

## Nd-Isotopes in Selected Mantle-Derived Rocks and Minerals and Their Implications for Mantle Evolution

Asish R. Basu and Mitsunobu Tatsumoto

<sup>1</sup> Department of Geological Sciences, University of Rochester, Rochester, NY 14627, USA

<sup>2</sup> Branch of Isotope Geology, U.S. Geological Survey, MS 963, Denver, Colorado 80225, USA

**Abstract.** The Sm–Nd systematics in a variety of mantle-derived samples including kimberlites, alnoite, carbonatite, pyroxene and amphibole inclusions in alkali basalts and xenolithic eclogites, granulites and a pyroxene megacryst in kimberlites are reported. The additional data on kimberlites strengthen our earlier conclusion that kimberlites are derived from a relatively undifferentiated chondritic mantle source. This conclusion is based on the observation that the  $\varepsilon_{\text{Nd}}$  values of most of the kimberlites are near zero. In contrast with the kimberlites, their garnet lherzolite inclusions show both time-averaged Nd enrichment and depletion with respect to Sm. Separated clinopyroxenes in eclogite xenoliths from the Roberts Victor kimberlite pipe show both positive and negative  $\varepsilon_{\text{Nd}}$  values suggesting different genetic history. A whole rock lower crustal scapolite granulite xenolith from the Matsoku kimberlite pipe shows a negative  $\varepsilon_{\text{Nd}}$  value of –4.2, possibly representative of the base of the crust in Lesotho. It appears that all inclusions, mafic and ultramafic, in kimberlites are unrelated to their kimberlite host.

The above data and additional Sm–Nd data on xenoliths in alkali basalts, alpine peridotite and alnoite–carbonatites are used to construct a model for the upper 200 km of the earth's mantle – both oceanic and continental. The essential feature of this model is the increasing degree of fertility of the mantle with depth. The kimberlite's source at depths below 200 km in the subcontinental mantle is the most primitive in this model, and this primitive layer is also extended to the suboceanic mantle. However, it is clear from the Nd-isotopic data in the xenoliths of the continental kimberlites that above 200 km the continental mantle is distinctly different from their suboceanic counterpart.

Reprint requests to: A.R. Basu

### Introduction

The success and the rapid development over the past decade of plate tectonics as a comprehensive working model of surficial earth movements have greatly increased interest in the processes in the upper mantle. The most direct source of information on the earth's upper mantle comes from ultramafic rocks from different tectonic environments. The suites of ultrabasic xenoliths from alkali olivine basalts and kimberlite volcanic pipes represent samples of the suboceanic and subcontinental upper mantle, whereas ultrabasic rocks of the “Alpine-type” represent mantle-exposures or diapiric rise of mantle material at spreading centers with subsequent emplacement and modification at subduction zones.

The application of Nd-isotopes in studying the history and evolution of the earth's upper mantle has received considerable attention in the current literature (e.g., DePaolo and Wasserburg 1976; Richard et al. 1976; O'Nions et al. 1977; Carlson et al. 1978; Basu and Tatsumoto 1978, 1979). Most of these studies have been restricted primarily to rocks of basaltic composition which are considered to be direct products of partial melting in the upper mantle. However, the general interpretation that melts of basaltic composition, particularly those which erupt through thick continental crust, represent primary melts from the mantle unmodified during ascent may not be valid.

In a preliminary study of Sm–Nd systematics of kimberlites and their ultrabasic inclusions, Basu and Tatsumoto (1978, 1979) noted that important information about the history and evolution of the earth's mantle can be obtained from these samples. This study showed that the initial  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios of kimberlites ranging in age between 90 and 1,300 m.y. from South Africa, India, and the United States are different from the corresponding ratios in the

peridotite inclusions but are identical to the bulk earth chondritic ratio. In the present paper, we have extended our data base of the previous study by analyzing the Sm—Nd systematics in a variety of mantle-derived samples including kimberlites, alnoite, carbonatite, pyroxene and amphibole inclusions in alkali basalts, eclogites and granulites in kimberlites and pyroxene megacryst in kimberlite. Our preference for these types of "more direct" samples of the upper mantle is due to the conclusion from several studies which indicate that these samples are brought to the surface by relatively rapid processes so that chances of intermixing with the superstratum are minimal.

### Selected Mantle-Derived Samples

#### *Kimberlites*

Recent experimental work (Eggler and Wendlandt 1979; Wyllie 1979) suggest that mantle peridotite has a univariant solidus in the presence of  $\text{CO}_2$  and  $\text{H}_2\text{O}$  and that kimberlitic liquids can be produced by partial melting of peridotite near this univariant solidus. Estimation of the pressure and temperature conditions of equilibration of garnet peridotite inclusions in kimberlites (Boyd 1973) indicates a minimum depth of origin of 180 km for the kimberlites of southern Africa. Kimberlite is the only rock type accessible for study which is known to have originated from such depths in the mantle. The kimberlites chosen for analysis in this study are fine-grained, bluish gray and consists mostly of a carbonate-silicate mixture. They also contain variable amounts of small phenocrysts of olivine and phlogopite set in a fine-grained matrix of serpentine, calcite, phlogopite, and magnetite-rich spinel. The ages of emplacement of all but two kimberlite pipes included in this study are discussed in Basu and Tatsumoto (1979).

The Avon diatreme of south-eastern Missouri yields an emplacement age of 390 m. y. by both the K—Ar and the Rb—Sr methods (Zartman et al. 1967). The Yakutian kimberlite analyzed in this study has not been dated. But it is on the Lower Oleneck and the zircons in the kimberlites from this area have yielded an age of 150 m. y. by the U—Pb method (Davis 1978).

#### *Alnoite and Carbonatites*

Alnoite greatly resembles kimberlite in groundmass petrography, inclusion contents and major and trace element chemistry. Both are considered to have origi-

nated at similar depths in the mantle. Alnoites are distinguished from kimberlites by the presence of melilitite in the groundmass of the former and by their generally lower  $\text{MgO}$  contents and lower  $\text{K}_2\text{O}/\text{Na}_2\text{O}$  ratios. The sample analyzed is from Malaita, Solomon Islands (Nixon and Boyd 1979) and is unique in the sense that it occurs in a typical oceanic environment. The sample is essentially a phlogopite-melilitite-olivine pyroxene breccia, dated at 34 m. y. old (Davis 1977), and contains a xenolith-suite similar to those found in continental kimberlites. The groundmass of this sample contains perovskite, magnetite, apatite, melanite, nepheline, phlogopite and glass (Nixon and Boyd 1979).

The two carbonatites selected for this study are from McClure Mountain, Colorado, and from Magnet Cove, Arkansas. They are essentially pure  $\text{CaCO}_3$  rock and are associated with alkaline syenitic igneous complexes. The McClure Mountain complex has been dated at 520 m. Y. old by K—Ar and Rb—Sr methods (Olson et al. 1977). The Magnet Cove complex is found to be 95 m. y. old by the K—Ar method (Zartman et al. 1967).

#### *Inclusions in Alkaline Basalts and Amphibole in Alpine-Type Peridotite*

Evidence from several sources (e.g., Ringwood 1975) indicate that the suboceanic uppermost mantle is spinel peridotitic in composition. Further, the heat flow, the gravity and the seismic data of the alkali basalt bearing continental rift systems indicate that the upper mantle beneath these rift zones is comparable to the suboceanic upper mantle in physical properties. The spinel lherzolites are most commonly found as xenoliths in alkali basalts and as massifs in alpine-type peridotites. The anhydrous minerals of these lherzolites such as olivine, orthopyroxene and clinopyroxene contain extremely low amounts of the large ion lithophile elements (Basu and Murthy 1977a and references therein). Basu and Murthy (1977b) showed that the hydrous mineral kaersutite, which is often associated with mantle-derived spinel lherzolites, are enriched in these trace elements as compared with the anhydrous silicates in the lherzolites. We have chosen two kaersutite samples for the present study — one is an inclusion in alkali basalt of Recent age from Dish Hill, California, the other is associated with the spinel lherzolite massif of the alpine-type in Lherz in the French Pyrenees. The lherzolite massif of Lherz may be considered to be a slice of the upper mantle emplaced sometime during the Tertiary orogenic movements. We also analyzed a diopside miner-

al separate from a spinel lherzolite inclusion in the Quaternary alkali basalt of the Rhine-Graben from Dreiser Weiher, West Germany. The fourth sample in this category is a whole rock garnet peridotite inclusion in a Recent alkali basalt from Salt Lake Crater in Oahu, Hawaii.

#### *Minerals in Garnet Peridotite Inclusions from Southern African Kimberlites*

The granular and sheared garnet lherzolite xenoliths in southern African kimberlites are possibly the best documented samples of the subcontinental upper mantle (Boyd 1973; MacGregor and Basu 1974). The granular group is considered to have originated at depths of 100–150 km whereas the sheared varieties are believed to be derived from a deeper 150–180 km depth interval. The garnet lherzolites selected for this study come from the Bultfontein and the Jagersfontein pipe in South Africa and the Matsoku pipe in Lesotho. It is interesting to note that the garnet lherzolites from the Lesotho area are thought to be of substantially deeper origin than the corresponding xenoliths from the Bultfontein pipe (Boyd 1978, personal communication). However, in any individual kimberlite pipe the granular garnet lherzolites are in general of shallower origin than the sheared varieties. For example in the case of the Bultfontein pipe, the sample B-101, a sheared xenolith, is derived from a deeper level in the mantle than the granular xenolith B-33 (Table 4).

#### *Eclogites, Granulites and Megacryst Inclusions in Kimberlites from Southern Africa*

During the explosive eruption, kimberlite includes within it a variety of eclogitic and granulitic inclusions in addition to the garnet peridotites. Further, the kimberlites also contain a suite of megacryst inclusions. We selected clinopyroxene mineral separates from three eclogites in the Roberts Victor pipe, one whole rock plagioclase-scapolite granulite of supposedly lower crustal origin from the Matsoku pipe, and one discrete diopside megacryst from the Mukorob pipe. The clinopyroxenes from the eclogitic xenoliths are different from those in the peridotitic xenoliths in that they are omphacitic with considerable amounts of  $\text{Na}_2\text{O}$  and  $\text{Al}_2\text{O}_3$ . MacGregor and Carter (1970) classified eclogitic xenoliths in kimberlites into two groups and considered that the group I eclogitic clinopyroxenes were less calcic than group II eclogitic clinopyroxenes. The samples we analyzed belong to both these groups.

#### **Analytical Methods and Data Presentation**

The analytical methods for determining Sm, Nd concentration and the Nd-isotopic composition are similar to those described by Nakamura et al. (1976). The whole rock and the hand-picked pure mineral separates were decomposed by  $\text{HF}-\text{HClO}_4-\text{HNO}_3$  mixture in teflon bombs. After repeated evaporation with  $\text{HClO}_4$ , the samples were finally dissolved in 4–5 ml of 2N-HCl in a teflon bomb on a hot plate. The main aliquot of 70% of the solution was used for the determination of the Nd-isotopic composition, the remainder of the solution was spiked with a composite ( $^{150}\text{SM}-^{146}\text{Nd}$ ) solution for the measurement of Sm and Nd concentrations. The rare earth elements (REE) were separated first in a large column in 6N-HCl. The final separation of Sm and Nd was accomplished in a micro column with a 0.2 M  $\alpha$ -hydroxyisobutyric acid solution with the pH previously adjusted to 4.495. Sm and Nd were loaded on Ta-filaments in a reducing gas atmosphere of 85%  $\text{N}_2$  and 15%  $\text{H}_2$  as phosphate and were measured by a triple filament mode in an NBS 30 cm 60 degree mass spectrometer equipped with on-line data acquisition and processing and magnetic field switching capabilities. Errors in the Sm and Nd concentration measurements were better than 0.3%. The measured  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios are normalized to  $^{150}\text{Nd}/^{144}\text{Nd}$  ratio of 0.23643, the uncertainties reported in the measured ratios are  $2\sigma$  mean and correspond to the last figures. In the data reported in tables 1–5, the initial  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios are estimated by assigning a 10% error in the age of the rock and an 0.1% error in the measured Sm/Nd ratios. From the initial ratios,  $\varepsilon_{\text{Nd}}$  value which is deviation of the ratio from the chondritic value at the rock age ( $T$ ) is also estimated by using the relation:

$$\varepsilon_{\text{Nd}} = \left[ \frac{(^{143}\text{Nd}/^{144}\text{Nd}) \text{ initial in sample}}{(^{143}\text{Nd}/^{144}\text{Nd}) \text{ in Juvinas at } T} - 1 \right] \times 10^4.$$

Juvinas is a eucrite-meteorite (Duke and Silver 1967) that gave a crystallization age of  $4.56 \times 10^9$  years by the Sm–Nd method (Lugmair 1974) and it has a Sm/Nd ratio very close to the chondritic ratio (Masuda et al. 1973). Therefore, Juvinas has been used to represent “the bulk chondritic earth” (Lugmair et al. 1976; Depaolo and Wasserburg 1976a). Here, we have used the best estimate for the present-day  $^{143}\text{Nd}/^{144}\text{Nd}$  ratio of bulk Juvinas to be 0.512636 with an initial value of 0.5068 at a time  $4.56 \times 10^9$  years before the present. For the  $^{147}\text{Sm}/^{144}\text{Nd}$  ratio of Juvinas we have used 0.1936 (Nakamura et al. 1976; Lugmair et al. 1976). Unruh et al. (1977) report almost identical numbers as those of Juvinas for a different achondrite, Pasamonte, which has a crystallization age of  $(4.56 \pm 0.09) \times 10^9$  years with an initial ratio of  $0.50681 \pm 0.00010$ .

The  $\varepsilon_{\text{Nd}}$  value of zero or near zero in mantle-derived samples will, therefore, indicate undifferentiated, primitive mantle source in terms of Sm/Nd ratios. Positive or negative departures from the  $\varepsilon_{\text{Nd}}$  value of zero in other samples indicate at least one episode of fractionation in the Sm/Nd ratios of their source material with respect to the same ratios in a chondritic mantle.

#### **Results and Discussion**

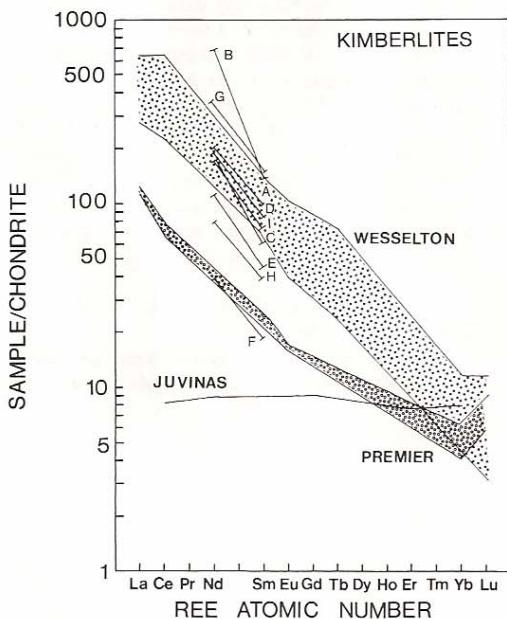
##### *Kimberlites*

Tables 1–5 show the results of the experimental determinations of Sm–Nd contents and Nd-isotopic compositions of the various mantle-derived samples selected for this study. Figures 1–3 show some of these results graphically.

**Table 1.** Sm, Nd contents and the measured  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios in the kimberlites. Also shown are the pipe emplacement ages and the  $\varepsilon_{\text{Nd}}$  values at the time of emplacement of each of these kimberlites

Kimberlite pipe	Sm (ppm)	Nd (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$	Age ( $\times 10^6$ years)	$^{143}\text{Nd}/^{144}\text{Nd}$ Initial	$\varepsilon_{\text{Nd}}$
<i>South Africa</i>							
Bultfontein (B-109)	20.163	126.463	0.1010	$0.512669 \pm 42$	90	$0.512610 \pm 42$	$+1.7 \pm 0.8$
Benfontein (Carbonatitic) (Ben 1)	28.243	423.495	0.0695	$0.512625 \pm 32$	90	$0.512584 \pm 32$	$+1.2 \pm 0.6$
DeBeers (FRB-372)	29.24	225.39	0.0784	$0.512632 \pm 30$	90	$0.512585 \pm 30$	$+1.2 \pm 0.6$
Premier (P-1)	3.791	24.555	0.0932	$0.511752 \pm 27$	1,300	$0.510956 \pm 82$	$-0.5 \pm 1.5$
<i>Southern India</i>							
L-1	17.254	119.353	0.0874	$0.511987 \pm 37$	940	$0.511448 \pm 66$	$+0.1 \pm 1.2$
L-2	9.205	69.551	0.0800	$0.511906 \pm 30$	940	$0.511413 \pm 65$	$-0.6 \pm 1.2$
<i>Colorado-Wyoming</i>							
Nix-2	12.642	116.305	0.0657	$0.512369 \pm 19$	377	$0.512207 \pm 30$	$+1.0 \pm 0.6$
<i>Southeastern Missouri</i>							
Avon (77-1)	8.134	49.058	0.1002	$0.512450 \pm 20$	390	$0.512190 \pm 30$	$+1.0 \pm 0.6$
<i>Yakutia (USSR)</i>							
Obnazennaya (FRB-552)	15.101	118.465	0.0770	$0.512668 \pm 40$	150	$0.512612 \pm 40$	$+3.2 \pm 0.8$

Data for the kimberlites from South Africa, India and Colorado are from Basu and Tatsumoto (1979)



**Fig. 1.** Chondrite-normalized Sm, Nd concentrations in the various kimberlites analyzed in this study. The complete REE patterns of several kimberlites from the Wesselton pipe and from the Premier pipe are also shown, taken from the literature (Fesq et al. 1975; Mitchell and Brunfelt 1977). The REE pattern in the basaltic achondrite, Juvinas is from (Schnetzler and Philpotts 1969). *A* and *I* are the same Kimberlites as in Fig. 2

Table 1 shows the Sm–Nd data for nine kimberlites along with the best estimates of their ages of emplacement. Figure 1 shows the chondrite-normalized REE patterns of kimberlites, taken from the literature (Fesq et al. 1975; Mitchell and Brunfelt 1975), and from our high-precision Sm–Nd determinations by the isotope-dilution method. The data on seven kimberlites have already been reported by us (Basu and Tatsumoto 1979). These data are reproduced in Table 1 along with the new analyses of kimberlites. The additional two analyses further strengthen our earlier conclusion that kimberlites are derived from a relatively undifferentiated chondritic mantle source. This conclusion is based on the observation that the  $\varepsilon_{\text{Nd}}$  values of most of the kimberlites are near zero, with the exception of the Yakutian (USSR) kimberlite. The slightly higher ( $+3.2 \pm 0.8$ ) positive  $\varepsilon$  value for this kimberlite, compared to the others, may be due to an error in the estimation of its age.

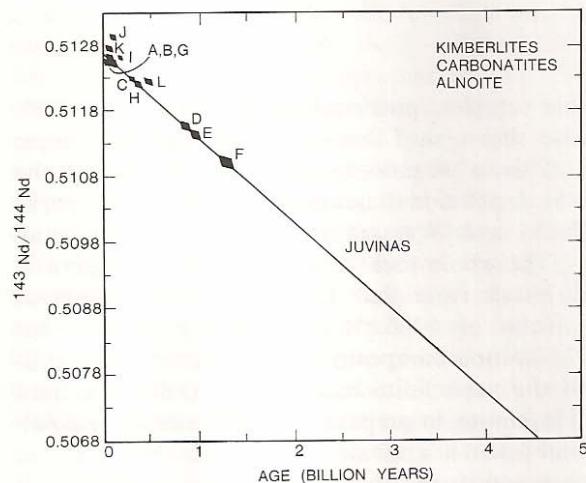
Traditionally, the very high incompatible element concentration, such as the light REE, in kimberlites have been explained by enrichment of these elements in the source materials for kimberlites (e.g., Frey et al. 1977), or by volatile transfer (Loubet et al. 1972).

Our data on the kimberlites do not allow us to evaluate these processes critically. However, the Sm—Nd data of the kimberlites show, at least, that the source of kimberlites could not have been fractionated from a chondritic REE pattern for a long period of time prior to the generation of the kimberlite. In addition, the ultimate source of these incompatible elements must be, by the constraints of the Sm—Nd data, chondritic. If we arbitrarily take the REE pattern of Juvinas which is approximately 8 times enriched in the REE compared to chondrites to be representative of the Kimberlite's source in the mantle, then it requires a 0.4% melting of a garnet lherzolite with a garnet to clinopyroxene ratio of 17:3 to produce the REE pattern of the Premier pipe in Fig. 1 using available solid-liquid partitioning data of the earth elements. The observed variable REE concentrations in different samples of kimberlite (Table 1, Fig. 1) may be attributed to variable silicate-carbonate ratios

in the kimberlitic matrix. For example, the carbonate-rich kimberlite from Benfontein (Table 1, Fig. 1) shows the highest enrichment in the light REE whereas the silicate-rich, carbonate-poor, Premier kimberlite shows lowest light REE concentration.

Figure 2 demonstrates the remarkable correlation between the initial Nd isotopic ratios of the nine kimberlites and the Juvinas growth curve during a time period of 90 to 1,300 m.y. before present. This correlation strongly indicates that the kimberlite's source is relatively primeval and chondritic in composition. We would like to emphasize that kimberlites are the only rock type that shows this correlation consistently in space and time. As mentioned earlier, kimberlites are also the only rock-type known to be derived from ~200 km within the earth. These observations can provide important constraints on the nature and evolution of the earth's mantle.

DePaolo and Wasserburg (1976a, b) observed that the initial  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios of continental igneous rocks, including acidic and basic varieties, indicated their derivation from a reservoir with chondritic REE pattern. They further suggested that the reservoir for these continental igneous rocks may represent primary material remaining since the formation of the earth. These authors did not analyze any kimberlite, although DePaolo (1978) later reported two analyses of kimberlites with  $\varepsilon$  values widely deviated, on both the positive and the negative side (+3.6 and -11) of the bulk earth chondritic value. Since kimberlites usually contain plenty of country rock inclusions, one may need a careful sample selection. We regard the anomalous results in DePaolo's analyses of kimberlites to be due to the presence of exotic rock fragments which are not related to the 'true kimberlite'. The data presented here clearly indicate the uniqueness of the kimberlite's source region in the mantle.



**Fig. 2.** The initial  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios of the kimberlites, alnoite, and carbonates are shown with reference to the Juvinas growth curve in time versus  $^{143}\text{Nd}/^{144}\text{Nd}$  space. A to I are the following kimberlites: A=Bulffontein; B=Benfontein (carbonatitic); C=Nix 2; D=L1; E=L2; F=Premier; G=DeBeers; H=Avon; I=Yakutian; J=Magnet Cove carbonatite; K=Alnoite; L=McClure Mountain Carbonatite

#### Alnoite and Carbonatites

Table 2 and Fig. 2 show the Sm—Nd data for these three samples. The alnoite, a rock very similar to

**Table 2.** Sm—Nd data in the Alnoite and in the carbonatites

Sample number	Rock type	Locality	Age	Sm (ppm)	Nd (ppm)	$(^{147}\text{Sm}/^{144}\text{Nd})$	$(^{143}\text{Nd}/^{144}\text{Nd})$ Measured	$(^{143}\text{Nd}/^{144}\text{Nd})$ Initial	$\varepsilon_{\text{Nd}}$
PHN-3544	Alnoite	Malaita Solomon Island	34 m.y.	24.424	143.65	0.1028	$0.512802 \pm 35$	$0.512775 \pm 35$	$+3.7 \pm 0.7$
419X	Carbonatite	McClure Mountains Colorado	520 m.y.	43.034	321.73	0.0808	$0.512540 \pm 19$	$0.512265 \pm 19$	$+5.6 \pm 0.4$
MC-1	Carbonatite	Magnet Cove Arkansas	95. m.y.	8.656	61.295	0.0853	$0.512967 \pm 15$	$0.512914 \pm 15$	$+7.6 \pm 0.3$

**Table 3.** Sm—Nd data in inclusions in alkali basalts and in amphibole from an alpine-type peridotite. Rb—Sr data in the two samples of amphiboles are from Basu (1978)

Sample number	Mineral or rock type	Locality	Age	K (ppm)	Rb (ppm)	Sr (ppm)	Ba	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}$	Sm (ppm)	Nd	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$	$\varepsilon_{\text{Nd}}$
DW-2	Diopside in lherzolite inclusion in alkali basalt	Dreiser Weiher West Germany	Quaternary	—	—	—	—	—	—	1.961	5.810	0.2040	0.51285 ± 20	+4.1 ± 0.4
H-13	Kaersutite inclusion in alkali basalt	Dish Hill California	Recent	22,010	11.23	487.9	137.1	0.0666	0.70273 ± 5	4.479	15.664	0.1730	0.513088 ± 30	+8.8 ± 0.6
FL-4B	Kaersutite in Alpine type lherzolite	Lherz, French Pyrenees	Tertiary(?)	13,173	5.815	511.1	163.5	0.0329	0.70306 ± 7	4.421	9.686	0.2758	0.513038 ± 50	+7.8 ± 1.0
66-Sal-1	Garnet lherzolite inclusion in alkali basalt of Salt Lake Crater	Oahu, Hawaii	Recent	—	—	—	—	—	—	—	—	—	0.513080 ± 20	+8.6 ± 0.4

K, Rb, Ba and Sr data from Basu (1978)

kimberlite but with clear chemical differences, shows a small positive  $\varepsilon$  value which indicates that its source region has a time-averaged Sm/Nd greater than the bulk earth value. The general range of  $\varepsilon$  values of the carbonatites is very similar to that found in the present-day ocean island alkali basalts. This similarity suggests that the suboceanic mantle source of ocean island alkali basalts is also present beneath the continents from where the carbonatites are derived. It is also noteworthy that the sources of these carbonatites are unrelated to the mantle-source of kimberlites which have a distinctive chondritic Sm/Nd character as shown in the previous section. This difference also suggests that the carbonatites associated with the kimberlites (such as the Benfontein sample) and those associated with alkalic complexes (such as the Magnet Cove and the McClure Mountain samples) have different petrogenetic histories.

#### Inclusions in Alkali Basalt and Kaersutite in Alpine Peridotite

The four samples analyzed in this category show  $\varepsilon_{\text{Nd}}$  values between +4.1 to +8.8, similar to the range found in ocean island basalts. The diopside in the spinel lherzolite from Dreiser Weiher shows the lowest  $\varepsilon_{\text{Nd}}$  value of +4.1. The two kaersutite samples from two different continents and with different modes of occurrences have identical Nd-isotopic compositions. The Sr-isotopic composition of these am-

phibole samples, previously published (Basu 1978), are also shown in Table 3. The Nd and Sr isotopic data of these amphiboles also fall well within the Nd—Sr correlation diagram for young volcanic rocks (DePaolo and Wasserburg 1976b; O'Nions et al. 1977). The whole rock garnet lherzolite inclusion in alkali basalt from Salt Lake Crater, Oahu, shows a  $\varepsilon_{\text{Nd}}$  value of +8.6. It is interesting to note that the Nd-isotopic composition of this xenolith is identical to the nepheline basalts from Oahu (Coffrant and Tatsumoto, in preparation). This similarity possibly indicates a cognate relationship between the xenolith and its host basalt.

#### Minerals in Garnet Peridotite Inclusions from Kimberlites

Some of the analyses in Table 4 on the xenolithic minerals were published earlier (Basu and Tatsumoto 1979). In general, the Nd-isotopic composition of the xenolithic minerals are different from their host rock, kimberlite, suggesting an accidental mode of origin of these xenoliths. In xenolith sample B-33, the nearly identical Nd-isotopic composition in coexisting diopside and garnet suggests attainment of isotopic equilibration under upper mantle conditions. The intermediate isotopic composition of the phlogopite, between the diopside-garnet and the host kimberlite (sample B-33, Table 4), suggests possible contamination from the kimberlite. Since diopside and garnet are the only major reservoirs of the rare earth elements in the

**Table 4.** Sm—Nd systematics in minerals in garnet-peridotite inclusions from southern African kimberlites

Sample number	Mineral	Pipe	Age of Pipe	Sm (ppm)	Nd (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$ Measured	$^{143}\text{Nd}/^{144}\text{Nd}$ Initial	$\varepsilon_{\text{Nd}}$
<b>I (Granular Lherzolite)</b>									
B-33	Diopside			2.283	21.032	0.066	$0.512188 \pm 54$	$0.512145 \pm 54$	$-7.3 \pm 1.1$
B-33	Garnet	Bulfontein	90 m.y.	1.711	4.657	0.222	$0.512201 \pm 32$	$0.512057 \pm 32$	$-9.1 \pm 0.6$
B-33	Phlogopite			0.147	0.867	0.102	$0.512492 \pm 41$	$0.512425 \pm 41$	$-1.9 \pm 0.8$
PHN-2771	Diopside (in phlogopite rich lherzolite)	Bulfontein	90 m.y.	2.100	8.073	0.1572	$0.512901 \pm 32$	$0.512808 \pm 32$	$+5.6 \pm 0.6$
<b>II (Sheared Lherzolite)</b>									
PHN-2819	Garnet	Jagersfontein	90 m.y.	0.6545	0.8363	0.4730	$0.513370 \pm 35$	$0.513092 \pm 35$	$+11.1 \pm 0.7$
LMA-2	Diopside	Matsoku	90 m.y.	2.077	8.183	0.1534	$0.513005 \pm 30$	$0.512915 \pm 30$	$+7.7 \pm 0.6$
B-101	Garnet	Bulfontein	90 m.y.	2.763	4.291	0.390	$0.512274 \pm 46$	$0.512045 \pm 56$	$-9.3 \pm 1.1$

Data on samples B-33 and B-101 are from Basu and Tatsumoto (1979)

xenolith B-33, the bulk rock probably has a light REE-enriched pattern. Furthermore, the Nd-isotopic composition of this whole rock xenolith also indicates a time-averaged, light REE-enriched source. This result is particularly important in view of the observation that the granular xenoliths in kimberlites are usually depleted in terms of their major element composition (Boyd 1973). Such light REE enrichment of previously depleted mantle could result from secondary metasomatic processes involving reactions with differentiated liquids from below. Once depleted in basaltic constituents, such xenolithic mantle material becomes refractory and acts as traps for the mobile constituents in the mantle (Jordan 1978). It is remarkable that no young mantle-derived volcanic rock has a Nd-isotopic signature similar to B-33.

The separated garnet from the sheared lherzolite in the Bulfontein pipe (Table 4) also shows a time-averaged Nd enrichment with respect to Sm. If the Nd-isotopic composition of the garnet is representative of the bulk rock, then we might infer that a substantial part of the subcontinental mantle, as represented by the two xenoliths, has  $\varepsilon_{\text{Nd}}$  values, of the order of  $-9$ . Three other xenolithic minerals in Table 4 from three different pipes, including Bulfontein, show positive  $\varepsilon_{\text{Nd}}$  values indicating light REE depletion in all these xenoliths. The data clearly indicate the existence of vertically heterogeneous, and geologically complex subcontinental mantle beneath southern Africa.

#### *Eclogites, Granulite and Megacryst Inclusion in Kimberlite*

The data for a few samples analyzed in this category are shown in Table 5. If we assume isotopic equilibra-

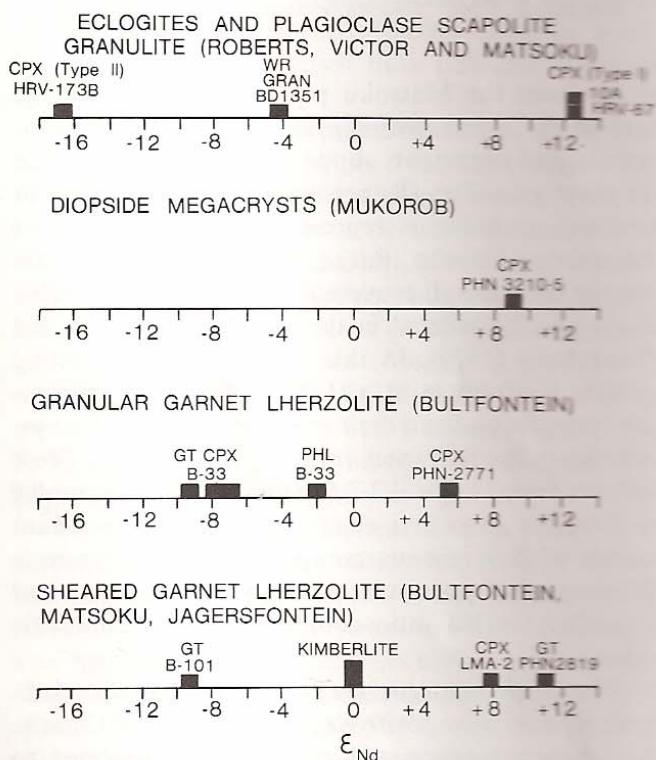


Fig. 3.  $\varepsilon_{\text{Nd}}$  in xenolithic minerals and in granulite inclusion in southern African kimberlites

tion prevailed between the coexisting garnets and pyroxenes in the eclogite, the data shown in Table 5 support the petrologic classification of the two types of eclogites (MacGregor and Carter 1970). The widely varying  $\varepsilon_{\text{Nd}}$  values between the two types of eclogites suggest, different crystal liquid fractionation in ancient times in the formation of these eclogites beneath the South African continent.

The whole rock plagioclase scapolite granulite xe-

**Table 5.** Sm—Nd data in eclogitic clinopyroxenes, granulite and clinopyroxene megacryst in southern African kimberlites

Sample Number	Mineral and Rock Type	Pipe Name	Age (Pipe)	Sm (ppm)	Nd (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$	( $^{143}\text{Nd}/^{144}\text{Nd}$ ) Measured	( $^{143}\text{Nd}/^{144}\text{Nd}$ ) Initial	$\varepsilon_{\text{Nd}}$
10A	Clinopyroxene in Type I Eclogite	Roberts Victor	90 m.y.	2.390	—	—	$0.513202 \pm 22$	$0.513155 \pm 44^*$	$+12.4 \pm 0.8$
HRV-67	Clinopyroxene in Type I Eclogite	Roberts Victor	90 m.y.	0.621	—	—	$0.513212 \pm 41$	$0.513165 \pm 41^*$	$+12.5 \pm 0.8$
HRV-173B	Clinopyroxene in Type II Eclogite	Roberts Victor	90 m.y.	1.957	14.898	0.0794	$0.511727 \pm 22$	$0.511680 \pm 22$	$-16.4 \pm 0.4$
BD 1351	Plagioclase-scapolite granulite (Whole rock)	Matsoku	90 m.y.	0.688	2.280	0.1824	$0.512412 \pm 24$	$0.512305 \pm 24$	$-4.2 \pm 0.5$
PHN-3210-5	Diopside Megacryst	Mukorob	90 m.y.	1.723	6.520	0.1600	$0.513086 \pm 20$	$0.512992 \pm 20$	$+9.2 \pm 0.4$

\* The initial  $^{143}\text{Nd}/^{144}\text{Nd}$  was estimated by assuming  $^{147}\text{Sm}/^{144}\text{Nd}$  to be same as in sample number HRV-173B

nolith from the Matsoku pipe in Lesotho (90 m.y. age) shows a negative  $\varepsilon_{\text{Nd}}$  value of  $-4.2$ . Various petrological arguments support a deep crustal origin for these granulites (Rogers and Nixon 1975). If our analyzed granulite is representative of the base of the crust in Lesotho, the  $\varepsilon_{\text{Nd}}$  value of  $-4.2$  for this sample contrasts the average modern crustal value of  $\varepsilon_{\text{Nd}}$  ( $-17$ ) assumed in the study by DePaolo and Wasserburg (1979). In this regard, it is interesting to note Coffrant et al.'s (1980, private communication) suggestion from their study of the Sm—Nd systematics in the Stillwater complex of Montana. These authors found  $\varepsilon_{\text{Nd}} = -2.7$  for the Stillwater complex at 2740 m.y. ago and suggested that the dominant source of this igneous complex was either from a differentiated upper mantle or lower crust which had a smaller Sm/Nd ratio compared to the chondritic value.

The diopside megacryst in kimberlite in the Mukorob pipe shows a positive  $\varepsilon_{\text{Nd}}$  value of  $+9.2$ . Clearly, this discrete megacryst is a xenocryst, unrelated to the host kimberlites which typically show  $\varepsilon_{\text{Nd}}$  value near zero.

In summary, the data presented here clearly show that all inclusions, mafic and ultramafic, in kimberlites are unrelated to their kimberlite host. The kimberlites are derived from a deeper, unique and relatively primitive mantle reservoir with a chondritic Sm/Nd signature.

### Origin of Kimberlite

Our data from nine kimberlites, from four different continents and ranging in age from 90 to 1,300 m.y.

before present, suggest their derivation from an undifferentiated, unique mantle reservoir, with an identical chondritic Sm/Nd ratio. The primary minerals in the groundmass of the kimberlites analyzed are olivine, phlogopite and calcite. Phlogopite, a possible source for  $\text{H}_2\text{O}$  in the mantle, is characteristically absent in the sheared lherzolite xenoliths, believed to be derived from a deeper source than the phlogopite-bearing granular xenoliths (Boyd 1973). The initial Nd-isotopic ratios in the kimberlites are markedly different from those in the xenoliths, including the phlogopite. This relationship suggests derivation of the kimberlitic liquid from a source considerably deeper than the sheared xenoliths analyzed in this study. Therefore, we conclude that phlogopite is absent from this source.

It has been established experimentally that both  $\text{H}_2\text{O}$  and  $\text{CO}_2$  can affect the composition of a partial melt in a peridotitic mantle (Eggler 1975). The effect of  $\text{CO}_2$  is known to produce silica-undersaturated melts, similar to kimberlitic liquide and experimental petrologists agree that kimberlitic liquids can be produced by a small degree of partial melting of garnet lherzolite containing  $\text{H}_2\text{O}$  and  $\text{CO}_2$ . (Eggler and Wendlandt 1979; Wyllie 1979). We suggest a model in which the parental material of kimberlites has a composition very close to carbonaceous chondrites. After the accretion of the earth, the silicate portions of the carbonaceous chondrites must have been transformed into a garnet lherzolite mineralogy at appropriate depths in the mantle due to pressure-induced phase transformation. Melting relations of the carbonaceous chondrite, Allende, at high temperatures and pressures show an early segregation of a sulfide

phase from the meteorite (Kushiro and Seitz 1974). Although still controversial (Clark et al. 1972), this early separation of a Fe-Ni sulfide melt may have taken place during core-mantle differentiation, after accretion, for the case of the earth. But such a process should not change the Sm/Nd ratio in the silicate portion of the mantle, although the absolute abundances of the rare earth elements may have increased considerably by this process. As the source material for kimberlite in our model, we assume at least a four-phase (olivine+enstatite+diopside+garnet±a carbonate phase, magnesite) primitive, chondritic rock which melts in the presence of H<sub>2</sub>O and CO<sub>2</sub>. Experimental results suggest kimberlitic liquid can be produced from the above assemblage over a temperature interval of 200°–300° C above the solidus at pressures of 55 kb (Egler and Wendlandt 1979).

### Implication for Mantle Evolution

Most models for the origin and evolution of the earth suggest total segregation of the mantle from the Fe-Ni core early in the history of the earth. If it occurs, this differentiation into a silicate mantle and a metallic core may not change the Sm/Nd ratio of the mantle if all the REE enter the silicate mantle during the process. A closed system evolution of this silicate mantle may supply igneous rocks with chondritic Nd-isotopic signature throughout earth's history. In this context, the Rb-Sr and U-Pb systematics in the mantle-derived rocks are useful. Recent studies (De-Paolo and Wasserburg 1976b; O'Nions et al. 1977) have shown that there is an overall negative correlation between <sup>87</sup>Sr/<sup>86</sup>Sr and <sup>143</sup>Nd/<sup>144</sup>Nd ratios in oceanic basalts. This correlation suggests decrease in Rb/Sr ratio in the mantle has been accompanied by increase in the Sm/Nd ratios and vice versa. From this correlation, it has also been suggested that the <sup>87</sup>Sr/<sup>86</sup>Sr ratios in the primitive or unfractionated mantle is 0.7045. However, if the <sup>87</sup>Sr/<sup>86</sup>Sr ratio of 0.7045 is regarded as the most primitive for the earth, then the Rb/Sr ratio for such an earth is lower than the chondritic ratio. The Pb-isotopic composition of oceanic alkali basalts, some of which are similar to kimberlites in Nd and Sr isotopic composition, indicate that the source mantle has a time averaged enrichment of U relative to Pb (Tatsumoto 1978). Thus, it appears that although the kimberlites are derived from a mantle source with a chondritic Sm/Nd ratio, this source region has higher U/Pb and lower Rb/Sr ratios with respect to chondrites. These differences in U/Pb and Rb/Sr ratios have been attributed to the entry of Pb and Rb into the core during core-mantle differentiation (Hall and Murthy 1971;

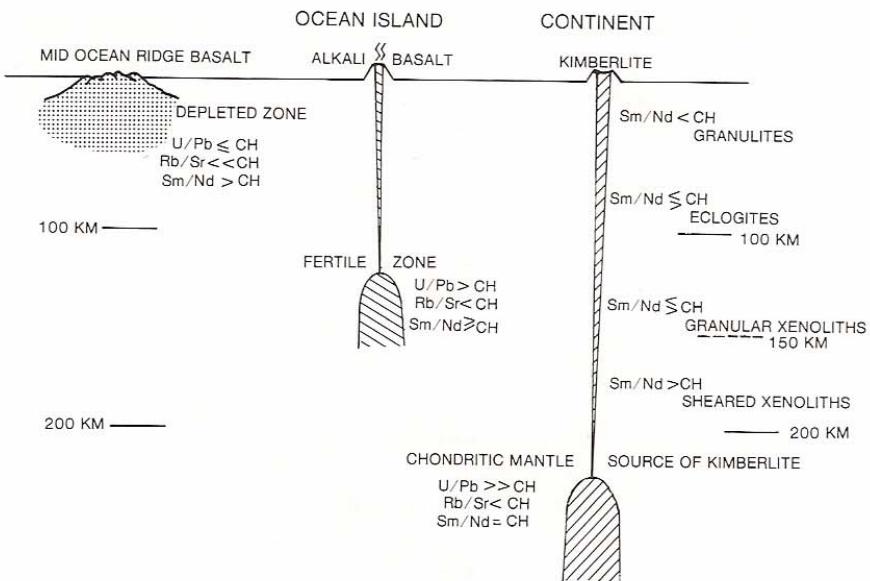
Vidal and Dosso 1978). Such an interpretation, however, does not allow the kimberlitic source in the mantle to be truly undifferentiated; rather, it suggests the kimberlites were derived from a source that is at least one step removed from the primordial chondritic material that accreted to the earth.

Chemical analyses of twenty-five kimberlites from the Lesotho area show an average CO<sub>2</sub> content of 4.58 wt.% (Gurney and Ebrahim 1973). This CO<sub>2</sub> is mostly locked as carbonate in the kimberlite groundmass, which is also the major host for the rare earth elements. In the light of our Nd-isotopic data for the kimberlites, we are inclined to believe that the source of these kimberlites including the CO<sub>2</sub> is unfractionated and did not participate in core-mantle differentiation. The failure of Sr and Pb isotopic data to conform to this conclusion may be due to the fact that both Sm and Nd are rare earth elements and their geochemical behavior is more predictable than the radioactive parent-daughter pairs, U-Pb and Rb-Sr, which have different chemical affinities.

With the above interpretation of our kimberlite data, we next evaluate the observed variations in the U-Pb and Rb-Sr systems in mantle-derived oceanic basalts with reference to a chondritic mantle. The two contrasting types of basalts of the ocean basins, the mid-ocean ridge tholeiitic basalts (MORB) and alkalic basalts of ocean islands (ABOI), are characterized by their trace element contents as well as by the isotopic ratios of Pb, Sr, and Nd. The MORB are characterized by low concentrations of K, U, Th, P, Ti and the light REE, and by low radiogenic Pb, Sr, but more radiogenic Nd.

In contrast, the ABOI are enriched in these above elements and show more radiogenic Pb and Sr but less radiogenic Nd. Gast et al. (1964) and Tatsumoto (1966) explained these differences in Pb and Sr isotopic composition by heterogeneities in the source mantle chemistry and by the differentiation history of the mantle. Recent data on the Pb, Sr and Nd isotopic composition of oceanic basalts suggest that the source region of MORB has lower U/Pb, Rb/Sr and higher Sm/Nd ratios than the source regions of ABOI in the mantle. This relationship indicates ABOI source to be less depleted than the source for MORB. There is some agreement among geochemists (e.g., Schilling 1973; Sun et al. 1975) that ABOI are derived from plumes rising from a deeper mantle. To this existing knowledge of heterogeneity in the uppermantle, we now add the new data on kimberlites and associated inclusions, and on other mantle-derived samples as presented here.

Figure 4 shows schematically the Sm/Nd, Rb/Sr and U/Pb ratios in basalt and kimberlite source re-



**Fig. 4.** Schematic diagram showing relative variation of U/Pb, Rb/Sr, and Sm/Nd ratios with respect to chondritic (CH) ratios in a vertically and laterally heterogeneous mantle

gions in the mantle compared to the same ratios in chondrites. As already mentioned, the source of kimberlite at depths greater than or equal to 200 km has chondritic Sm/Nd ratios, but shows higher U/Pb and lower Rb/Sr ratios than the respective chondritic values. In our model, this part of the mantle is the most primitive and is overlain by a less primitive mantle, the "fertile Zone" which still retains higher U/Pb and lower Rb/Sr ratios than chondrites, but has similar or higher Sm/Nd ratio than chondrites. This high Sm/Nd ratio may later be lowered by secondary enrichment of the light REE and the same process may result in an increased Rb/Sr ratio. The source for MORB, the shallower zone in the model, is depleted in most large ion lithophile elements (Gast 1968). Such depletion results in a lower or similar chondritic U/Pb ratio, considerably lower Rb/Sr ratio than chondrites, and in a higher Sm/Nd ratio than chondrites. The different trace elemental ratios in various levels of the mantle result by the extraction of variable amounts of melt in the past from an initially uniform mantle reservoir, which, in our model, is the same as the source for kimberlites. The processes of extraction of melt and melting associated with diapirism within the mantle cause the mantle to become heterogeneous, both vertically and laterally, with time. The most important feature of this model is the increasing degree of fertility of the mantle with depth. It is also suggested here that the primitive mantle source of kimberlites is ubiquitous beneath continents as well as beneath ocean basins. This is because some alkalic basalts and carbonatites from ocean islands show a chondritic Nd-isotopic composition (Basu 1979).

The model presented here does not incorporate convective flow patterns in the mantle which are believed to be necessary to drive the lithospheric plates.

Many models of convective flow have been proposed in the current literature. Obviously, the nature of these models must be constrained by the scale of mantle-heterogeneity proposed in our model. It is clear from the xenolith data in the continental kimberlites that above 200 kms the continental mantle is distinctly different from their suboceanic counterpart (Fig. 4). This conclusion is based on the observation that both positive and negative values of  $\varepsilon_{\text{Nd}}$  are found in the mantle xenoliths of the kimberlites. In contrast, the suboceanic mantle represented by mid-ocean ridge basalts typically show positive  $\varepsilon_{\text{Nd}}$  values around +8 (DePaolo and Wasserburg 1976b) or around +4 and ranging down to zero in some alkalic basalts of ocean islands (Basu 1979). The garnet Iherzolite inclusion (66 SAL-1) in alkali basalt of Salt Lake Crater in Oahu is possibly a representative sample of the suboceanic mantle beneath Hawaii. This sample also shows an  $\varepsilon_{\text{Nd}}$  value +8.6 (Table 3). To our knowledge there is no suboceanic mantle-derived sample which shows a negative  $\varepsilon_{\text{Nd}}$  value. Therefore, we are convinced that the subcontinental mantle above a 200 km depth, represented by the xenoliths in kimberlite, is isotopically distinct and different in geologic history from the suboceanic mantle of comparable depths.

Wasserburg and DePaolo (1979) recently proposed a model of earth structure in which they inferred an essentially undifferentiated mantle at depths below 600 km. Their conclusion is based on their Nd-isotopic data which suggest some continental flood basalts to be derived from a chondritic source. However, there is no petrogenetic scheme that restricts the formation of tholeiitic flood basalts from mantle material derived only from depths below 600 km. Further, it is difficult to comprehend how partial melts originating from such depths erupt on the surface

in large volumes for long periods of time without intermixing with the overlying mantle. Although our data do not preclude the existence of primitive mantle at 600 km and below, we have restricted our model to a depth of 200 km which is the minimum estimated depth of derivation of kimberlitic liquid.

**Acknowledgements.** We thank Drs. F.R. Boyd, Jr., B. Doe, P.J. Jackson, W.P. Leeman, I.D. MacGregor, and P.H. Nixon for providing samples analyzed in this study. We also thank Dr. Zell Peterman and an anonymous reviewer for constructive comments on the manuscript. This research was supported by NASA Interagency transfer order T-2407 A.

## References

- Basu AR, Murthy VR (1977a) Ancient lithospheric lherzolite xenolith in basalt from Baja California. *Earth Planet Sci Lett* 35:238–246
- Basu AR, Murthy VR (1977b) Kaersutites, suboceanic low-velocity zone, and the origin of mid-oceanic ridge basalts. *Geology* 5:365–368
- Basu AR (1978) Trace elements and Sr-isotopes in some mantle-derived hydrous minerals and their significance. *Geochim Cosmochim Acta* 42:659–668
- Basu AR, Tatsumoto M (1978) Nd-isotopes in mantle-derived rocks and minerals and the evolution of the earth's mantle. *Geol Surv Open-File Rep* 78–701:28–20
- Basu AR (1979) Nd isotopes and noble gases in the mantle: Evidence for primeval, unmelted layers in the earth's mantle. *Abstr Trans Am Geophys Union* 60, 46:934
- Basu AR, Tasumoto M (1979) Sm–Nd systematics in kimberlites and in the minerals of garnet lherzolite inclusions. *Science* 205:388–401
- Boyd FR (1973) A pyroxene geotherm. *Geochim Cosmochim Acta* 37:2533–2546
- Carlson RW, Macdougall JD, Lugmair GW (1978) Differential Sm/Nd evolution in oceanic basalts. *Geophys Res Lett* 5:229–232
- Clark SP, Turekian K, Grossman L (1972) Model for early history of the earth. In EC Robertson (ed): *The Nature of the Solid Earth*. McGraw Hill, New York, pp 3–18
- Davis GL (1978) Zircons from the mantle. *US Geol Surv Open-File Rep* 78–701:86–88
- DePaolo DJ, Wasserburg GJ (1976a) Nd isotopic variation and petrogenetic models. *Geophy Res Lett* 3:249–252
- DePaolo DJ, Wasserburg GJ (1976b) Inferences about magma sources and mantle structure from variations of  $^{143}\text{Nd}/^{144}\text{Nd}$ . *Geophys Res Lett* 3:743–746
- DePaolo DJ (1978) Nd and Sr isotope systematics of young continental igneous rocks. *US Geol Surv Open-File Rep* 78–701:91–93
- DePaolo DJ, Wasserburg GJ (1979) Petrogenetic mixing models and Nd, Sr isotopic patterns. *Geochim Cosmochim Acta* 43:615–627
- Duke MB, Silver LT (1967) Petrology of eucrites, howardites and mesosiderites. *Geochim Cosmochim Acta* 31:1637–1665
- Eggler DH, Wendlandt RF (1979) Experimental studies on the relationship between kimberlite magmas and partial melting of peridotite. In: FR Boyd, HOA Meyer (eds) *Kimberlites, Diatremes and Diamonds: Their Geology, Petrology and Geochemistry*. Am Geophys Union 1:330–338
- Fesq HW, Kable EJD, Gurney JJ (1975) Aspects of the geochemistry of kimberlites from the Premier mine, and other selected South African occurrences with particular reference to the rare earth elements. *Phys Chem Earth* 9:687–707
- Frey FA, Ferguson J, Chappell BW (1977) Petrogenesis of South African and Australian Kimberlite suites. Extended *Abstr 2nd Int Kimb Conf* Santa Fe, New Mexico
- Gast PW (1968) Trace element fractionation and the origin of tholeiitic and alkaline magma types. *Geochim Cosmochim Acta* 32:1057–1086
- Gast PW, Tilton GR, Hedge C (1964) Isotopic composition of lead and strontium from Ascension and Gough Islands. *Science* 145:1181–1185
- Hall H, Murthy VR (1971) Early chemical history of the earth: Some critical elemental fractionation. *Earth Planet Sci Lett* 11:239–244
- Jordan T (1978) Composition and development of the continental tectosphere. *Nature* 274:544–548
- Kushiro I, Seitz MG (1974) Experimental studies on the Allende chondrite and the early evolution of terrestrial planets. *Carnegie Inst Washington Yearb* 73:448–451
- Loubet M, Bernat M, Javoy M, Allegre CJ (1972) Rare earth contents in carbonatites. *Earth Planet Sci Lett* 14:226–232
- Lugmair GW (1974) Sm–Nd ages: A new dating method, abstr. Meteoritics 9:369
- Masuda A, Nakamura N, Tanaka T (1973) Fire structure of mutually normalized rare-earth patterns of chondrites. *Geochim Cosmochim Acta* 37:239–248
- Mitchell RH, Brunfelt AO (1975) Rare earth element geochemistry of kimberlites. *Phys Chem Earth* 9:671–686
- MacGregor ID, Basu AR (1974) Thermal structure of the lithosphere – a petrologic model. *Science* 185:1007–1011
- MacGregor ID, Carter JL (1970) The chemistry of clinopyroxenes and garnets of eclogite and peridotite xenoliths from the Roberts Victor Mine, South Africa. *Phys Earth Planet Interiors* 3:391–397
- Nakamura N, Tatsumoto M, Nunes PD, Unruh DM, Schwab AP, Wildeman TR (1976) 4.4-b.y.-old clast in boulder 7, Apollo 17: a comprehensive chronological study by U–Pb, Rb–Sr and Sm–Nd methods. *Proc Lunar Sci Conf* 7th. *Geochim Cosmochim Acta, Suppl* 7:2309–2333
- Nixon PH, Boyd FR (1979) Garnet bearing lherzolites and discrete nodule suites from the Malaita alnoite, Solomon Islands, SW Pacific, and their bearing on oceanic mantle composition and geotherm. In: FR Boyd, HOA Meyer (eds) *The Mantle Sample: Inclusions in Kimberlites and other volcanics*. Am Geophys Union 2:400–423
- Olson JC, Marvin RF, Parker RL, Mehnert HH (1977) Age and tectonic setting of lower paleozoic alkalic and mafic rocks, carbonatites, and thorium vents in south central Colorado. *J Res US Geol Surv* 5:673–687
- O'Nions RK, Hamilton PJ, Evensen NM (1977) Variations in  $^{143}\text{Nd}/^{144}\text{Nd}$  and  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios in oceanic basalts. *Earth Planet Sci Lett* 34:13–22
- Richard P, Shimizu N, Allegre CJ (1976)  $^{143}\text{Nd}/^{144}\text{Nd}$ , a natural tracer: an application to oceanic basalts. *Earth Planet Sci Lett* 31:269–278
- Ringwood AE (1975) Composition and petrology of the Earth's Mantle. McGraw Hill New York, p 618
- Rogers N, Nixon PH (1975) Geochemistry of lower crustal granulite xenoliths from Lesotho kimberlites. *Ann Rep Res Inst African Geol, Univ of Leeds*, pp 38–41
- Schilling, J-G (1973) Iceland mantle plume: geochemical study of Reykjanes Ridge. *Nature* 242:565–571
- Schnetzler CC, Philpotts, JA (1970) Partition coefficients of rare earth elements between igneous matrix material and rock forming mineral phenocrysts – II. *Geochim Cosmochim Acta* 34:331–340
- Sun SS, Tatsumoto M, Schilling JG (1975) Mantle plume mixing

- along the Reykjanes Ridge Axis: lead isotopic evidence. *Science* 190:143–147
- Tatsumoto M (1966) Genetic relations of oceanic basalts as indicated by lead isotopes. *Science* 153:1094–1101
- Tatsumoto M (1978) Isotopic composition of lead in oceanic basalt and its implication to mantle evolution. *Earth Planet Sci Lett* 38:63–87
- Unruh DM, Nakamura N, Tatsumoto M (1977) History of the Pasamonte achondrite: Relative susceptibility of the Sm–Nd, Rb–Sr, and U–Pb systems to metamorphic event. *Earth Planet Sci Lett* 37:1–12
- Wyllie PJ (1979) Kimberlite magmas from the system Peridotite –CO<sub>2</sub>–H<sub>2</sub>O. In: FR Boyd, HOA Meyer (eds) *Kimberlites, Diatremes and Diamonds: Their Geology, Petrology, and Geochemistry*. Am Geophys Union 1:319–329
- Zartman RE, Brock MR, Heyl AV, Thomas HM (1967) K–Ar and Rb–Sr ages of some alkalic intrusive rock from central and eastern United States. *Am J Sci* 265:848–870

Received April 30, 1980; Accepted August 15, 1980