307	144	6	300	60	3	296	141	12
Ba/Rb	14.8	8.9	6	28.5	17.5	16	32.7	12.5	12
Ba/Sr	2.16	1.61	6	1.06	0.43	17	1.16	0.46	12
Ba/Zr	3.26	2.05	6	2.42	1.61	17	2.46	1.25	12
Rb/Sr	0.170	0.091	6	0.096	0.223	16	0.037	0.012	12
Ni/Co	0.594	0.227	6	1.41	0.70	3	1.93	0.92	12
Cr/Ni	1.32	0.64	6	1.12	0.58	3	1.39	0.79	12
Ti/P	8.67	1.75	8	9.27	3.29	17	9.95	1.87	19
Th/U	7.60	0.0	1	0.0	0.0	0	0.0	0.0	0
Mg#	42.4	9.0	8	43.1	7.2	17	50.8	7.5	20

TABLE IV
Central Karoo low-MgO Basalts

Variable	Pronksberg High-K Mean	S.D.	N	Moshesh's Ford Fm. Mean	S.D.	N	Kraai River Fm. Mean	S.D.	N	Vaalkop Fm. Mean	S.D.	N
SiO_2	53.66	0.68	7	52.47	0.43	19	54.17	1.04	24	52.94	0.36	11
TiO_2	1.01	0.01	7	1.03	0.06	19	0.87	0.03	24	1.12	0.04	11
Al_2O_3	16.23	0.31	7	15.98	0.46	19	15.23	0.24	24	15.50	0.15	11
Fe_2O_3*	10.21	0.11	7	10.21	0.41	19	10.07	0.28	24	10.47	0.25	11

TABLE IV (cont.)

Variable	Pronksberg High-K Mean	S.D.	N	Moshesh's Ford Fm. Mean	S.D.	N	Kraai River Fm. Mean	S.D.	N	Vaalkop Fm. Mean	S.D.	N
MnO	0.23	0.05	7	0.18	0.05	19	0.20	0.04	24	0.22	0.04	11
MgO	6.45	0.31	7	5.94	0.52	19	6.58	0.59	24	6.40	0.17	11
CaO	6.75	0.21	7	10.36	0.46	19	10.05	0.49	24	9.55	0.88	11
Na_2O	3.35	0.40	7	2.49	0.26	19	2.12	0.17	24	2.53	0.47	11
K_2O	1.90	0.30	7	1.13	0.11	19	0.56	0.28	24	1.04	0.36	11
P_2O_5	0.20	0.01	7	0.21	0.01	19	0.15	0.01	24	0.22	0.01	11
Cs	0.0	0.0	0	0.331	0.190	4	0.236	0.259	2	0.0	0.0	0
Rb	38	6.3	7	20	3.9	19	21	11.6	24	27	11.1	11
Ba	649	104	7	264	51	18	173	43	23	276	63	11
Sr	524	90	7	309	22	19	214	40	24	279	77	11
Th	0.0	0.0	0	3.03	0.23	4	3.34	0.58	2	0.0	0.0	0
U	0.0	0.0	0	0.717	0.051	4	0.940	0.115	2	0.0	0.0	0
Zr	139	2	7	146	9	19	118	11	24	117	6	11
Hf	0.0	0.0	0	3.38	0.19	4	2.45	0.26	2	0.0	0.0	0
Nb	16	1.1	7	16	1.3	19	4.8	0.97	24	7.1	0.83	11
Cr	235	9	7	273	38	19	264	42	24	338	70	11
V	161	9	7	193	38	19	240	17	24	254	6	11
Sc	0.0	0.0	0	27	1.2	9	33	2.0	4	0.0	0.0	0
Ni	72	3.5	7	70	6.6	18	51	8.6	24	23	1.9	11
Co	40	1.8	7	41	4.0	19	38	3.0	24	45	2.4	11
Ga	16.0	0.0	2	17.3	0.2	3	0.0	0.0	0	0.0	0.0	0
Pb	0.0	0.0	0	4.3	0.76	4	6.0	0.81	2	0.0	0.0	0
Zn	87	7.4	7	83	4.9	18	83	5.3	24	90	5.0	11
Cu	75	10.0	7	72	6.0	18	63	5.5	24	43	13.8	11
Y	26	0.9	7	26	1.6	19	28	1.4	24	29	1.6	11
Zr/Nb	8.78	0.49	7	9.12	0.51	19	25.1	3.3	24	16.6	1.5	11
Zr/Y	5.41	0.21	7	5.56	0.19	19	4.19	0.29	24	4.07	0.09	11
Zr/Hf	0.0	0.0	0	42.3	3.8	4	44.4	0.4	2	0.0	0.0	0
K/Rb	415	18	7	518	240	19	269	118	24	346	80	11
K/Ba	24.5	3.7	7	36.3	5.0	18	25.4	8.8	23	30.9	7.6	11
K/Sr	31.1	7.5	7	30.5	3.2	19	22.9	13.1	24	34.4	16.8	11
K/Zr	114	18	7	64.2	3.6	19	40.2	21.5	24	74.2	25.5	11
K/Nb	1004	190	7	586	56	19	1012	561	24	1228	442	11
K/Y	616	101	7	357	28	19	167	87	24	302	106	11
Ba/Rb	17.3	2.8	7	14.9	8.2	18	11.0	4.8	23	12.7	8.0	11
Ba/Sr	1.27	0.30	7	0.863	0.173	18	0.833	0.261	23	1.1	0.33	11
Ba/Zr	4.69	0.81	7	1.81	0.31	18	1.48	0.39	23	2.36	0.52	11
Rb/Sr	0.075	0.018	7	0.064	0.013	19	0.101	0.062	24	0.108	0.063	11
Ni/Co	1.81	0.08	7	1.73	0.17	18	1.33	0.18	24	0.526	0.052	11
Cr/Ni	3.28	0.14	7	3.96	0.65	18	5.22	0.70	24	14.5	3.2	11
Ti/P	6.77	0.33	7	6.65	0.23	19	7.95	0.50	24	6.90	0.22	11
Th/U	0.0	0.0	0	4.22	0.19	4	3.55	0.18	2	0.0	0.0	0
Mg#	59.2	1.4	7	57.2	1.7	19	60.0	1.8	24	58.4	0.9	11

Variable	Lesotho Fm. Mean	S.D.	N	Omega Fm. Mean	S.D.	N	Springbok Flats Mean	S.D.	N
SiO_2	51.50	0.78	49	50.93	0.78	13	51.10	1.20	5
TiO_2	0.95	0.06	49	0.93	0.10	13	1.32	0.26	5
Al_2O_3	15.69	0.53	49	15.83	0.61	13	14.45	1.08	5
Fe_2O_3*	10.96	0.43	49	10.97	0.49	13	13.36	1.13	5
MnO	0.16	0.02	49	0.24	0.04	13	0.18	0.02	5
MgO	7.01	0.53	49	7.10	1.08	13	6.30	0.27	5
CaO	10.69	0.61	49	11.00	0.89	13	10.61	0.53	5
Na_2O	2.17	0.32	49	2.37	0.40	13	1.96	0.21	5
K_2O	0.70	0.21	49	0.50	0.14	13	0.53	0.19	5
P_2O_5	0.16	0.02	49	0.14	0.02	13	0.19	0.03	5
Cs	0.077	0.051	4	0.0	0.0	0	0.0	0.0	0
Rb	12	8.7	49	10	6.4	13	7.5	5.0	5
Ba	177	46	47	153	44	12	235	76	5
Sr	192	31	49	217	38	13	185	45	5
Th	1.27	0.26	4	0.0	0.0	0	0.0	0.0	0
U	0.286	0.048	4	0.0	0.0	0	0.0	0.0	0
Zr	94	12.4	49	80	12.0	13	117	10	5
Hf	2.26	0.28	4	0.0	0.0	0	0.0	0.0	0
Nb	4.9	1.39	49	3.1	0.74	12	3.7	0.68	5
Cr	283	61	49	341	40	13	156	16	5
V	240	19	49	238	24	13	285	40	5
Sc	33	2.9	36	0.0	0.0	0	0.0	0.0	0
Ni	94	15.4	49	104	34	13	57	10.1	5
Co	48	2.5	49	50	4.8	13	51	7.5	5

(*continued*)

TABLE IV (cont.)

Variable	Lesotho Fm. Mean	S.D.	N	Omega Fm. Mean	S.D.	N	Springbok Flats Mean	S.D.	N
Ga	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0
Pb	2.9	0.40	4	0.0	0.0	0	0.0	0.0	0
Zn	86	9.5	49	77	7.8	13	94	5.0	5
Cu	87	11.5	49	88	5.9	13	150	22	5
Y	24	2.0	49	25	2.6	13	31	2.5	5
Zr/Nb	20.8	6.6	49	27.1	5.7	12	32.7	5.8	5
Zr/Y	3.85	0.34	49	3.16	0.24	13	3.79	0.21	5
Zr/Hf	42.2	1.3	4	0.0	0.0	0	0.0	0.0	0
K/Rb	552	189	46	489	177	13	678	215	5
K/Ba	33.1	7.4	47	27.8	7.8	12	18.9	4.3	5
K/Sr	31.2	11.6	49	19.4	5.5	13	25.3	12.9	5
K/Zr	62.3	18.3	49	52.0	13.0	13	37.9	14.9	5
K/Nb	1259	443	49	1479	574	12	1207	418	5
K/Y	238	67	49	164	41	13	144	57	5
Ba/Rb	17.6	7.7	44	19.7	10.1	12	38.4	16.8	5
Ba/Sr	0.951	0.324	47	0.713	0.232	12	1.31	0.51	5
Ba/Zr	1.90	0.46	47	1.96	0.46	12	2.03	0.66	5
Rb/Sr	0.068	0.045	46	0.046	0.026	13	0.044	0.036	5
Ni/Co	1.95	0.29	49	2.05	0.48	13	1.14	0.26	5
Cr/Ni	3.05	0.70	49	3.51	0.89	13	2.82	0.68	5
Ti/P	8.22	1.13	49	9.21	0.80	13	9.35	1.32	5
Th/U	4.43	0.38	4	0.0	0.0	0	0.0	0.0	0
Mg#	59.5	2.3	49	59.8	3.0	13	52.0	2.5	5

TABLE V
Dolerite Types with no Volcanic Equivalent

Variable	Hangnest Dolerites Mean	S.D.	N	Rooirand Dolerites Mean	S.D.	N
SiO_2	53.92	0.41	10	49.49	0.98	38
TiO_2	1.10	0.17	10	2.14	0.64	38
Al_2O_3	15.80	0.84	10	13.68	0.96	38
Fe_2O_3*	9.99	0.92	10	15.21	1.67	38
MnO	0.16	0.01	10	0.22	0.02	38
MgO	6.49	0.65	10	5.87	0.78	38
CaO	9.23	0.18	10	10.34	0.88	38
Na_2O	2.20	0.15	10	2.41	0.21	38
K_2O	0.89	0.10	10	0.42	0.21	38
P_2O_5	0.22	0.04	10	0.22	0.10	38
Cs	0.0	0.0	0	0.0	0.0	0
Rb	22	2.7	10	11	6.8	38
Ba	318	42	10	128	82	38
Sr	201	9	10	190	33	38
Th	0.0	0.0	0	0.0	0.0	0
U	0.0	0.0	0	0.0	0.0	0
Zr	156	25	10	144	59	38
Hf	0.0	0.0	0	0.0	0.0	0
Nb	4.8	0.97	10	7.5	3.56	31
Cr	368	107	10	125	63	38
V	193	19	10	351	56	38
Sc	0.0	0.0	0	36	3.3	35
Ni	3.6	1.55	10	67	24.0	38
Co	40	1.1	10	53	2.8	38
Ga	19	0.7	10	0.0	0.0	0
Pb	0.0	0.0	0	0.0	0.0	0
Zn	91	9.6	10	110	25	38
Cu	19	3.1	10	287	97	38
Y	27	4.0	10	36	9.5	38
Zr/Nb	32.8	3.1	10	24.0	6.6	31
Zr/Y	5.76	0.25	10	3.84	0.87	38
Zr/Hf	0.0	0.0	0	0.0	0.0	0
K/Rb	344	25	10	367	103	38
K/Ba	23.5	2.5	10	30.7	7.7	38
K/Sr	36.9	4.3	10	18.0	7.1	38
K/Zr	48.4	7.7	10	25.9	14.0	38
K/Nb	1594	319	10	534	148	31
K/Y	279	44	10	97.4	44.9	38
Ba/Rb	14.7	1.5	10	12.4	3.4	38
Ba/Sr	1.59	0.24	10	0.639	0.331	38
Ba/Zr	2.05	0.18	10	0.871	0.396	38
Rb/Sr	0.108	0.015	10	0.054	0.027	38
Ni/Co	0.090	0.040	10	1.26	0.40	38
Cr/Ni	113	29	10	1.84	0.57	38
Ti/P	6.80	0.31	10	14.4	3.4	38
Th/U	0.0	0.0	0	0.0	0.0	0
Mg#	59.9	4.7	10	47.0	5.6	38

TABLE VI
Karoo Basic Lavas and Intrusives from Namibia

	Etendeka Fm. (T)			Etendeka Fm. (A)			Etendeka Fm. (H)			Kalkrand Basalt Fm.		
Variable	Mean	S.D.	N	Mean	S.D.	N	Mean	S.D.	N	Mean	S.D.	N
SiO_2	53.57	1.88	39	52.04	1.52	12	46.91	0.30	5	50.73	0.58	4
TiO_2	1.38	0.26	39	1.20	0.12	12	1.31	0.25	5	0.94	0.06	4
Al_2O_3	14.17	0.81	39	16.21	1.05	12	15.42	0.71	5	15.58	0.39	4
Fe_2O_3*	12.61	1.00	39	10.97	0.78	12	12.85	1.31	5	10.08	1.16	4
MnO	0.18	0.01	39	0.16	0.01	12	0.19	0.02	5	0.16	0.01	4
MgO	5.25	1.58	39	5.92	1.02	12	7.94	1.04	5	7.71	0.35	4
CaO	8.59	1.09	39	10.10	1.07	12	12.65	0.53	5	10.64	0.35	4
Na_2O	2.52	0.38	39	2.00	0.38	12	2.24	0.38	5	2.97	0.62	4
K_2O	1.54	0.55	39	1.21	0.51	12	0.36	0.19	5	1.04	0.23	4
P_2O_5	0.19	0.05	39	0.18	0.03	12	0.13	0.03	5	0.15	0.02	4
Cs	0.575	0.389	4	1.05	0.00	1	0.158	0.051	2	0.0	0.0	0
Rb	51	21.7	39	32	16.3	12	10	8.4	5	14	2.6	4
Ba	349	112	39	330	93	12	122	73	5	212	40	4
Sr	229	47	39	268	50	12	246	69	5	234	22	4
Th	5.82	2.33	9	5.18	1.89	4	0.395	0.035	2	0.0	0.0	0
U	1.37	0.59	7	1.48	0.36	3	0.00	0.00	0	0.0	0.0	0
Zr	165	47	39	146	25	12	75	17.2	5	82	8.6	4
Hf	4.53	1.43	4	4.38	0.00	1	1.47	0.19	2	0.0	0.0	0
Nb	10	3.8	39	12	3.0	12	8.3	4.32	5	4.0	2.65	3
Cr	64	117.4	39	118	47	12	158	92	5	305	12	4
V	301	57	39	232	18	12	327	45	5	225	11	4
Sc	35	4.5	36	36	2.5	12	35	2.6	5	0.0	0.0	0
Ni	53	57.8	39	99	28.4	12	141	56	5	93	5.3	4
Co	49	7.7	39	50	5.4	12	58	2.3	5	47	3.9	4
Ga	18.5	1.6	11	0.0	0.0	0	0.0	0.0	0	16.4	0.0	1
Pb	12.0	7.9	12	16	15.8	4	3.6	0.01	2	0.0	0.0	0
Zn	99	13.7	39	85	8.2	12	68	5.9	5	82	5.6	4
Cu	99	49.2	39	83	16.2	12	176	27	5	88	37.4	4
Y	31	5.4	39	24	2.9	12	21	2.2	5	23	0.5	4
Zr/Nb	16.7	3.3	39	12.3	3.3	12	10.7	4.7	5	26.9	12.8	3
Zr/Y	5.35	0.67	39	6.06	0.44	12	3.59	0.55	5	3.53	0.35	4
Zr/Hf	39.1	2.0	4	42.9	0.0	1	41.3	1.9	2	0.0	0.0	0
K/Rb	262	47	39	360	128	12	364	103	5	620	100	4
K/Ba	37.7	10.6	39	30.7	11.9	12	25.0	5.8	5	42.5	16.3	4
K/Sr	59.4	27.0	39	39.6	20.4	12	11.5	4.8	5	37.6	11.9	4
K/Zr	78.0	20.6	39	68.4	26.1	12	38.2	16.2	5	107	32	4
K/Nb	1289	374	39	851	383	12	357	92	5	2996	1835	3
K/Y	417	117	39	413	158	12	141	73	5	372	82	4
Ba/Rb	7.74	3.99	39	13.9	10.2	12	15.1	5.6	5	15.5	3.3	4
Ba/Sr	1.56	0.50	39	1.29	0.57	12	0.464	0.172	5	0.903	0.141	4
Ba/Zr	2.11	0.38	39	2.27	0.59	12	1.54	0.62	5	2.59	0.43	4
Rb/Sr	0.238	0.124	39	0.128	0.082	12	0.036	0.021	5	0.060	0.015	4
Ni/Co	1.02	0.92	39	1.96	0.47	12	2.44	0.92	5	1.99	0.09	4
Cr/Ni	0.980	0.731	39	1.23	0.47	12	1.05	0.44	5	3.26	0.13	4
Ti/P	10.2	1.6	39	9.30	1.07	12	14.2	1.8	5	8.51	0.86	4
Th/U	4.71	1.43	7	4.20	1.53	3	0.0	0.00	0	0.0	0.0	0
Mg#	48.9	8.5	39	55.3	5.2	12	58.6	5.5	5	63.7	3.7	4

TABLE VII
Karoo Intrusive and Extrusive Intermediate Rocks

	Pronksberg Dacite			Dikkop Dacite			Roodehoek Dacite		
Variable	Mean	S.D.	N	Mean	S.D.	N	Mean	S.D.	N
SiO_2	65.40	0.16	12	64.97	0.09	4	66.35	0.36	7
TiO_2	0.78	0.01	12	0.80	0.01	4	0.78	0.01	7
Al_2O_3	17.13	0.12	12	17.28	0.09	4	16.01	0.08	7
Fe_2O_3*	6.35	0.08	12	6.55	0.06	4	6.03	0.16	7
MnO	0.17	0.01	12	0.17	0.01	4	0.16	0.01	7
MgO	2.36	0.08	12	2.36	0.03	4	2.49	0.09	7
CaO	2.77	0.17	12	2.77	0.31	4	2.56	0.25	7
Na_2O	3.38	0.19	12	2.55	0.15	4	2.49	0.18	7
K_2O	1.44	0.09	12	2.33	0.58	4	2.95	0.13	7
P_2O_5	0.21	0.01	12	0.22	0.00	4	0.19	0.01	7
Cs	8.94	0.81	2	0.0	0.0	0	0.0	0.0	0
Rb	146	32	12	141	30	4	123	4	7
Ba	761	20	12	788	50	4	650	31	7
Sr	323	15	12	307	13	4	256	17	7
Th	14.0	0.5	2	0.0	0.0	0	0.0	0.0	0
U	4.37	0.16	2	0.0	0.0	0	0.0	0.0	0
Zr	203	3	12	202	5	4	227	3	7
Hf	4.75	0.45	2	0.0	0.0	0	0.0	0.0	0
Nb	13	0.7	12	14	2.2	4	11	0.7	7
Cr	54	2.6	12	49	1.7	4	86	5.8	7

(*continued*)

TABLE VII (cont.)

Variable	Pronksberg Dacite Mean	S.D.	N	Dikkop Dacite Mean	S.D.	N	Roodehoek Dacite Mean	S.D.	N
V	68	6.5	12	69	1.8	4	91	5.4	7
Sc	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0
Ni	28	1.5	12	27	0.6	4	23	2.0	7
Co	19	0.6	12	18	0.3	4	20	1.0	7
Ga	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0
Pb	27	0.6	2	0.0	0.0	0	0.0	0.0	0
Zn	97	2.7	12	100	1.1	4	87	3.9	7
Cu	27	1.2	12	27	0.8	4	22	2.2	7
Y	31	1.2	12	31	1.9	4	31	1.0	6
Zr/Nb	15.1	0.8	12	14.9	1.9	4	20.6	1.2	7
Zr/Y	6.49	0.20	12	6.46	0.36	4	7.39	0.19	6
Zr/Hf	42.5	4.0	2	0.0	0.0	0	0.0	0.0	0
K/Rb	86.4	22.7	12	136	8	4	199	8	7
K/Ba	15.8	1.1	12	24.9	7.3	4	37.6	0.9	7
K/Sr	37.1	2.9	12	63.5	17.6	4	96.0	8.7	7
K/Zr	59.1	3.9	12	95.7	23.1	4	108	6	7
K/Nb	895	74	12	1405	320	4	2219	148	7
K/Y	384	31	12	622	166	4	802	59	6
Ba/Rb	5.49	1.44	12	5.90	2.01	4	5.30	0.29	7
Ba/Sr	2.36	0.11	12	2.57	0.07	4	2.55	0.24	7
Ba/Zr	3.75	0.10	12	3.92	0.31	4	2.86	0.16	7
Rb/Sr	0.456	0.115	12	0.463	0.111	4	0.481	0.034	7
Ni/Co	1.52	0.09	12	1.48	0.04	4	1.14	0.14	7
Cr/Ni	1.92	0.17	12	1.80	0.09	4	3.72	0.37	7
Ti/P	5.04	0.24	12	5.07	0.04	4	5.69	0.18	7
Th/U	3.20	0.01	2	0.0	0.0	0	0.0	0.0	0
Mg#	46.0	0.9	12	45.3	0.4	4	48.7	0.8	7

TABLE VII (cont.)

Variable	Belmore Andesite Mean	S.D.	N	Etendeka Fm. Latite Mean	S.D.	N
SiO_2	63.24	1.28	8	59.23	0.26	4
TiO_2	0.79	0.02	8	2.29	0.04	4
Al_2O_3	15.84	0.18	8	13.87	0.05	4
Fe_2O_3*	7.09	0.46	8	11.21	0.19	4
MnO	0.18	0.03	8	0.13	0.01	4
MgO	3.24	0.42	8	1.70	0.07	4
CaO	4.95	0.57	8	4.23	0.40	4
Na_2O	2.26	0.31	8	2.48	0.12	4
K_2O	2.25	0.33	8	4.42	0.35	4
P_2O_5	0.17	0.00	8	0.44	0.01	4
Cs	4.64	0.00	1	1.04	0.00	1
Rb	104	23	8	154	6	4
Ba	571	81	8	1100	33	4
Sr	295	57	8	215	22	4
Th	11.5	0.0	1	18.1	0.0	1
U	3.02	0.00	1	2.00	0.00	1
Zr	203	10	8	457	5	4
Hf	4.38	0.00	1	10.3	0.0	1
Nb	11	1.1	8	26	0.9	4
Cr	89	22.7	8	16	1.8	4
V	104	15	8	62	5.9	4
Sc	0.0	0.0	0	20.0	0.8	4
Ni	32	7.3	6	6.1	0.90	3
Co	23	3.6	8	24	1.5	4
Ga	0.0	0.0	0	0.0	0.0	0
Pb	22	0.0	1	32	0.0	1
Zn	84	2.5	8	147	6	4
Cu	37	5.5	7	21	1.9	4
Y	31	2.0	8	57	2.7	4
Zr/Nb	18.8	1.3	8	17.4	0.4	4
Zr/Y	6.61	0.20	8	7.99	0.37	4
Zr/Hf	43.9	0.0	1	44.3	0.0	1
K/Rb	193	68	8	238	11	4
K/Ba	33.6	7.7	8	33.3	1.8	4
K/Sr	65.2	15.0	8	173	32	4
K/Zr	92.5	15.7	8	80.3	5.8	4
K/Nb	1746	367	8	1393	69	4
K/Y	611	102	8	641	44	4
Ba/Rb	5.69	1.21	8	7.16	0.13	4
Ba/Sr	1.98	0.33	8	5.17	0.68	4
Ba/Zr	2.80	0.26	8	2.41	0.05	4

(Continued)

TABLE VII (cont.)

Variable	Belmore Andesite Mean	S.D.	N	Etendeka Fm. Latite Mean	S.D.	N
Rb/Sr	0.365	0.096	8	0.723	0.107	4
Ni/Co	1.41	0.10	6	0.246	0.030	3
Cr/Ni	2.61	0.54	6	2.65	0.12	3
Ti/P	6.32	0.19	8	7.24	0.18	4
Th/U	3.80	0.00	1	9.03	0.00	1
Mg#	51.2	1.9	8	25.8	0.5	4

TABLE VIII
Acid Volcanics from the Lebombo and Nuanetsi areas

Variable	Jozini Fm. (Zulu.) Mean	S.D.	N	Jozini Fm. (Swazi.) Mean	S.D.	N	Jozini Fm. (C. Leb.) Mean	S.D.	N	Jozini Fm. (N. Leb.) Mean	S.D.	N
SiO_2	70.68	1.65	49	69.25	0.77	3	69.50	0.04	2	68.85	1.66	10
TiO_2	0.50	0.15	49	0.53	0.05	3	0.57	0.05	2	0.59	0.12	10
Al_2O_3	12.65	0.42	49	12.61	0.08	3	12.89	0.15	2	13.03	0.25	10
Fe_2O_3*	6.34	0.86	49	6.93	0.53	3	6.42	0.40	2	6.50	1.41	10
MnO	0.10	0.03	49	0.15	0.04	3	0.14	0.00	2	0.14	0.03	10
MgO	0.35	0.17	49	0.23	0.14	3	0.55	0.12	2	0.47	0.19	10
CaO	1.47	0.60	49	1.82	0.34	3	1.98	0.33	2	2.19	0.62	10
Na_2O	3.16	0.41	49	3.82	0.08	3	3.19	0.04	2	3.47	0.46	10
K_2O	4.61	0.55	49	4.56	0.25	3	4.59	0.48	2	4.62	0.64	10
P_2O_5	0.14	0.06	49	0.12	0.01	3	0.16	0.01	2	0.15	0.06	10
Cs	1.29	0.29	2	0.0	0.0	0	0.0	0.0	0	0.549	0.116	2
Rb	130	24	49	116	20	7	133	13	2	121	9	10
Ba	1475	266	49	1412	0	1	1320	22	2	1545	248	10
Sr	153	27	49	161	16	7	184	39	2	269	94	10
Th	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0
U	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0
Zr	1085	56	49	1195	157	7	1155	84	2	1044	70	10
Hf	26.6	2.6	2	0.0	0.0	0	0.0	0.0	0	27	4.4	2
Nb	84	5.1	49	77	5.8	7	93	0.2	2	92	7.4	10
Cr	7.5	1.66	30	0.0	0.0	0	11	0.3	2	6.9	1.84	10
V	6.2	2.33	8	0.0	0.0	0	6.4	2.89	2	6.8	1.38	2
Sc	13	2.3	33	0.0	0.0	0	11	0.2	2	12	2.6	10
Ni	3.8	0.0	1	0.0	0.0	0	0.0	0.0	0	7.8	5.16	7
Co	5.2	2.08	5	0.0	0.0	0	0.0	0.0	0	4.5	0.0	1
Ga	24	1.4	12	0.0	0.0	0	24	0.0	1	24	2.8	4
Pb	22	2.7	2	0.0	0.0	0	0.0	0.0	0	51	43.9	2
Zn	135	17	49	0.0	0.0	0	124	31	2	133	28	10
Cu	8.8	3.12	49	0.0	0.0	0	13	2.0	2	30	37.1	10
Y	129	60	49	118	12	7	115	16	2	95	15.7	10
Zr/Nb	13.0	0.9	56	15.4	1.6	7	12.5	0.9	2	11.4	0.7	10
Zr/Y	8.93	1.46	56	10.1	1.2	7	10.1	0.6	2	11.2	1.7	10
Zr/Hf	43.9	5.1	2	0.0	0.0	0	0.0	0.0	0	38.4	0.7	2
K/Rb	298	31	49	302	8	3	287	3	2	316	29	10
K/Ba	26.7	5.4	49	25.8	0.0	1	28.9	2.5	2	24.9	1.7	10
K/Sr	260	71	49	222	20	3	215	67	2	155	45	10
K/Zr	35.5	5.4	49	29.6	4.3	3	33.3	5.9	2	37.1	7.6	10
K/Nb	457	52	49	482	9	3	412	42	2	421	73	10
K/Y	317	70	49	318	8	3	337	80	2	426	163	10
Ba/Rb	11.6	2.3	49	11.5	0.0	1	9.97	0.77	2	12.8	1.7	10
Ba/Sr	9.83	1.87	49	8.29	0.00	1	7.37	1.69	2	6.21	1.66	10
Ba/Zr	1.36	0.23	49	1.05	0.00	1	1.15	0.10	2	1.50	0.33	10
Rb/Sr	0.865	0.319	56	0.720	0.090	7	0.748	0.228	2	0.489	0.135	10
Ni/Co	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0
Cr/Ni	1.86	0.0	1	0.0	0.0	0	0.0	0.0	0	1.21	0.80	7
Ti/P	5.39	1.86	49	6.21	0.47	3	5.00	0.21	2	6.37	2.55	10
Th/U	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0
Mg#	11.2	3.73	49	7.08	3.27	3	16.4	3.4	2	14.2	5.1	10

(*continued*)

TABLE VIII (cont.)

	Mbuluzi Fm.			Mkutshane Beds			Twin Ridge Beds			Nuanetsi Rhyolites		
Variable	Mean	S.D.	N	Mean	S.D.	N	Mean	S.D.	N	Mean	S.D.	N
SiO_2	71.05	1.06	23	69.82	3.20	2	65.37	4.24	6	71.57	2.86	19
TiO_2	0.51	0.07	23	0.90	0.34	2	0.97	0.40	6	0.44	0.24	19
Al_2O_3	12.45	0.22	23	12.14	0.11	2	13.67	0.80	6	12.89	0.78	19
Fe_2O_3*	5.73	0.76	23	6.81	1.60	2	7.96	2.17	6	5.23	1.24	19
MnO	0.12	0.02	23	0.08	0.00	2	0.16	0.03	6	0.09	0.05	19
MgO	0.39	0.18	23	0.47	0.16	2	0.79	0.44	6	0.40	0.24	19
CaO	1.83	0.32	23	2.33	0.87	2	2.60	0.89	6	1.39	0.85	19
Na_2O	3.38	0.19	23	3.74	0.29	2	3.47	0.35	6	2.89	0.91	19
K_2O	4.42	0.40	23	3.55	0.22	2	4.71	0.81	6	5.03	0.76	19
P_2O_5	0.12	0.02	23	0.18	0.06	2	0.29	0.15	6	0.08	0.09	19
Cs	1.05	0.00	1	0.293	0.128	2	0.665	0.154	2	0.993	0.378	2
Rb	133	8	23	97	20.2	9	117	14	13	157	29	16
Ba	1260	14	2	559	63	2	1360	164	5	1640	464	16
Sr	137	20	23	181	41	9	188	38	13	85	32.1	16
Th	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0
U	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0
Zr	862	50	23	293	61	9	1060	87	13	763	127	16
Hf	25	0.0	1	8.2	2.57	2	23.1	3.3	2	19.6	0.7	2
Nb	74	3.2	23	14	2.9	9	76	7.1	13	102	13	15
Cr	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	13	1.6	3
V	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	5.4	4.08	3
Sc	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	10	0.0	1
Ni	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	4.5	0.00	1
Co	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	6.5	0.45	3
Ga	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	19.2	1.6	2
Pb	19	0.0	1	210	188	2	24	5.0	2	20	3.6	2
Zn	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	112	23	4
Cu	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	6.3	2.32	4
Y	131	13	23	42	9.5	9	101	8	13	83	14.6	16
Zr/Nb	11.7	0.6	23	20.5	1.8	9	14.0	0.8	13	7.60	1.57	16
Zr/Y	6.64	0.51	23	6.96	0.56	9	10.5	0.7	13	9.33	0.92	17
Zr/Hf	34.0	0.0	1	37.5	0.4	2	43.2	1.9	2	40.5	1.7	2
K/Rb	279	27	22	272	31	2	330	19	6	261	19	16
K/Ba	30.0	1.3	2	52.9	2.7	2	27.3	1.2	5	26.6	7.4	16
K/Sr	276	46	22	206	42	2	192	49	6	538	186	16
K/Zr	43.2	4.2	22	98.6	23.6	2	36.7	4.6	6	55.4	16.1	16
K/Nb	503	40	22	2009	447	2	521	60	6	406	80	15
K/Y	289	32	22	722	252	2	382	63	6	507	104	16
Ba/Rb	9.21	0.64	2	5.13	0.32	2	12.0	0.8	5	10.8	4.3	17
Ba/Sr	9.63	0.76	2	3.93	1.00	2	6.51	1.30	5	21.0	6.1	17
Ba/Zr	1.50	0.02	2	1.86	0.35	2	1.28	0.04	5	2.16	0.60	17
Rb/Sr	0.993	0.189	23	0.579	0.243	9	0.657	0.179	13	2.09	0.73	17
Ni/Co	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.738	0.000	1
Cr/Ni	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	3.34	0.00	1
Ti/P	6.06	0.48	23	7.01	0.06	2	4.82	0.46	6	9.43	3.74	19
Th/U	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0
Mg#	13.5	4.5	23	13.7	1.3	2	18.6	5.3	6	14.9	7.2	19

TABLE IX
Acid Volcanics in the Etendeka Formation

	Quartz Latite			Dacite		
Variable	Mean	S.D.	N	Mean	S.D.	N
SiO_2	68.00	0.66	19	68.62	0.63	3
TiO_2	0.95	0.07	19	0.91	0.03	3
Al_2O_3	12.89	0.17	19	13.30	0.29	3
Fe_2O_3*	6.61	0.70	19	6.14	0.42	3
MnO	0.10	0.02	19	0.10	0.02	3
MgO	1.26	0.19	19	1.25	0.17	3
CaO	2.74	0.50	19	3.54	0.35	3
Na_2O	2.69	0.46	19	3.28	0.69	3
K_2O	4.46	0.91	19	2.57	0.57	3
P_2O_5	0.29	0.02	19	0.28	0.00	3
Cs	8.40	4.78	3	10.0	0.0	1
Rb	175	26	19	177	76	3
Ba	627	43	17	634	24	3
Sr	131	25	19	194	37	3
Th	13.9	1.8	3	14.0	0.0	1
U	4.28	0.37	3	4.65	0.00	1
Zr	279	16	19	292	8	3
Hf	6.58	0.36	3	6.61	0.00	1
Nb	22	1.5	19	25	2.9	3
Cr	10	10.74	17	7.5	2.19	3
V	53	14.3	17	50	9.7	3
Sc	20	1.0	19	19.0	1.7	3
Ni	4.5	4.85	6	1.8	0.06	2
Co	13	2.1	15	11	1.9	3
Ga	15.7	0.7	2	0.0	0.0	0
Pb	27	2.7	3	30	0.0	1
Zn	78	10.0	19	83	3.8	3
Cu	42	24.9	19	24	7.7	3
Y	37	2.4	19	37	1.6	3
Zr/Nb	12.8	1.1	19	11.6	1.1	3
Zr/Y	7.53	0.25	19	7.84	0.16	3
Zr/Hf	41.5	1.5	3	42.8	0.0	1
K/Rb	212	20	19	146	90	3
K/Ba	59.7	13.1	17	33.7	7.7	3
K/Sr	319	230	19	111	25	3
K/Zr	134	32	19	73.1	16.5	3
K/Nb	1712	429	19	854	222	3
K/Y	1009	251	19	572	121	3
Ba/Rb	3.66	0.57	17	4.06	1.71	3
Ba/Sr	5.14	1.84	17	3.35	0.72	3
Ba/Zr	2.27	0.15	17	2.17	0.15	3
Rb/Sr	1.47	0.83	19	0.954	0.467	3
Ni/Co	0.355	0.360	5	0.154	0.029	2
Cr/Ni	4.77	5.54	6	4.71	0.96	2
Ti/P	4.50	0.29	19	4.52	0.18	3
Th/U	3.25	0.41	3	3.02	0.00	1
Mg#	30.4	3.5	19	31.9	3.6	3

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