PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
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Mantle heterogeneity beneath southern Africa: evidence from the volcanic record†

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The scale, timing and development of mantle heterogeneity beneath southern Africa is assessed by reference to data obtained from mantle derived igneous rocks and, to a lesser extent, from peridotites contained in kimberlite. Sr isotope data for ultrabasic and basic igneous rocks ranging in age from 3.5 Ga komatiites to Tertiary olivine melilitites indicate that heterogeneity existed at 3 Ga and was well established by 2 Ga, and also suggest progressive development of variability in Sr isotope ratios in the mantle source regions involved. Detailed evaluation of Sr isotope and incompatible element and inter-element ratios, together with rare earth element patterns, of the widespread Jurassic Karroo volcanics shows that the overall compositional variability of these volcanics is best explained by (horizontal) mantle heterogeneity. Both depletion and enrichment pre-Karroo processes appear to have affected the parental mantle source regions. Evidence for such enrichment is provided by kimberlite peridotite nodules that have been subjected to mantle metasomatic processes, leading to the development of phlogopite and the amphibole potassic richterite, with consequent enrichment of incompatible elements.

INTRODUCTION

Deep-seated nodules contained in kimberlites clearly indicate that the upper mantle is compositionally heterogeneous on the scale sampled by these magmatic events (see, for example, Gurney & Harte, this symposium). Key questions to be asked regarding mantle heterogeneity are: (1) On what scale is the mantle heterogeneous? (2) When did the mantle become heterogeneous, or was it always so? (3) Has the mantle become progressively more heterogeneous with geologic time? This paper considers whether mantle-derived igneous rocks exposed in southern Africa can resolve some of these questions.

In attempting to relate the composition of igneous rocks to their parental mantle compositions, we believe that isotopic data and ratios of incompatible elements are the most relevant data available for this purpose and the most pertinent information that we can present at this time. We shall also comment briefly on the role of metasomatism with regard to upper mantle differentiation.

Sr ISOTOPIC VARIATION WITH TIME

Southern Africa is almost unique in having well preserved basic and ultrabasic igneous rocks ranging in age from komatiites of *ca.* 3.5 Ga (Jahn & Shih 1974) to Tertiary olivine melilitites (Moore 1976). Sr isotope data for mantle-derived igneous rocks in southern Africa have been

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TABLE 1. SUMMARY OF SELECTED STRONTIUM ISOTOPE DATA FOR SOUTHERN AFRICAN ULTRABASIC AND BASIC IGNEOUS ROCKS

(References are denoted by numbers in parentheses.)

group or formation	age/Ga, technique, reference	^{87}Sr/^{86}Sr initial ratios and references	comments
1. Onverwacht Group, Barberton Mountain Land, South Africa	3.50, Rb–Sr (1)	0.70048 ± 5	internal isochron on density separates
	assumed 3.50, Rb–Sr (2)	0.6992–0.7008	best preserved komatiite samples
	assumed 3.50, Rb–Sr (3)	0.7000	anorthosite
2. Midlands–Bulawayan greenstone belt, Rhodesia	3.08, Rb–Sr (4)	0.70113 ± 6	preferred isochron by using selected samples
3. Usushwana igneous Complex, Swaziland	2.87, Rb–Sr (5)	0.7031 ± 3	initial ratio for mafic rocks only; age based on acid rocks
4. Shabani greenstone belt, Rhodesia	2.76, Rb–Sr (4)	0.7029 ± 2	isochron
5. Midlands–Bulawayan greenstone belt, Rhodesia	2.75, Rb–Sr (4)	0.7014 ± 1	average isochron (see 2, above)
6. Salisbury greenstone belt, Rhodesia	2.73, Rb–Sr (4)	0.70121 ± 7	isochron
7. Maliyami Formation greenstones, Rhodesia	2.72, Rb–Sr (6)	0.7010 ± 2	isochron
8. Modipe gabbro, Botswana	2.61, Rb–Sr (7)	0.7007 ± 6	isochron
9. Bulawayo area greenstones, Rhodesia	2.54, Rb–Sr (6)	0.7015 ± 2	isochron
10. Lower Bulawayan greenstones, Rhodesia	2.53, Rb–Sr (6)	0.7034 ± 6	isochron
11. Great Dyke, Rhodesia	2.51, Rb–Sr (8)	0.70261 ± 4	isochron
12. Ventersdorp lavas, South Africa	*ca.* 2.2, Rb–Sr (9)	0.7016-0.7056	preferred age; higher initial ratios may be due to alteration
13. Bushveld Igneous Complex, South Africa	2.10, Rb–Sr (8)	0.70563 ± 2	isochron, transition zone
	2.14, Rb–Sr (8)	0.70735 ± 8	isochron, upper zone
14. Matsap Formation, South Africa	2.07, Rb–Sr (10)	0.7046 ± 3	isochron
15. Haib volcanics, Orange River region, South Africa	1.96, Rb–Sr (11)	0.7033 ± 5	isochron
16. Losberg igneous intrusion, South Africa	1.91, Rb–Sr (5)	0.7064 ± 24	isochron
17. Mashonaland dolerites, Rhodesia	1.91, Rb–Sr (12)	0.705 ± 2	isochron
18. Swartkop intrusive, Namaqualand, South Africa	*ca.* 1.9, Rb–Sr (13)	0.7012 ± 6	preferred isochron by using selected samples
19. Marydale Formation, South Africa	1.90, Rb–Sr (14)	0.7040 ± 3	isochron
20. Trompsburg intrusive, South Africa	1.37, Rb–Sr (5)	0.7043 ± 4	initial ratio for mafic rocks only; age based on acid rocks
21. Umkondo dolerites, Rhodesia	*ca.* 1.1, Rb–Sr (9)	0.706–0.712	age based on micas separated from individual samples
22. Karroo volcanics, South Africa	*ca.* 0.19, K–Ar (15)	0.7034–0.7112 (9)	initial ratios based on K–Ar age
23. Kimberlites, South Africa and Lesotho	*ca.* 0.09, U–Pb (16)	0.7038–0.7084 (17)	initial ratios based on zircon ages
24. Olivine melilitites, Namaqualand, South Africa	*ca.* 0.04–0.07, K–Ar (18)	0.7033–0.7041 (9)	initial ratios based on K–Ar ages

Notes. Numbers attached to Group or Formation are the same as those used in Fig. 1. The actual data reported by individual authors have been used; in many cases isochrons are actually errorchrons.

References. 1, Jahn & Shih (1974); 2, Smith *et al.* (1980); 3, Allsopp *et al.* (1973); 4, Jahn & Condie (1976); 5, Davies *et al.* (1970); 6, Hawkesworth *et al.* (1975); 7, McElhinney (1966); 8, Hamilton (1977); 9, this paper, unpublished data; 10, Crampton (1974); 11, Reid (1979); 12, Compston & McElhinney (1975); 13, Reid (1977); 14, Cornell (1977); 15, Fitch & Miller (1971); 16, Davis *et al.* (1976); 17, Barrett & Berg (1975); 18, Moore (1976).

selected from the literature and combined with our own previously unpublished data. The assembled data are presented in table 1 and figure 1.

It is important to note that the bars in figure 1 representing initial Sr isotope ratios have been derived *either* by using the initial ratio plus or minus one standard deviation derived from isochrons/errorchrons obtained by the various authors *or*, where no age can be derived from the Sr isotope data, by using an age determined by another technique to calculate the initial ratio for individual samples and hence the large range in initial ratios for some suites as depicted in figure 1.

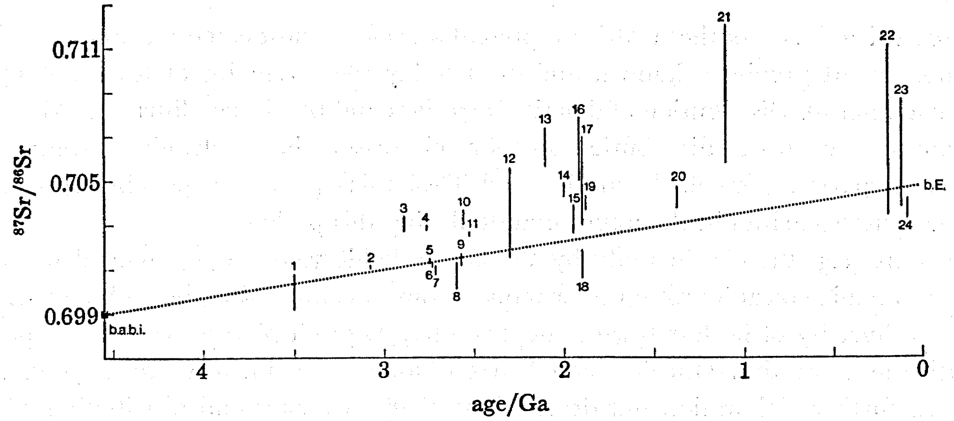

FIGURE 1. Variation of initial ^{87}Sr/^{86}Sr ratios with time for ultrabasic and basic igneous rocks from southern Africa: b.a.b.i., basaltic achondrite best initial ratio (Papanastassiou & Wasserburg 1969); b.E., bulk Earth initial ratio (O'Nions *et al.* 1979). Numbers used correspond to those in table 1 in the column headed 'group or formation'. 1, Onverwacht volcanics; 2, 4–7, 9, 10, Rhodesian greenstones; 3, Usushwana Complex; 8, Modipe gabbro; 11, Great Dyke; 12, Ventersdorp lavas; 13, Bushveld Complex; 14, Matsap Formation; 15, Haib volcanics; 16, Losberg intrusion; 17, Mashonaland dolerites; 18, Swartkop intrusive; 19, Marydale Formation; 20, Trompsburg intrusive; 21, Umkondo dolerites; 22, Karroo volcanics; 23, Cretaceous kimberlites; 24, Namaqualand olivine melilitites.

Since it is generally accepted that Sr isotope ratios are not changed by partial melting or fractional crystallization processes (see accompanying contributions by Allègre *et al.* and O'Nions *et al.* in this symposium), the variability in initial ratios shown in figure 1 can most reasonably be attributed either to compositional heterogeneity in the mantle or to processes of contamination or alteration. Figure 1 suggests that mantle-derived igneous rocks show increasing variability in initial Sr isotope ratio with geological time. If this pattern is to be explained by a crustal contamination process at the time of emplacement, this implies that essentially all such rocks have suffered crustal contamination, many to a very large extent. While this possibility cannot be excluded, since crustal contamination has been suggested for some continental tholeiites (see, for example, Faure *et al.* 1974), it is more likely that figure 1 indicates progressive development of variability in Sr isotope ratios in the mantle source regions beneath southern Africa which could have arisen by a variety of mechanisms. We particularly emphasize the range of calculated initial ratios for the Karroo volcanics (190 Ma) which will be discussed in detail in the next section.

In view of the alteration effects (see, for example, Smith & Erlank 1978; Smith *et al.* 1980) which might have affected the oldest volcanics, commonly referred to as greenstones, it cannot definitely be concluded from figure 1 when the uppermost part of the mantle underwent its first major differentiation, or indeed whether such an event ever occurred, since such assumptions

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

are model-dependent as to whether the Earth accreted homogeneously or not. Although this paper does not deal with typical continental acidic rocks, cognisance should also be taken of the range in initial Sr isotope ratios (0.7006–0.7060) reported by Davies & Allsopp (1976) for 3.0–3.4 Ga granitic rocks from the Kaapvaal craton in southern Africa, and which may also be suggestive of early mantle differentiation.

Geochemistry of Karroo volcanics

(*a*) *General*

The Karroo volcanics of southern Africa represent one of the most extensive and voluminous tholeiitic flood basalt provinces known, and even today there remains at least 140000 km^2 of Karroo lava outcrop. Distribution of dolerite intrusives and basalt xenoliths from kimberlite pipes indicate an even wider distribution and for this reason these volcanics (together with Mesozoic counterparts in Brazil, Antarctica and Tasmania) provide a possible opportunity to assess gross heterogeneities in the upper mantle during this period.

Early accounts (e.g. the classic study by Walker & Poldervaart (1949) tended to suggest that the Karroo mafic volcanics were rather monotonous in composition, but subsequent work has revealed a diversity of both extrusive (nephelinites, Mg-rich picritic basalts, shoshonites, together with the more abundant common Karroo basalts) and intrusive rock types. Space does not allow further elaboration but descriptions of the diversity and distribution of these volcanics, together with representative analyses, may be found in Cox & Hornung (1966), Cox *et al.* (1967), Vail *et al.* (1969), Cox (1971, 1972) and Cox & Jamieson (1974). These workers first recognized the existence of Karroo geochemical provinces, notably along the Lebombo monocline (see, for example, fig. 1 in Cox 1971), and this work has since been actively pursued in the form of a South African National Geodynamics programme involving several workers at South African universities in collaboration with K. G. Cox and coworkers at Oxford. We present here some of the data already obtained which appear to bear on the question of mantle heterogeneity. Discussion will be limited to volcanic types and will not include layered and other mafic intrusions such as those described by Saggerson & Logan (1970).

(*b*) *Strontium isotope data*

The large range in ^{87}Sr/^{86}Sr initial ratios for Karroo volcanics of presumed or known Jurassic age (*ca.* 190 Ma) has already been commented on. All recent available data for these basic volcanics (less than 54% SiO$_2$) are presented in the form of a conventional Rb–Sr isochron plot in figure 2. The rocks analysed were especially chosen for their freshness and there is no reason to suspect that the large spread exhibited is due to alteration. Inferences to be drawn from figure 2 are few but important, namely: (*a*) there is no indication of a 190 Ma isochron relationship, which is the approximate K–Ar age of typical Jurassic Karroo volcanics (Fitch & Miller 1971); (*b*) although the overall trend is steep there is no indication of a 1620 Ma 'mantle isochron' as suggested by Brooks & Hart (1978) on the basis of earlier strontium isotope data; (*c*) some of the data points plot to the left of the 4.6 Ga reference line, which is suggestive of recent pre-Karroo Rb depletion in the mantle source areas involved.

With regard to the possibility of bulk crustal contamination, the Sr isotope data do not exhibit positive correlations with elements such as SiO$_2$, K$_2$O and Rb which are typically enriched in the continental crust relative to the underlying mantle. This point is illustrated in figure 3 which contains data for *only* the Central Karroo region (this includes the Stormberg and Drakensberg basalts and associated dolerites from the Central Karroo basin). Any contamination process must clearly be of a selective nature in view of the lack of positive correlation as shown by data such as those depicted in figure 3. We present in figure 4 isotopic data that we have obtained for another specific region, namely the southernmost portion of the Lebombo monocline (including Swaziland). Note that the rhyolites (which overlie the basalts) plot on an approximate 190 Ma reference line, which projects back through some of the basalts and

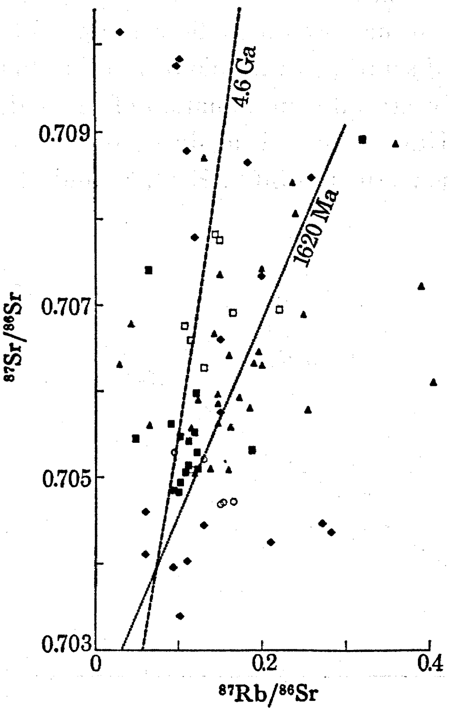

FIGURE 2. Isochron plot for mafic Karroo volcanics. ■, Nuanetsi; ○, northern Lebombo; ◆, southern Lebombo; ▲, Central Region; □, Namibia. 1620 Ma reference line after Brooks & Hart (1978). Data are from this study, Manton (1968), Norry (1977) and Cleverly (1977).

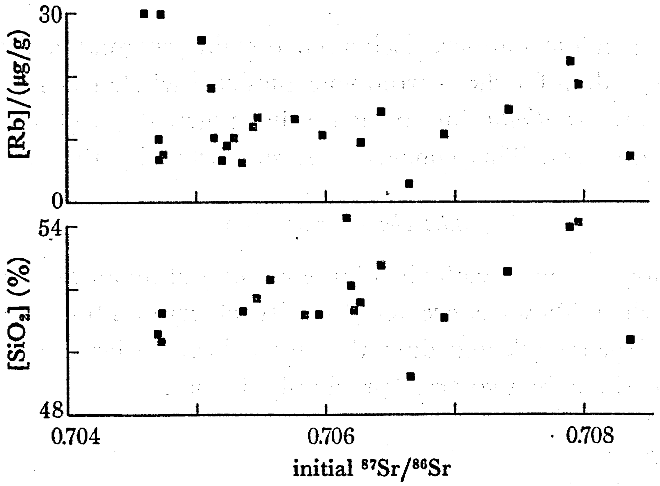

FIGURE 3. Plot of initial ^{87}Sr/^{86}Sr ratios against SiO$_2$ and Rb for mafic Karroo volcanics from the Central Karroo province. Data are from this study.

dolerites to a low initial Sr isotope ratio of *ca.* 0.704, with the bulk of the basalts and dolerites having higher ratios extending up to 0.711. Manton (1968) obtained similar data for the rhyolites of Swaziland but only analysed two basalts from this area. The low initial Sr isotope ratios of the rhyolites and some of the mafic rocks suggest that these (or their precursors in the case of the rhyolites) are of mantle derivation. The higher ratios in the other mafic varieties could then be ascribed to crustal contamination. If this is so then the question arises as to why only the basalts and dolerites are contaminated, since these and the rhyolites must have been erpted through closely connected fissures. An alternative explanation is that the rhyolites are derived from the (lower?) crust. In this case the mafic varieties with higher ratios would have to be contaminated with a crustal source, as yet unknown, other than that which gave rise to the rhyolites. Lack of evidence for crustal contamination of the mafic varieties is provided by the fact that, as in the Central Karroo, there is again no positive correlation between initial strontium isotope ratio and elements such as SiO_2, K_2O, Sr and Rb in these rocks.

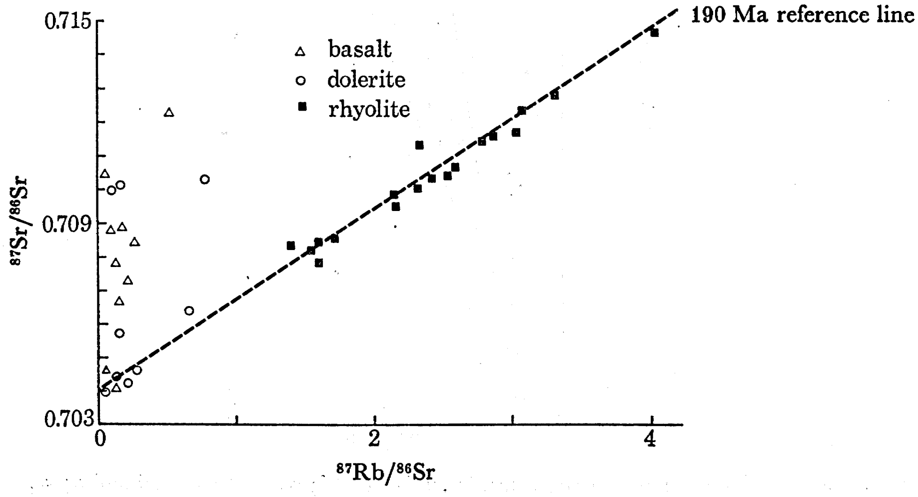

FIGURE 4. Isochron plot for Karroo volcanics from the southern portion of the Lebombo structure. Data are from this study, Manton (1968) and Cleverly (1977).

Although the situation in the southern Lebombo remains enigmatic, the *overall* evidence provided by the Sr isotope data for the Karroo volcanics as a whole leads us to conclude that the variations observed are *essentially* due to mantle heterogeneity, and are not the result of crustal contamination processes. This conclusion is supported by the elemental variations reported below.

(*c*) *Inter-element variations*

As indicated previously, we have available a large amount of major and trace element data for Karroo volcanics, which shows a greater diversity of composition than recognized by Walker & Poldervaart (1949). Selected data that we believe to best represent source area compositions are presented for the two areas previously discussed.

(i) *Central Karroo Province*

Intensive studies carried out by members of Rhodes University on the southernmost portion of the Karroo basalts in the Barkly East district (Drakensberg Subgroup), together with dolerites extending southwards towards the coast, are reported by Lock *et al.* (1974), Robey (1976) and Pemberton (1978). These workers have demonstrated that volcanic units that are stratigraphically distinctive show systematic compositional differences. Three major basaltic Formations have been recognized, namely, the Moshesh's Ford Formation at the base of the succession, comprising the Donnybrook and Drumbo basalt members, followed by the Kraai River Formation, and then the Lesotho Formation (Lock *et al.* 1974). The last is volumetrically dominant, compositionally similar to basalts analysed by Cox & Hornung (1966), and it is now clear that most dolerites in the Central Karroo province are compositional equivalents (Robey 1976).

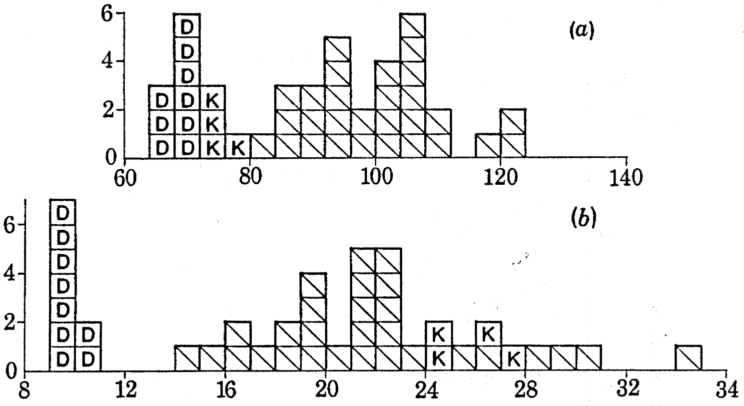

FIGURE 5. Histograms of (*a*) TiO_2/Zr and (*b*) Zr/Nb ratios for basalts from the Barkly East district of the Central Karroo province. Data from Pemberton (1978). D, Drumbo basalts of the Moshesh's Ford Formation; K, Kraai River Formation; cross hatching, Lesotho Formation.

The early products of volcanism in the Central Karroo are compositionally diverse relative to the Lesotho Formation and include minor tholeiitic andesites (*ca.* 58–62% SiO_2) occurring near the base of the volcanic succession. Basalts from the Moshesh's Ford and Kraai River Formations are enriched in incompatible elements relative to the overlying Lesotho Formation, and the three formations have distinctive incompatible inter-element ratios. For example, data presented by Pemberton (1978), as shown in figure 5, clearly demonstrate systematic differences in TiO_2/Zr and Zr/Nb ratios. Available partition coefficient data for Zr and Nb (McCallum & Charette 1978) for likely mantle or fractionating phases strongly suggest that it is not possible for the basalts of these three formations to be related by varying degrees of simple partial melting of a homogeneous source region with or without subsequent crystal fractionation. Our unpublished rare earth element (r.e.e.) data support this contention. We also believe that the systematic compositional differences shown in figure 5 would be extremely difficult to attribute to crustal contamination processes, and therefore agree with Pemberton (1978) that the mantle source region for these basalts is compositionally heterogeneous, perhaps on a vertical scale.

(ii) *Lebombo chemistry*

The Lebombo monocline is a major flexure whose axis runs in a general south–north direction for some 700 km from Natal to Rhodesia (the Nuanetsi area) before continuing further in a northeasterly direction (see fig. 1 in Cox 1971). In general, the volcanic succession is composed of a thick sequence of basaltic rocks, followed by similar thicknesses of rhyolitic rocks, and capped again by basaltic rocks in certain regions. The nephelinites, Mg-rich picrites and shoshonites, which generally occur towards the base of the succession, are confined to the northern part of the Lebombo structure and to the Nuanetsi area. Further details regarding distribution and thicknesses may be found in Cox (1971).

Cox *et al.* (1967) first drew attention to the fact that the Rhodesian Karroo lavas, and specifically those from Nuanetsi, contain concentrations of K, Ti, P, Ba, Sr and Zr that are abnormally high for tholeiitic rocks. In contrast, basalts from Swaziland and Lesotho were shown to have lower concentrations of these elements, similar to those found in other continental tholeiites. Subsequent work by Jamieson & Clarke (1970), Cox (1972) and Cox & Jamieson (1974) has highlighted the fact that the incompatible element concentrations in the Nuanetsi area do not vary inversely with MgO concentration. For example, many Mg-rich picrites contain higher concentrations of these elements than do the Mg-poor basalts. The purpose of this section is to further discuss the chemistry of the lower basaltic rocks from the Lebombo structure. Specifically, it should be noted that previous work has centred around Swaziland and the Nuanetsi area, whereas in our current study the change in chemistry along the whole length of the structure is being investigated, together with changes in chemistry through the stratigraphic succession.

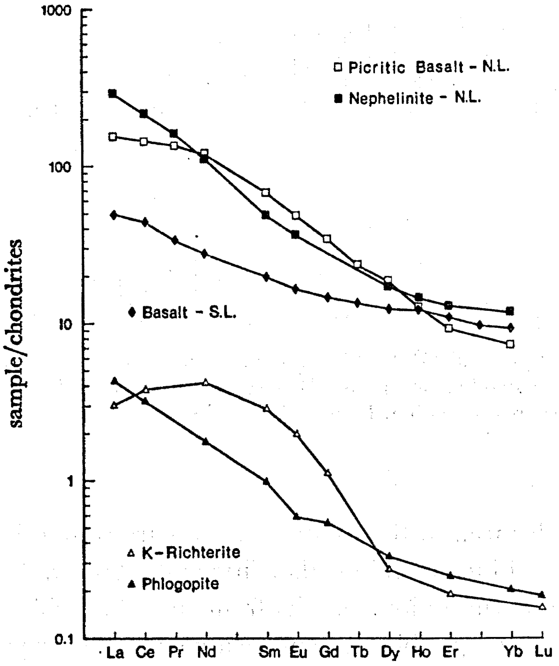

Figure 6. R.e.e./chondrite normalized plot for Karroo lavas and separated minerals from a peridotite nodule from the Bultfontein mine. Mineral data supplied by K. Aoki. S.L., Southern Lebombo; N.L., northern Lebombo.

Our data show that the rocks of the northern Lebombo are very similar to those at Nuanetsi; they are enriched in incompatible elements and show no simple correlation with MgO content.

However, the change in chemistry along the Lebombo is not gradual, rather there is a sudden increase in incompatible element content occurring north of Swaziland near the Sabie river area. A further general observation we have made is that at the southern end of the Lebombo, where only Mg-poor basalts are present, no systematic changes in chemistry can be noticed through the succession.

We shall illustrate changes in chemistry and draw certain conclusions by reference to r.e.e. data. South of Swaziland the basalts have r.e.e. contents and patterns (see figure 6 for one example) similar to those of the Moshesh's Ford Formation of the Central Karroo Province. Such patterns are not exceptional for continental tholeiites and do not provide any evidence which might explain the high Sr isotope ratios of these basalts (figure 4) and thus the problem of possible crustal contamination still remains.

North of Swaziland and the Sabie river section, greater levels of r.e.e. enrichment and conspicuously steeper r.e.e. patterns are observed. Of particular importance to this section, however, are the level of r.e.e. enrichment and the shape of the r.e.e. patterns in specific rock types, as shown in figure 6 for two of the samples that we have analysed from this area. The nephelinite (5.0 % MgO) has a distinctive concave upwards pattern but in view of its low MgO content, consistent with the idea that such rocks are produced by small degrees of partial melting, it is probable that the r.e.e. pattern is not representative of the source area involved. Similar patterns are in fact observed for kimberlites which are also believed to be produced by small degrees of partial melting (Mitchell & Brunfelt 1975). What are surprising, however, are both the level of r.e.e. enrichment and the shape of the r.e.e. pattern in the picritic basalt. With regard to the level of enrichment, and since the picritic basalt contains 23.0 % MgO, the possibility of crustal contamination can be excluded (this probably also applies to the nephelinite). Furthermore, the high MgO content, implying a high degree of partial melting (these lavas are considered to represent liquid compositions (Cox & Jamieson 1974)) strongly suggests that the r.e.e. pattern is indicative of the source involved (the peculiar shape of the pattern will be discussed later) and that the source is substantially enriched in r.e.e., correlating with an enrichment in K and incompatible elements.

Given the facts presented above, the simplest interpretation is that the nephelinite and picritic basalt, while geographically related, are derived from different source areas. This conclusion can only be avoided under special circumstances, for example if the bulk r.e.e. partition coefficients in the (same) source are close to unity, or if the Cox & Jamieson (1974) model of wall-rock equilibration operates in such a way as to selectively enrich the picritic basalt lavas. However, whether this is so or not the large disparity in the r.e.e. data, together with K and incompatible elements, between the northern and southern Lebombo basalts, leads us to conclude that large-scale horizontal mantle heterogeneity is present underneath this structure.

A final point concerns the nature of the sources involved, in particular the enriched nature of the northern Lebombo and Nuanetsi areas. Reference to figure 6 indicates that the picritic basalt has an unusual Z shaped r.e.e. pattern, being somewhat flattened at both ends and steep in the middle. We are not aware of other basaltic lavas that show this pattern, nor can such a pattern be produced by combinations of likely 'normal' mantle minerals, if the partition coefficient data in the literature are consulted (e.g. Arth 1976). Thus both an enriched and unusual source is implied, and brief mention will now be made to the type of mantle that could be suitable and the type of process that might produce such a mantle source.

Upper mantle metasomatism

It has become increasingly apparent that metasomatic processes have affected mantle derived nodules (Harte *et al.* 1975; Lloyd & Bailey 1975; Aoki 1976; Erlank 1976; Erlank & Rickard 1977). If the chemical, mineralogical and textural evidence for metasomatic replacement is accepted, and if it can be shown that the events are unrelated to contamination by the enclosing host rock during emplacement and are thus of mantle origin, then the nature, scale and timing of such events are potentially important when considering mantle differentiation and enrichment processes.

The metasomatic process described by Aoki (1976), Erlank (1976) and Erlank & Rickard (1977) for mantle derived peridotite nodules contained in kimberlite appears to be of mantle origin. Sr isotope studies carried out by Erlank & Shimizu (1977) on nodules from the Bultfontein kimberlite show that the process is unrelated to emplacement of the kimberlite *ca.* 90 Ma ago (Davis *et al.* 1976), since all the peridotite nodules have measured Sr-isotope and Rb/Sr ratios that are substantially higher than the enclosing kimberlite. Furthermore, the data presented by Erlank & Shimizu (1977), together with additional unpublished data by one of us (H. L. A.), suggest that the process occurred *ca.* 150 Ma ago. However, this age may have no geological significance and the 'isochron' could be a mixing line. The point that we wish to make is that evidence for similar metasomatic processes is present in peridotite nodules from other kimberlites in South Africa and in Lesotho, and hence we consider the scale of such mantle processes to be extensive. Furthermore, there is intrinsically no reason why similar processes could not have occurred at earlier times.

The process described above is chemically characterized by the introduction of K (Rb, Ba). This normally leads to the development of phlogopite, but where the metasomatism is more extensive, as particularly shown by some Bultfontein peridotites, the rare amphibole potassic richterite forms. Variable introduction of elements such as Ti, Sr, Zr and Nb also occurs; the development of an unidentified opaque phase in a few nodules with Ba, Sr and Zr present at the percentage level is reported by Erlank & Rickard (1977).

From the evidence presented above it can be speculated that if such a process or processes had occurred in pre-Karroo times then it would, by its very nature, operate in such a way as to produce mantle heterogeneity. Under extreme conditions the resultant enrichment of K and incompatible elements could be such as to produce the sort of mantle source required for the generation of the northern Lebombo and Nuanetsi basaltic lavas, at least for these elements. Evidence for a pre-Karroo event of this type in this area is lacking, but some data do exist that can be used in a circumstantial manner to support these suggestions. Figure 6 shows r.e.e. data for separated phlogopite and K-richterite from a peridotite from the Bultfontein kimberlite. The absolute contents of r.e.e. in the two minerals are too low to produce the r.e.e. contents in the picritic basalt, since the two minerals would be expected to completely melt under the large degrees of melting required to produce the picritic basalt. Even if this does not occur and the respective partition coefficients are very low, simple calculation (bearing in mind also the expected dilution effects of olivine and other minerals) indicates that this would not result in the r.e.e. enrichment required. These arguments apply to simple systems and it is possible that a process such as zone refining (Harris 1957) or wall rock equilibration (Cox & Jamieson 1974) might selectively extract r.e.e. from these minerals during magma ascent. What is important, however, is the shape of the r.e.e. patterns of the two minerals, since we have previously indicated that r.e.e. mineral data in the literature cannot easily produce the peculiar r.e.e. pattern of the picritic basalt. Combination of the phlogopite and K-richterite data results in a r.e.e. pattern that shows a remarkable similarity to that of the picritic basalt, and provides a clue to some of the possible mineralogy of the source regions of the latter.

We conclude by inferring that upper mantle differentiation, in the form of the metasomatic processes described above, will not only lead to mantle heterogeneity on a large scale, but can produce the type of enriched mantle that appears to be necessary to generate the distinctive Mg-rich lavas from the northern Lebombo and Nuanetsi areas. In our opinion such processes would not have been part of the Karroo event, but would have occurred in pre-Karroo times as far as the northern Lebombo and Nuanetsi areas are concerned. If the time interval were substantially pre-Karroo, then the enrichment of K (and probably Th and U) with consequent heat generation, together with enriched H_2O content, would be important factors in the subsequent generation of the high-MgO picritic basalts from these areas.

CONCLUSIONS

In our introduction we indicated that we would attempt to answer certain key questions regarding the mantle beneath southern Africa. In this brief account we believe that we have presented evidence that contributes towards an understanding of mantle heterogeneity beneath southern Africa and our conclusions are summarized according to the listing of these key questions in our introduction.

1. Our data indicate that the mantle is horizontally heterogeneous on a large scale. This is shown particularly by the Jurassic Karroo volcanics from southern Africa since the *overall* compositional variability of these basaltic lavas appears to be best explained by mantle heterogeneity rather than by processes such as variable partial melting, fractional crystallization and crustal contamination. This conclusion is based on Sr isotope and incompatible element and inter-element (including r.e.e. patterns) variations. Some Karroo lavas (together with earlier lavas in the southern African volcanic record) are apparently derived from enriched mantle sources and it is suggested that this enrichment might be caused by earlier and non-Karroo related mantle metasomatic processes. In all of the Karroo provinces that we have studied, examples also occur of samples with unsupported radiogenic ^{87}Sr, and unless this is due to preferential crustal contamination of Sr, these appear to be derived from source regions that have undergone recent Rb depletion. Thus both enrichment and depletion pre-Karroo events are implied, with consequent development of mantle heterogeneity. Such heterogeneity could generate a steep trend as in figure 2 without an old age being necessarily implied. Although indications of vertical heterogeneity are present (Central Karroo area), we cannot yet define the scale of such possible heterogeneity.

2. It is not possible to assess reliably from Sr isotope data when the mantle developed its heterogeneity, since the oldest volcanics are mostly greenstones and may have been affected by alteration processes. The indications are that heterogeneity existed at *ca.* 3 Ga ago and was well established by *ca.* 2 Ga.

3. The important question as to whether the mantle has become progressively more heterogeneous with time (i.e. two-stage or multistage differentiation) is not easily answered. However, the Sr isotope data do suggest progressive development of variability in Sr isotope ratios in the mantle source regions beneath southern Africa, since the younger (and fresher) volcanics exhibit a greater spread in initial Sr isotope ratios when compared with the older volcanics.

In seeking to provide more definitive answers to the questions that we have posed, we consider that there are two imprints, broadly speaking, that require better evaluation when dealing with continental volcanics, namely alteration processes in the older volcanics and crustal contamination in the younger varieties. Apart from the approach adopted here, i.e. the use of Sr isotope and inter-element ratios, it seems likely that Pb and Nd isotope data would be helpful in solving these problems.

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