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Evolution of the Continental Lithosphere: Evidence from Volcanics and Xenoliths in Southern Africa

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Abstract

The geology of southern Africa offers a rare opportunity to study the evolution of a segment of continental lithosphere because its rocks range in age from 3.6 Ga to Recent, and over the last 200 Ma both the upper mantle and the crust have been sampled by Karoo and Tertiary volcanism and as xenoliths in kimberlite pipes. The available data indicate that most of the mantle xenoliths and Karoo volcanics have lower $^{143}Nd/^{144}Nd$ and higher $^{87}Sr/^{86}Sr$ ratios than the bulk earth. Thus they were either derived from source regions which were both 'old' and had lower Sm/Nd and higher Rb/Sr than the bulk earth—or they at least contain a contribution from such a source. It is envisaged that crustal contamination will tend either to generate some broad mixing relation between the original magma and the crustal component, and/or disrupt any pre-existing relationship between isotope and parent/daughter trace element ratios with the result that the two become 'decoupled'. Locally some of the Karoo basalts appear to have been contaminated with Archaean crust, but the majority of these volcanics and the mantle xenoliths have not been affected significantly by crustal contamination processes. Rather, different styles of trace element enrichment are recognized in both mantle xenoliths and Karoo basalts, and with time these result in different trends on ϵ_{Nd} versus ϵ_{Sr} diagrams. The low $^{143}Nd/^{144}Nd$ and high $^{87}Sr/^{86}Sr$ ratios of many basalts and mantle xenoliths suggest that they at least are derived from within the continental lithosphere; since that is where variations in Sm/Nd and Rb/Sr are likely to persist for long enough to generate the observed range in Nd- and Sr-isotopes. Finally, the evolution of the sub-continental lithosphere beneath southern Africa is provisionally described in terms of a two-stage model. Much of the lithosphere appears to have stabilized 1.4–1.0 Ga ago, which is also the time of significant crustal growth within the Namaqua-Natal mobile belts. It is argued that the two are related, and that increasing the area of stable continental crust also increased the volume and perhaps even the thickness, of material incorporated into the sub-continental lithosphere. Karoo magmatism at ~190 Ma was then followed by, and may have been responsible for, a second mantle enrichment event now observed in the modal metasomatism of K-richterite bearing peridotite xenoliths.

Introduction

Geophysical considerations suggest that the continental lithosphere is 100–250 km thick and that 60–80% of it consists of upper mantle rocks attached to the base of the continental crust (Jordan, 1978). It is rigid and presumably isolated from the areas of active convection within the upper mantle, and some arguments suggest that it may stabilize shortly after the last major thermal event in the overlying crust (Oxburgh and Parmentier, 1978). Much of the mantle within the lithosphere is therefore likely to be old enough for trace element heterogeneities to be mirrored by variations in radiogenic isotopes. Moreover, since any old segments of the sub-continental mantle will be susceptible to the effects of later events, they may also represent a rare opportunity to investigate polyphase evolution within the upper mantle. This contribution reviews work on continental basalts and both crustal and mantle xenoliths from kimberlite pipes in southern Africa in the context of the evolution of the continental lithosphere in that area. Specifically, it addresses such questions as the age of the lithosphere, the timing and nature of trace element enrichment events, whether basalts are derived from within the continental lithosphere, and the extent to which basalts and mantle xenoliths sample similar source regions in the upper mantle.

The importance of trace elements in the study of igneous rocks and upper mantle processes owes much to the radioactive decay schemes involving Rb-Sr, Sm-Nd and U, Th and Pb. These result in isotopic differences used widely to identify and to evaluate the nature of different source terrains. Ideally, such source terrains should have evolved undisturbed over long periods of time so that the isotope composition of, for example, Sr may be related simply to the parent/daughter trace element ratio, in this case Rb/Sr. However, in many basaltic rocks there is no such simple relationship between isotope and trace element ratios (Norry and Fitton, this volume). The majority have isotope compositions suggesting that they sampled upper mantle material which had been depleted in LREE (high Sm/Nd) and had low Rb/Sr ratios for much of its history, and yet the trace element contents of many of these rocks imply that their source regions had high concentrations of LREE, Rb and Sr, and relatively low Sm/Nd and high Rb/Sr ratios. Thus their isotope and trace element ratios are 'decoupled', presumably because their source regions were enriched in trace elements so recently that there has been insufficient time for their isotope compositions to reflect the changes in trace element ratios.

Some decoupling of isotopes and trace elements is probably inevitable in a convecting upper mantle, since the latter is a dynamic system and individual segments are unlikely to remain undisturbed for long periods of time. Unfortunately, however, that limits the potential of radiogenic isotope studies precisely because there has often been too little time for variations in trace element ratios to be mirrored by coherent variations in isotope composition. Yet, as implied above, there is one area of the upper mantle where theoretically at least such limitations may be overcome, and that is within the continental lithosphere.

Regional geology

The geology of southern Africa is unique in that it preserves a record of major orogenic and magmatic events ranging in age from 3600–30 Ma. Archaean rocks (3.6–2.5 Ga) are preserved in cratonic nucleii surrounded by mobile belts containing varying proportions of new and reworked crustal material (Figure 1). For example, considerable volumes of new crust appear to have been generated in the formation of the Namaqua-Natal belt in the upper Proterozoic (1.4–1.0 Ga, Barton *et al.*, 1981; Rogers and Hawkesworth, 1982); whereas in the Pan African terrain of northern Namibia many of the igneous rocks were derived from pre-existing Proterozoic crust (Hawkesworth and Marlow, 1983). Yet of even greater significance to any potential study of the lithosphere is that after these orogenic episodes and the subsequent stabilization of the crust, both the crust and the underlying sub-continental mantle were sampled by widespread Karoo magmatism from ~190 Ma, kimberlite emplacement in the Cretaceous, and mid-Tertiary alkaline volcanism.

The Karoo igneous rocks form one of the classic flood basalt provinces (Cox, 1980). Radiometric ages vary from early Jurassic to early Cretaceous (190–120 Ma, Fitch and Miller, in prep.; Erlank *et al.*, in prep.), and today remnants of lavas occur scattered across an area in excess of 3.5×10^6 km^2 (Figure 1). In addition the underlying Karoo sedimentary sequences are host

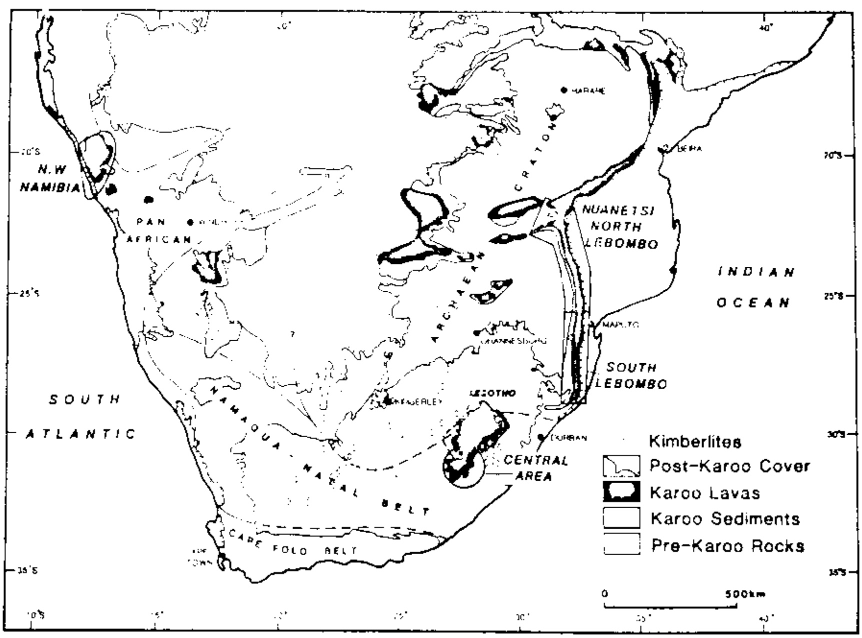

Figure 1 Geological sketch map of southern Africa illustrating the four sub-areas where Karoo volcanic rocks have been studied in most detail, and the distribution of kimberlite pipes

to an extensive swarm of dykes and sills. Basaltic rock types of tholeiitic character are dominant throughout the Karoo province, but volumetrically important sequences of acid volcanics occur along both the eastern and western margins of the province, and high-Mg basalts (or picrites) are a feature of the area around Nuanetsi. Most of the available geochemical and isotopic data have been reported on rocks from four sub-areas between which there are some clear differences in both isotope and trace element compositions: (a) Nuanetsi-north Lebombo; (b) south Lebombo; (c) Central area; and (d) northwest Namibia (see Figure 1 and references in Erlank, in prep.). The rocks from Nuanetsi and north Lebombo are characterized by unusually high incompatible element contents, viz. ~900 ppm Sr, ~350 ppm Zr, and ~65 ppm Nd compared with ~230 ppm, ~90 ppm and 14 ppm respectively, in for example the dominant basalts of the Central area. Yet these rocks have similar $^{87}Sr/^{86}Sr$ ratios, and they in turn are significantly lower than those of the northwest Namibia basalts. In the south Lebombo there is some evidence that the rocks have been affected by interaction with the continental crust (see later discussion), but the trace element characteristics of uncontaminated basalts appear to be similar to those in the Central area.

Kimberlites are volatile-rich potassic, ultrabasic intrusive rocks with a distinctive inequigranular texture due to the presence of macrocrysts in an essentially microporphyritic matrix (Clement *et al.*, 1977). Studied widely as the principal source of natural diamond, they also contain a variety of xenoliths of both crustal and upper mantle rocks. In southern Africa kimberlites occur both on the Archaean craton and in the surrounding mobile belts. Some were emplaced in the Precambrian (Premier, Transvaal) and in the Permian (Dokolwayo, Swaziland), but the majority intrude the Carboniferous-Jurassic sediments and lavas of the Karoo and are therefore post-Jurassic. Radiometric ages indicate a protracted period of kimberlite intrusion from ~140 Ma to 80 Ma with the most intensive periods at 140, 120 and 90–80 Ma (Dawson, 1980, and references therein). Pressure/temperature estimates on xenolith material range from 5–20 kbar at 500–850°C for lower crustal granulites (Griffin *et al.*, 1979; Robey, 1982) and up to 70 kbar at 1450°C for the higher temperature garnet peridotites, although the age and significance of any inferred geothermal gradients are still debated (see Harte, this volume).

After the main phase of kimberlite activity in the Cretaceous there was a period of late Cretaceous-mid Tertiary alkaline magmatism, particularly in the western areas of southern Africa. The rocks are exposed in sporadic pipe-like intrusions which tend to be either predominantly ultrabasic in composition, or to consist largely of more salic nephelinites and phonolites. The ultrabasic pipes have attracted attention because their olivine melilitites might be genetically related to kimberlites (McIver and Ferguson, 1979; Moore, 1980). Isotope data are scanty, but the rocks which have been analysed for Nd- and Sr-isotopes are from centres with K/Ar ages in the range 65–32 Ma (Marsh *et al.*, 1981).

Karoo volcanic rocks

$^{143}Nd/^{144}Nd$ VERSUS $^{87}Sr/^{86}Sr$ AND Sm/Nd VERSUS Rb/Sr VARIATIONS

The volcanic rocks of the Karoo have been the subject of a detailed programme of field mapping and geochemical and isotope analysis affiliated to the International Geodynamics programme since 1974. Although work has concentrated on rocks from four sub-areas, as illustrated in Figure 1, it is a measure of the scale of the project that high quality major and trace element analyses have been determined by XRF on over a thousand specimens, and that several hundred rocks have been analysed for Sr-isotopes. The results of this programme are to be published in a volume edited by A.J. Erlank, and many of the ideas outlined here were developed in the writing of that volume. In particular the $^{87}Sr/^{86}Sr$ results have been compiled by Bristow *et al.* (in prep.) and the combined Nd- and Sr-isotope variations are discussed by Hawkesworth *et al.* (in prep.).

The available present day $^{143}Nd/^{144}Nd$ ratios on Karoo rocks vary from 0.51303–0.51168, and in those samples present day $^{87}Sr/^{86}Sr$ are in the range 0.70305–0.72671. Initial isotope ratios are calculated at 190 Ma for the rocks of the Central area, Nuanetsi and the Lebombo, and at 121 Ma for those from northwest Namibia (see Figure 1), and presented in the ϵ notation in Figure 2.

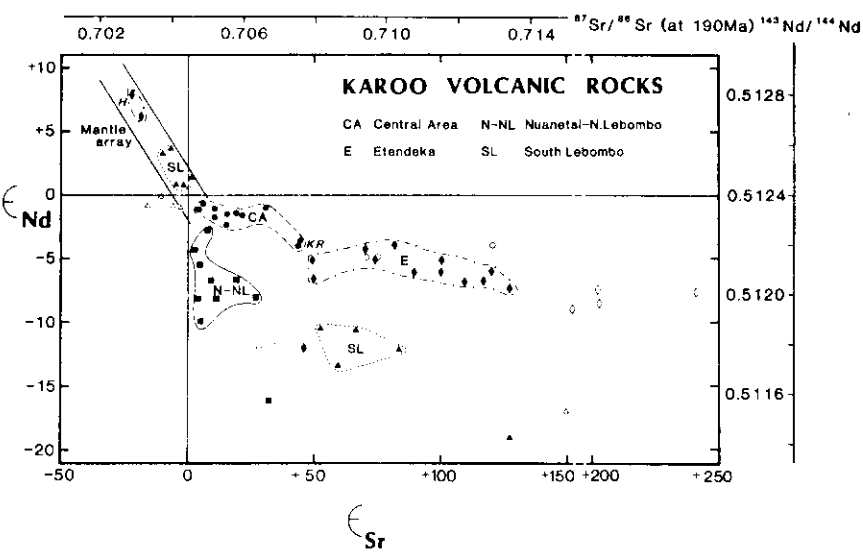

Figure 2 Initial Nd- and Sr-isotope variations in Karoo volcanic rocks (after Hawkesworth *et al.*, in prep.). H—Horingbaai dolerites from northwest Namibia; KR—Kraai River basalts from the Central area. Circles—Central area; squares—Nuanetsi-north Lebombo; triangles—south Lebombo; diamonds—northwest Namibia. Filled symbols are for samples with less than 58% SiO_2, open symbols more than 58% SiO_2

On such diagrams the origin represents the estimated Nd- and Sr-isotope composition of the bulk earth at a particular time—in this case, at the time of formation of the Karoo lavas. The majority of recent mantle-derived rocks have lower $^{87}Sr/^{86}Sr$ and higher $^{143}Nd/^{144}Nd$ ratios than the bulk earth and they tend to plot on, or close to, the so-called 'mantle array' in the top left quadrant of Figure 2. Moreover, that implies that such rocks were derived from source regions which had lower Rb/Sr and higher Sm/Nd ratios than the bulk earth, i.e. they were relatively depleted in the more incompatible elements, for much of their history. Conversely, source rocks with higher Rb/Sr and lower Sm/Nd ratios than the bulk earth will, with time, develop positive ϵ_{Sr} and negative ϵ_{Nd} values and so plot in the bottom right quadrant.

Only seven (that is, ~14%) of the Karoo rocks analysed have positive ϵ_{Nd} values similar to those found in the majority of recent mantle-derived rocks. Most of the rest have both positive ϵ_{Sr} and negative ϵ_{Nd} and so plot in the bottom right quadrant of Figure 2. An important feature of these isotope variations, and one which may often be significant when considering results from other volcanic provinces, is that much of the observed range of ϵ values is due to the composition of samples from volumetrically trivial rock units. For example, all but the basal 100–150 m of the 1500 m pile of Karoo lavas presently preserved in the Central area consists of Lesotho type basalts, and of the 21 analysed, 20 have ϵ_{Sr} in the range 2 to 22 (0.7048–0.7060), and one has ϵ_{Sr} = 35 (0.7069). By contrast the basal 100–150 m presently includes six different stratigraphic units (including the Kraai River Formation, KR, Figure 2): the rocks vary from basalts with low incompatible element contents to dacites with 1.5–2.6% K_2O, and ϵ_{Sr} = 6 to 120 (0.7049–0.7129) (Marsh and Eales, in prep., Bristow *et al.*, in prep.).

Nonetheless, the majority of Karoo volcanic rocks are basalts, and they include a number of different magma-types which have been recognized primarily on the basis of different trace element features. Although more than

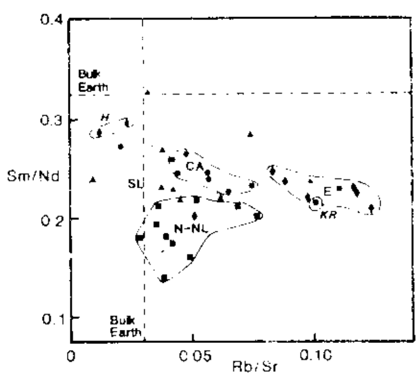

Figure 3 Sm/Nd versus Rb/Sr for selected Karoo volcanic rocks for which Nd- and Sr-isotope analyses are available. Note that the enclosed south Lebombo rocks are the high ϵ_{Sr}, low ϵ_{Nd} SL samples in Figure 2. Symbols as in Figure 2

one magma type may be found in any particular area, viz. the Lesotho and Kraai River basalts of the Central area mentioned above, the four sub-areas identified on Figure 1 tend to be characterized by different magma types: for example, the basalts of Nuanetsi-north Lebombo have significantly higher incompatible element contents than those from elsewhere.

The Sm/Nd and Rb/Sr ratios of those Karoo basalts which have also been analysed for Nd- and Sr-isotopes are illustrated in Figure 3. Rocks from different sub-areas tend to plot in different fields corresponding to the different magma types and, as far as is known, there is little systematic variation of trace element ratios with, for example, fractionation within any of these fields. Moreover, when all the available trace elements are considered there are surprisingly few samples with compositions intermediate between different magma types.

It has been recognized for several years that while trace element enriched basalts tend to have high Rb, Sr and LREE contents and low Sm/Nd ratios, their Rb/Sr ratios vary—presumably depending on the nature of the enrichment processes (Hawkesworth *et al.*, 1979c). Similar trends can also be seen in the Karoo rocks in Figure 3: samples from the Central area and the Etendeka of northwest Namibia exhibit a range in Rb/Sr but little change in Sm/Nd, whereas the Nuanetsi-north Lebombo rocks which have higher incompatible element abundances, and hence lower Sm/Nd ratios, also have relatively low Rb/Sr ratios. Of even greater regional significance however, are the similarities which exist in the trends for Sm/Nd versus Rb/Sr (Figure 3) and initial Nd- and Sr-isotope compositions (see Figure 2).

Although the Horingbaai dolerites of northwest Namibia and some of the basalts from the south Lebombo plot on the 'mantle array' in Figure 2, the vast majority of Karoo rocks have positive ϵ_{Sr} and negative ϵ_{Nd} values and so fall in the bottom right quadrant. Yet within that quadrant there appear to be two distinct trends. Rocks from the Central area and the Etendeka of northwest Namibia show large variations in ϵ_{Sr} with relatively little change in ϵ_{Nd} resulting in flat-lying arrays which are in sharp contrast to the near vertical trend exhibited by the lavas of Nuanetsi and north Lebombo. Moreover, such trends are similar to those seen on the Sm/Nd versus Rb/Sr diagram (see Figure 3). The high ϵ_{Sr} basalts from the south Lebombo appear to have intermediate isotope compositions, but because their isotope and trace element ratios plot in different relative positions in Figures 2 and 3, they are thought to be 'decoupled'.

In summary, we would emphasize the following:

1. The *relative* positions of the Central area, Etendeka, Nuanetsi-north Lebombo, and even the Horingbaai fields on the Sm/Nd versus Rb/Sr diagram are similar to those on the ϵ_{Nd} versus ϵ_{Sr} diagram. Thus, at least in these areas, the majority of isotope and parent/daughter trace element ratios are mutually consistent; although it is noticeable that the Etendeka and Kraai River basalts have similar Rb/Sr but different initial Sr-isotope ratios.

2. In contrast, the high ϵ_{Sr} lavas from the south Lebombo do *not* plot in the same relative positions in Figures 2 and 3: their isotope and trace element ratios are 'decoupled'.
3. Although the relative positions of the fields in Figures 2 and 3 are similar, their positions in relation to the estimated composition of the bulk earth on each diagram are different. Qualitatively, the Sm/Nd ratios of most of the basalts would have to be increased by ~15% for the difference between their Sm/Nd ratios and that of the bulk earth to be consistent with the difference between their observed and the bulk earth $^{143}Nd/^{144}Nd$ ratios, that is, their ϵ_{Nd} values. One interpretation of this discrepancy is that it is evidence that the processes of partial melting and fractionation *en route* to the surface (see discussions by Cox, 1980, and this volume) resulted in basalts whose Sm/Nd ratios were on average ~15% less than those in their source regions, and that their Rb/Sr ratios were little changed, but at present this is not well understood.

RELATIVE ROLES OF CRUSTAL CONTAMINATION AND MANTLE TRACE ELEMENT ENRICHMENT PROCESSES

Much has been written about the relative roles of these processes in the genesis of continental igneous rocks. The evidence from mantle xenoliths (Erlank *et al.*, 1982; Jones *et al.*, 1982; and Menzies, this volume) and many intraplate basalts in both continental and oceanic areas (Gast, 1968; Hawkesworth *et al.*, 1979c; Norry *et al.*, 1980) demonstrates that some portions of the upper mantle are enriched in incompatible elements relative to present estimates of primitive mantle (see Thompson *et al.*, this volume) and the inferred sources of MOR basalts (Pearce, this volume). However, there are also continental volcanic provinces where stable isotope studies in particular have indicated that mantle-derived magmas have been contaminated with significant quantities of crustal material *en route* to the surface (Graham and Harmon, this volume; Thirlwall and Jones, this volume). The debate is not therefore about *whether* these processes take place, for the evidence for both is surely overwhelming, but over the criteria by which they may best be recognized.

The question of whether particular igneous rocks contain material from both the upper mantle and the continental crust is hampered by misunderstandings which are both geological and semantic—principally because 'crustal contamination' has been used differently by different authors. Specifically, confusion seems to have arisen because it has been argued that continental material may (a) be present in the source of some mantle-derived rocks (White and Hofmann, 1982; Hofmann and White, 1982), and (b) be introduced by contamination of mantle-derived magmas as they pass up through the continental crust (Carlson *et al.*, 1981; Mahoney *et al.*, 1982; Thompson *et al.*, 1982). Clearly these are different processes, and the term 'crustal contamination' is here reserved for the latter.

Erosion of the continental crust releases continental material into the oceans, both in solution and as sedimentary detritus. Interaction with sea water, particularly in the hydrothermal systems active along mid-ocean ridges, and sedimentation then ensures that the oceanic crust contains a component of continental material which on subduction is returned to the upper mantle. Some of this recycled material is released almost immediately from the subducted slab and observed in island arc and continental margin volcanics (Hawkesworth, 1982), but the rest may be redistributed in the upper mantle and subsequently influence the source of some intraplate volcanic rocks (White and Hofmann, 1982).

Destructive plate margin volcanics are arguably a special case because it is generally accepted that they are hybrid rocks containing material from both the subducted slab and the overriding mantle wedge (Pearce, this volume). However, the trace element and isotope characteristics of intraplate basalts presumably reflect upper mantle processes, and whether or not particular aspects may be attributed successfully to recycled continental crust, such arguments are essentially about the origins of inferred trace element patterns in upper mantle rocks. Thus that debate differs sharply from the one about the extent to which continental volcanic rocks have been contaminated with crustal material *en route* to the surface—crustal contamination *sensu stricto*. The latter changes the composition of the magmas and hence it is likely either to generate some broad mixing relation between the original magma and a crustal component, and/or to disrupt any pre-existing relationship between isotope and trace element ratios with the result that the two become 'decoupled'.

It is important to emphasize that decoupling between radiogenic isotope and the relevant parent/daughter trace element ratios can reflect a number of different processes. However, in all cases it indicates that there has been a comparatively recent event which has either affected the trace element ratios more than the isotope ratios, or vice versa. The available evidence suggests that when decoupling is due to mantle processes the basalts (see Norry and Fitton, this volume) and mantle xenoliths (Menzies, this volume), tend to be enriched in incompatible elements and have low Sm/Nd, and often slightly high Rb/Sr ratios, with high $^{143}Nd/^{144}Nd$ and low $^{87}Sr/^{86}Sr$. By contrast, if the decoupling reflects crustal contamination $^{87}Sr/^{86}Sr$ may typically be higher, and $^{143}Nd/^{144}Nd$ lower, than would be expected from the relevant trace element ratios in the rocks themselves.

One of the striking features of the Nd- and Sr-isotope results on the Karoo rocks is that over 80% have positive ϵ_{Sr} and negative ϵ_{Nd} values and so plot in the bottom right quadrant of Figure 2. Thus they were either derived from source regions which were both 'old' and had higher Rb/Sr and lower Sm/Nd ratios than the bulk earth—or they at least contain a contribution from such a source. In practice the problem of interpretation can usefully be considered in two parts: first, whether the isotope and trace element ratios, particularly in the basaltic rocks, are similar to those in their source regions, or whether they have been affected by the addition of some extra component during melting or *en route* to the surface. Second, whether the observed isotope compositions were predominantly inherited from the continental crust or the upper mantle. Unfortunately however, while high Rb/Sr and low Sm/Nd ratios are typical of many rocks in the continental crust, it has already been argued that the evidence from both mantle xenoliths and incompatible element enriched basalts demonstrates that they also occur in some areas of the upper mantle. Thus similar Nd- and Sr-isotope ratios can result in crustal and mantle rocks *provided both are left undisturbed for similar periods of time* and, as outlined in the introduction, that might well occur within the continental lithosphere.

The $^{143}Nd/^{144}Nd$ and $^{147}Sm/^{144}Nd$ ratios of Karoo rocks are presented in Figure 4, and Figure 5 summarizes comparable data on crustal and mantle xenoliths from southern African kimberlite pipes (Menzies and Murthy, 1980b; Basu and Tatsumoto, 1980; Erlank *et al.*, 1982; Rogers and Hawkesworth, 1982; Hawkesworth *et al.*, in prep.). Both figures are isochron diagrams and positive straight lines between individual data points and the bulk earth have slopes which correspond to their model Nd, or T^{Nd}_{CHUR}, ages (De Paolo and Wasserburg, 1976, and more general discussion by Hawkesworth and van Calsteren, 1983). In addition simple two component mixing will also produce

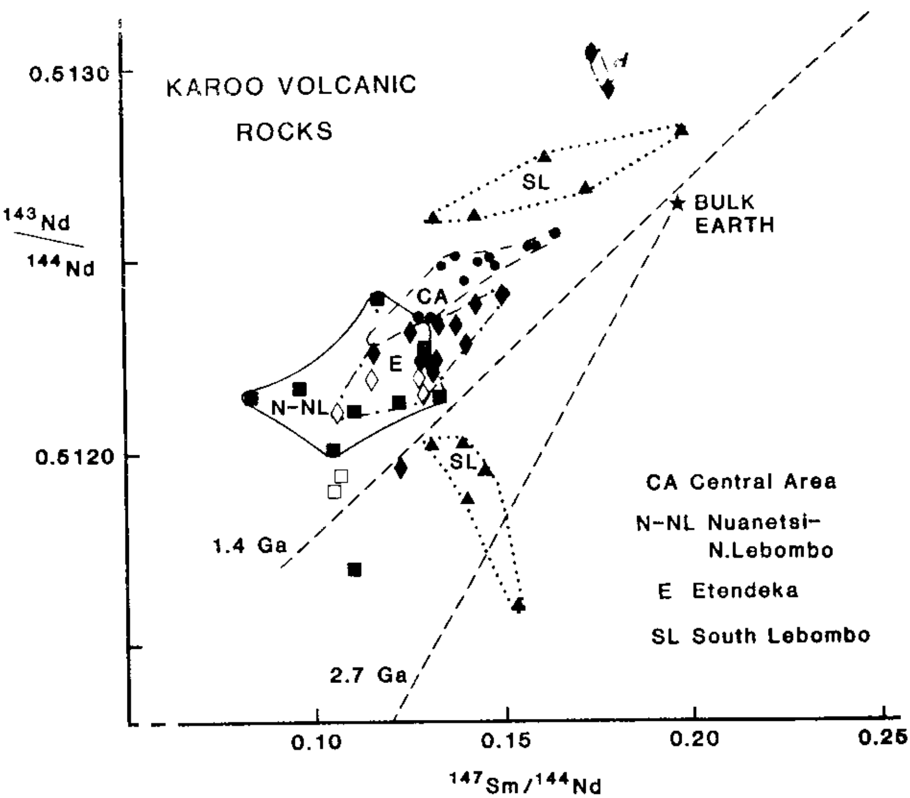

Figure 4 $^{143}Nd/^{144}Nd$ versus $^{147}Sm/^{144}Nd$ for the Karoo volcanic rocks (after Hawkesworth *et al.*, in prep.). 1.4 and 2.7 Ga reference lines are from the crustal xenolith data in Figure 5. Symbols as in Figure 2

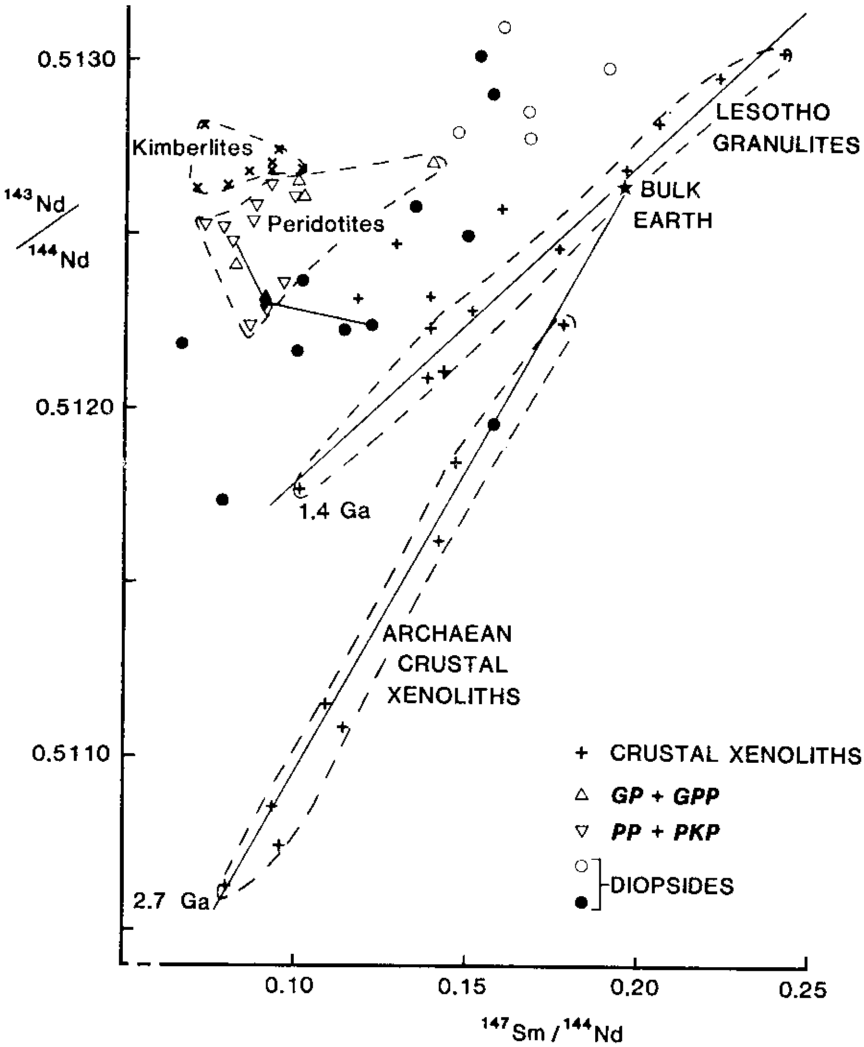

Figure 5 $^{143}Nd/^{144}Nd$ and $^{147}Sm/^{144}Nd$ variations in crustal and mantle xenoliths from southern Africa. Data from Basu and Tatsumoto (1980), Menzies and Murthy (1980b), Kramers *et al.* (1981), Erlank *et al.* (1982), Rogers and Hawkesworth (1982), Hawkesworth *et al.* (1982b) and Hawkesworth, Menzies and Erlank (unpublished). The solid line links co-existing diopside, K-richterite and their whole rock peridotite. Filled circles—diopsides from mantle peridotites; open circles—diopside megacrysts; filled diamond—K-richterite; GP—garnet peridotite; GPP—garnet phlogopite peridotite; PKP—phlogopite K-richterite peridotite; PP—phlogopite peridotite

linear trends in such diagrams, with either a positive or negative slope (Langmuir *et al.*, 1978).

The majority of Karoo rocks plot in a broad linear array in Figure 4, with the most obvious exceptions being the five high ϵ_{Sr}, low ϵ_{Nd} (or $^{143}Nd/^{144}Nd$)

basalts from the south Lebombo. Significantly they comprise the group whose isotope and trace element ratios were most clearly decoupled (see Figures 2 and 3) and, since the sample with the lowest $^{143}Nd/^{144}Nd$ ratio (L348) contains small fragments of what appear to be partially digested granitic material (Cox and Bristow, in prep.) and has a model Nd age of 3.6 Ga, it seems reasonable to conclude that this group of basalts has been contaminated with Archaean crust.

The rest of the Karoo lavas tend to have broadly coherent isotope and trace element ratios, and most participants in the Karoo programme now believe that crustal contamination has had little significant effect on the chemistry of these rocks. The key word is 'significant' and, interestingly, how that is defined depends largely on the objectives of the particular project. If the aim is simply to show that a continental volcanic rock contains some crustal materials, then clearly even a minute amount of contamination is significant. However, the aims of this study were to evaluate mantle processes in the source of the Karoo basalts and to compare them with those inferred from mantle xenoliths, and in that context crustal contamination only becomes significant when it has had more effect than, for example, local intra-area source heterogeneity and late-stage alteration. Specifically, it becomes significant if it is even partially responsible for the *position* of the isotope and trace element fields for the different magma types in diagrams such as Figures 2, 3 and 4, rather than just for some of the scatter *within* those fields—which might well be due to interaction with crustal materials.

The crux of the argument is that the Karoo basalts include a number of different magma types with different trace element characteristics. Within the Central area, for example, several magma types are recognized on the basis of trace element ratios such as Ti/Zr and Zr/Nb, and it has been shown that the observed variations in these ratios are extremely unlikely to be due to crustal contamination processes (Marsh and Eales, in prep.). On a regional scale, that is, between the different sub-areas in Figure 1, there are consistent differences in a range of trace elements (Duncan *et al.*, in prep.; Cox, this volume) and these are reflected in the separate Sm/Nd versus Rb/Sr fields in Figure 3, and apparently accompanied by coherent variations in Nd- and Sr-isotopes (see Figure 2). Thus if crustal contamination was responsible for the latter, it implies that it was also responsible for many of the trace element characteristics of the different magma types.

There are many objections to such an explanation for the different magma types in the Karoo, not least the sheer volume of contaminant needed to influence so dramatically the composition of the estimated 1×10^6 km^3 of basalt. There would, for example, have to be a specific contaminant for each magma type, at least with respect to Rb/Sr and Sm/Nd, and each batch of contaminated magma would have to be well homogenized, since even though different magma types are sometimes interbedded there is little or no compositional gradation between them. Furthermore, if the flat-lying and near vertical trends on the ϵ_{Nd} versus ϵ_{Sr} diagram (see Figure 2) were attributed to crustal contamination, the former would presumably reflect high Rb/Sr upper crustal rocks and the latter low Rb/Sr lower crustal granulite-facies rocks (e.g. Carter *et al.*, 1978b). Yet granulites tend to have low U/Pb ratios, and hence with time unradiogenic Pb-isotope compositions; in contrast to the rocks of Nuanetsi-north Lebombo which, although they plot on the near vertical trend in Figure 2, have comparatively radiogenic Pb-isotope ratios (Betton *et al.*, in prep.). It is therefore unlikely that the compositions of these Karoo rocks can be attributed to granulite contamination.

Other difficulties with the widespread crustal contamination hypothesis can be illustrated with the results in Figure 4. It has already been argued that the negative trend of the low $^{143}Nd/^{144}Nd$ south Lebombo basalts could be due to interaction with Archaean crust. However, if the positive trend defined by the majority of Karoo results in Figure 4 was also due to crustal contamination, the slope of the trend implies that the contaminant was upper Proterozoic in age (that is, it would plot on or above the 1.4 Ga reference isochron). Yet these basalts crop out on Archaean, Proterozoic, and Pan African basement (see Figure 1), and there is no clear link between the age of the basement and the distribution of Karoo magma types. Moreover, it is particularly difficult to envisage why upper Proterozoic continental crust should be responsible for the isotope and trace element composition of lavas erupted on to an Archaean craton. In detail, if the isotope and trace element characteristics of the Nuanetsi-north Lebombo rocks were due to crustal contamination of, for example, the high $^{143}Nd/^{144}Nd$ south Lebombo lavas (see Figures 2 and 4), then ~70–80% of their Nd and Sr contents would be of crustal origin. Yet these rocks include high-Mg picrites (Cox and Jamieson, 1974), and since the assimilation of that amount of crust would consume so much latent heat that the magmas would evolve to lower MgO compositions, such a model is considered unlikely (see also Cox, this volume).

In contrast to the near vertical ϵ_{Nd} versus ϵ_{Sr} trend of the Nuanetsi-north Lebombo rocks, the Etendeka basic volcanics of northwest Namibia exhibit a range in ϵ_{Sr} and relatively little variation in ϵ_{Nd} (see Figure 2). They crop out on Pan African crust (see Figure 1) which had similar ϵ_{Nd} values at that time (Hawkesworth and Marlow, 1983) but detailed modelling has so far failed to demonstrate interaction of these basic volcanics with such crust. In particular, the basic rocks are interbedded with acid volcanics (quartz latites), see Figure 2, which represent the best evidence for crustal melting contemporaneous with basaltic volcanism, and which have similar Nd- and Sr-isotope characteristics to some of the basement rocks. However, combined major, trace element and isotopic modelling shows no evidence for significant interaction between the basic volcanics and either the acid lavas or their inferred source regions. Thus although both the field and isotopic relationships might suggest that the flat-lying ϵ_{Nd} versus ϵ_{Sr} trend in the basic rocks is due to crustal contamination, this is not supported by detailed study, and it stresses the need for integrated major, trace element and isotope modelling when considering such possibilities (Erlank *et al.*, in prep.).

In summary, the possible effects of crustal contamination have been discussed in some detail, primarily because they must be understood before the nature of the source regions of continental basalts can be evaluated. We envisage that crustal contamination will tend either to decouple any pre-existing coherent patterns between isotope and parent/daughter trace element ratios, and/or introduce broad mixing relations between the original magma(s) and any crustal components. In the case of the Karoo, 'decoupling' between isotope and trace element ratios has been observed in a group of south Lebombo basalts where it appears to be due to contamination with Archaean crust, but in most of the rocks analysed the Nd- and Sr-isotope ratios vary coherently from one magma type to another. Such coherent variations have proved extremely difficult to model satisfactorily by crustal contamination and they are presently believed to have been a feature of the sub-continental mantle in this area—a conclusion which is supported further by the available Nd- and Sr-isotope results on mantle xenoliths in kimberlite pipes (see Figure 5 and related discussions).

Crustal xenoliths

In southern Africa diamondiferous kimberlite pipes tend to be confined to the cratonic areas, something which has provoked much speculation as to why that should be and to the exact position of the boundaries of the Archaean terrain (see Figure 1). A popular explanation is that the cratons are underlain by an old, cold and thick continental lithosphere within which the upper mantle is by implication different from that beneath the mobile belts (for example, Gurney and Harte, 1980). Yet interestingly, no comparable link has been observed between the age of the basement and the distribution of different magma types within the Karoo lavas (previous section, and Hawkesworth *et al.*, in prep.).

Crustal xenoliths in kimberlite pipes offer one way of determining the age of basement rocks in areas where they do not crop out at the surface. In southern Africa anhydrous granulite xenoliths tend only to occur in pipes within the mobile belts (Griffin *et al.*, 1979), so that the absence of granulites may be an indication that a particular kimberlite was emplaced through Archaean crust. Granulites typically have low Rb/Sr ratios and thus are difficult to date by the Rb-Sr method, however, they can be enriched or depleted in LREE and so theoretically at least the Sm-Nd method is more likely to provide useful age information. Rogers and Hawkesworth (1982) analysed 14 whole rock granulite xenoliths from pipes in northern Lesotho and ten of the samples scattered about an errorchron corresponding to an age of 1.4 ± 0.1 Ga (MSWD = 28), with an initial Nd ratio only slightly higher than that of the bulk earth at that time (see Figure 5). The four remaining granulites plotted above that errorchron, but because they had both low Nd contents (less than 6 ppm Nd) and lower $^{143}Nd/^{144}Nd$ ratios than typical kimberlites at the time of emplacement, they may have been affected by interaction with the kimberlite.

The age of 1.4 Ga compares well with the model Sr age of 1.3 Ga obtained from the average Rb/Sr and $^{87}Sr/^{86}Sr$ ratios of the seven granulites with more than 800 ppm Sr, and it was interpreted as a reasonable estimate of the maximum age of the lower crust beneath Lesotho.

The investigation of the Lesotho granulites suggested that important age information could be obtained by whole rock analysis of xenolith material, provided it contained reasonable concentrations of Nd and Sr, and this has since been confirmed by work on xenoliths from other areas in southern Africa (Hawkesworth *et al.*, 1982b). Five samples from kimberlite pipes on the Archaean craton, and two of upper crustal gneisses from the pipes in northern Lesotho yielded model Nd ages of 2.9–2.4 Ga, and these analyses are also reproduced in Figure 5. The xenoliths from on the craton were selected primarily as a test of the method and thus their Archaean model ages are most encouraging, but the north Lesotho results are particularly intriguing because they indicate that along the southeast margin of the craton Archaean upper crustal rocks are underlain by a Proterozoic lower crust. The lack of basic granulites (Griffin *et al.*, 1979) and the Archaean model ages of three moderately high-P xenoliths from on the craton (Hawkesworth *et al.*, 1982b) suggest that this age structure is restricted to the boundary with the surrounding mobile belts, and that such Proterozoic lower crustal material does not extend far beneath the craton.

Model Nd ages, or T^{Nd}_{CHUR}, are effectively calculated from the slope of a two point isochron between the present day $^{143}Nd/^{144}Nd$ and $^{147}Sm/^{144}Nd$ ratios of the individual whole rock sample and those of the bulk earth (see Figure 5). For continental rocks these ages tend to reflect the time that they or their precursors were derived from the upper mantle, primarily because the generation of continental crust results in a marked reduction in Sm/Nd compared with most upper mantle source regions, and subsequent remobilization by erosion and sedimentation or magmatic activity then appears not to fractionate Sm/Nd ratios significantly (McCulloch and Wasserburg, 1978). Similarly, Sm-Nd whole rock isochrons on continental rocks which pass through or close to the point for the bulk earth (see Figure 5) are likely to represent maximum ages, rather than some later episode in their crustal history.

Mineral ages, and particularly those on xenolith material, are much more problematic. In near surface metamorphic rocks, whole rock ages often date the formation of the rock, whereas ages determined on minerals separated from within a particular rock may reflect cooling after the last major thermal event. Furthermore, such mineral cooling ages are believed to date the time the rock cooled through different temperatures, known as blocking temperatures, which vary depending on the decay scheme used and the minerals analysed (Dodson, 1973). For xenoliths the problem is that, although the majority are metamorphic rocks, they have often been at conditions of pressure and temperature above, or close to, the likely blocking conditions for different mineral systems for considerable periods of time before being caught up in the kimberlite magma—which might also disturb any pre-existing mineral equilibria. Mineral results from Lesotho granulites include ages of 1500 and 1050 Ma from U-Pb on zircons (Davis, 1977) and 1000 and 714 Ma using the K/Ar method on a mica and hornblende respectively (Harte *et al.*, 1981). However, although to the best of our knowledge no Sm-Nd analyses have been published on separated minerals from south African crustal xenoliths, results on garnet-feldspar and garnet-pyroxene pairs from crustal xenoliths in the Midland Valley of Scotland and Kilbourne Hole, New Mexico yield ages analytically indistinguishable from the time of emplacement of the volcanic pipes (van Breemen and Hawkesworth, 1980; Richardson *et al.*, 1980). Thus for reasons which are still poorly understood, the existing data suggest that the Sm-Nd system equilibrates during emplacement, while the K/Ar system, which should have lower blocking temperatures, appears to preserve older, pre-emplacement ages.

Mantle xenoliths

Kimberlite pipes contain a wide range of different ultrabasic and basic xenoliths which can be shown to have originated in the upper mantle. Many have been little studied, and 'new finds' undoubtedly await discovery in the small mountains of xenoliths which still mark the sites of early diamond mines. Inevitably, classifications are therefore in a state of flux, and several exist reflecting the different perspectives of individual authors. Harte (this volume) has reviewed the more common categories of xenoliths and they include three types of peridotite which are distinguished on textural and mineralogical criteria, and are particularly relevant to the present discussion:

1. Coarse, typically granular, 'cold' Mg-rich peridotites are abundant and widely distributed. They tend to have only small amounts of clinopyroxene and garnet, and hence to be relatively 'infertile', that is, depleted in those major elements which are concentrated in basalt. Incompatible elements by contrast are often enriched, resulting in a characteristic 'decoupling' of major and trace elements that is usually explained by some combination of basalt extraction followed by trace element enrichment (Shimizu, 1975b).
2. Deformed, or sheared, 'hot' peridotites are less abundant than the course varieties, but they typically have more fertile major element compositions and, paradoxically, less enrichment in incompatible elements: for example, published REE patterns are near-chondritic (Nixon *et al.*, 1981). Mineral studies indicate that this group of sheared xenoliths reflect higher temperature conditions than the coarse granular peridotites and this, coupled with their deformed appearance, has prompted speculation that they were derived either from the base of the lithosphere (Boyd and Nixon, 1973), or from zones of deformation around rising diapirs of possible proto-kimberlite magma (Gurney and Harte, 1980).

3. Peridotites showing textural evidence for modal metasomatism, either along discrete veins, or more pervasively through the host rock. Associated minerals may include phlogopite, amphiboles, ilmenite, rutile and unusual opaques, and these usually signal the introduction of a spectacular range of trace elements depending on the character of the particular metasomatism (see Erlank *et al.*, 1982; Jones *et al.*, 1982; and Harte, this volume). However, the common critical feature is that modal metasomatism describes *in situ* chemical and mineralogical change within the mantle that pre-dates the incorporation of the xenolith into the kimberlite magma.

In general, modal metasomatism can occur both in granular or sheared peridotites; but what is less clear is the extent to which, in view of their chemical differences, sheared 'hot' peridotites can be the deformed equivalents of coarse granular peridotites, or whether they represent two chemically distinct zones in the upper mantle—one which tends to be deformed, and the other less so.

A more specific classification has been developed by Erlank and his co-workers (Erlank and Richard, 1977; Erlank *et al.*, 1982) from their work on xenoliths from the Bultfontein pipe near Kimberley (see Figure 1). They recognize, using mineralogy as a basis for interpreting chemical variations, four different types of peridotite: 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. All samples tend to be depleted in basaltic constituents, such as Ca and Al, and enriched in trace elements, as described above for the common granular peridotites. In detail, however, the garnet-bearing (GP and GPP) and garnet-free (PP and PKP) peridotites exhibit different patterns of trace element enrichment which, with time, result in systematic differences in Nd- and Sr-isotopes.

The available $^{143}Nd/^{144}Nd$ and $^{147}Sm/^{144}Nd$ results on peridotite whole rocks and separated diopsides and one K-richterite are summarized in Figure 5. The relationship between the mineral and the whole rock analyses is illustrated by the solid line joining co-existing diopside, K-richterite, and whole rock points, and in general the diopsides have much higher Nd concentrations and lower $^{143}Nd/^{144}Nd$ ratios than their host rocks (Menzies and Murthy, 1980b; Erlank *et al.*, 1982). Thus, in contrast with the mineral equilibria observed in crustal xenoliths, these diopsides and their host rocks were not in isotopic equilibrium at the time of their emplacement in the kimberlite ($\sim$90 Ma). The simplest interpretation is that because of their low Nd contents (all but one have between 1–6 ppm Nd) the compositions of the whole rock samples have been more readily affected by interaction with material with high $^{143}Nd/^{144}Nd$ ratios. In practice that could either be due to contamination with the host kimberlite *en route* to the surface (many of the peridotite analyses plot close to the field for kimberlites in Figure 5), or to interaction with LREE enriched (and therefore low Sm/Nd), high $^{143}Nd/^{144}Nd$ mantle fluids *before* the xenoliths were caught up in the kimberlite. However, in either case it implies (a) that before the inferred change in the peridotite whole rock compositions, the range in their Nd-isotope ratios was greater, and extended to lower $^{143}Nd/^{144}Nd$ values, than that observed today; and (b) that the $^{143}Nd/^{144}Nd$ ratios of the diopsides are the best available indication of the Nd-isotope composition of these fragments of the upper mantle before the event which appears to have changed their whole rock values.

The diopside with the lowest $^{143}Nd/^{144}Nd$ ratio in Figure 5 is from an eclogite (Basu and Tatsumoto, 1980), but the remainder are from a variety of peridotite types including both GPP and PKP. Significantly, many plot within the main trend of the Karoo lavas in Figure 4, and thus support the earlier conclusion that the trace element and Nd- and Sr-isotope ratios of the latter primarily reflect mantle processes, and have been little affected by crustal contamination. Most of the $^{143}Nd/^{144}Nd$ and $^{147}Sm/^{144}Nd$ ratios of the lavas and the diopsides from mantle peridotites are lower than those of the bulk earth indicating that both the xenoliths and the Karoo volcanics were derived from upper mantle source regions which had been variously enriched in LREE for considerable periods of time. Moreover, because most of the data plot above, and arguably with a slightly shallower slope, than the 1.4 Ga reference lines in Figures 4 and 5, 1.4 Ga is a reasonable upper limit for the age of these LREE enriched mantle source regions, which probably stabilized in the period 1.4–1.0 Ga. Notice, however, that one diopside in Figure 5 has a 2.7 Ga model Nd age and that coupled with some of the Pb-isotope data on inclusions in diamonds and on omphacites in eclogites (Kramers, 1979), indicates that at least patches of relict Archaean mantle also survived.

Most mantle peridotites have low Rb/Sr ratios (< 0.07) with the result that $^{87}Sr/^{86}Sr$ ratios change slowly with time and it is often difficult to obtain useful age information from the Rb-Sr decay system. Nonetheless significant variations are observed in the $^{87}Sr/^{86}Sr$ ratios of both the Karoo volcanics and mantle xenoliths, and these are summarized in Figure 6. Most of the data on mantle xenoliths are on material from Kimberley and Lesotho (see Figure 1), and thus they are compared with the initial $^{87}Sr/^{86}Sr$ ratios of those Karoo rocks from the three nearest sub-areas (CA, SL, N-NL) on which Nd-isotopes have been determined, and which for reasons outlined earlier are believed not to have been contaminated by continental crust.

Eight diopside megacrysts have initial Sr-isotope ratios in the range 0.7028–0.7040 at 90 Ma, the time of kimberlite emplacement (Kramers, 1979; Kramers *et al.*, 1981). These include samples from both Kimberley and Lesotho, that is, within and on the margin of the Archaean craton, and the low values are compatible with their high $^{143}Nd/^{144}Nd$ ratios (see Figure 5). Such Nd- and Sr-isotope ratios are well within the range commonly observed in oceanic island basalts (see White and Hofmann, 1982, and references therein) and are therefore consistent with crystallization from magmas derived from beneath the continental lithosphere (Gurney and Harte, 1980; Harte, this volume).

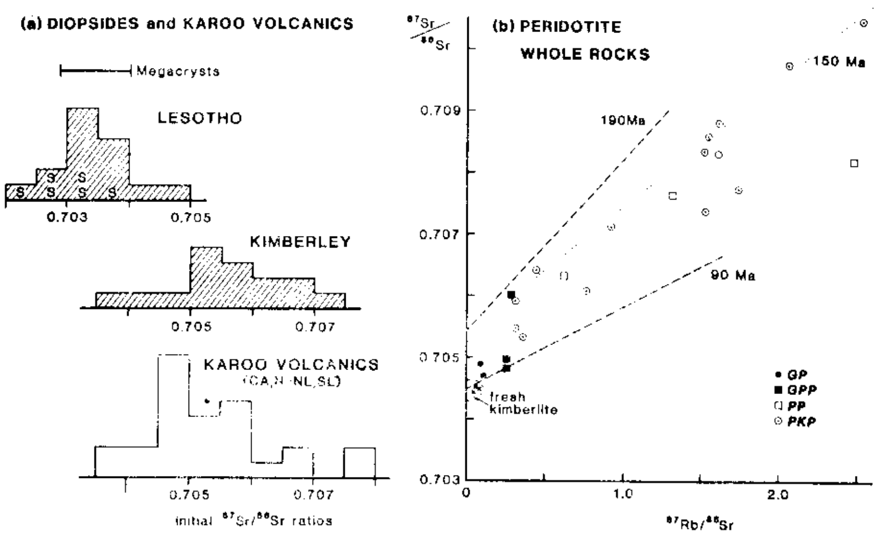

Figure 6 (a) Initial Sr-isotope variations in mantle diopsides and selected Karoo volcanics, and (b) $^{87}Sr/^{86}Sr$ versus $^{87}Rb/^{86}Sr$ diagram for peridotite xenoliths. Data from Kramers (1977, 1979), Menzies and Murthy (1980b), Kramers *et al.* (1981), Erlank *et al.* (1982), Allègre *et al.* (1982) and Hawkesworth *et al.* (in prep.). Initial ratios for the diopsides calculated at 90 Ma; S in the Lesotho data denotes diopsides from sheared peridotites. Abbreviations as in Figure 5

The diopsides from mantle peridotites exhibit a greater range in $^{87}Sr/^{86}Sr$ and, for reasons which are still poorly understood, they appear to differ systematically between Lesotho (0.7024–0.7050) and Kimberley (0.7037–0.7075, with one analysis of 0.7134) (Kramers, 1977; Menzies and Murthy, 1980b; Allegrè *et al.*, 1982). One interpretation is that these differences are simply a feature of the upper mantle beneath the cratonic areas compared with that beneath the surrounding mobile belts. The higher $^{87}Sr/^{86}Sr$ of the diopsides from Kimberley might be due to the presence of old upper mantle material which was not present beneath the surrounding mobile belts, consistent with the observation that diamondiferous kimberlites tend to be confined to cratonic areas. However, no clear differences were observed in the isotope composition of Karoo volcanics erupted on and off the Archaean craton, and it is noticeable that most of the lavas from Lesotho for example (CA, Figures 1 and 2) have higher $^{87}Sr/^{86}Sr$ ratios than the mantle diopsides from kimberlite pipes in that area. Thus an alternative, and to us more preferable explanation, is that the difference in $^{87}Sr/^{86}Sr$ between the diopsides of Kimberley and Lesotho is more a reflection of the rock types studied than an indication of major differences in the nature of the upper mantle. The samples analysed from Lesotho apparently contain very little, if any, primary phlogopite, whereas particularly the higher $^{87}Sr/^{86}Sr$ ratios from the Kimberley area were obtained on diopsides from GPP and PKP rocks. Nonetheless, more work is clearly needed before these two interpretations can be assessed satisfactorily.

Mantle diopsides have very low Rb/Sr ratios, far too low to generate the observed range in $^{87}Sr/^{86}Sr$ in those from Kimberley (Figure 6a) even over the 4.5 Ga since the formation of the earth. However, because many whole rock samples have low Rb and Sr contents and are therefore susceptible to alteration, the $^{87}Sr/^{86}Sr$ ratios of the diopsides are probably the best available indication of the Sr-isotope composition of the whole rock peridotites before the event which also affected their Nd-isotope ratios (see Figure 5 and discussion). That event may have also affected the Rb/Sr ratios of the whole rocks samples and thus they cannot be used to calculate reliable ages for the trace element enrichment in the mantle source regions. Yet the range of Sr-isotopes in the xenoliths and the Karoo lavas is consistent with the variations in Nd-isotopes which have already been attributed to trace element variations predominantly present since the Proterozoic (see Figures 4 and 5). For example, a peridotite which had the same $^{87}Sr/^{86}Sr$ ratio as the bulk earth 1.4 Ga ago, and was then enriched in trace elements so that its Rb/Sr = 0.07, would have had $^{87}Sr/^{86}Sr = 0.7068$ at 90 Ma, which is near the upper end of the range in mantle diopsides from Kimberley (see Figure 6a).

One exceptional suite of rocks which has high enough Rb and Sr contents and Rb/Sr ratios for that decay scheme to yield useful independent information are the garnet-free, PP and PKP whole rocks from the Kimberley area (Figure 6b, after Erlank *et al.*, 1982). Their Rb/Sr ratios range from 0.1–0.8 with the result that $^{87}Sr/^{86}Sr = 0.7055–0.7105$ could have been generated in just 150 Ma, as indicated by the dotted reference line in Figure 6b. Yet in practice it is extremely difficult to establish the age significance of such a scatter of whole rock results. Thus included for comparison on Figure 6b are reference lines for the main Karoo event at 190 Ma with an average initial $^{87}Sr/^{86}Sr$ ratio taken from the histogram in Figure 6a, and for kimberlite emplacement at 90 Ma with an initial Sr ratio of ~ 0.7045. Since all the nodule data plot between these lines we may reasonably conclude that they reflect an event which took place between 190 Ma and 90 Ma. The preferred interpretation is that the observed Sr-isotope composition of the PP and PKP rocks is due primarily to a sharp increase in Rb/Sr brought about by metasomatism not long after the main Karoo event (Erlank and Shimizu, 1977; Erlank *et al.*, 1980).

Significantly the high present day $^{87}Sr/^{86}Sr$ ratios in these xenoliths cannot be attributed to contamination from the host kimberlite, because at 90 Ma the kimberlites had *lower* $^{87}Sr/^{86}Sr$ ratios than any of the PP and PKP rocks analysed (see Figure 6b). If interaction with the host kimberlite did occur it would have tended to reduce the $^{87}Sr/^{86}Sr$ ratios of the xenoliths, which in turn implies that the observed Sr-isotope variation is a minimum estimate of that present in the mantle beneath Kimberley today.

In summary, different trace element enrichment events have been inferred from the study of Nd- and Sr-isotopes in mantle-derived rocks in southern Africa. The Sm-Nd system is more applicable to the dating of old LREE enriched material, and both the Karoo volcanics and mantle xenoliths provide evidence for the stabilization of LREE enriched portions of the upper mantle

~1.4–1.0 Ga ago. By contrast the Rb-Sr system is only likely to yield independent age information if unusually high Rb/Sr ratios are generated. Reassuringly, the average model Sr age of the high Rb/Sr Kraai River basalts from the Central area (see Figure 2) is 1.2 Ga (Hawkesworth *et al.*, in prep.), but the rest of the Sr-isotope data on Karoo volcanics and mantle diopsides are simply consistent with the upper Proterozoic age inferred from the Sm-Nd system; whereupon the range in $^{87}Sr/^{86}Sr$ suggests that these portions of trace element enriched mantle had Rb/Sr < 0.08. However, the garnet-free PP and PKP rocks have much higher Rb/Sr ratios (0.1–0.8) and they scatter about a 150 Ma reference line on an Rb-Sr isochron diagram (see Figure 6). Whatever their exact geochronological significance these data clearly reflect a second much younger trace element enrichment event, and the preferred interpretation is that it took place not long after the main Karoo magmatism at 190 Ma, and that it was responsible for the modal metasomatism observed in the PP and PKP rocks. Note also that this event is much too young to have been detected by the Sm-Nd system.

Trace element enrichment processes

Trace elements have been used widely, and with increasing success, to model processes of magmatic evolution and at least to constrain what may occur during partial melting (Gast, 1968; Allègre and Minster, 1978; Claque and Frey, 1982). However, comparatively little is understood about the processes which determine the inferred trace element variations in the mantle source rocks. Discriminant analysis has identified trends of trace element enrichment

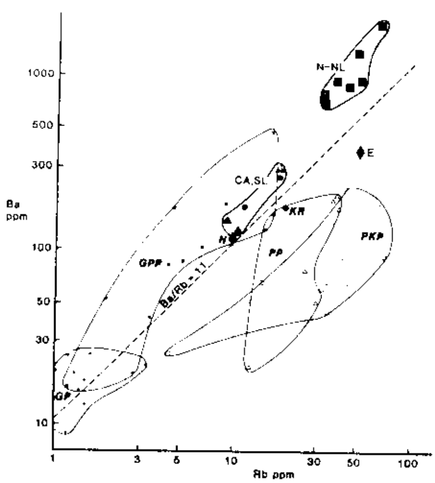

Figure 7 Ba versus Rb for mantle peridotites (after Erlank *et al.* (1982)) and Karoo volcanics. Abbreviations as in Figures 2 and 5. The variations in the Karoo volcanics are illustrated using average values compiled by Duncan *et al.* (in prep.)

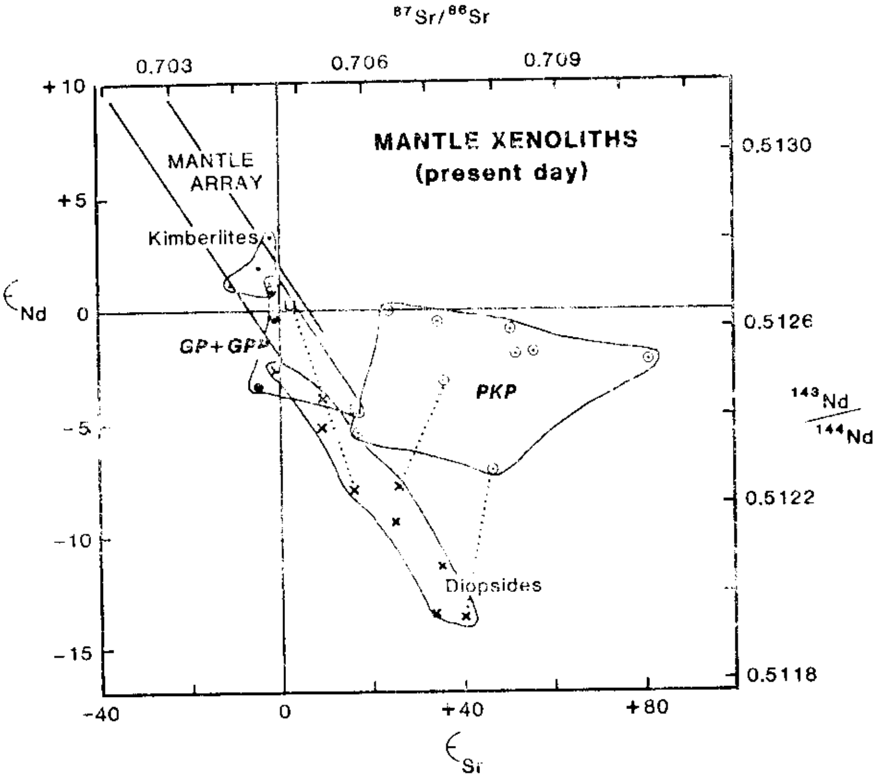

Figure 8 Present day Nd- and Sr-isotopic variations in mantle xenoliths and kimberlites from southern Africa (Menzies and Murthy, 1980b; Kramers *et al.*, 1981; Erlank *et al.*, 1982). Crosses—diopsides; other symbols and abbreviations as in Figure 6b

and depletion in the sources of basalts, and many studies have recognized that there are different styles of enrichment reflected by significant variations in the ratios between broadly 'incompatible' elements (e.g. Pearce and Cann, 1973; Tarney *et al.*, 1980; Pearce, 1982). In this section we briefly explore some of the similarities and differences in the patterns of trace element and isotope enrichment observed in the Karoo volcanics and the mantle xenoliths.

The discussion of isotope variations emphasized that PP and PKP xenoliths had much higher Rb/Sr ratios than the GP and GPP rocks and the majority of basic Karoo volcanics (see Figures 3 and 6b). Erlank *et al.* (1982) made a similar point on a diagram of Ba versus Rb (Figure 7) which illustrates that while both garnet-free and garnet-bearing peridotites can be similarly enriched in Ba, the former have much higher Rb contents. Both groups of peridotites are similarly enriched in LREE (compare their Sm/Nd ratios in Figure 5) although garnet-bearing rocks predictably have higher HREE contents (Erlank *et al.*, 1982). Thus two styles of trace element enrichment can be identified in these mantle xenoliths: both increase the concentrations of elements such as the LREE and Ba, but that seen in the PP and PKP rocks is characterized by much higher Rb (and K) contents. In practice these may well represent idealized end-members between which all gradations exist, but they have an important bearing on the study of radiogenic isotopes because their similar Sm/Nd and different Rb/Sr ratios should, with time, generate very different Nd- and Sr-isotope characteristics.

Figure 8 summarizes some of the available Nd- and Sr-isotope data on mantle xenoliths from the Kimberley area, and present-day compositions range from 0.5127–0.5120 for $^{143}Nd/^{144}Nd$ to 0.704–0.710 for $^{87}Sr/^{86}Sr$ (Menzies and Murthy, 1980b; Erlank *et al.*, 1982). The host basaltic kimberlites have higher Nd- and lower Sr-isotope ratios than most of the xenoliths, so that contamination by the kimberlite would have tended to increase $^{143}Nd/^{144}Nd$ and decrease $^{87}Sr/^{86}Sr$ in the xenoliths. Conversely, the observed variations in Nd- and Sr-isotope ratios in Figure 8 presumably represent a minimum estimate of the actual range of isotope compositions present in the upper mantle beneath Kimberley today. The dotted lines link co-existing diopsides and host rocks, and primarily reflect their different $^{143}Nd/^{144}Nd$ ratios already considered in connection with Figure 5. However, of particular relevance to the present discussion is that the garnet-free and garnet-bearing peridotites plot in separate fields consistent with their relative differences in Sm/Nd and Rb/Sr. GPP and GP rocks have low Rb/Sr ratios and plot on, or to the left of, the mantle array in Figure 8, whereas the high Rb/Sr PKP rocks are displaced to significantly higher $^{87}Sr/^{86}Sr$.

The discussion of the Karoo volcanics emphasized that relative differences in both Sm/Nd versus Rb/Sr and ϵ_{Nd} versus ϵ_{Sr} were also a feature of some magma types (see Figures 2 and 3), and these too may be recognized and compared with the xenolith data in Figure 7. Average Rb and Ba contents range from 10 and 119 ppm in the Horingbaai dolerites from Namibia to 55 and 920 ppm for the high-Mg picrites at Nuanetsi (Duncan *et al.*, in prep.); but in most of the magma types Rb/Ba varies little and the enrichment trend is similar to that observed in the GPP rocks. LREE contents increase, and so Sm/Nd decreases, with increasing Rb and Ba—but there is relatively little change in Rb/Sr. Thus with time this 'style of enrichment' results in a range of $^{143}Nd/^{144}Nd$, with fairly constant $^{87}Sr/^{86}Sr$, and hence a steep, near-vertical trend on an ϵ_{Nd} versus ϵ_{Sr} diagram, as illustrated by the Nuanetsi-north Lebombo rocks in Figure 2. In contrast the two magma types which have slightly higher Rb/Ba ratios (Kraai River and the Etendeka, Figure 7), are those which have relatively high $^{87}Sr/^{86}Sr$ ratios and hence lie on flat-lying trends on Figure 2. For these elements, and these isotope systems, they therefore exhibit a comparable style of enrichment to that observed in the garnet-free PP and PKP mantle xenoliths.

Although these results are extremely encouraging because they suggest that similarities do exist in the styles of trace element enrichment observed in both mantle xenoliths and continental basalts, it is clearly most important that they should be investigated further with a much greater variety of trace elements. However, this approach is presently frustrated by a shortage of high precision, multi-element analyses on mantle rocks.

Evolution of the sub-continental lithosphere

One of the striking aspects of the results on peridotite xenoliths and the Karoo volcanics in southern Africa is that while there is some evidence to suggest that the styles of trace element enrichment may be similar, it is also clear that they record events which took place at different times. In this section various pieces of evidence are brought together into a speculative model for the evolution of the sub-continental lithosphere beneath southern Africa. Many aspects are still open to alternative interpretations, but it is included as an illustration of the sorts of objectives which may be [illegible] by continued detailed study.

The 1.4–1.0 Ga Namaqua-Natal [illegible] belts around the Archaean cratons (see Figure 1) represent a [illegible] considerable volumes of new crust were generated, and [illegible] marked a large increase in the area of stable crust in southern Africa (Barton *et al.*, 19[illegible]; Rogers and Hawkesworth, 1982). Although there is some evidence that a few relict portions of Archaean mantle survived, most of the observed $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ variations in apparently uncontaminated Karoo basalts and mantle xenoliths could have been generated from the inferred Rb/Sr and Sm/Nd ratios in their source regions in 1.4–1.0 Ga (see Figures 4 and 5). It is, therefore, envisaged that the stabilization of these trace element enriched portions of the upper mantle was related to the formation of the Namaqua-Natal belt, on the presumption that increasing the area of stable continental crust will also increase the volume, and perhaps even the thickness, of material incorporated into the sub-continental lithosphere. Interestingly, many Karoo volcanics have trace element features, such as relatively low Nb contents (Hawkesworth *et al.*, in prep.) and low Ti/Y ratios (Cox, this volume) which are commonly observed in destructive plate margin basalts (Pearce, this volume). If these features are as old as the inferred Rb/Sr versus Sm/Nd variations, they could be due to subduction during the Namaqua-Natal event and thus support the suggestion that such processes are important in the formation of the sub-continental lithosphere (Oxburgh and Parmentier, 1978).

The subsequent evolution of the lithosphere is divided into two stages, and the changing $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ ratios are illustrated schematically in Figure 9. Stage I is from the stabilization of the lithosphere at 1.4–1.0 Ga to the main Karoo magmatic event at 190 Ma, and during this time the Nd- and Sr-isotope variations observed in the uncontaminated Karoo rocks (N-NL, CA, SL, Figure 9) evolved in response to the inferred variations of Sm/Nd and Rb/Sr in their source rocks. This event was then followed by metasomatism, which is most clearly developed in the PP and PKP xenoliths, but whose wider effects are still poorly understood.

The discussion of Figure 5 pointed out that the Nd-isotopic disequilibrium between diopsides and their host peridotites could reflect either contamination from kimberlite, or infiltration of the xenoliths by a high $^{143}Nd/^{144}Nd$ (and hence presumably low $^{87}Sr/^{86}Sr$) fluid before they were incorporated in the kimberlite. In either case it was argued that the diopsides offered the best indication of the isotope compositions of these fragments of mantle before their whole rock systems were disturbed, which in turn suggests that at that time they plotted along an extension of the 'mantle array' (see Figure 8). Thus we feel justified in extrapolating the isotope evolution of the diopsides back to before both the kimberlite (90 Ma) and the metasomatic events as a further indication of the isotope composition of mantle material at, for example, 190 Ma (Figure 9).

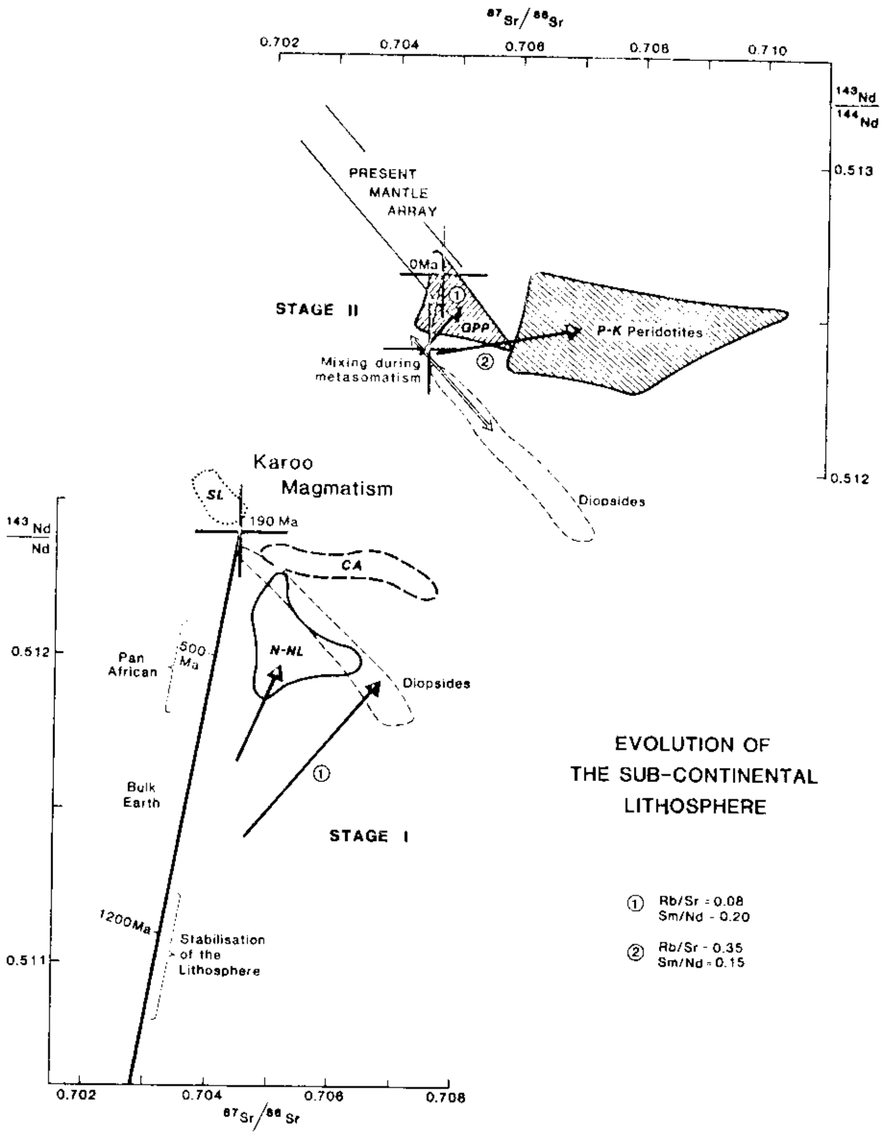

Figure 9 Schematic illustration of the proposed evolution of Nd- and Sr-isotope ratios within the sub-continental lithosphere of southern Africa. Stage I from 1.4–1.0 Ga to 190 Ma, stage II from the post-Karoo metasomatism to the present day

One interpretation is that the disturbance of the whole rock systems took place during the second mantle enrichment event which resulted in the modal metasomatism of the PP and PKP rocks (see Figure 6b). Prior to this event most samples lay on an extension of the mantle array and they are believed to have reflected trace element variations which had stabilized in the Proterozoic (Figure 5, and Stage I, Figure 9). Metasomatism then took place in response to the infiltration of fluids into the lithosphere soon after the Karoo event at 190 Ma; and while it appears to have had relatively little effect on the Nd-isotope composition of the diopsides, it increased the $^{143}Nd/^{144}Nd$, and probably reduced the $^{87}Sr/^{86}Sr$ ratios of the whole rock peridotites. The isotope compositions of both garnet-bearing and garnet-free peridotites seem to have been similarly affected (see Figure 5) and the majority may have moved up the mantle array to compositions near that of the bulk earth, as illustrated by the schematic mixing line in Figure 9. This marks the start of Stage II.

During metasomatism garnet-free PP and PKP assemblages developed locally, and because of their high Rb/Sr ratios they generated $^{87}Sr/^{86}Sr$ ratios of 0.7055–0.7105 in a comparatively short period (~150 Ma. Figure 6b) and now plot well to the right of the mantle array (path 2 in Figure 9). Where garnet phlogopite assemblages occurred, they tended to have much lower Rb/Sr ratios, and so evolved along steeper paths in Figure 9 to the present GPP field. In this model the slopes of the tie-lines between present day whole rock and diopside compositions (see Figure 8) are due primarily to the Rb/Sr ratios of the whole rock peridotites over the last 150 Ma: those with higher Rb/Sr ratios tend to have higher ϵ_{Sr} values and hence the tie-lines to their diopsides are more likely to have positive slopes.

The above interpretation is just one of several which are tenable at the time of writing, but it envisages that the different types of peridotite were affected, albeit variously, by the young metasomatic event and it illustrates the type of two-stage model required to explain the xenolith results. The important point is that whatever the correct explanation, garnet-free and garnet-bearing peridotites have different Nd- and Sr-isotope characteristics consistent with their different trace element patterns, and that similar variations are observed in the Karoo volcanic rocks. The present data suggest that the older, Proterozoic enrichment tended to generate low Sm/Nd and relatively low Rb/Sr ratios, akin to the Nuanetsi volcanics and the GPP rocks, so that most of the enriched rocks evolved on, or to the left of, the mantle array. However, it is much more difficult to assess the overall character of the younger (~150 Ma) event, primarily because there has been too little time for distinctive isotope compositions to evolve in anything but unusually high Rb/Sr rocks (PP and PKP peridotites, see Figure 6b).

Finally, there are a few magmatic rocks in southern Africa which post-date the estimated age of the young metasomatism. Fresh basaltic kimberlites have similar Nd- and Sr-isotope ratios to the bulk earth (Kramers *et al.*, 1981), but interestingly micaceous kimberlites have recently been shown to have higher $^{87}Sr/^{86}Sr$ and lower $^{143}Nd/^{144}Nd$ ratios suggesting that they may have been derived from 'old' trace element enriched lithosphere, similar to that described in Figure 9 (C. Smith, pers. comm., 1983). Most of the mafic Tertiary alkaline volcanics by contrast have initial $^{87}Sr/^{86}Sr$ ratios in the range 0.70325–0.70385 and ϵ_{Nd} = +2.0 to +4.0 (Marsh *et al.*, 1981).

Conclusions

1. Lower $^{143}Nd/^{144}Nd$ and higher $^{87}Sr/^{86}Sr$ ratios than those of the bulk earth do occur in upper mantle rocks in continental areas, and great care must be taken in using these data to assess the effects of crustal contamination.
2. Crustal contamination is likely either to generate some broad mixing relation between the original magma and a crustal component, and/or to disrupt any pre-existing relationship between isotope and parent/daughter trace element ratios with the result that the two become 'decoupled'. Some of the Karoo basalts from the south Lebombo appear to have been contaminated with Archaean crust, but the majority of Karoo rocks studied have probably not been affected significantly by crustal contamination processes (see also Cox, this volume).
3. Different styles of trace element enrichment have been recognized in both mantle xenoliths and Karoo basalts, and with time these result in different trends on ϵ_{Nd} versus ϵ_{Sr} diagrams (see Figures 2 and 8).
4. The high $^{87}Sr/^{86}Sr$ and low $^{143}Nd/^{144}Nd$ ratios of many Karoo basalts and, for example, the separated diopsides from mantle peridotites (Menzies and Murthy, 1980b), suggest that they were derived from within the continental lithosphere; since that is where variations in Sm/Nd and Rb/Sr are likely to persist for long enough to generate the observed range in Nd- and Sr-isotopes (see also Cohen *et al.*, 1982).
5. Beneath southern Africa much of the sub-continental lithosphere appears to have stabilized 1.4–1.0 Ga ago (see Figures 4 and 5), which is also the time of significant crustal growth within the Namaqua-Natal mobile belts (see Figure 1). It is envisaged that the two are related, and that increasing the area of stable continental crust also increases the volume and perhaps even the thickness, of material incorporated into the sub-continental lithosphere.
6. Metasomatism took place after, and apparently in response to, the Karoo volcanism, and present evidence suggests that while many of the Karoo basalts were generated within the lithosphere, metasomatism took place in response to fluids derived from outside the lithosphere—presumably from the convecting upper mantle.

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