Mineralogy and Petrology (2002) 74: 323–342

Mineralogy
and Petrology



# Geochemistry and petrogenesis of sodic and potassic mafic alkaline rocks in the Deccan Volcanic Province, Mumbai Area (India)

**L. Melluso**[1], **S. F. Sethna**[2], **M. D'Antonio**[1], **P. Javeri**[2], and **L. Bennio**[1]

[1] Dipartimento di Scienze della Terra, Università Federico II, Napoli, Italy
[2] Department of Geology, St. Xavier's College, Mumbai, India

With 6 Figures

Received January 14, 2000;
revised version accepted September 28, 2001

**Summary**

Major element, trace element, Sr- and Nd-isotopes and mineral chemical data are reported for alkaline rocks (lamprophyres, tephrites, melanephelinites, nephelinites and nepheline syenites) cross-cutting the Deccan Trap lava flows south (Murud-Janjira area) and north of Mumbai (Bassein). These rocks range from sodic to potassic and have a large span in MgO (12–2 wt%). The lamprophyres have high content of incompatible elements (e.g., $TiO_2 > 3.8$ wt%, Nb > 130 ppm, Zr > 380 ppm, Ba > 1200 ppm), and relatively high initial (at 65 Ma) $^{143}Nd/^{144}Nd$ (0.5128) and low $^{87}Sr/^{86}Sr$ (0.7038–0.7042). They are likely to be small-degree melts (2–3%) of volatile- and incompatible element-enriched mantle sources, similar to other alkaline rocks in the northern Deccan, though slightly more potassium-rich. The nepheline-rich rocks have highly porphyritic textures (up to 57% phenocrysts of diopside ± olivine), and anomalously low contents of incompatible elements (e.g., $TiO_2 < 1.3$ wt%, Nb < 24 ppm, Zr < 100 ppm) indicating that they could not represent liquid compositions. Moreover, their very low initial $^{143}Nd/^{144}Nd$ ratios (0.5116–0.5120), at $^{87}Sr/^{86}Sr = 0.7045$–0.7049, are unusual in the rocks related to the Deccan Traps and identify a new end-member in this province, that could be identified as "Lewisian-type" lower crust and/or enriched mantle. The melting episode that generated these alkaline rocks likely occurred close to the base of the ca. 100 km-thick Indian lithosphere, very shortly after the main eruption of the Deccan tholeiites.

## Introduction

The Deccan Traps are one of the largest continental flood basalt provinces formed during the Gondwana break-up. The volcanic rocks cover an area of about half a million square kilometers onland, with an estimated maximum thickness of about 4000 m (*Peng* et al., 1994). The age of the bulk of this volcanic province seems to be well constrained at about 65–67 Ma ago (*Allègre* et al., 1999; *Hofmann* et al., 2000 and references therein). The volcanic rocks form a succession of basaltic lava flows of tholeiitic affinity with minor amounts of picrite basalts, basaltic andesites, potassium-rich transitional basalts and more evolved rocks (cf. *Mahoney*, 1988; *Melluso* et al., 1995; *Peng* et al., 1994; *Mahoney* et al., 1985; *Peng* and *Mahoney*, 1995). The flows are cross-cut by mafic dyke swarms, locally abundant in the Narmada–Tapti rift and in the coastal area, which are almost coeval or only slightly younger than the flows (*Melluso* et al., 1999 and references therein).

Rocks belonging to the alkaline clan, often associated with carbonatites are minor in the Deccan province. They occur in the western and northern areas as intrusive complexes and dykes, along the major rift zones in the Deccan Volcanic Province: the east–west-trending Narmada–Tapti rift, with the neighbouring carbonatite-alkaline complexes of Amba Dongar and Phenai Mata, the northernmost

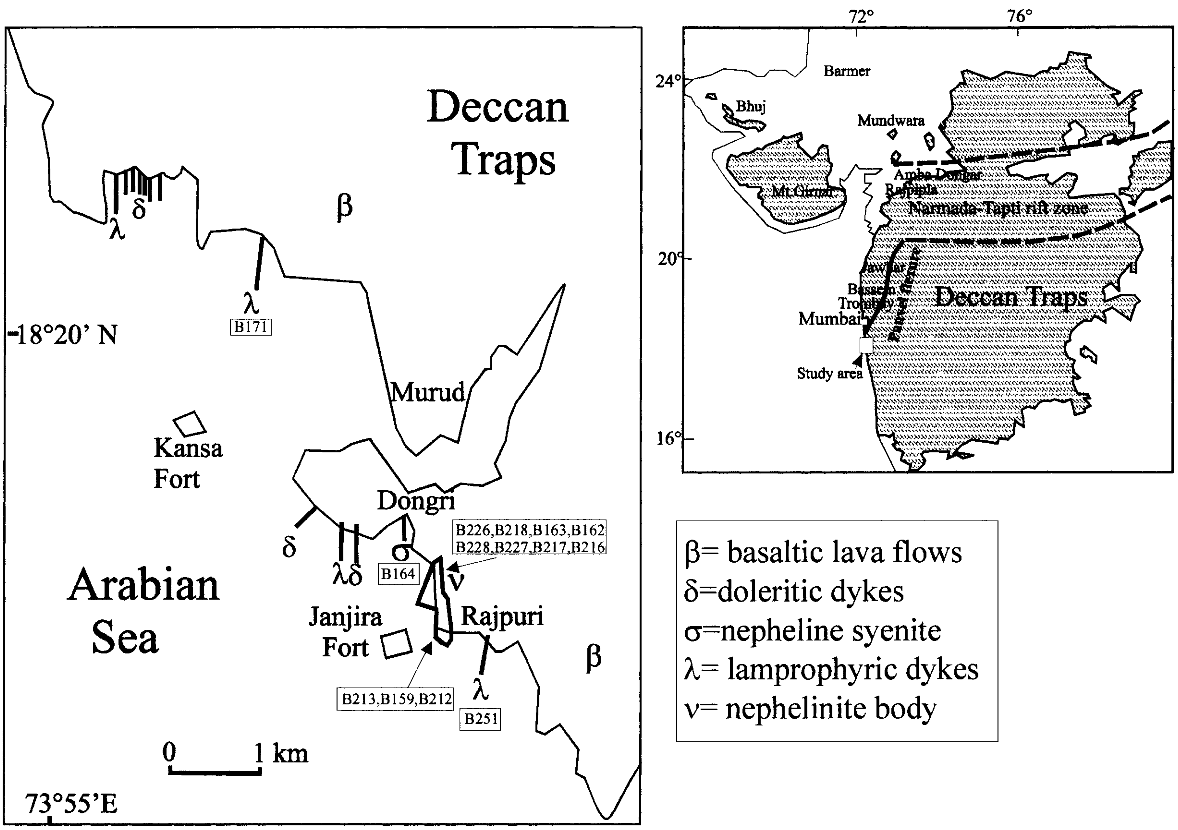


Fig. 1. Sketch map of the Murud-Janjira area (redrawn after *Sethna* and *D'Sa*, 1991), with location of the samples of this study. The main localities of Deccan-related alkaline intrusions are shown in the inset

complexes (e.g., Barmer, Mundwara, Sarnu Dandali), and the western coastal rifted margin, west of the Panvel Flexure. In this latter area there are stray occurrences of nepheline syenites at Jawhar and Murud, a nephelinite body that shows ijolitic, melteigitic and pyroxenitic differentiates at Murud-Janjira and lamprophyres at Trombay, Bassein, and close to Murud. In addition to the zones mentioned above there are stray occurrences of alkaline rocks at Mount Girnar and neighbouring areas in Saurashtra, and Bhuj, in Kutch (Fig. 1). Alkaline intrusions thought to be related to the Deccan province have also been found in the Seychelles archipelago (*Devey* and *Stephens*, 1992).

The alkaline rocks of the western coastal area have been found in scattered outcrops close to Mumbai (Bassein, Trombay and Murud-Janjira; Fig. 1). Unlike their counterparts in the Narmada and Cambay rifts, these received comparatively minor interest in the most recent literature (cf. *Dessai* et al., 1990; *Sethna* and *Mousavi*, 1994; *Mahoney* et al., 1985). This work gives new petrological, chemical and Sr–Nd-isotopic data on these rocks, which are the southernmost alkaline intrusions described in the Deccan igneous province. These data provide further insights on the relationships between the sources of tholeiitic and alkaline rocks in this part of the Deccan.

## Field geology of the western coastal Deccan Traps and of the Murud area

The geology of the Deccan Traps along the western coastal margin differs considerably from the major part of the province, owing to the westerly dipping character of the lava flows to the west of the Panvel flexure. East of Mumbai, the flexure is north–south and trends north–northwest to the north of Mumbai, and south–southwest to the south of Mumbai, moving out into the Arabian Sea just north of Murud. To the west of the Panvel flexure, the lava flows show westerly dips ranging from 5° to 25°. Along the entire length of the zone west of the Panvel flexure there are a number of dykes which trend almost north–south and intrude the westerly dipping basalt flows. In the area pertinent to this study (Fig. 1), most dykes are dolerites of tholeiitic affinity. A few dykes are lamprophyric and nepheline syenitic, with a body of intrusive nephelinite. The doleritic dykes range in width from 1 to 10 m. Along their length, these dykes cannot be traced for any distance, due to the lack of good exposure, except for a few outcrops in the intertidal shore. The lamprophyric dykes are generally smaller in size and range in width from 0.5 to 3 m. The nephelinite body, which occurs as a stock-like intrusion into the horizontal basaltic flows, belonging to the *Poladpur* Fm. (*Subbarao* and *Hooper*, 1988), crops out on the sea shore, close to Rajpuri (*Sethna* and *D'Sa*, 1991, Fig. 1) and extends north–south for almost 1 km. The maximum width of the body is 200 m.

## Analytical techniques

Seventeen samples were analysed for major and trace elements at Napoli with an X-Ray fluorescence spectrometer (Philips PW1400), according to methods and analytical uncertainties described in *Melluso* et al. (1999). Loss on ignition (L.O.I.)

was analysed with standard gravimetric techniques after igniting powders at 1000°C in a muffle furnace, and $Na_2O$ was analysed with Atomic Absorption Spectrophotometry (Napoli). Rare earth element data for two samples were obtained with Inductively Coupled Plasma-Mass Spectrometry at NGRI, Hyderabad, India. Mineral compositions were obtained with a WDS-EDS-equipped CAMECA SX50 electron microprobe at CNR-CSQEA, Rome, utilizing silicates and oxides as standards. For isotopic analyses, 0.3 g of powder were strongly leached with warm 6N HCl for 30 minutes, then rinsed thoroughly in pure sub-boiling double-distilled water, and finally dissolved with high purity HF–$HNO_3$–HCl mixtures. Sr and Nd were extracted by conventional ion-exchange chromatographic techniques. The total blank was ca. 6 ng Sr and 4 ng Nd. Measurements were made using a VG354 double-collector thermal ionisation mass spectrometer (Napoli) running in peak jumping mode, by normalizing to $^{86}Sr/^{88}Sr = 0.1194$ and $^{146}Nd/^{144}Nd = 0.7219$ for mass fractionation effects. The quoted error is twice the standard deviation of the mean ($2\sigma$) and is $\pm 1 \times 10^{-5}$. Repeated analyses of NBS-987 standard yielded a mean value of $^{87}Sr/^{86}Sr = 0.71024 \pm 1$ (N = 50) and the La Jolla Nd standard a mean value of $^{143}Nd/^{144}Nd = 0.511826 \pm 10$ (N = 26).

## Classification, petrography and mineral compositions

The rocks of the Mumbai coastal area have been classified on the basis of phenocryst abundances, grain size, and according to the $R_1$–$R_2$ diagram (*De La Roche* et al., 1980). The rocks are: 1) melanephelinites (or *melteigites*, utilising the intrusive equivalent); 2) nephelinites; 3) lamprophyres; 4) tephrite; 5) nepheline syenites; 6) clinopyroxenites. Representative mineral compositions for these lithotypes are given in Table 2. Additional information on the mineral phases is given in *Dessai* et al. (1990).

1) Melanephelinites (*melteigites*) (B226, B218, B163, B162, B213, B159, B212) are generally fresh, holocrystalline, and strongly porphyritic (22–57 vol%), with phenocrysts of clinopyroxene and minor olivine, set in a finer-grained mesostasis made up of the same phases together with nepheline, phlogopite, perovskite, apatite and oxides. Olivine ($Fo_{88-84}$) has inclusions of Cr-bearing spinel ($Cr_2O_3 = 16.3$ wt%), and is often altered to calcite and chlorite. Colourless, homogeneous diopside {Mg# [atomic Mg/(Mg + Fe + Mn)] from 0.88 to 0.80} is euhedral to rounded. Sometimes, green cores with colourless rims are observed. The $TiO_2$ content of pyroxene is moderate to low (0.63–1.32 wt%). A few microlites of the groundmass are Fe-rich salite [Mg# = 0.57; $TiO_2 = 0.96$ wt%; $Na_2O = 2.29$ wt%]. Nepheline ($Ne_{65-68}Ks_{29-33}Sil_{3-4}$) is abundant as small microlites in the groundmass or enclosed in clinopyroxene rims. Fluorine-rich, Ti-poor phlogopite (F = 4.8 wt%; $TiO_2 < 2$ wt%; Mg# = 0.88) is interstitial, as are apatite, perovskite and Ti-magnetite. No feldspar is observed. Calcite and analcime are the most important secondary minerals.
2) Nephelinites (B228, B227, B217, B216) have phenocrysts of slightly corroded diopside (Mg# = 0.83; $TiO_2$ ca. 1 wt%) and euhedral, often altered, nepheline ($Ne_{63}Ks_{33}Sil_4$), and are generally porphyritic (12–28 vol%, nepheline

10-20 vol%), Olivine is rare and completely altered. Magnetite is ubiquitous as microphenocrysts, whereas apatite and perovskite are accessory phases. Calcite, chlorite and analcime are secondary minerals.

3) Lamprophyres (B251, B171). Following *Rock* (1987) the samples are *monchiquites*. The sample B251 is subaphyric, with microphenocrysts of Ti-phlogopite (Mg# from 0.82 to 0.79; $TiO_2 > 4$ wt%), diopside-salite (Mg# from 0.83 to 0.79) and spinel ($Cr_2O_3$ from 31.8 to 0.4 wt%). Clinopyroxene is found as corroded microphenocrysts and tiny microlites in the groundmass, and has much higher $TiO_2$ than the pyroxene of the nepheline-rich rocks ($TiO_2$ from 2.29 to 3.47 wt%). Analcime and zeolites are secondary phases. The sample B171 is slightly porphyritic, with phenocrysts and microphenocrysts of Ti-phlogopite (Mg# from 0.83 to 0.75; $TiO_2$ ca. 5 wt%), olivine ($Fo_{85-77}$) and minor salite (Mg# from 0.77 to 0.75; $TiO_2$ from 2.03 to 3.40 wt%). Spinel ($Cr_2O_3$ from 42.9 to 0.1 wt%) and slightly Si-rich nepheline ($Ne_{70-71}Ks_{18}Sil_{11-12}$) are microphenocrysts or groundmass phases.
4) Tephrite (B46). This dyke outcrops at Bassein, north of Mumbai (Fig. 1). It is porphyritic for sector-zoned, salitic clinopyroxene (Mg# from 0.75 to 0.74; $TiO_2$ from 1.2 to 2.1 wt%), abundant Ti-magnetite, and rare, euhedral, completely chloritised, olivine phenocrysts. Feldspar laths (albitic in composition, likely secondary) and biotite are observed as tiny microlites in an altered groundmass.
5) Nepheline syenite (B164). This rock has green, Na-rich clinopyroxene (Mg# from 0.53 to 0.16; $Na_2O$ from 2.42 to 8.6 wt%; $TiO_2$ from 0.45 to 2.37 wt%), sometimes found in glomero-porphyritic clusters, and subordinate biotite (Mg# from 0.53 to 0.51), in a very strongly altered, feldspar-bearing, matrix with nepheline, clinopyroxene laths, and rare apatite. Secondary analcime is also present.
6) Apatite-magnetite clinopyroxenites (B166-166M). These are xenoliths in the nepheline syenite (B164). They have autallotriomorphic texture, with subhedral medium-to-large green, salitic clinopyroxene (Mg# from 0.77 to 0.52; $TiO_2$ from 0.58 to 1.16 wt%), with apatite and Ti-magnetite. Intercumulus material is completely altered.

## Major and trace element geochemistry

The lamprophyres and the tephrite B46 have $Na_2O/K_2O \leq 1$ (Table 1), thus showing *potassic* affinity. However, it is likely that some low $Na_2O$ contents are the result of alteration. One lamprophyre and the tephrite have hypersthene (+olivine) in their norms (B251, 8.9%, B46, 4.3%). Relatively high L.O.I. values in our data set, like in that of *Dessai* et al. (1990) (i.e., 2.9–8.9 wt%; Table 1), olivine chloritisation, secondary phases in the groundmass and argillification of feldspars, indicate significant alteration, with element mobilisation. The melanephelinites and nephelinites are *sodic* ($Na_2O/K_2O > 2$), have 14.8 to 30% CIPW normative nepheline; some of these rocks are also larnite normative (0.6–1.8%) and/or peralkaline (1.1–7.4% acmite + sodium metasilicate).

The rocks span a large range of MgO (from 12.4 to 2.2 wt%). Lamprophyres and melanephelinites have the highest MgO, Cr and Ni (12.4–8 wt%, 750–190 ppm and 267–95 ppm, respectively), with the highest values found in the lamprophyre B251. $Al_2O_3$, $Na_2O$, and $K_2O$ increase, and $Fe_2O_{3t}$, CaO, Ni, Sc, V, and Cr

Table 1. *Classification, major elements, trace elements, and elemental ratios of the alkaline dykes of Murud-Janjira. The composition of melanephelinites from Paraguay, South Africa and Italy is reported for comparison (data from* Bristow, *1984;* Comin Chiaramonti *and* Gomes, *1996;* Beccaluva *et al., 1998). Elements analysed by ICP-MS are given in italics.* lamp *lamprophyres;* tph *teprite;* m-ne *melanephelinites;* ne *nephelinites;* px *clinopyroxenites;* nsy *nepheline syenite*

| Sample | B251 | B171 | B46 | B226 | B218 | B163 | B162 | B213 | B212 | B159 | B228 | B227 | B217 | B216 | B164 | B166 | B166m | Melanephelinites | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Classif | lamp | lamp | tph | m-ne | m-ne | m-ne | m-ne | m-ne | m-ne | m-ne | ne | ne | ne | ne | nsy | px | px-ap | av Paraguay | 602 Sicily | KP82 Karoo |
| $SiO_2$ | 45.23 | 44.93 | 47.66 | 46.74 | 45.15 | 46.02 | 46.68 | 46.61 | 46.64 | 48.55 | 46.44 | 46.80 | 46.21 | 46.22 | 53.34 | 46.23 | 42.02 | 42.51 | 43.03 | 44.54 |
| $TiO_2$ | 4.73 | 4.07 | 3.97 | 1.17 | 1.29 | 1.28 | 1.28 | 1.12 | 1.10 | 1.23 | 1.25 | 1.51 | 1.60 | 1.60 | 0.29 | 0.92 | 0.69 | 2.12 | 2.50 | 2.94 |
| $Al_2O_3$ | 7.28 | 8.38 | 9.66 | 10.22 | 10.86 | 10.81 | 10.08 | 10.61 | 11.49 | 11.04 | 13.96 | 13.45 | 12.95 | 13.51 | 19.30 | 13.09 | 9.88 | 13.57 | 14.26 | 7.56 |
| $Fe_2O_3t$ | 15.14 | 15.37 | 16.19 | 10.46 | 10.59 | 10.21 | 10.63 | 9.73 | 9.28 | 10.76 | 10.13 | 10.86 | 11.91 | 11.70 | 6.28 | 9.50 | 7.42 | 11.41 | 10.45 | 15.02 |
| MnO | 0.26 | 0.23 | 0.18 | 0.20 | 0.23 | 0.21 | 0.21 | 0.20 | 0.20 | 0.19 | 0.21 | 0.23 | 0.25 | 0.24 | 0.19 | 0.20 | 0.13 | 0.21 | 0.18 | 0.18 |
| MgO | 12.40 | 10.08 | 8.28 | 11.51 | 11.42 | 10.83 | 10.55 | 10.31 | 9.77 | 9.39 | 7.47 | 6.04 | 5.10 | 4.63 | 2.22 | 4.32 | 3.59 | 9.28 | 9.98 | 8.05 |
| CaO | 11.28 | 11.33 | 8.46 | 13.91 | 12.93 | 12.71 | 14.29 | 12.11 | 12.08 | 11.75 | 12.86 | 12.05 | 10.00 | 11.16 | 7.54 | 12.40 | 17.65 | 10.35 | 12.69 | 10.79 |
| $Na_2O$ | 0.80 | 2.60 | 2.17 | 3.48 | 4.36 | 5.34 | 3.94 | 6.93 | 7.31 | 4.93 | 5.34 | 6.49 | 8.37 | 7.71 | 4.63 | 4.33 | 4.39 | 5.60 | 3.69 | 5.68 |
| $K_2O$ | 2.19 | 2.08 | 2.75 | 1.40 | 1.96 | 2.10 | 1.36 | 1.78 | 1.50 | 1.68 | 1.13 | 1.08 | 1.98 | 1.74 | 5.26 | 2.66 | 1.95 | 1.81 | 1.04 | 0.80 |
| $P_2O_5$ | 0.80 | 0.92 | 0.69 | 0.91 | 1.22 | 0.47 | 0.98 | 0.59 | 0.63 | 0.49 | 1.21 | 1.49 | 1.63 | 1.49 | 0.96 | 6.35 | 12.26 | 1.16 | 1.41 | 0.88 |
| LOI | 6.30 | 3.36 | 3.18 | 5.68 | 5.43 | 4.95 | 5.45 | 3.04 | 3.69 | 2.93 | 7.29 | 5.76 | 5.66 | 6.61 | 8.91 | 3.35 | 5.47 | 2.07 | | |
| Cl | 68 | 320 | 40 | 413 | 253 | 73 | 119 | 503 | 201 | 307 | 808 | 288 | 326 | 421 | 2522 | 2827 | 1379 | | | |
| S | 225 | 391 | 8 | 315 | 316 | 1316 | 412 | 1084 | 652 | 819 | 211 | 467 | 1546 | 842 | 228 | 270 | 247 | | | |
| Sc | 30 | 26 | 19 | 22 | 21 | 24 | 24 | 20 | 18 | 26 | 18 | 13 | 10 | 12 | 7 | 5 | 4 | | | 20 |
| V | 378 | 293 | 302 | 237 | 507 | 377 | 273 | 228 | 226 | 244 | 254 | 332 | 315 | 318 | 54 | 143 | 165 | | 231 | 208 |
| Cr | 755 | 437 | 313 | 219 | 191 | 312 | 185 | 366 | 320 | 360 | 145 | 180 | 130 | 67 | 4 | 36 | 71 | 514 | 372 | 62 |
| Ni | 267 | 284 | 163 | 135 | 116 | 139 | 95 | 132 | 126 | 142 | 66 | 69 | 63 | 42 | 8 | 31 | 33 | 252 | 271 | 135 |
| Zn | 123 | 163 | 152 | 84 | 86 | 84 | 88 | 67 | 74 | 80 | 87 | 106 | 130 | 118 | 112 | 105 | 62 | | | 62 |
| Rb | 67 | 57 | 101 | 49 | 34 | 48 | 40 | 53 | 58 | 43 | 22 | 29 | 64 | 48 | 77 | 25 | 18 | 54 | 18 | 29 |
| Sr | 1170 | 1796 | 1798 | 1449 | 674 | 1114 | 1758 | 855 | 652 | 611 | 2300 | 1947 | 1234 | 1077 | 3042 | 1273 | 875 | 1075 | 1157 | 1039 |
| Y | 27 | 37 | 31 | 20 | 15 | 14 | 17 | 18 | 18 | 18 | 21 | 25 | 25 | 27 | 22 | 30 | 30 | 33 | 33 | 24 |
| Zr | 376 | 407 | 437 | 60 | 64 | 51 | 63 | 65 | 75 | 85 | 56 | 90 | 108 | 125 | 264 | 125 | 122 | 131 | 149 | 195 |
| Nb | 180 | 189 | 131 | 22 | 19 | 19 | 22 | 16 | 24 | 18 | 29 | 35 | 39 | 40 | 70 | 37 | 22 | 99 | 100 | 109 |

(*continued*)

Table 1 (*continued*)

| Sample | B251 | B171 | B46 | B226 | B218 | B163 | B162 | B213 | B212 | B159 | B228 | B227 | B217 | B216 | B164 | B166 | B166m | Melanephelinites | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Classif | lamp | lamp | tph | m-ne | m-ne | m-ne | m-ne | m-ne | m-ne | m-ne | ne | ne | ne | ne | nsy | px | px-ap | av Paraguay | 602 Sicily | KP82 Karoo |
| Ba | 1338 | 1233 | 808 | 1208 | 879 | 984 | 942 | 937 | 1134 | 876 | 901 | 1216 | 1404 | 1626 | 739 | 707 | 317 | 1028 | 981 | 655 |
| La | *176.3* | 208 | 161 | *7* | *10.8* | 16 | 9 | | 12 | 9 | 20 | 25 | 12 | 14 | 23 | 26 | 37 | 115 | 88.2 | |
| Ce | *311.4* | 344 | 265 | 23 | *20.8* | 47 | 24 | 23 | 29 | 50 | 50 | 43 | 50 | 50 | 25 | 75 | 89 | 181 | 164 | |
| Nd | *138.6* | 133 | 106 | 16 | *14.5* | 13 | 12 | 10 | 17 | 18 | 25 | 16 | 12 | 20 | 11 | 32 | 43 | 110 | 85 | |
| Sm | *15.6* | | | | *2.5* | | | | | | | | | | | | | | | |
| Hf | *11.0* | | | | *1.6* | | | | | | | | | | | | | | | |
| Th | *21.9* | | | | *0.9* | | | | | | | | | | | | | | | |
| K/Nb | 101 | 91 | 174 | 535 | 849 | 899 | 502 | 930 | 523 | 786 | 329 | 252 | 422 | 358 | 619 | 590 | 720 | 151 | 86 | 61 |
| Zr/Nb | 2.1 | 2.2 | 3.3 | 2.7 | 3.3 | 2.6 | 2.8 | 4.1 | 3.1 | 4.8 | 2.0 | 2.5 | 2.8 | 3.1 | 3.7 | 3.3 | 5.4 | 1.3 | 1.5 | 1.8 |
| Ba/Nb | 7.5 | 6.5 | 6.2 | 55 | 46 | 51 | 42 | 59 | 48 | 49 | 32 | 34 | 36 | 40 | 10 | 19 | 14 | 10.4 | 9.8 | 6.0 |
| Zr/Y | 13.9 | 11.0 | 13.9 | 2.9 | 4.2 | 3.8 | 3.7 | 3.6 | 4.1 | 4.7 | 2.6 | 3.6 | 4.3 | 4.6 | 11.9 | 4.2 | 4.1 | 4.0 | 4.5 | 8.1 |
| Ti/V | 75 | 83 | 79 | 30 | 15 | 20 | 28 | 29 | 29 | 30 | 29 | 27 | 31 | 30 | 32 | 39 | 25 | | 65 | 85 |

Table 2. **a** *Representative chemical analyses of olivine, clinopyroxene and oxides*. **b** *Representative chemical analyses of mica, nepheline and accessory phases. Mg# = atomic Mg/(Mg + Fe + Mn).* e *early*; l *late*

**a**

| | Pyroxene | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | lamp | | | | tph | | m-ne | | | | | | | ne | | nsy | | | px-ap | |
| | B251 | B251 | B171 | B171 | B46 | B46 | B212 | B212 | B212 | B212 | B212 | B212 | B213 | B217 | B217 | B164 | B164 | B164 | B166 | B166 |
| | e | l | l | l | e | e | e | l | l | e | l | l | l | l | e | l | l | l | e | e |
| $SiO_2$ | 52.04 | 49.44 | 50.34 | 48.29 | 51.84 | 50.78 | 52.60 | 54.26 | 54.67 | 51.47 | 52.77 | 51.56 | 54.65 | 52.42 | 52.91 | 51.84 | 50.69 | 51.64 | 52.86 | 51.58 |
| $TiO_2$ | 2.03 | 3.40 | 2.29 | 3.47 | 1.67 | 2.09 | 1.11 | 0.81 | 0.70 | 0.96 | 1.37 | 0.96 | 0.63 | 1.07 | 0.96 | 2.09 | 1.20 | 0.88 | 0.85 | 0.88 |
| $Al_2O_3$ | 1.62 | 3.35 | 2.02 | 3.55 | 2.19 | 2.36 | 1.86 | 0.27 | 0.24 | 3.14 | 1.02 | 1.39 | 0.11 | 2.17 | 1.65 | 0.66 | 3.23 | 1.98 | 1.81 | 1.13 |
| FeO | 5.32 | 6.91 | 7.55 | 7.03 | 8.00 | 8.28 | 6.00 | 4.16 | 3.92 | 5.78 | 5.88 | 13.00 | 3.90 | 5.34 | 5.43 | 23.64 | 15.40 | 14.90 | 7.27 | 14.00 |
| MnO | 0.05 | 0.09 | 0.20 | 0.01 | 0.39 | 0.32 | 0.06 | 0.23 | 0.07 | 0.13 | 0.13 | 0.29 | 0.07 | 0.10 | 0.26 | 0.36 | 0.35 | 0.39 | 0.14 | 0.53 |
| MgO | 15.14 | 13.79 | 14.20 | 13.59 | 14.09 | 13.79 | 15.01 | 15.95 | 16.26 | 14.30 | 14.60 | 9.99 | 16.37 | 15.04 | 15.37 | 2.49 | 7.68 | 8.55 | 14.22 | 8.96 |
| CaO | 23.63 | 22.68 | 22.89 | 22.76 | 21.89 | 22.01 | 23.35 | 23.34 | 23.55 | 23.26 | 22.82 | 20.09 | 24.06 | 23.89 | 23.73 | 8.25 | 17.26 | 18.50 | 23.14 | 19.59 |
| $Na_2O$ | 0.48 | 0.73 | 0.46 | 0.66 | 0.76 | 0.61 | 0.61 | 0.84 | 0.83 | 0.70 | 1.00 | 2.29 | 0.64 | 0.61 | 0.47 | 8.57 | 3.84 | 2.97 | 0.93 | 2.56 |
| $Cr_2O_3$ | 0.00 | 0.00 | 0.06 | 0.09 | 0.07 | 0.13 | 0.00 | 0.00 | 0.20 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.16 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| sum | 100.31 | 100.39 | 100.01 | 99.45 | 100.90 | 100.36 | 100.60 | 99.86 | 100.44 | 99.74 | 99.59 | 99.57 | 100.43 | 100.63 | 100.95 | 97.90 | 99.65 | 99.81 | 101.22 | 99.23 |
| Mg# | 0.83 | 0.78 | 0.77 | 0.77 | 0.75 | 0.74 | 0.82 | 0.87 | 0.88 | 0.81 | 0.81 | 0.57 | 0.88 | 0.83 | 0.83 | 0.16 | 0.46 | 0.50 | 0.77 | 0.52 |

| | Olivine | | | | | | | Oxide | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | lamp | | m-ne | | | | | lamp | | | tph | m-ne |
| | B171 | B171 | B163 | B163 | B212 | B212 | | B251 | B171 | B171 | B46 | B212 |
| | e | l | e | l | e | l | | l | e | l | e | e |
| $SiO_2$ | 40.81 | 39.56 | 39.83 | 39.69 | 39.46 | 39.46 | | | | | | |
| $TiO_2$ | | | | | | | | 18.31 | 8.91 | 20.06 | 23.56 | 5.63 |
| $Al_2O_3$ | | | | | | | | 2.21 | 4.44 | 1.91 | 2.10 | 1.54 |
| FeO | 13.74 | 21.04 | 11.44 | 14.70 | 14.91 | 12.45 | | 64.37 | 45.39 | 63.84 | 67.43 | 66.72 |
| MnO | 0.32 | 0.55 | 0.32 | 0.57 | 0.59 | 1.29 | | 1.52 | 0.37 | 0.96 | 4.24 | 1.86 |
| MgO | 45.73 | 39.52 | 46.48 | 44.28 | 43.96 | 45.43 | | 1.76 | 7.48 | 1.41 | 0.11 | 3.54 |
| CaO | 0.19 | 0.20 | 0.20 | 0.41 | 0.4 | 0.5 | | | | | | |
| $Cr_2O_3$ | | | | | | | | 3.98 | 31.08 | 6.88 | 0.50 | 16.26 |
| NiO | 0.52 | 0.41 | 0.24 | 0.12 | 0.17 | 0.08 | | | | | | |
| sum | 101.31 | 101.28 | 98.51 | 99.77 | 99.49 | 99.21 | | 92.15 | 97.67 | 95.06 | 97.94 | 95.55 |
| Fo | 85.3 | 76.5 | 87.6 | 83.8 | 83.5 | 85.5 | Mg# | 0.07 | 0.32 | 0.05 | 0.00 | 0.17 |

**b**

| | Brown mica | | | | | | | | | Nepheline | | Perovskite | | Apatite |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | lamp | | | | m-ne | nsy | | lamp | | m-ne | ne | m-ne | lamp | lamp |
| | B251 | B251 | B171 | B171 | B212 | B164 | B164 | B217 | B171 | B212 | B217 | B163 | B251 | B251 |
| | e | l | e | l | l | e | l | l | l | l | e | l | l | l |
| $SiO_2$ | 38.81 | 37.25 | 39.39 | 38.84 | 41.62 | 36.63 | 35.97 | 42.45 | 45.52 | 41.77 | 41.60 | | | 1.05 |
| $TiO_2$ | 4.10 | 5.60 | 5.54 | 5.24 | 1.89 | 2.86 | 2.98 | | | | | 53.35 | 55.60 | |
| $Al_2O_3$ | 13.22 | 13.73 | 11.32 | 11.71 | 8.44 | 13.59 | 13.48 | 32.10 | 31.39 | 32.13 | 32.16 | | | 0.10 |
| FeO | 7.60 | 8.90 | 10.32 | 10.07 | 5.71 | 20.04 | 20.55 | 1.86 | 1.49 | 1.86 | 1.58 | 0.69 | 0.99 | 0.31 |
| MnO | 0.22 | 0.18 | 0.06 | 0.14 | 0.14 | 0.15 | 0.27 | | | | | | | |
| MgO | 19.66 | 19.34 | 18.61 | 18.66 | 24.78 | 12.89 | 12.19 | | | | | | | 0.15 |
| CaO | 0.00 | 0.00 | 0.07 | 0.11 | 0.00 | 0.35 | 0.00 | 0.08 | 0.46 | 0.12 | 0.18 | 33.41 | 35.07 | 51.99 |
| $Na_2O$ | 0.95 | 0.65 | 0.68 | 0.76 | 0.40 | 0.31 | 0.77 | 14.12 | 15.77 | 14.83 | 14.04 | 2.80 | 1.00 | 0.02 |
| $K_2O$ | 8.89 | 8.77 | 9.00 | 8.82 | 10.10 | 9.40 | 8.93 | 9.31 | 5.34 | 9.00 | 9.60 | 0.55 | | 0.05 |
| $P_2O_5$ | | | | | | | | | | | | | | 38.29 |
| SrO | | | | | | | | | | | | | 1.29 | 1.45 |
| BaO | 0.33 | 1.32 | 1.33 | 1.47 | 1.85 | 0.70 | 0.04 | | | | | | | |
| F | 0.53 | 1.38 | 0.00 | 0.00 | 4.84 | 0.00 | 0.00 | | | | | 0.31 | 0.24 | 3.44 |
| sum | 94.31 | 97.12 | 96.32 | 95.82 | 99.77 | 96.92 | 95.18 | 99.92 | 99.97 | 99.71 | 99.15 | 91.11 | 94.19 | 96.85 |
| Mg# | 0.82 | 0.79 | 0.76 | 0.77 | 0.88 | 0.53 | 0.51 | | | | | | | |

decrease with decreasing MgO (Fig. 2; Table 1). $TiO_2$ is highly variable in the most Mg-rich samples (1.1 to 4.4 wt% $TiO_2$) and has the lowest value in the nepheline syenite (0.26 wt% $TiO_2$). The pyroxenites are rich in CaO and $P_2O_5$ and low in MgO (3.4 wt%).

The content of many major and trace elements is inconsistent with the derivation of sodic and potassic rock types from common mantle-derived parental magmas. Particularly relevant is the much higher abundance of La, Ce, Nb, Zr, Y, V, Cr, Ni, $Fe_2O_{3t}$, Zn, and $TiO_2$, in lamprophyres and tephrite B46 than in melanephelinites and nephelinites. These differences are observed in rocks with similar MgO content, and therefore are much greater than would be expected from differentiation processes (Table 1; Fig. 2). These variable compositions are

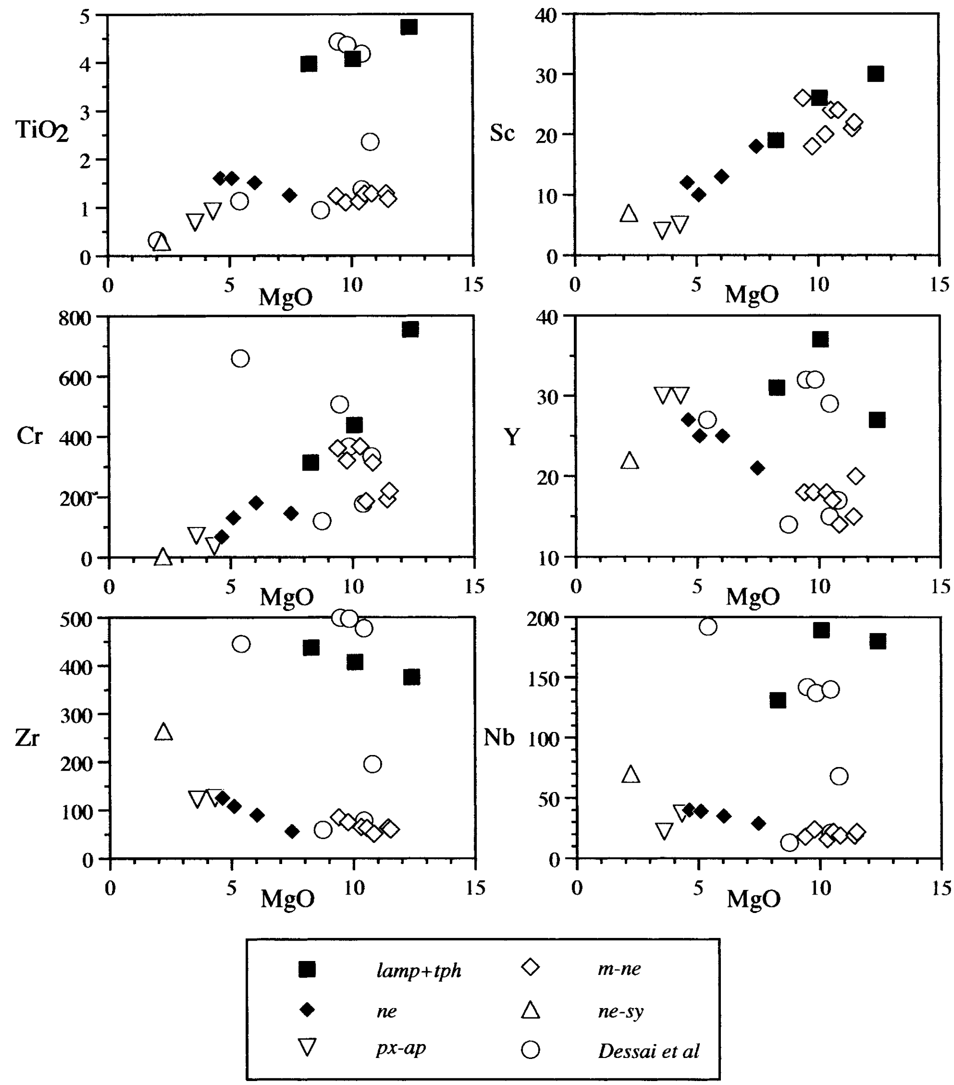


Fig. 2. Representative variation diagrams vs. MgO wt% of the alkaline rocks of the Murud-Janjira area. Open circles: data set published by *Dessai* et al. (1990) on the Murud rocks

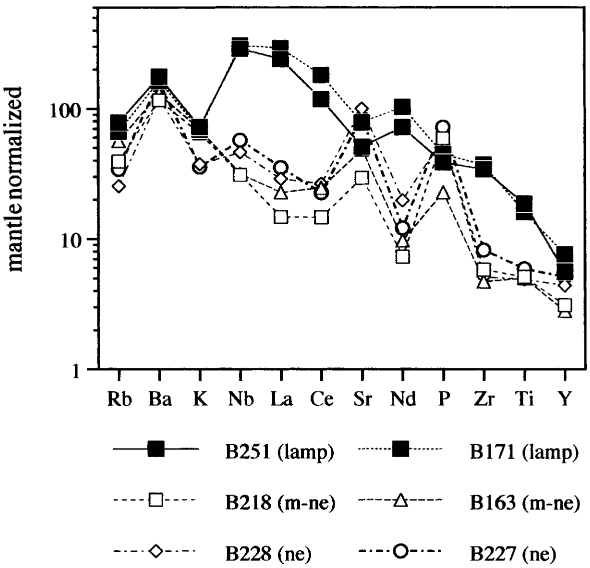


Fig. 3. Primordial mantle-normalised incompatible element patterns (normalisation values from *Wood*, 1979) of Mg-rich Murud-Janjira alkaline rocks

observed also in the data set published by *Dessai* et al. (1990) on the Murud rocks. The volatile elements Cl and S are variable, and reach the highest values in the pyroxenites and nepheline syenite (Table 1), reflecting phase-related enrichment and/or alteration processes.

The Murud mafic rocks have low Zr/Nb ratios (Zr/Nb = 2–4), regardless of the widely variable absolute abundances of the two elements and of the chemical affinity. On the other hand, many elemental ratios distinguish lamprophyres and nepheline-rich rocks (e.g., Ba/Nb, Zr/Y, K/Nb, Ti/V; cf. Table 1). The Ba/Nb ratio of the lamprophyres (Ba/Nb = 6.2–7.5) is typical of average ocean island basalts (cf. *Sun* and *McDonough*, 1989), whereas is much higher in the nepheline-rich rocks (Ba/Nb = 34–59; Table 1), and more similar to that observed in continental crust and subduction-related mafic volcanics (e.g., *Wedepohl*, 1995; *Hawkesworth* et al., 1991). In the mantle-normalised diagrams (Fig. 3), the lamprophyres have peaks at Ba and Nb, with no negative Ti anomalies. The patterns of the nepheline-rich rocks are instead characterised by relatively high large ion lithophile element (Rb, Ba, Sr) abundance over light rare earths (La, Ce, Nd) and high field strength elements (Nb, Ti, Zr), again with no negative Ti anomalies.

## Sr- and Nd-isotopic composition

The mafic rocks of this study have a narrow initial Sr-isotopic range [$^{87}Sr/^{86}Sr$ = 0.7039–0.7049; $\varepsilon_{Sr(65)} = -7.1$ to $+6.6$; Table 3]. The lowest $^{87}Sr/^{86}Sr$ were analysed in the lamprophyres and in tephrite B46 (0.7039–0.7042). The Nd-isotopic composition of the lamprophyre B251 and the Bassein sample B46 are almost identical [$^{143}Nd/^{144}Nd$ = 0.51278 and 0.51276, respectively], and indicate the derivation of both from a time-integrated light rare earth element-depleted source relative to chondrite. The Nd model age of the sample B251 is 284 Ma, assuming evolution from depleted mantle (with $^{143}Nd/^{144}Nd$ = 0.5131 and $^{147}Sm/^{144}Nd$ = 0.24). The nepheline-rich rocks have broadly similar $^{87}Sr/^{86}Sr$ (0.7045–0.7049)

Table 3. *Sr and Nd isotopic composition of Murud-Janjira dykes. The analyses are also given recalculated to 65 Ma. The decay constants used are:* $\lambda^{87}Rb = 1.42 \times 10^{-11}\ a^{-1}$, *and* $\lambda^{147}Sm = 6.54 \times 10^{-12}\ a^{-1}$

| Sample | $^{87}Sr/^{86}Sr$ | $^{87}Sr/^{86}Sr_i$ | $^{143}Nd/^{144}Nd$ | $^{143}Nd/^{144}Nd_i$ | $\varepsilon Nd$ | $\varepsilon Nd_i$ | $^{87}Rb/^{86}Sr$ |
|---|---|---|---|---|---|---|---|
| B226 | 0.70478 | 0.70468 | 0.51175 | 0.51171 | −17.3 | −16.2 | 0.097 |
| B163 | 0.70501 | 0.70489 | 0.51185 | 0.51181 | −15.4 | −14.6 | 0.126 |
| B212 | 0.70478 | 0.70454 | 0.51179 | 0.51175 | −16.5 | −15.6 | 0.258 |
| B227 | 0.70480 | 0.70476 | 0.51196 | 0.51192 | −13.2 | −12.5 | 0.044 |
| B251 | 0.70435 | 0.70420 | 0.51281 | 0.51278 | 3.4 | 4.4 | 0.166 |
| B171 | 0.70424 | 0.70415 | | | | | 0.092 |
| B46 | 0.70408 | 0.70393 | 0.51279 | 0.51276 | 3.0 | 3.4 | 0.163 |
| B164 | 0.70938 | 0.70931 | | | | | 0.073 |
| B166M | 0.70558 | 0.70552 | | | | | 0.058 |

with no appreciable difference between olivine-bearing and olivine-free nephelinites, and very low $^{143}Nd/^{144}Nd$ (0.51196–0.51175; $\varepsilon_{Nd(65)} = -12.5$ to $-16.2$), indicating derivation from source materials with very low time-integrated Sm/Nd ratios. The Nd model ages, assuming for the samples a $^{147}Sm/^{144}Nd$ ratio of 0.1 (Table 1), are 1.3–1.4 Ga.

The nepheline syenite (B164) has high $^{87}Sr/^{86}Sr$ (0.7093), consistent with extensive interaction with hydrothermal fluids and/or seawater, and crustal contamination processes. Its pyroxenite inclusion B166M has lower $^{87}Sr/^{86}Sr$ (0.7055). Pyroxenites are usually less sensitive to alteration processes; therefore, the $^{87}Sr/^{86}Sr$ and the Mg-rich nature of their clinopyroxene is indicative of less $^{87}Sr/^{86}Sr$-rich magmas from which the pyroxenites cumulated.

## Discussion

### *Low pressure differentiation processes*

Two groups of alkaline rocks with distinct paragenesis, chemical and isotopic affinities have been found south of Mumbai. They cross-cut the flood basalt sequence, and are the southernmost alkaline rocks found in the Deccan Traps. The lamprophyres are mica-rich and potassic, and therefore do not have clear equivalents in the Deccan-related alkaline rocks in the north.

Melanephelinites and nephelinites have generally low content of incompatible elements. As an example, their Zr range (50–100 ppm) is more typical of average normal MORB (mid ocean ridge basalt)-tholeiitic magmas (cf. *Sun* and *McDonough*, 1989). This is unusual, taking into account the very high content of these elements in alkaline rocks with similar degree of silica undersaturation found in the rocks of the northern Deccan intrusive complexes (*Gwalani* et al., 1993; *Sethna*, 1989; *Simonetti* et al., 1998), and in the lamprophyres. In a general way, the comparison with representative compositions of melanephelinites in the world (Table 1) indicates distinct depletion in incompatible elements of the Murud samples. The lamprophyres and the Bassein sample plot generally within the field of the mafic alkaline rocks of the northern Deccan [which range in composition from melilitites (Barmer), through nephelinites and basanites (Bhuj, Amba Dongar, Mundwara), to nepheline syenites and phonolites (Amba Dongar, Mundwara, Sarnu Dandali; *Simonetti* et al., 1998; *Srivastava*, 1988)], whereas melanephelinites and nephelinites plot displaced towards the compositional range of their clinopyroxene (and olivine) (Fig. 4). The petrographic and chemical features thus indicate that the melanephelinites should be considered a mush of magma and cumulus crystals. The most important effect of this mush is the dilution of major and trace elements not hosted within the cumulus phases, and the enrichment in $SiO_2$ (due to the relatively high content of this oxide in diopside). Moreover, also compatible or moderately compatible trace elements (e.g., Cr, Ni, V, Sc) of melanephelinites tend to plot off a likely liquid line of descent (Fig. 2). It is also noted that the maximum amount of dilution with cumulus clinopyroxene and olivine crystals (57%) cannot lower the incompatible element content of the nephelinites starting from the contents of the lamprophyres (four to ten times higher in Nb, Zr, Ti and light REE; Table 1). Therefore, the magmas which generate the nephelinitic rocks were less incompatible element-rich than those of the lamprophyres. Major element mass balance calculations utilizing the chemical composition of the phenocrysts indicate that the transition from melanephelinites to nephelinites (e.g., from B213 to B216), if possible through 32% subtraction of

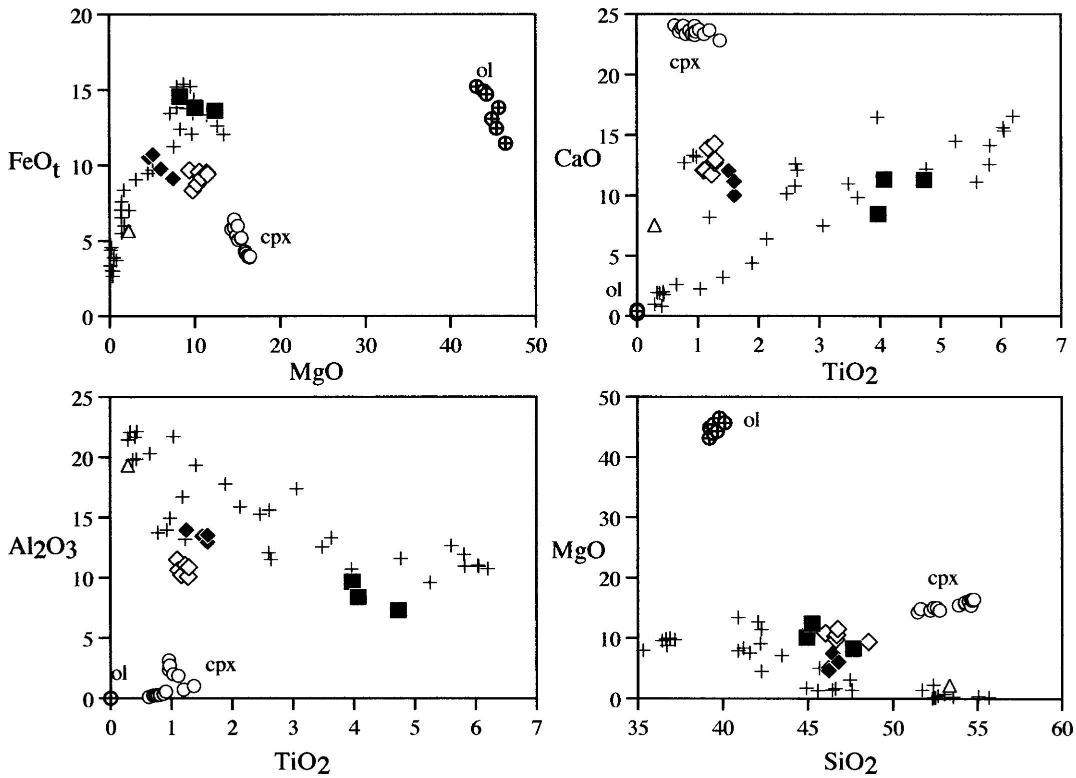


Fig. 4. Representative variation diagrams, with the Murud alkaline rocks and those of alkaline rocks of northern Deccan (data from *Simonetti* et al., 1998 and *Srivastava*, 1988, crosses). The composition of clinopyroxene and olivine of the melanephelinites is also shown

diopside (58%), olivine (28%), nepheline (14%) and small amounts of oxide cumulus (0.9%), has high residuals ($\Sigma R^2 = 1.13$). This is taken as another evidence that at least the melanephelinites cannot be considered as true liquids.

The presence, in the Mumbai area, of scattered outcrops of evolved rocks like phonotephrites, nepheline syenites and quartz trachytes, and their relationships with the strongly alkaline rocks of this study, is also important. The close field association of nephelinites and carbonatites is well known, and very thin carbonate-rich dykes cross-cut the Murud nephelinite body (cf. *Sethna* and *D'Sa*, 1991). *Yoder* and *Tilley* (1962) pointed out that mela-nephelinitic compositions plot at, or very close to, the thermal (and chemical) barrier between melilite- and feldspar-bearing silica-undersaturated rocks. Feldspar is lacking from the Murud sodium-rich rocks of this study, and some of them are also larnite normative; moreover, perovskite (which is not commonly found in equilibrium with feldspar) is an accessory phase. Therefore, it is highly unlikely that melanephelinites and nephelinites can produce felsic, alkali feldspar-rich, nepheline syenites/phonolites or less silica undersaturated (or even silica oversaturated) syenitic/trachytic residual magmas through closed-system fractionation processes. Feldspar-rich felsic rocks are usually late differentiates of basanitic or alkali basaltic parental magmas (which might have suffered also crustal contamination; cf. *Brotzu* et al., 1997).

### *Mantle sources of the Mumbai alkaline rocks*

Very few data are reported on the lamprophyres of the Mumbai area. The Trombay island dyke reported by *Mahoney* et al. (1985) has $(^{87}Sr/^{86}Sr)_{65} = 0.70415$ and $(^{143}Nd/^{144}Nd)_{65} = 0.512805$, and therefore is isotopically akin to the lamprophyres of this study. These lamprophyres have isotopic ratios plotting close to the range of the Ambenali Fm. basalts [$^{87}Sr/^{86}Sr = 0.7038$–$0.7056$ and $^{143}Nd/^{144}Nd = 0.51274$–$0.51300$], and have lower $^{87}Sr/^{86}Sr$ than the Mahableshwar-Kolhapur Fm. basalts [$^{87}Sr/^{86}Sr = 0.7042$–$0.7054$ and $^{143}Nd/^{144}Nd = 0.51233$–$051287$; *Cox* and *Hawkesworth*, 1985; *Lightfoot* and *Hawkesworth*, 1988; *Lightfoot* et al., 1990; Fig. 5]. These two basalt formations are widespread in southern Deccan, and are thought to be poorly contaminated during the ascent to the surface. The lamprophyric rocks plot within the range observed in the alkaline rocks of northern Deccan [$^{87}Sr/^{86}Sr = 0.7036$–$0.7057$ and $^{143}Nd/^{144}Nd = 0.51287$–$0.51269$; *Simonetti* et al., 1998], and have distinctly lower $^{143}Nd/^{144}Nd$ than the present-day products of the Reunion- Mauritius- Rodrigues hot spot [$^{87}Sr/^{86}Sr = 0.7036$–$0.7044$, $^{143}Nd/^{144}Nd = 0.51280$–$0.51289$; *Fisk* et al., 1988; *Baxter* et al., 1985; inset of Fig. 5]. Clear differences are observed with the compositions of the lowest $^{87}Sr/^{86}Sr$ and highest $^{143}Nd/^{144}Nd$ Dhandhuka-Botad borehole basalts in Gujarat (*Peng* and *Mahoney*, 1995; Fig. 5) and with the basalts of the lower rocks of the Western Ghats lava pile (Jawhar to Khandala Fms.; *Peng* et al., 1994). The isotopic composition of the Murud lamprophyres and that of the alkaline complexes of northern Deccan indicate the presence of a similar mantle reservoir with higher $^{87}Sr/^{86}Sr$ and lower $^{143}Nd/^{144}Nd$ than typical MORB-asthenosphere ($^{87}Sr/^{86}Sr < 0.7030$ and $^{143}Nd/^{144}Nd > 0.5130$; cf. *Hart*, 1988). The source of the lamprophyric rocks has isotopic evidence for relatively

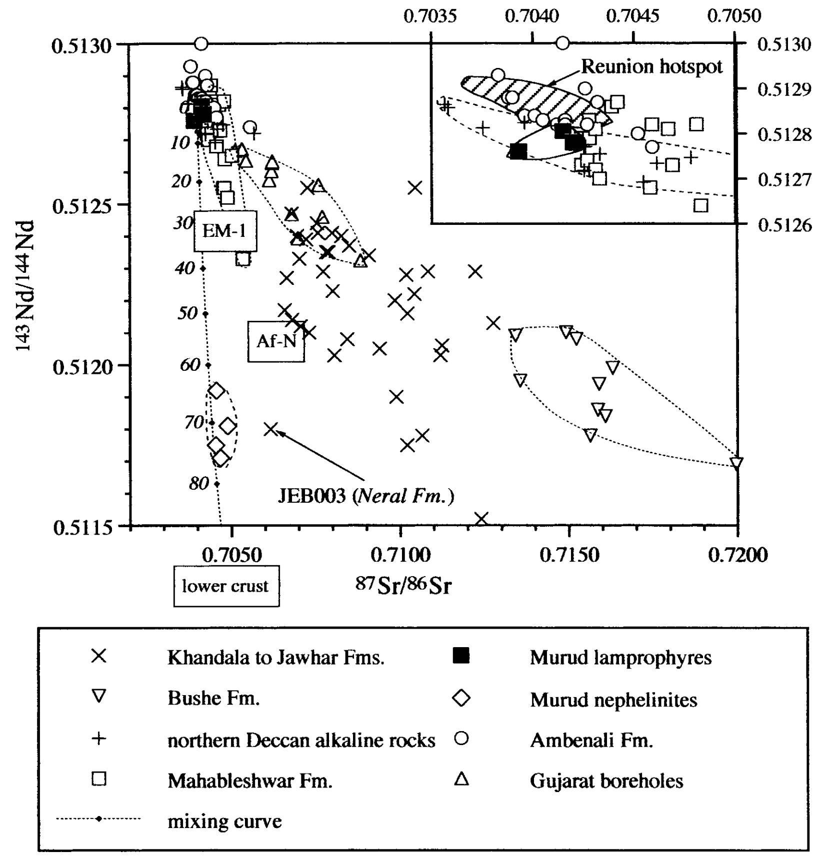


Fig. 5. $^{87}Sr/^{86}Sr$–$^{143}Nd/^{144}Nd$ diagram for the samples of this study and the Trombay island lamprophyre (*Mahoney* et al., 1985), together with samples of various basalt formations of the Deccan Traps. See the discussion section for the data sources. EM-1 end member from *Hart* (1988) and Afanasy-Nikitin seamount basalts (Af-N) from *Mahoney* et al. (1996). End-members of the mixing curve: granulitic lower crust: Sr = 285 ppm, Nd = 27 ppm (*Gao* et al., 1998), $^{87}Sr/^{86}Sr = 0.7050$; $^{143}Nd/^{144}Nd = 0.5112$ (*Halliday* et al., 1993); mantle-derived nephelinite: Sr = 900 ppm; Nd = 40 ppm; $^{87}Sr/^{86}Sr = 0.7040$; $^{143}Nd/^{144}Nd = 0.5128$

young enrichment (< 300 Ma) by volatile-rich fluids and melts, possibly coming from the asthenosphere (*Sen*, 1995).

The lamprophyres of Murud-Janjira are potassic and volatile-rich. Their chemistry does not have obvious analogues in the tholeiitic lava pile of the Western Ghats, and in the alkaline complexes further north (cf. *Simonetti* et al., 1998). It should be reminded that rare potassium-rich lava flows (subalkaline or weakly alkaline) are found intercalated with "normal" tholeiites at Rajpipla, northwestern Deccan. These potassic rocks are thought to be generated by melting of enriched lithospheric mantle (*Krishnamurthy* and *Cox*, 1980; *Mahoney* et al., 1985; *Melluso* et al., 1995).

The very high incompatible element contents of the lamprophyres, and the low values of the Zr/Nb ratio observed in all the Murud alkaline rocks, are features typical of low degree melts generated from incompatile element-enriched mantle. Indeed, assuming a source similar to the average lithospheric mantle composition of *McDonough* (1990; Zr = 21 ppm and Nb = 4.8 ppm, i.e., an enriched source for these two elements, relative to primitive mantle) and using a non-modal fractional melting model (melting modes and melt/liquid distribution coefficients from *Johnson*, 1998), the Zr and Nb abundances of the lamprophyric rocks could be justified by low degrees of partial melting (2–3%). These values are well within the range usually considered for generating strongly alkaline melts (< 4–6%; cf. *Frey* et al., 1978). The genesis of lamprophyres is usually related to melting of volatile-rich mantle, possibly containing phlogopite, carbonate and/or amphibole (cf. *Olafsson* and *Eggler*, 1983). It is also known that volatile-rich phases do not seem to be stable along high-temperature (plume-type) adiabatic cooling paths at any pressure (cf. *Class* and *Goldstein*, 1997). Current estimates of the temperature of the sub-Deccan mantle involved in the basalt petrogenesis are in the order of 1400 °C (*Melluso* et al., 1995; *Sen*, 1995), i.e., higher than normal mantle (~1280 °C; *McKenzie* and *Bickle*, 1988). However, the stability range of amphibole, carbonate and phlogopite, and the volatile-rich solidus could be crossed by cooling along a conductive geotherm (Fig. 6). Given the estimated lithospheric thickness in this area of Deccan (ca. 100 km, equivalent to ca. 30 kbar; *Negi* et al., 1986), the intersection of the conductive geotherm with the solidus of volatile-bearing peridotite could have been reached within the lower lithosphere (Fig. 6). As a conclusion, the source of the Murud alkaline lamprophyres could be located in a metasomatised lithospheric mantle.

The very unradiogenic $^{143}Nd/^{144}Nd$ of the nepheline-rich rocks has no analogues in the alkaline rocks of northern Deccan (cf. *Simonetti* et al., 1998). The isotopic composition of the nepheline-rich rocks is to be related to an end-member poorly documented in the Deccan province so far. The Sr–Nd-isotopic composition of these rocks is more extreme than the EM-1 end-member of present-day oceanic basalts (cf. *Hart*, 1988) and than the values observed in the basalt samples recovered on the Afanasy-Nikitin Rise, located in the Indian Ocean south of India and Sri Lanka ($\varepsilon Nd = -8$ at $^{87}Sr/^{86}Sr = 0.7066$; Fig. 5). The latter rocks are

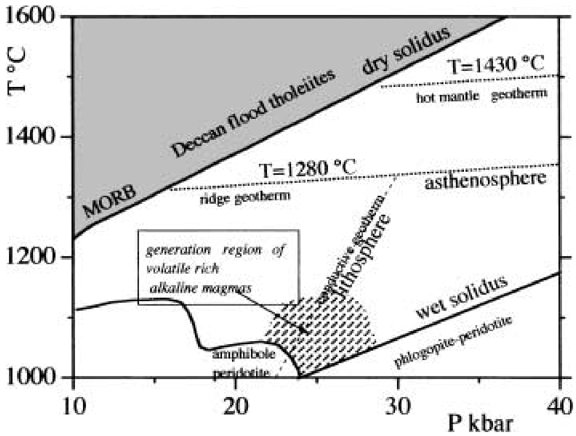


Fig. 6. P-T diagram with some inferred characteristics of the Deccan Trap mantle, and possible sources of the alkaline volcanism (*Melluso* et al., 1995; *Sen*, 1995; *Olafsson* and *Eggler*, 1983; *McKenzie* and *Bickle*, 1988)

interpreted as formed after melting of delaminated continental mantle (*Mahoney* et al., 1996). The nephelinites lie in a far extension of the trend of the Mahableshwar basalts and plot close to the isotopic composition of a unique Mg-rich tholeiitic basalt of the Neral Fm. (sample JEB003 of *Peng* et al., 1994; Fig. 5), north of the study area.

The strongly alkaline affinity of the Murud nephelinites indicates their ultimate mantle derivation, but their unusual chemical and isotopic composition could not be a primary feature, being the result of extensive contamination of a mantle-derived magma with "Lewisian-like" mafic, granulitic lower crust. This latter is known to be characterised by low time-integrated Rb/Sr and Sm/Nd (cf. *Halliday* et al., 1993), in a way similar to the basalt JEB003. A mixing model between average "Lewisian-like" mafic granulites and a mantle-derived melt with the chemical and isotopic composition of the lamprophyres (see Fig. 5) indicates that about 65–75% mixing with lower crust is needed to match the isotopic composition of the Murud nephelinites, and could be $>90\%$ if we assume the composition of Mundwara, Paraguay or Sicilian nephelinites as the uncontaminated, mantle-derived end-member. The amount of crust to fit the composition of the nephelinites is obviously difficult to reconcile with their highly alkaline nature, even though some chemical characteristics of these rocks (e.g., their high Ba/Nb ratios) could still indicate interaction with crustal materials. As isotopic values similar to those of the nephelinites were observed by *Cohen* et al. (1984) in both lower crustal mafic granulites and mantle-derived ultramafic nodules of the east African rift, we suggest the possibility that the chemical and isotopic composition of the nephelinites was inherited by low-degree melting of a mantle source that could have been chemically and isotopically modified by subducted, old, "Lewisian-like", lower crustal rocks.

## Conclusions

The alkaline intrusions of Murud-Janjira are mica-rich lamprophyres and nepheline-rich rocks with widely variable geochemical features. The lamprophyres represent volatile-rich, small-degree melts (2–3%), and bear little evidence of differentiation. The anomalously low incompatible element content of the nepheline-rich rocks is thought to be the result of enrichment of Mg-rich clinopyroxene and olivine in nepheline-rich, incompatible-element-poor, mantle-derived, melts. Very strong chemical and isotopic differences between lamprophyres and nephelinites suggest distinct evolution histories in the source regions. The petrological and geochemical evidence indicates that regionally associated sodic and potassic alkaline rocks were the product of melting of very heterogeneous, volatile ($CO_2 + H_2O + F$)-rich pockets of lithospheric mantle, possibly stabilised at different times (Precambrian to Mesozoic). These sources melted after the seaward flexuring of the west coast, and shortly after, or very close to, the heating event related to the eruption of the Deccan Traps. The low-$^{143}Nd/^{144}Nd$ component of the Murud nephelinites deserves further investigation, and implies a careful reconsideration of the relative contribution of lithospheric and sub-lithospheric (MORB-like and/or plume-derived) components in the petrogenesis of the *mafic* magmas of the Deccan Province.

**Acknowledgements**

We thank *M. Serracino*, *V. Monetti*, *A. Canzanella*, and *A. Carandente* for their technical assistance in the data acquisition, and *V. Morra*, *E. M. Piccirillo* and two anonymous reviewers for critical reading of the manuscript and useful suggestions. This work was supported by MURST grants (PRIN 1998–2000 to *P. Brotzu*).

**References**

*Allègre CJ*, *Birck JL*, *Capmas F*, *Courtillot V* (1999) Age of the Deccan traps using $^{187}Re$–$^{187}Os$ systematics. Earth Planet Sci Lett 170: 197–204

*Baxter AN*, *Upton BGJ*, *White WM* (1985) Petrology and geochemistry of Rodrigues Island, Indian Ocean. Contrib Mineral Petrol 89: 90–101

*Beccaluva L*, *Siena F*, *Coltorti M*, *Di Grande A*, *Lo Giudice A*, *Macciotta G*, *Tassinari R*, *Vaccaro C* (1998) Nephelinitic to tholeiitic magma generation in a transtensional tectonic setting: an integrated model for the Hyblean volcanism, Sicily. J Petrol 39: 1547–1576

*Bristow JW* (1984) Nephelinites of the north Lebombo and south–east Zimbabwe. Spec Publ Geol Soc S Afr 13: 87–104

*Brotzu P*, *Gomes CB*, *Melluso L*, *Morbidelli L*, *Morra V*, *Ruberti E* (1997) Petrogenesis of coexisting $SiO_2$-undersaturated to $SiO_2$-oversaturated felsic igneous rocks: the alkaline complex of Itatiaia, southeastern Brazil. Lithos 40: 133–156

*Class C*, *Goldstein SL* (1997) Plume-lithosphere interactions in the ocean basins: constraints from the source mineralogy. Earth Planet Sci Lett 150: 245–260

*Cohen RS*, *O'Nions RK*, *Dawson JB* (1984) Isotope geochemistry of xenoliths from East Africa: implications for development of mantle reservoirs and their interaction. Earth Planet Sci Lett 68: 209–220

*Comin Chiaramonti P*, *Gomes CB* (1996) Alkaline magmatism in central-eastern Paraguay. Relationships with coeval magmatism in Brazil. EDUSP-FAPESP, São Paulo, 464 pp

*Cox KG*, *Hawkesworth CJ* (1985) Geochemical stratigraphy of the Deccan Traps at Mahabaleshwar, Western Ghats, India, with implication for open system processes. J Petrol 26: 355–387

*De La Roche H*, *Leterrier J*, *Grandclaude P*, *Marchal E* (1980) A classification of volcanic and plutonic rocks using $R_1$–$R_2$ diagram and major element analyses. Its relationships with current nomenclature. Chem Geol 29: 183–210

*Dessai AG*, *Rock NMS*, *Griffin BJ*, *Gupta D* (1990) Mineralogy and petrology of some xenolith-bearing dykes associated with Deccan magmatism, south of Bombay, India. Eur J Mineral 2: 667–685

*Devey CW*, *Stephens WE* (1992) Deccan-related magmatism west of the Seychelles – India rift. In: *Storey BC*, *Alabaster T*, *Pankhurst RJ* (eds) Magmatism and the causes of continental breakup. Geol Soc Spec Publ 68: 271–291

*Fisk MR*, *Upton BGJ*, *Ford CE*, *White WM* (1988) Geochemical and experimental study of the genesis of magmas of Reunion Island, Indian Ocean. J Geophys Res 93: 4933–4950

*Frey FA*, *Green DH*, *Roy SD* (1978) Integrated models of basalt petrogenesis: a study of quartz-tholeiites to olivine melilitites from south eastern Australia utilizing geochemical and experimental petrological data. J Petrol 19: 463–513

*Gao S*, *Luo T-C*, *Zhang B-R*, *Zhang H-F*, *Han Y-W*, *Zhao Z-D*, *Hu Y-K* (1998) Chemical composition of the continental crust as revealed by studies in East China. Geochim Cosmochim Acta 62: 1959–1975

*Gwalani LG, Rock NMS, Chang W-J, Fernandez S, Allegre CJ, Prinzhofer A* (1993) Alkaline and carbonatites of Amba Dongar and adjacent areas, Deccan Igneous Province, Gujarat, India. 1. Geology, petrography and petrochemistry. Mineral Petrol 47: 219–253

*Halliday AN, Dickin AP, Hunter RN, Davies GR, Dempster TJ, Hamilton PJ, Upton BGJ* (1993) Formation and composition of the lower continental crust. J Geophys Res 98: 581–607

*Hart SR* (1988) Heterogeneous mantle domains: signatures, genesis and mixing chronologies. Earth Planet Sci Lett 90: 273–296

*Hawkesworth CJ, Hergt JM, Ellam RM, McDermott F* (1991) Element fluxes associated with subduction related magmatism. Phil Trans Roy Soc Lond A 335: 393–405

*Hofmann C, Feraud G, Courtillot V* (2000) $^{39}Ar/^{40}Ar$ dating of mineral separates and whole rocks from the Western Ghats lava pile: further constraints on duration and age of the Deccan traps. Earth Planet Sci Lett 180: 13–27

*Johnson KTM* (1998) Experimental determination of partition coefficients for rare earth and high-field strength elements between clinopyroxene, garnet and basaltic melt at high pressures. Contrib Mineral Petrol 133: 60–68

*Krishnamurthy P, Cox KG* (1980) A potassium-rich alkalic suite from the Deccan Traps, Rajpipla, India. Contrib Mineral Petrol 73: 179–189

*Lightfoot PC, Hawkesworth CJ* (1988) Origin of Deccan Trap lavas: evidence from combined trace element and Sr-, Nd- and Pb-isotope data. Earth Planet Sci Lett 91: 89–104

*Lightfoot PC, Hawkesworth CJ, Devey CW, Rogers NW, Van Calsteren PWC* (1990) Source and differentiation of Deccan Trap lavas: implications of geochemical and mineral chemical variations. J Petrol 31: 1165–1200

*Mahoney JJ* (1988) Deccan Traps. In: *Macdougall JD* (ed) Flood basalts. Kluwer, Dordrecht, pp 151–194

*Mahoney JJ, Macdougall JD, Lugmair GW, Gopalan K, Krishnamurthy P* (1985) Origin of contemporaneous tholeiitic and K-rich alkalic lavas: a case study from the northern Deccan Plateau, India. Earth Planet Sci Lett 72: 39–53

*Mahoney JJ, White WM, Upton BGJ, Neal CR, Scrutton RA* (1996) Beyond EM-1: lavas from Afanasy-Nikitin Rise and the Crozet Archipelago, Indian Ocean. Geology 24: 615–618

*McDonough WF* (1990) Constraints on the composition of the continental lithospheric mantle. Earth Planet Sci Lett 101: 1–18

*McKenzie DP, Bickle MJ* (1988) The volume and composition of melt generated by extension of the lithosphere. J Petrol 29: 625–679

*Melluso L, Beccaluva L, Brotzu P, Gregnanin A, Gupta AK, Morbidelli L, Traversa G* (1995) Constraints on the mantle sources of the Deccan Traps from the petrology and geochemistry of the basalts of Gujarat State (Western India). J Petrol 36: 1393–1432

*Melluso L, Sethna SF, Morra V, Khateeb A, Javeri P* (1999) Petrology of the mafic dyke swarm of the Tapti river in the Nandurbar area (Deccan volcanic province). In: *Subbarao KV* (ed) Deccan Volcanic Province – WD West Volume. Mem Geol Soc India 43: 735–756

*Negi JG, Pandey OP, Agrawal PK* (1986) Super-mobility of hot Indian lithosphere. Tectonophysics 131: 147–156

*Olafsson M, Eggler DH* (1983) Phase relations of amphibole, amphibole-carbonate, and phlogopite-carbonate peridotite: petrologic constraints on the asthenosphere. Earth Planet Sci Lett 64: 305–315

*Peng ZX, Mahoney JJ* (1995) Drillhole lavas in the Deccan Traps and the evolution of the Reunion plume. Earth Planet Sci Lett 134: 169–185

*Peng ZX*, *Mahoney JJ*, *Hooper PR*, *Harris C*, *Beane JE* (1994) A role for lower continental crust in flood basalt genesis? Isotopic and incompatible element study of the lower six formations of the Western Deccan Traps. Geochim Cosmochim Acta 58: 267–288

*Rock NMS* (1987) The nature and origin of ultramafic lamprophyres: alnöites and allied rocks. J Petrol 27: 155–196

*Sen G* (1995) A simple petrologic model for the generation of Deccan Trap magmas. Int Geol Rev 37: 825–850

*Sethna SF* (1989) Petrology and geochemistry of the acid, intermediate and alkaline rocks associated with the Deccan Trap basalts. Mem Geol Soc India 10: 69–90

*Sethna SF*, *D'Sa CPR* (1991) Occurrence of ijolite with veinlets of carbonatite in the Deccan Trap at Murud-Janjira, Maharashtra, India. J Geol Soc India 37: 257–263

*Sethna SF*, *Mousavi M* (1994) Geology and petrochemistry of Deccan Traps along a part of the western coastal tract, India. In: *Subbarao KV* (ed) Volcanism. Wiley Eastern Ltd, pp 233–251

*Simonetti A*, *Goldstein SL*, *Schmidberger SS*, *Viladkar SG* (1998) Geochemical and Nd, Pb and Sr isotope data from Deccan alkaline complexes – inferences for mantle sources and plume-lithosphere interaction. J Petrol 39: 1847–1864

*Srivastava RK* (1988) Alkaline and peralkaline rocks of Rajasthan. In: *Leelanandam C* (ed) Alkaline rocks. Mem Geol Soc India 15: 3–24

*Subbarao KV*, *Hooper PR* (1988) Reconnaissance map of Deccan basalt group in the western Ghats, India. In: *Subbarao KV* (ed) Deccan flood basalts. Geol Soc India Mem 10

*Sun S-s*, McDonough WF (1989) Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. In: *Saunders AD*, *Norry MJ* (eds) Magmatism in the Ocean Basins. Geol Soc Spec Publ 42: 313–345

*Wedepohl KH* (1995) The composition of the continental crust. Geochim Cosmochim Acta 59: 1217–1232

*Wood DA* (1979) A variably veined sub-oceanic upper mantle-genetic significance for mid-ocean ridge basalts from geochemical evidence. Geology 7: 499–503

*Yoder HS Jr*, *Tilley CE* (1962) Origin of basaltic magmas: an experimental study of natural and synthetic rock systems. J Petrol 3: 342–532

Authors' addresses: *L. Melluso*, *M. D'Antonio*, and *L. Bennio*, Dipartimento di Scienze della Terra, Università Federico II, Via Mezzocannone 8, I-80134 Napoli, Italy; *S. F. Sethna* and *P. Javeri*, Department of Geology, St. Xavier's College, 400001 Mumbai, India