

# Isotopic data from the Amba Dongar Carbonatite Complex, west-central India: Evidence for an enriched mantle source

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## Abstract

Initial  $^{206}\text{Pb}/^{204}\text{Pb}$  (19.05–19.19),  $^{207}\text{Pb}/^{204}\text{Pb}$  (15.72–15.74) and  $^{208}\text{Pb}/^{204}\text{Pb}$  (39.72–40.16) ratios, and  $\epsilon_{\text{Sr}}$  (+15.1 to +19.2) and  $\epsilon_{\text{Nd}}$  (–1.6 to –0.8) -values for the calciocarbonatites from the Cretaceous (~60 Ma) Amba Dongar complex, Gujarat (India) are relatively uniform. The isotopic ratios for the ferrocarnatites, however, are slightly more variable, in particular the initial  $^{206}\text{Pb}/^{204}\text{Pb}$  (18.94–19.28),  $^{207}\text{Pb}/^{204}\text{Pb}$  (15.66–15.81) and  $^{208}\text{Pb}/^{204}\text{Pb}$  (39.55–40.05) ratios.  $\delta^{13}\text{C}$  (–4.20 to –3.58‰) and  $\delta^{18}\text{O}$  (+8.80 to +10.02‰) isotopic ratios for the calciocarbonatites plot within or close to the field defined for primary magmatic carbonatites, whereas the ferrocarnatites are characterized by much higher  $\delta^{13}\text{C}$  (–4.29 to –1.62‰) and  $\delta^{18}\text{O}$  (+13.73 to +24.67‰) -values.

Variations in Pb, C and O isotopic data from ferrocarnatites are attributed to fluid activity that is probably related to formation of associated massive fluorite deposits, known to be of low-temperature hydrothermal origin. In contrast, the high abundances of Nd (average 1191 ppm) and Sr (average 4261 ppm) from the calciocarbonatites, which buffer their initial Nd and Sr isotopic ratios against crustal contamination, and their “mantle-like” C and O isotopic ratios suggest that their isotopic ratios are probably inherited from their mantle source.

The initial Nd and Sr isotopic ratios from the Amba Dongar calciocarbonatites indicate derivation from a Rb/Sr- and Nd/Sm-enriched mantle source quite different to most young (<200 Ma) carbonatites which have signatures that lie between HIMU and EM I mantle components. The isotopic ratios from the Amba Dongar calciocarbonatites are similar to proximal alkaline complexes of similar age and the least contaminated Deccan flood basalts. We propose, therefore, that the Réunion hot spot responsible for the Deccan flood basalts may have had some bearing on producing the parental melt that generated the Amba Dongar carbonatite.

## 1. Introduction

Carbonatite complexes are useful for deciphering the nature of the sub-continental upper mantle (SCUM)

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because of their: (1) deep-seated origin; (2) widespread occurrence in continental areas; (3) low viscosity that enables them to sample large mantle volumes (Richter, 1985; McKenzie, 1985); and (4) high Nd and Sr abundances, well in excess of crustal abundances, that buffer their primary isotopic signatures against changes brought about by crustal contamination (Bell and Blenkinsop, 1989). Regions of continental rifting, such as the East African Rift Valley

System, are normally associated with numerous carbonatite–nephelinite centres, that are ideal for monitoring the isotopic evolution of the sub-continental mantle. Nd and Sr isotopic ratios from several young (< 40 Ma) East African carbonatite complexes have already shown mantle heterogeneity and evidence for the binary mixing of two mantle components, possibly HIMU (high- $^{238}\text{U}/^{204}\text{Pb}$  mantle end-member) and EM I (enriched mantle-I end-member) (Bell and Blenkinsop, 1987a). Bell and Blenkinsop (1987a) also suggested that the isotopic variations from East African carbonatites may be controlled by the partial melting of mantle minerals (e.g., clinopyroxene and garnet) with distinct isotopic signatures.

Nd and Sr isotope ratios from North American carbonatites (e.g., Bell et al., 1982; Bell and Blenkinsop, 1987b; Tilton et al., 1987) suggest derivation from a common Rb/Sr- and Nd/Sm-depleted mantle source. The same is true for most carbonatites from other continents (e.g., Nelson et al., 1988). Isotopic data from Indian carbonatites, however, are comparatively rare. Earlier work by Deans and Powell (1968) showed variable Sr isotopic ratios (0.7021 to 0.7070) from four Indian carbonatite complexes (Amba Dongar, Newania, Panwad and Sevathur), and those from Amba Dongar were the most radiogenic of all carbonatite complexes studied to that date. Nd, Pb and Sr isotope ratios from the Sung Valley carbonatites (Fig. 1) show that parts of India are underlain by a time-integrated, Nd/Sm-depleted but Rb/Sr- and U/Pb-enriched mantle source (Krishna et al., 1991).

This present study focusses on high-precision Nd, Pb, C, O and Sr isotopic ratios from the Amba Dongar carbonatite in an attempt to assess: (1) the evolution of the parental carbonatite melt; (2) the nature of the subcontinental mantle below the Narmada Rift in west-central India; and (3) the genetic relationship, if any, between the mantle sources responsible for the magmatism at Amba Dongar and the proximal Deccan flood basalts.

## 2. Geology

The five regions of carbonatite–alkalic magmatism that occur in India (Fig. 1) are all related to major rift structures (Krishnamurthy, 1988). One of these, the Narmada Rift, in west-central India, hosts the Chhotta

Udaipur carbonatite–alkalic ‘‘province’’, which covers an area of  $\sim 1200\text{ km}^2$  (Viladkar, 1981) and contains the largest number of alkaline centres associated with the late stages of Deccan volcanism (Gwalani et al., 1993). The Amba Dongar carbonatite (Fig. 2), the first carbonatite to be identified in India (Sukheswala and Udas, 1963), forms part of the Chhotta Udaipur ‘‘province’’. K–Ar dates from Amba Dongar include a value of  $37.5 \pm 2.5\text{ Ma}$  from a pyroxene from a nephelinite (Deans and Powell, 1968), and  $61 \pm 2$  and  $76 \pm 2\text{ Ma}$  from feldspar separates from related fenites (Deans et al., 1972). These dates suggest that the Amba Dongar complex was emplaced either at the same time or slightly later than the main period of Deccan volcanism at 65 Ma ago (Courtilot et al., 1988; Duncan and Pyle, 1988; Baksi and Farrar, 1991). A  $^{40}\text{Ar}/^{39}\text{Ar}$  age of 65 Ma (biotite from alkali olivine gabbro; Basu et al., 1993) from the Phenai Mata intrusion, an undersaturated alkalic complex also located within the Narmada Rift and fairly close to Amba Dongar, lends support to a late Cretaceous episode of alkalic and carbonatitic igneous activity. Slightly older  $^{40}\text{Ar}/^{39}\text{Ar}$  ages of 68.5 Ma have been obtained from the Sarnu and Mundawara

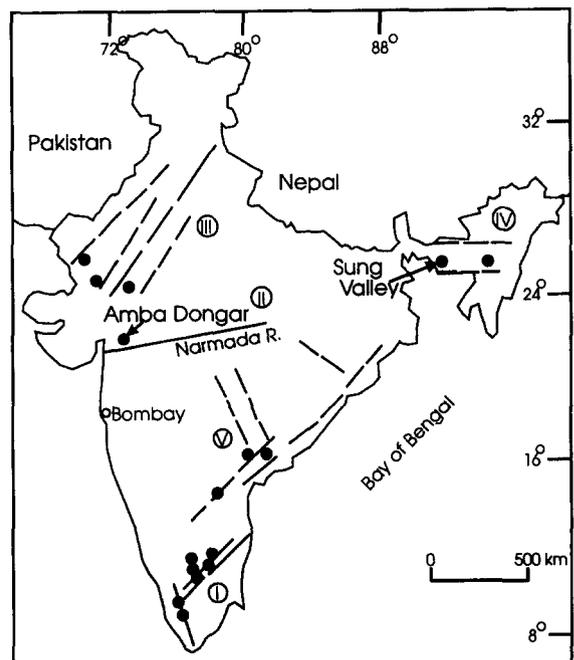


Fig. 1. Major rift structures (dashed lines) of India (I = Eastern Ghat; II = Narmada; III = Aravalli; IV = Assam–Meghalaya; V = Cuddapah Godavari). Dots represent carbonatite complexes (map modified after Krishnamurthy, 1988).

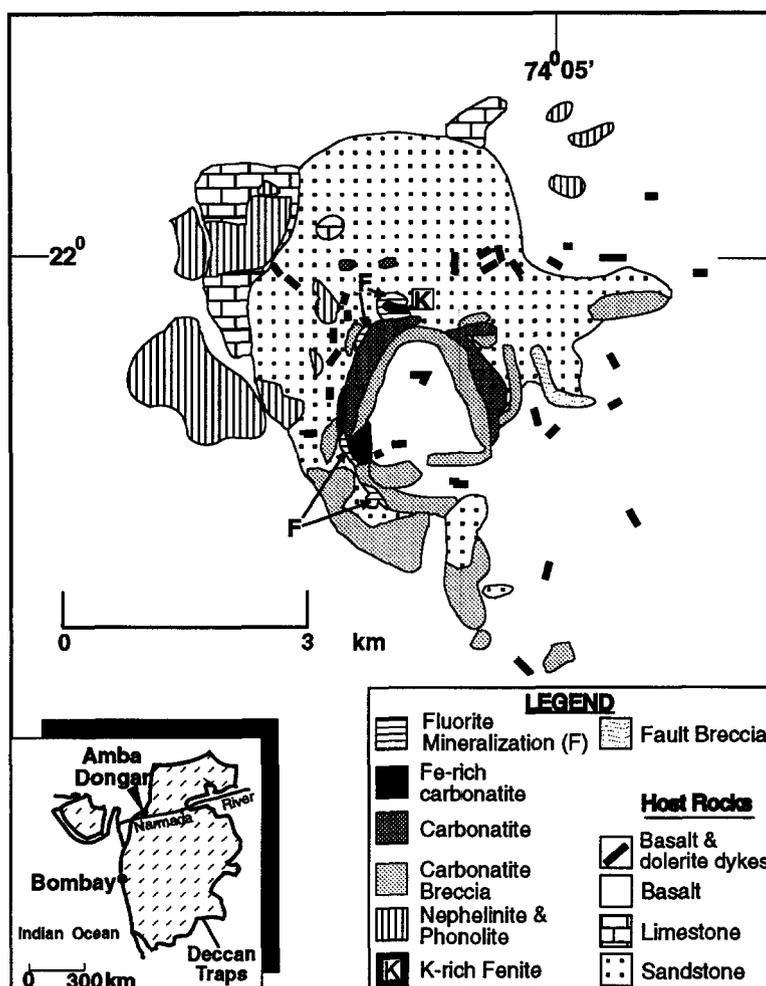


Fig. 2. Geologic map of the Amba Dongar carbonatite complex (modified after Viladkar, 1981). *Inset* shows locality of the Amba Dongar complex at the northern extremity of the Deccan Traps and within the Narmada Rift Valley.

alkalic complexes within the Cambay Graben, north of the Narmada Rift (Basu et al., 1993).

The Amba Dongar carbonatite intruded the Bagh limestones and sandstones of Cretaceous age, as well as the Deccan basalts (Fig. 2), and Precambrian Dharwar basement. Although the latter is not exposed at Amba Dongar, it does outcrop in the northern parts of the Chotta Udaipur alkalic province (Viladkar, 1981). Consisting of an innermost ring of carbonatite breccia rimmed by calciocarbonatite, the Amba Dongar carbonatite is intruded by ferrocyanatite plugs and dykes, and cored by basalt (Fig. 2, Viladkar, 1981). In addition, there are two phases of alvikite dykes, an earlier (phase I) contemporaneous with intrusion of

calciocarbonatites, and a later, more Fe–Mn-rich (phase II). Plugs of nephelinite and nephelinitic breccia, as well as phonolite dykes intrude the surrounding sandstone and basalt (Fig. 2). The Amba Dongar complex also hosts the largest fluorite deposit ( $11.6 \cdot 10^6 \text{ t}^1$  at 30%  $\text{CaF}_2$ ; Deans et al., 1973) associated with a carbonatite complex (Notholt et al., 1990).

### 2.1. Petrography and chemistry

The carbonatites from Amba Dongar have been extensively studied in terms of petrography (Viladkar,

<sup>1</sup> 1 t = 1 metric tonne =  $10^3 \text{ kg}$ .

1981; Viladkar and Wimmenauer, 1992), and major- and trace-element chemistry (Viladkar, 1981; Viladkar and Dulski, 1986; Viladkar and Wimmenauer, 1992). Emplacement began with the calciocarbonatites (sovitites of Viladkar, 1981), and this was followed by the ferrocarnatites (ankeritic carbonatite of Viladkar, 1981), some of which are fluorite-bearing. The ferrocarnatites can be subdivided into two phases (I: dykes, and II: plugs; Viladkar and Wimmenauer, 1992) on the basis of Nb, Sr, Th and Zr abundances. The final phase of igneous activity at Amba Dongar involved formation of the massive fluorite deposits (Viladkar, 1981; Viladkar and Dulski, 1986; Viladkar and Wimmenauer, 1992), concentrated at the contact between the country rocks and the carbonatite.

An increase in Fe, Mn (Viladkar, 1981; Viladkar and Wimmenauer, 1992) and rare-earth element (REE) concentrations (Viladkar and Dulski, 1986) from calciocarbonatite to ferrocarnatite to fluorite-bearing ferrocarnatite, are similar to trends shown by other carbonatites (Woolley and Kempe, 1989). Characteristic features of the calciocarbonatites include low concentrations of MgO (0.11–4.55 wt%) and enrichment of Sr over Ba (Viladkar and Wimmenauer, 1992). All of the Amba Dongar carbonatites are light REE (LREE) -enriched, with the ferrocarnatites showing greater mantle-normalized values than the calciocarbonatites (Viladkar and Dulski, 1986). The variations in major- and trace-element, and REE data are attributed by Viladkar and Wimmenauer (1992) to closed-system crystal fractionation of a carbonatite magma.

### 3. Analytical methods

Analytical procedures for Nd and Sr are similar to those described in Simonetti and Bell (1993). Carbonatite samples were dissolved in an HCl–HNO<sub>3</sub> mixture under pressure for at least 24 hr. Pb was separated in HBr and HCl using a two-column (0.5 and 0.2 ml) anion ion-exchange chemistry with AG1-X8 (100–200 mesh) resin. Samples are loaded onto a “clean” (alternate washes of double-distilled 6 N HCl and nanopure H<sub>2</sub>O) 0.5-ml column and purified using 1 N HBr and 3 N HCl washes. The Pb is eluted from the first column using 6 N HCl; the same procedure is followed for the second 0.2-ml column chemistry. Nd and Sr blanks are

~0.5 ng; those for Pb range from 0.2 to 1.5 ng. Nd and Sr were analyzed using a double Re filament technique, and all isotope ratios were measured on a Finnigan<sup>®</sup> MAT 261 multicollector solid-source mass spectrometer, operated in the static mode. Samples for Pb isotopic analysis were run on a single Re filament using silica gel and phosphoric acid.

## 4. Isotopic results

### 4.1. Radiogenic isotopes

Nd, Pb and Sr isotopic ratios from Amba Dongar are given in Tables 1 and 2 and shown in Figs. 3 and 4. Attempts to date the carbonatite samples using Rb–Sr and Sm–Nd isotope systematics were unsuccessful because of the restricted spread in Rb/Sr and Sm/Nd ratios. Because these ratios are so low, the back corrections for the supported radiogenic component to the present-day <sup>143</sup>Nd/<sup>144</sup>Nd and <sup>87</sup>Sr/<sup>86</sup>Sr ratios are relatively small (Table 1).

Sr isotopic ratios from the Amba Dongar carbonatites are variable (0.70549–0.70628), and all fall within the range of values previously obtained by Deans and Powell (1968). Most of the calciocarbonatites have similar initial <sup>143</sup>Nd/<sup>144</sup>Nd ratios. All nine carbonatite samples from Amba Dongar plot in the lower right-hand quadrant of the Nd–Sr plot (Fig. 3), a finding which is quite unlike the Nd and Sr isotopic data from most young (<200 Ma) carbonatites studied to date (summarized in Bell and Blenkinsop, 1989). Most of the latter fall within the depleted quadrant.

Present-day Pb isotopic ratios are considered to approximate initial ratios because of the relatively young age of the complex (~60 Ma). The data from Amba Dongar, shown in Fig. 4, plot to the right of the Stacey and Kramers (1975) Pb evolution curve and above the Northern Hemisphere Reference Line (NHRL) (Hart, 1988). Compared to the Pb isotopic ratios from other carbonatites (Fig. 4), those from the Amba Dongar carbonatites contain similar <sup>206</sup>Pb/<sup>204</sup>Pb but higher <sup>207</sup>Pb/<sup>204</sup>Pb and <sup>208</sup>Pb/<sup>204</sup>Pb ratios. The <sup>206</sup>Pb/<sup>204</sup>Pb isotope ratios from Amba Dongar are relatively uniform (19.04–19.28) but the <sup>207</sup>Pb/<sup>204</sup>Pb ratios (15.66–15.81) are variable, and in Fig. 4A define a near-vertical array.

Table 1  
Nd and Sr isotope ratios from Amba Dongar carbonatites

Sample	Rb (ppm)	Sr (ppm)	$^{87}\text{Sr}/^{86}\text{Sr}_{(M)}$ (atomic)	$^{87}\text{Sr}/^{86}\text{Sr}_{(I)}$	$\epsilon_{\text{Sr}}^{(*)}$	Sm (ppm)	Nd (ppm)	$^{143}\text{Nd}/^{144}\text{Nd}_{(M)}$ (atomic)	$^{143}\text{Nd}/^{144}\text{Nd}_{(I)}$	$\epsilon_{\text{Nd}}^{(**)}$
<i>Calciocarbonatites:</i>										
185 v/a	220	4,160	0.70576	0.70563	+17.1	100	690	0.51251	0.51248	-1.6
89 a/2	0.7	6,810	0.70549	0.70549	+15.1	20	120	0.51256	0.51252	-0.8
89 a/10	36.2	3,500	0.70579	0.70577	+19.0	250	1,560	0.51252	0.51248	-1.6
89 a/10 (duplicate)			0.70581					0.51257		
89 a/1	1.2	2,580	0.70578	0.70578	+19.2	270	2,400	0.51252	0.51249	-1.4
<i>Ferrocarnatites:</i>										
12 v/a	0.4	3,100	0.70581	0.70581	+19.6	120	940	0.51256	0.51253	-0.6
13 v/a	7.1	1,120	0.70628	0.70626	+26.0	150	1,280	0.51252	0.51249	-1.4
114 v/a	1.2	2,130	0.70581	0.70581	+19.6	30	270	0.51253	0.51251	-1.0
29 v/a	0.5	3,250	0.70566	0.70566	+17.5	100	2,520	0.51254	0.51253	-0.6
1114 v/a	0.5	3,930	0.70576	0.70576	+18.9	40	290	0.51251	0.51248	-1.6

M = measured isotopic ratios; I = calculated initial isotopic ratios (assuming an age of 60 Ma). Isotope results normalized to  $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$  and  $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ . NBS 987 Sr standard =  $0.71025 \pm 0.00002$ ; La Jolla Nd standard =  $0.51186 \pm 0.00002$ ; and BCR-1  $^{143}\text{Nd}/^{144}\text{Nd} = 0.51266 \pm 0.00002$ . Uncertainties of Nd and Sr abundances, determined by isotope dilution (details in Bell et al., 1987), is  $\pm 0.5\%$ . Concentrations of Nd and Sm in BCR-1 were determined at 28.52 and 6.48 ppm, respectively.

\*Epsilon values calculated using present-day  $(^{87}\text{Sr}/^{86}\text{Sr})_{\text{BE}} = 0.7045$  and  $(^{87}\text{Rb}/^{86}\text{Sr})_{\text{BE}} = 0.083$  (BE = bulk Earth;  $\lambda = 1.42 \cdot 10^{-11} \text{ a}^{-1}$ ); and  $(^{143}\text{Nd}/^{144}\text{Nd})_{\text{CHUR}} = 0.512638$  and  $(^{147}\text{Sm}/^{144}\text{Nd})_{\text{CHUR}} = 0.1967$  (CHUR = chondritic uniform reservoir;  $\lambda = 6.54 \cdot 10^{-12} \text{ a}^{-1}$ ), and assuming an age of 60 Ma for the Amba Dongar carbonatite complex.

Correlations between initial  $^{207}\text{Pb}/^{204}\text{Pb}$  and initial  $^{206}\text{Pb}/^{204}\text{Pb}$  isotope ratios for many other carbonatites yield linear arrays that, if interpreted as secondary isochrons, generate ages that are always older than the geological age of the carbonatite (Kwon et al., 1989). This is not always, however, true for all carbonatites (Andersen and Taylor, 1988). Regression lines through the initial  $^{207}\text{Pb}/^{204}\text{Pb}$ – $^{206}\text{Pb}/^{204}\text{Pb}$  isotopic arrays from young East African complexes (Grünenfelder et al., 1986) define a slope similar to that of the oceanic regression line (Tatsumoto, 1978). In fact, the linear arrays shown by many older Canadian carbonatite complexes were considered by Kwon et al. (1989) as reflecting the oceanic regression line at different times in the past. The Pb isotopic array for Amba Dongar shown in Fig. 4A, if interpreted as a secondary isochron, yields a meaningless age similar to the age of the Earth ( $\sim 4.55 \text{ Ga}$ ). The vertical array shown in Fig. 4 may be attributed to crustal contamination. An array similar to that shown in Fig. 4 from Sabinyo volcano

in Uganda, was attributed by Vollmer and Norry (1983) to binary mixing between continental crust and shoshonitic magma. Pb isotopic ratios from the Amba Dongar calciocarbonatites, however, show no correlation with C, O, or Sr isotopic values, which suggests that either the isotopic systems were decoupled during any contamination process, or that the contaminant did not have a sufficiently high concentration of Pb to affect the Pb isotope composition of the melt.

#### 4.2. Stable isotopes

Carbon and oxygen stable isotope analyses from the Amba Dongar carbonatites are given in Table 3. C and O isotopic ratios from most of the Amba Dongar calciocarbonatites plot within or close to the "primary" magmatic carbonatite box (Fig. 5, Keller and Hoefs, 1995), while C (up to  $-1.62\%$ ) and O ( $+15.81$  to  $+24.67\%$ ) from the ferrocarnatites are much heavier (Fig. 5). Although two of the calciocarbonatites

Table 2  
Whole-rock Pb isotopic ratios from Amba Dongar carbonatites

Sample	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$
<i>Calciocarbonatites:</i>			
185 v/a	19.05	15.73	40.16
89 a/2	19.19	15.72	40.02
89 a/10	19.05	15.72	39.72
89 a/10 (duplicate)	19.09	15.79	39.96
89 a/1	19.06	15.74	39.79
<i>Ferrocarnatites:</i>			
12 v/a	19.07	15.70	39.68
13 v/a	19.28	15.81	40.05
114 v/a	19.04	15.66	39.55
29 v/a	18.94	15.73	39.65
1114 v/a	19.07	15.69	39.63

A fractionation of 0.10% was applied to all measured Pb isotopic ratios based on average analysis of NBS 982 Pb standard. Pb isotopic ratios are assumed to be close to initial values because of the age of the complex and the generally low U/Pb and Th/Pb ratios of carbonatites (e.g., Grünfelder et al., 1986; Nelson et al., 1988; Kwon et al., 1989).

plot just outside of the “primary” magmatic carbonate box (Fig. 5), the C and O data from these two samples are well within the range of values that can be attributed to crystal fractionation (Deines, 1989).

Several processes could produce the trend toward isotopically heavier C and O for the ferrocarnatites. These include crustal interaction during magma emplacement, Rayleigh fractionation, or derivation of C from different mantle sources (Deines, 1989). Rayleigh fractionation, however, is unlikely since it cannot produce  $\delta^{18}\text{O}$ -values much greater than +17‰ (Deines, 1989) and certainly not as high as the ferrocarnatite values from Amba Dongar.

Dolomite and calcite stable isotope analyses from two ferrocarnatites (12 v/a, 29 v/a) show that calcite has higher  $\delta^{13}\text{C}$ - and  $\delta^{18}\text{O}$ -values than the coexisting dolomite. Such a feature has already been documented for other calcite–dolomite pairs from carbonatites, including those from the Fen complex, Norway (Andersen, 1987) and Chilwa Island, Malawi (Simonetti and Bell, 1994). On the basis of available O isotopic data from carbonate minerals, equilibrium isotopic fractionation between calcite and dolomite should produce only a small enrichment (+1 to

+2‰) in the  $\delta^{18}\text{O}$  of dolomite (Deines, 1989) at high temperatures (~500°C). The isotopic fractionation shown by the calcite–dolomite pairs from samples 12 v/a and 29 v/a is probably the result of secondary processes. A plot of  $\delta^{18}\text{O}$  vs.  $^{87}\text{Sr}/^{86}\text{Sr}$  isotopic ratios for the Amba Dongar carbonatites define a near-horizontal array (Fig. 6).

## 5. Discussion

### 5.1. Evolution of the Amba Dongar ferrocarnatites

#### 5.1.1. Crustal contamination/binary mixing

One of the reasons for the relatively constant Sr isotopic ratios coupled with an increase in the  $\delta^{18}\text{O}$ -values might be crustal contamination (Fig. 6). Hyperbolic arrays, such as that shown in Fig. 7, can be generated by binary mixing. Taking the host Bagh sandstone with an average Sr content (60 ppm) and initial  $^{87}\text{Sr}/^{86}\text{Sr}$  (0.76817) ratio (Simonetti, 1994) as one end-member, and a second end-member similar to the calciocarnatite with the lowest Sr isotopic ratio (0.70549, sample 89a/2), the calculated binary mixing curve, shown in Fig. 7A, does not coincide with the trend shown by the ferrocarnatite data. In order to produce significant shifts in the Sr isotopic ratio of the magma, more than 80% contaminant is needed in the mixture, a finding that presents serious problems both in preserving the carbonatitic nature of the melt, and in finding the sufficient amount of heat required for assimilation. The high Sr contents (>2000 ppm) for most of the Amba Dongar carbonatites make it unlikely that bulk assimilation of continental crust can change the primary isotopic ratio of the carbonatites by simple binary mixing. The fact there is a large variation in Nd abundances (120–2520 ppm) for the Amba Dongar carbonatites and no change in  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios is a further argument against crustal contamination.

#### 5.1.2. Assimilation–fractional crystallization (AFC)

If the assimilation–fractional crystallization model (AFC, DePaolo, 1981) is used with the same two end-members, the results shown in Fig. 7B still demand large amounts of assimilation ( $R = 0.25$ – $0.30$ , mass of assimilant/mass of original magma), and precipitation of minerals that have Sr partition coefficients >1. Although minerals with high partition coefficients for

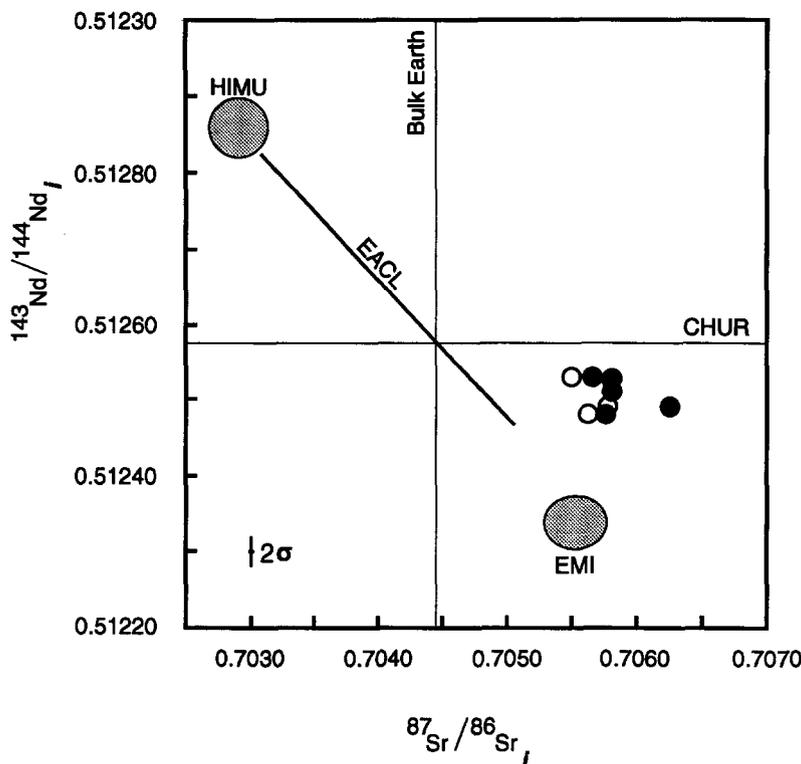


Fig. 3. Initial  $^{143}\text{Nd}/^{144}\text{Nd}$  vs.  $^{87}\text{Sr}/^{86}\text{Sr}$  isotope ratios from Amba Dongar carbonatites. *Open circles* = calciocarbonatites; *solid circles* = ferrocarbonatites. EACL from Bell and Blenkinsop (1987a). HIMU and EMI fields from Hart (1988). Present-day CHUR and bulk-Earth values (0.512638 and 0.7045, respectively) are corrected to 60 Ma ago. It should be cautioned that the EACL is based on data from young (0–40 Ma) carbonatites, and only the slope can be used for comparative purposes.

Sr, such as apatite, calcite and pyrochlore (e.g., Hogarth, 1989), have crystallized in the Amba Dongar complex, the mass of contaminant needed for the AFC model presents similar problems to those encountered using the simple binary mixing model.

### 5.1.3. Groundwater interaction

One explanation for the elevated  $\delta^{18}\text{O}$ -values of the ferrocarbonatites might be sub-solidus groundwater interaction. The known carbonate– $\text{H}_2\text{O}$  oxygen fractionation values (e.g., Deines, 1989) and the typically negative  $\delta^{18}\text{O}$ -values for meteoric groundwaters (e.g., Hoefs, 1987), require that any interaction with groundwater must have occurred at low temperatures ( $< 250^\circ\text{C}$ ; Deines, 1989). Alteration of the ferrocarbonatites by groundwater may be related to the low-temperature ( $112\text{--}150^\circ\text{C}$ ; Roedder, 1973) hydrothermal cycle responsible for the formation of the massive fluorite deposits, given that ferrocarbonatite

emplacement and fluorite deposition are closely related in time (Viladkar, 1981). On the basis of experimentally determined calcite– $\text{H}_2\text{O}$  fractionation factors (O'Neil et al., 1969), however, the extreme enrichment in  $\delta^{18}\text{O}$ -values ( $> +20\text{‰}$ ) shown by several ferrocarbonatites samples requires much lower temperatures ( $\leq 50^\circ\text{C}$ ) during groundwater interaction.

In calculating a water/rock ratio an estimate of  $\delta^{18}\text{O}$ -values for meteoric water is required. Estimates of  $-5$  to  $0\text{‰}$ , based on present-day values for the entire continent of India (Sheppard, 1986) are not unreasonable since 60 Ma ago west-central India was located over the Réunion hot spot, Indian Ocean, close to the equator ( $\sim 20^\circ\text{S}$  latitude) which is a region characterized by low  $\delta^{18}\text{O}$ -values ( $\sim 0\text{‰}$ , Sheppard, 1986). The calculated water/rock weight ratio, using both open- and closed-system processes, for the Amba Dongar ferrocarbonatites (Taylor, 1979) is close to unity based on a range of  $\delta^{18}\text{O}$ -values ( $-5$  to  $0\text{‰}$ ) and experimen-

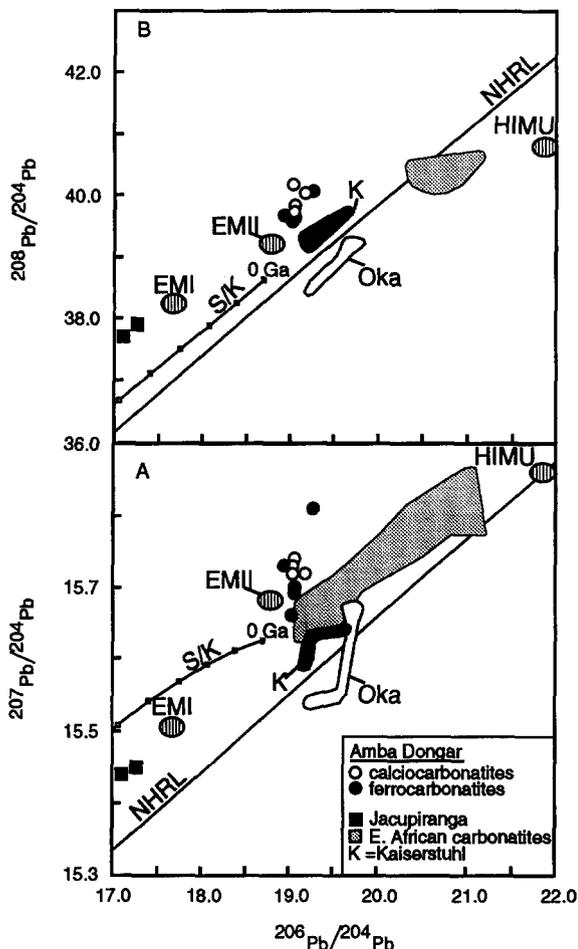


Fig. 4. Present-day Pb isotopic ratios from Amba Dongar carbonatites: (A)  $^{207}\text{Pb}/^{204}\text{Pb}$  vs.  $^{206}\text{Pb}/^{204}\text{Pb}$ ; and (B)  $^{208}\text{Pb}/^{204}\text{Pb}$  vs.  $^{206}\text{Pb}/^{204}\text{Pb}$ . NHRL from Hart (1984). S/K = Stacey and Kramers (1975) Pb evolution curve, squares are at a time interval of 200 Ma. EM I, EM II and HIMU fields from Hart (1988). Sources of Pb isotopic data from other complexes are as follows: Jacupiranga, Brazil (Nelson et al., 1988); Kaiserstuhl, Germany (Nelson et al., 1988; Schleicher et al., 1991); Oka, Québec, Canada (Grünenfelder et al., 1986); East Africa (Grünenfelder et al., 1986; Nelson et al., 1988; Simonetti and Bell, 1994, 1995). Symbols as in Fig. 3. Note that East African carbonatites field is smaller than in (A) because of the lack of Th concentrations needed to back-corrected measured values for Chilwa Island (Malawi) carbonatites (Simonetti and Bell, 1994).

tally-determined fractionation factors for temperatures  $< 50^\circ\text{C}$  (O'Neil et al., 1969). A water/rock ratio, based on the Sr isotope ratios, can also be calculated but this calculation requires an assessment of two unknowns, the  $^{87}\text{Sr}/^{86}\text{Sr}$  isotopic ratio and Sr content for meteoric water surrounding the Amba Dongar com-

plex  $\sim 60$  Ma ago. It is possible to calculate the Sr content needed in the meteoric water, assuming a minimum  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio for the meteoric water of 0.76817 (based on the average initial value from the Bagh sandstone; Simonetti, 1994), and using the water/rock ratio calculated with the O isotope data. Assuming an average Sr content of 2700 ppm for the ferrocarnatites and a water/rock ratio of  $\sim 1$  (based on the  $\delta^{18}\text{O}$ -values), a Sr content of  $\sim 26$  ppm for the meteoric groundwater would be sufficient to produce the Sr isotopic variation (0.70566–0.70626) for the ferrocarnatites. Although the Sr content of 26 ppm may seem to be unreasonably high, comparable values have been found in saline waters associated with the Sn- and fluorite-bearing granites of Cornwall, U.K. (Edmunds et al., 1987).

### 5.2. Mantle sources

Almost all of the Sr and Nd isotope ratios from carbonatites lie in the depleted quadrant of the Nd vs. Sr isotope correlation diagram. Notable exceptions include the Bearpaw Mountains carbonatite, Montana, U.S.A. (Dudás et al., 1987), Jacupiranga, Brazil (Roden et al., 1985), Walloway, Australia (Nelson et al., 1988) and Phalaborwa, South Africa (Eriksson, 1989). All except the Bearpaw Mountains carbonatite are located within the southern hemisphere. The initial Nd and Sr isotopic ratios from the Amba Dongar calciocarbonatites plot in the lower right-hand (enriched) quadrant of the Nd–Sr plot shown in Fig. 8, and Pb isotopic ratios plot above the NHRL (Hart, 1988) and to the right of the Stacey and Kramers (1975) Pb evolution curve (Fig. 4). These isotopic ratios suggest that the parental magma for the Amba Dongar calciocarbonatites was derived from a long-lived Rb/Sr-, Nd/Sm- and U/Pb-enriched mantle source.

There are many similarities between Amba Dongar and Jacupiranga. Not only do both have Nd and Sr isotopic ratios that indicate derivation from an enriched mantle source, but both have similar geological settings. Both are now located at continental margins, and both are coeval or slightly younger than the large outpourings of continental flood basalts (e.g., White and McKenzie, 1989).

Large flood basaltic provinces, located at continental margins (e.g., Deccan basalts, India; Paraná basalts, Brazil), are generally attributed to either upwelling

Table 3  
Stable isotope data from Amba Dongar carbonatites

Sample	Mineral	$\delta^{18}\text{O}_{\text{SMOW}}$ (‰)	$\delta^{13}\text{C}_{\text{PDB}}$ (‰)
<i>Calciocarbonatite:</i>			
89 a/1	calcite	+9.73	-3.61
89 a/2	calcite	+9.30	-4.12
89 a/10	calcite	+10.02	-3.58
185 v/a	calcite	+8.80	-4.20
<i>Ferrocarnatite:</i>			
12 v/a	calcite	+24.67	-2.58
	dolomite	+18.01	-1.79
	(duplicate)	+18.15	-1.84
13 v/a	calcite	+19.64	-2.34
	29 v/a	calcite	+23.23
(duplicate)		+24.25	-1.69
	dolomite	+13.73	-2.19
	(duplicate)	+14.07	-2.15
114 v/a	calcite	+18.38	-4.29
	(duplicate)	+18.27	-4.28
1114 v/a	calcite	+15.81	-3.70

$\text{CO}_2$  was analyzed on a VG® ISOGAS SIRA-12 fully automated, fixed triple-collector mass spectrometer. Overall reproducibility for single- and mixed-carbonate samples is  $\pm 0.10$  and  $\pm 0.15\%$ , respectively (G. St-Jean, pers. commun., 1992).  $\delta^{18}\text{O}$  isotopic ratios were calculated using  $\alpha$ -values of O and  $\text{CO}_2$ -carbonate: 1.01025 for calcite (25°C; Sharma and Clayton, 1965; Friedman and O'Neil, 1977); 1.01065 for dolomite (50°C; Rosenbaum and Sheppard, 1986).

asthenospheric mantle (mantle "plumes"), or lithospheric thinning towards the final stages of continental rifting (White and McKenzie, 1989). In fact, mantle plume activity may be the cause of continental rifting. Continental rifting between India and the Seychelles, which occurred  $\sim 65$  Ma ago, is thought to result from the Réunion hot spot activity. The Deccan flood basalts and alkaline magmatism along the Narmada Rift were produced at the same time. Roden et al. (1985) also proposed that alkaline magmatism at Jacupiranga was related to the Walvis Ridge, be it caused by a hot spot (Dietz and Holden, 1970) or a more complex thermal anomaly (Dingle and Simpson, 1976).

Fig. 9 shows isotopic data from Réunion and Amba Dongar, and Walvis Ridge and Jacupiranga in Pb–Pb and Sr–Pb isotope correlation diagrams. Some interesting features emerge from this figure. In both cases, the isotopic data from the carbonatites are significantly

different to those of the spatially-related plumes. In the case of the Jacupiranga carbonatite, Roden et al. (1985) attributed the differences in Nd and Sr isotope ratios to contamination of Walvis Ridge basalts with continental crust, but such a model is partly inconsistent with the stable isotope data they report, and the Pb isotopic data plotted in Fig. 9A. The similarity of the Pb and Sr isotopic data for the high-phosphorus tholeiites from the Paraná province (Hawkesworth et al., 1986; Petrini et al., 1987) to those from the Jacupiranga carbonatite (Roden et al., 1985) suggests that the isotope ratios from both tholeiite and carbonatite may be a reflection of an enriched mantle source.

The range of Sr isotopic ratios (0.7039–0.7046) obtained from alkali and olivine basalts from Réunion (McDougall and Compston, 1965; Dupré and Allègre, 1983) suggests derivation from a slightly depleted to

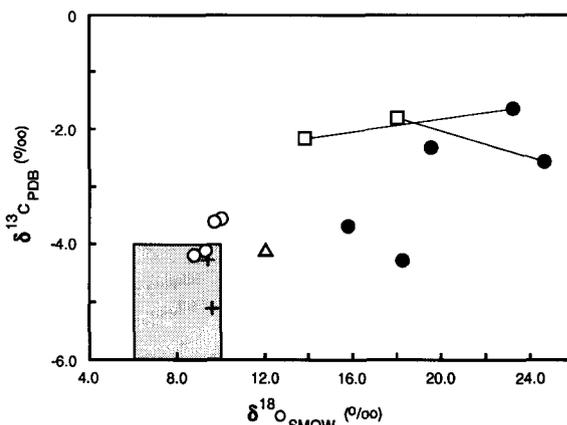


Fig. 5. Plot of  $\delta^{13}\text{C}_{\text{PDB}}$  vs.  $\delta^{18}\text{O}_{\text{SMOW}}$  for Amba Dongar carbonatites. Tie-lines join calcite–dolomite pairs from the same sample. Open circles = calcite from calciocarbonatites; filled circles = calcite from ferrocarnatites; open squares = dolomite from ferrocarnatites; plus signs = calciocarbonatite (Gwalani et al., 1993); open triangle = ferrocarnatite (Gwalani et al., 1993). Shaded box = mantle carbonatite box (from Keller and Hoefs, 1995).

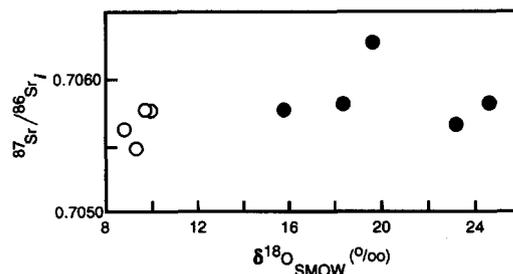


Fig. 6. Plot of  $\delta^{18}\text{O}_{\text{SMOW}}$  from calcites vs. initial  $^{87}\text{Sr}/^{86}\text{Sr}$  from corresponding whole-rock carbonatites. Symbols as in Fig. 5.

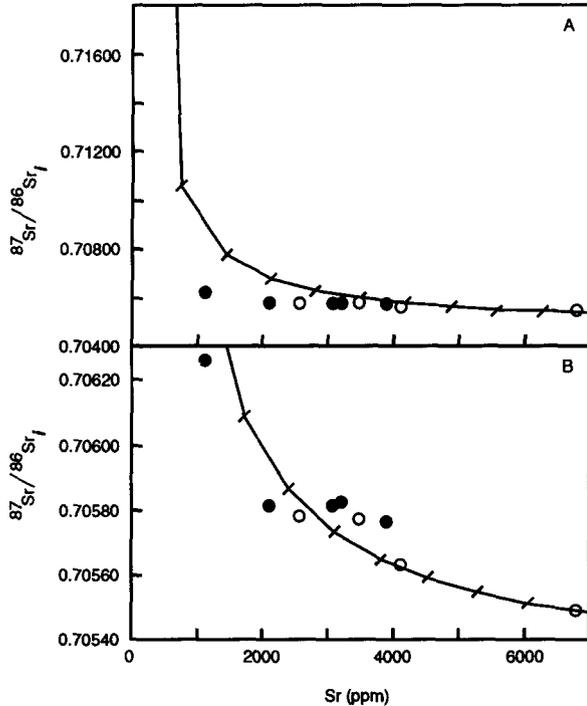


Fig. 7. Plot of initial  $^{87}\text{Sr}/^{86}\text{Sr}$  vs. Sr content for Amba Dongar carbonatites. Symbols as in Fig. 3.

- A. Curve represents results of binary mixing between parental carbonatite magma and Bagh sandstone (see text for details). Slashes are at a 10% interval.
- B. Curve represents results of AFC modelling (DePaolo, 1981) between parental carbonatite magma and Bagh sandstone.

slightly enriched mantle source, while their  $^{207}\text{Pb}/^{204}\text{Pb}$  and  $^{206}\text{Pb}/^{204}\text{Pb}$  isotopic ratios (Dupré and Allègre, 1983) plot to the right of the geochron and above the oceanic regression line (Tatsumoto, 1978). Compared to the Pb and Sr isotope ratios from the Réunion basalts, the Amba Dongar (Fig. 9) carbonatites have Pb isotopes ratios that partly overlap with those from Réunion, but their Sr isotopic ratios are significantly higher. The higher Sr isotopic ratios from the Amba Dongar calcicarbonatites may be attributed to processes related to plume activity below continental environments, such as interaction between a plume and ancient, Rb/Sr-enriched sub-continental lithosphere, or plume and continental crust. Contamination by continental crust is unlikely to produce the higher Sr isotopic ratios because of the “mantle-like”  $\delta^{13}\text{C}$ - and  $\delta^{18}\text{O}$ -values of some of the Amba Dongar calcicarbonatites. Mahoney et al. (1985) suggest that the alkaline volcanics associated with the predominantly tholeiitic volcanism

of the Deccan province may have been derived from phlogopite-rich veins from a recently metasomatized mantle source, whereas the tholeiites were instead derived from the non-metasomatized region of the enriched mantle source. Alternatively, the higher  $^{87}\text{Sr}/^{86}\text{Sr}$  isotope ratios from the Amba Dongar calcicarbonatites could be attributed to interaction between a plume and an enriched sub-continental mantle, similar to a modified EM II component ( $^{87}\text{Sr}/^{86}\text{Sr} > 0.707$ ;  $^{143}\text{Nd}/^{144}\text{Nd} < \text{CHUR}$ ;  $^{206}\text{Pb}/^{204}\text{Pb} > 19.0$ ;  $^{207}\text{Pb}/^{204}\text{Pb} > 15.60$ ; Hart, 1988) beneath west-central India. Although the Pb isotopic ratios from the Amba Dongar carbonatites plot close to the composition of the EM II mantle component (Hart, 1988), their Nd and Sr isotopic ratios are significantly different. The Réunion hot spot itself does not consist of a pure EM II component, since Pb and Sr isotopic ratios from the Réunion basalts lie along the “Lo-Nd” array which contains HIMU and EM I as its end-members (Hart et al., 1986).

The similarity of the Pb isotope ratios for the Amba Dongar calcicarbonatites to those which characterize the EM II mantle component, coupled with quite dif-

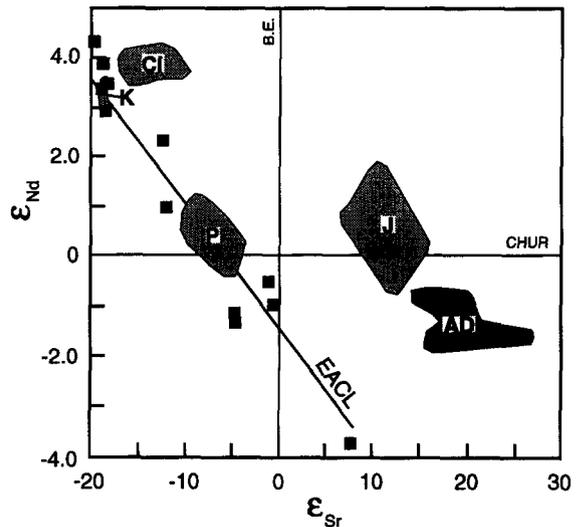


Fig. 8.  $\epsilon_{\text{Nd}}$  vs.  $\epsilon_{\text{Sr}}$  plot for isotope data from various carbonatite complexes. P = Panda Hill (116 Ma, Tanzania; Morriset, 1992); J = Jacupiranga (130 Ma, Brazil; Roden et al., 1985); CI = Chilwa Island (130 Ma, Malawi; Simonetti and Bell, 1994); K = Kanganakunde (130 Ma, South Africa; Ziegler, 1992). EACL and filled squares = isotopic data various East African carbonatite complexes (Bell and Blenkinsop, 1987a).  $\epsilon(T) = 10^4 \left( \frac{R_M}{R_R} - 1 \right)$ , where  $R_M$  is initial ratio at time  $T$ ; and  $R_R$  is isotopic ratio at time  $T$  of bulk Earth or chondritic uniform reservoir for Sr or Nd, respectively.

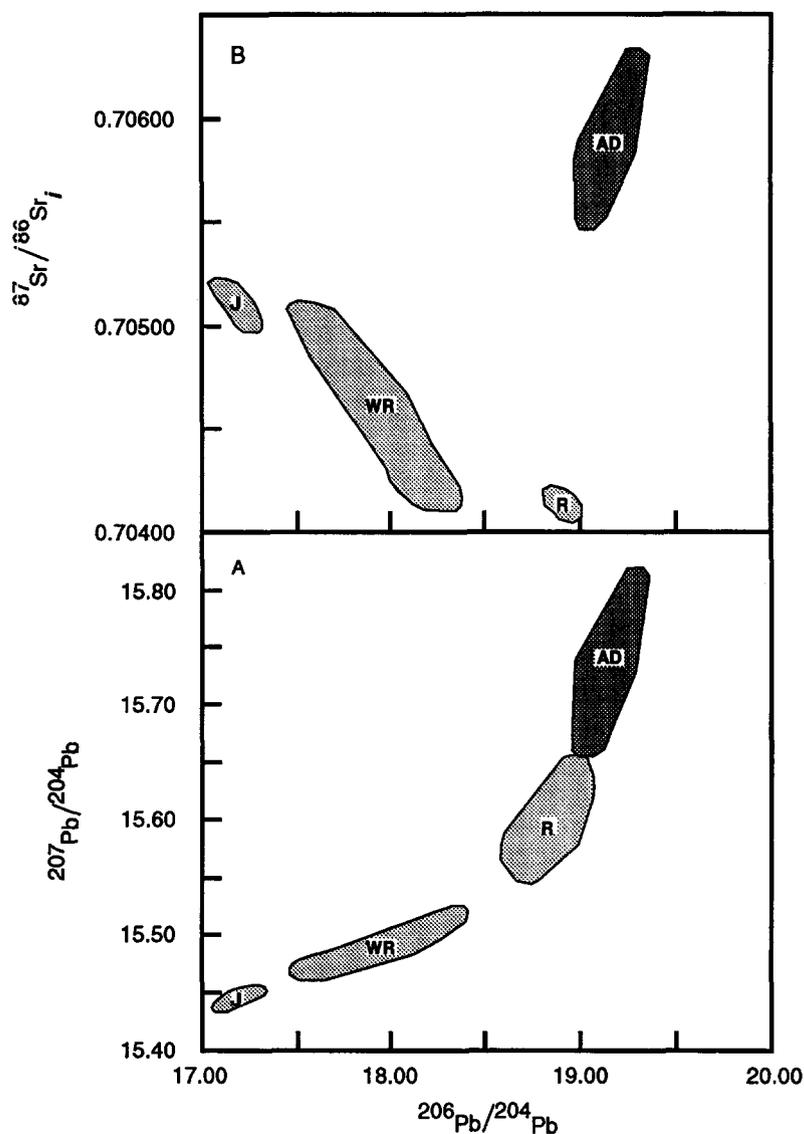


Fig. 9.  $^{207}\text{Pb}/^{204}\text{Pb}$  vs.  $^{206}\text{Pb}/^{204}\text{Pb}$  (A); and  $^{87}\text{Sr}/^{86}\text{Sr}_i$  vs.  $^{206}\text{Pb}/^{204}\text{Pb}$  (B). Fields of present-day Pb isotopic ratios from Amba Dongar (AD), Réunion, Indian Ocean (R) — data from Oversby (1972), Dupré and Allègre (1983), Hart (1984); Walvis Ridge, off Namibia (WR) — data from Richardson et al. (1982); Jacupiranga, Brazil (J) — data from Nelson et al. (1988).

ferent initial Nd and Sr initial ratios, require either modification of the EM II signature by a process that affected only the Nd and Sr, or an argument suggesting that the similar Pb isotopic ratios is entirely fortuitous. On the basis of the C and O isotope data from the calciocarbonatites, we have argued that their Nd, Pb and Sr isotope ratios are inherited from a mantle source, and this requires attributing the differences to processes that occur within the mantle. The isotopic systematics

of the different mantle components have been attributed to a variety of processes such as subduction of oceanic or continental crust, melt extraction, or metasomatism. Since mantle metasomatism is considered a required precursor to carbonatite and nephelinite magma derivation (e.g., Olafsson and Eggler, 1983; Eggler, 1989), metasomatism related to plume activity associated with the Réunion hot spot might be responsible for the observed difference in Nd and Sr isotope

ratios between those from the Amba Dongar calciocarbonatites and EM II.

On the basis of the limited Pb and Sr isotopic data from Réunion basalts, it is difficult to evaluate the role of the Réunion hot spot in the derivation of the Amba Dongar carbonatites. If they are not related to plume activity, then another alternative could involve direct melting of a mantle with enriched isotope characteristics perhaps a modified EM II source. The similarity between the isotopic data from the Amba Dongar carbonatites and those from the least contaminated Deccan flood basalts suggests derivation from a similar source region. Compared to the Réunion volcanics, the more radiogenic Sr isotope ratios from the Amba Dongar calciocarbonatites suggest that interaction with subcontinental lithosphere may have occurred during generation or ascent of the parental carbonatite magma. The abundant alkaline rocks found in the upper sections of Deccan flood basaltic sequences, from the northern region of the province, have isotopic compositions that overlap almost entirely with those from the tholeiitic volcanics and suggest an origin by partial melting of an isotopically similar source (Mahoney et al., 1985). In addition, most of the Nd and Sr isotopic data from the Deccan tholeiitic volcanics of the Mahabaleshwar area plot within the enriched quadrant of the anticorrelation plot, and possibly reflect partial melting of a heterogeneous and variably enriched mantle source (Cox and Hawkesworth, 1985).

## 6. Conclusions

(1) Trends between initial Sr isotopic ratios and Sr content,  $\delta^{18}\text{O}$ -values, and  $^{207}\text{Pb}/^{204}\text{Pb}$  and  $^{206}\text{Pb}/^{204}\text{Pb}$  ratios from the Amba Dongar ferrocarnatites are consistent with a model involving low-temperature groundwater interaction.

(2) On the basis of the deep-seated nature of their  $\delta^{18}\text{O}$ - and  $\delta^{13}\text{C}$ -values, the Nd, Pb and Sr isotopic ratios from the calciocarbonatites are considered mantle values.

(3) The Nd and Sr isotopic data from the Amba Dongar calciocarbonatites indicate derivation from a Rb/Sr- and Nd/Sm-enriched mantle source region.

Compared to most carbonatites world-wide, this almost unique, enriched isotopic signature for the Amba Dongar calciocarbonatites may be related to hot-

spot activity. Similar Nd and Sr isotopic ratios from other alkaline complexes, and the least contaminated Deccan flood basalts, suggest a common source region possibly related to "hot-spot" activity ~65 Ma ago. High  $^3\text{He}/^4\text{He}$  ratios, > 10, from pyroxene separates from two alkalic complexes associated with the early stages of Deccan flood basaltic volcanism (Basu et al., 1993), are consistent with the latter interpretation, although the low  $^3\text{He}/^4\text{He}$  ratios for alkali olivine gabbros from the Phenai Mata complex that lies close to Amba Dongar, are consistent with crustal contamination (Basu et al., 1993).

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