Elemental and Nd–Sr–Pb isotope geochemistry of flows and dikes from the Tapi rift, Deccan flood basalt province, India

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Abstract

The Deccan Traps are a large rift-associated continental flood basalt province in India, parts of which have been studied extensively in terms of geochemistry, palaeomagnetism and stratigraphy. However, the basalts of the Tapi rift in the central part of the province have been little-studied thus far. Two ENE–WSW-trending tectonic inliers of the Deccan basalts in this region, forming ridges rising from younger alluvium, are made up of basalt flows profusely intruded by basaltic dikes. Both of these ridges lie along a single lineament, although they are not physically continuous. The flows are aphyric, plagioclase-phyric and giant-plagioclase basalts, and the dikes are aphyric or plagioclase-phyric. We consider the two inliers to have been originally continuous, from the presence of bouldery remnants of a major dioritic gabbro dike along both. Samples of this dike from both ridges have previously yielded typical Deccan ages of 65.6 ± 0.5 Ma and 65.6 ± 0.6 Ma by the 40Ar–39Ar incremental heating technique. Initial Sr/Sr ratios and εNd(t) values, and present-day Pb isotopic ratios of most dikes indicate that they are isotopically similar to lavas of the Mahabaleshwar and Panhala Formations of the Western Ghats, about 450 km to the south. Their mantle-normalized trace element patterns have small Pb and Ba peaks. One dike has a strong Bushe Formation affinity and a Nd–Sr isotopic composition more extreme than that of any other Deccan rock yet sampled, with εNd(t) = −20.2 and (87Sr/86Sr)0.72315. Its mantle-normalized element pattern shows large Pb, Th and U peaks and large Nb–Ta troughs. Its elemental and isotopic chemistry reflects substantial continental contamination. The flows cut by the Mahabaleshwar-type dikes are isotopically similar to the Poladpur Formation lavas of the Western Ghats. Their mantle-normalized element patterns show modest peaks at Rb, Ba and Pb and rather low Nb and Ta relative to La, indicating that they have been contaminated to intermediate degrees. The mantle-normalized element patterns of all the flows and dikes show enrichment in the light rare-earth elements, with small or no Eu anomalies. The entire flow-dike sequence is similar to the Wai Subgroup of the Western Ghats, in terms of its elemental and isotopic chemistry and stratigraphic relationships. Wai Subgroup-like lavas (i.e., some of the younger magma types originally identified from the southern part of the Western Ghats) are previously known from the central, northern and northeastern Deccan, and many have been thought to be far-travelled flows erupted in the southwestern Deccan. Although at least the dikes, and probably the giant plagioclase basalt flows of our study area, are locally generated and emplaced, our new data extend the known outcrop area of these
widespread magma types substantially, and these magma types indeed appear to have a nearly province-wide distribution.

Keywords: Deccan; basalt; Tapi; rift; isotopes; geochemistry

1. Introduction

The Deccan flood basalt province covers today an area of 500,000 km² in western and central India (Fig. 1) after erosion and excluding the substantial area downfaulted into the Arabian Sea to the west (e.g., Mahoney, 1988). The combined stratigraphic thickness of these lavas in the well-studied Western Ghats region (boxed area in Fig. 1) is ~3000 m; no statistically significant age difference exists between lavas from the base and the top of this sequence, and its formal mean age is 67.5 ± 0.3 Ma (Duncan and Pyle, 1988). This immense volcanic outburst is generally ascribed to the birth of the Réunion hotspot beneath the northerly drifting Indian continent in the Late Cretaceous (e.g., Morgan, 1981). The stratigraphic framework of the Western Ghats region is known from detailed field, chemical, isotopic and palaeomagnetic studies (e.g., Cox and Hawkesworth, 1985; Beane et al., 1986; Lightfoot and Hawkesworth, 1988; Mahoney, 1988 and references therein; Subbarao, 1988 and references therein; Lightfoot et al., 1990; Peng et al., 1994), and a geological map is also available (Subbarao and Hooper, 1988). On the basis of geochemical characteristics and field markers, the Western Ghats stratigraphy has been divided into three subgroups and 11 formations (Table 1). All these lavas are thought to have been erupted from a group of randomly oriented apparent feeder dikes in a region near Igatpuri (Hooper, 1990), which is considered to be the center of an enormous shield volcano, and the lavas are nearly horizontal with regional southerly dips of < 0.5° in the region south of Igatpuri (Beane et al., 1986; Devey and Lightfoot, 1986). North of Igatpuri, however, the dips become slightly northerly and northeasterly (Subbarao et al., 1994).

Recent and ongoing work on the central part of the province to the east of Igatpuri has traced the Thakurvadi, Khandala and Poladpur Formations (Fms.) for several hundred kilometers (km) (Subbarao et al., 1994, 1998; Peng, 1998). The Poladpur, Ambenali and Mahabaleshwar Fms. also extend into the southeastern Deccan for hundreds of km from their type sections in the southwest (e.g., Mitchell and Widdowson, 1991). Lavas isotopically and chemically resembling the Ambenali, Poladpur, Khandala and Bushe Fms. have been described in the Mhow, Jabalpur and Chikaldara areas in the northeastern Deccan (Fig. 1), but because of their generally systematically higher Pb isotopic ratios, most appear to have been erupted from different feeder vents than the Western Ghats lavas (Peng et al., 1998).

Three major rift zones cross the Deccan province: the Narmada–Tapi rift zone (with the Satpura horst in between), the Cambay rift, and the West Coast rift belt (Fig. 1). They are marked by strong structural disturbance and faulting, high positive gravity anomalies, high heat flow, recent earthquake epicenters, possible Deccan magma chambers and intrusive bodies, regional dike swarms, and varied magmatism, which have led various workers (e.g., Sheth and Chandrasekharam, 1997a,b) to suggest that these rift belts had developed their own magmatic systems independent of the Western Ghats.

The stratigraphic status of the Deccan basalts of the Tapi rift region, between the Western Ghats and the Satpura range, has remained unknown and hardly any information has been published on their geochemistry or palaeomagnetism. This region shows an extensive cover of post-Deccan alluvium of the Tapi River, from which a few ridges of the basalts rise, with confused field relationships. These ridges are either tectonic inliers or regional dikes (Ravishanker, 1987; Guha, 1995; Sheth, 1998).

Two such ENE–WSW-trending ridges in the western part of the Tapi rift are made up of similar sequences of flows intruded by dikes, and the detailed field, chemical and isotopic studies we have
carried out on them form the subject of the present paper. The first ridge (named here the Shahada ridge) begins 7 km south of Shahada town (21°50'N, 74°30'E; see Fig. 2a). The other, Nandarde ridge, is seen at Nandarde village, 20 km north of Shirpur (21°20'N, 74°50'E).

2. Field geology

2.1. Shahada ridge

The Shahada ridge runs parallel to the Shahada–Shirpur road for about 6 km, in an ENE–WSW direction, parallel to the Narmada–Tapi regional tec-
Tectonic trend. At the Shirpur–Dondaicha road bifurcation (Fig. 2a), the road-cut exposes a plagioclase-phryic basalt flow in which a large multiple basaltic dike has been intruded. This dike is made up of three columnar rows, each ~ 6 m wide (the central row is an individual dike which has been intruded along the median plane of the earlier dike, splitting it in two). This central dike has been weathered to large (2–3 m) rounded boulders, which are scattered along the base of the ridge, its slopes and top. To the east, these boulders are exposed along the ridge top for its full length. Many small basaltic dikes are seen all along the ridge. The stratigraphic succession of the basalts constituting the ridge, obtained on an eastward, downhill traverse, is shown in Fig. 2b.

2.2. Nandarde ridge

The Nandarde ridge is similar to the Shahada ridge, and is made up of an aphyric basalt flow and a giant plagioclase basalt (GPB) flow (Fig. 2c). Many small dikes are present. They contain fragments of the GPB at the ridge top. This GPB flow is widely exposed to the north of Nandarde village as well. The bouldery dike at the Shahada ridge is also seen along this ridge.

Interestingly, the Shahada and Nandarde ridges seem to lie along a single lineament (dashed line in Fig. 2a), parallel to the regional tectonic trend and therefore reflecting some prominent structural control, although because of widespread alluvial cover, physical continuity between the ridges is absent. The flow stratigraphic sequences for the two ridges are also not exactly the same.
3. Petrography

All samples were studied in thin section on a Leitz-Laborlux petrological microscope. The minerals of the bouldery dike (SH43, SH50) are mainly plagioclase and clinopyroxene, with some subhedral sieve-textured opaques, orthoclase and minor secondary hornblende. These rocks have a moderately coarse grain size (3–5 mm) and subophitic texture. The anorthite contents of the plagioclases were determined using a three-axis universal stage (and later a JEOL energy-dispersive X-ray analyser) at IITB. Most plagioclase compositions fall towards the sodic end of the series, in the oligoclase (An10–30) range. Some labradorite grains are also present, however. The oligoclases contain many inclusions of prismatic apatite. The clinopyroxenes have optic axial angles 2V consistent with diopsidic augite. The modal compositions of the two dike samples are as follows: SH43 (Shahada): 43% plagioclase, 44% clinopyroxene, 8% opaques, 4% orthoclase and 1% secondary hornblende; SH50 (Nandarde): 51% plagioclase, 36% clinopyroxene, 9% opaques and 4% orthoclase. Because of the evolved plagioclase compositions, Sheth et al. (1997) termed these rocks dioritic gabbros. Their normative composition is quartz-bearing soda-gabbro. The other dikes and the flows appear to be ordinary tholeiitic basalts in thin section, with fine grain size and porphyritic±subophitic textures. Plagioclase is the most common phenocryst phase. However, the dike SH51 is unique in containing numerous clusters of well-crystallized, microscopic orthopyroxene ferro-enstatite. Each cluster contains hundreds of individual orthopyroxene grains, and such a phenomenon previously has not been described in any other Deccan rock except an E–W-trending, 40-km-long dike near Dhule (Keshav et al., 1998; Sheth, 1998). The origin of these clusters is presently being investigated (Chandrasekharan et al., in prep.).

4. Geochronometry

Radiometric dating of the Shahada and Nandarde bouldery dike by the 40Ar–39Ar incremental heating technique at Oregon State University yielded good plateau and isochron ages of ~ 66 Ma. The Shahada ridge sample (SH43) was dated at 65.6 ± 0.5 Ma and the Nandarde ridge sample (SH50) at 65.6 ± 0.6 Ma (five-step weighted mean plateau ages, 1σ). Complete 40Ar–39Ar results with plateau age and isochron age plots can be found in the work of Sheth et al. (1997).

5. Petrochemistry

5.1. Analytical methods

Major-element compositions of selected flow and dike samples, determined by inductively coupled plasma-atomic emission spectrometry (ICP-AES) at the Regional Sophisticated Instrumentation Center, IITB, are reported in Table 2. Trace-element data, also reported in Table 2, were obtained using inductively coupled plasma-mass spectrometry (ICP-MS) at the University of Hawaii, where the isotope dilution and isotope ratio measurements were also performed. Sample preparation and mass spectrometric techniques for measurement of Pb, Nd and Sr isotopic ratios and isotope dilution abundances of Pb, Nd, Sm, Sr and Rb are closely similar to methods described by Mahoney et al. (1991). The results, standard reference values and estimated analytical uncertainties are presented in Table 3. ICP-AES major and trace element data for the dioritic gabbro bouldery dike samples (SH43, SH50) can be found in the work of Sheth et al. (1997).

5.2. Discussion

The isotopic ratios for four dike samples, including the bouldery dike samples (SH43, SH50, SH41 and SH51, where t = 66 Ma), are closely similar to each other. Their eNd(t) values are slightly positive (+ 1.4 to +1.7), and on plots of eNd(t) vs. 87Sr/86Sr, and eNd(t) vs. present-day 206Pb/204Pb, data for these dikes plot within the isotopic arrays of the Mahabaleshwar and Panhala Fms. of the Western Ghats (Fig. 3a and b). In addition, plots of present-day Pb isotopic ratios (Fig. 4a–c) show that the data for the dikes plot precisely within the Mahabaleshwar Fm. field.
Table 2
Major- and trace-element compositions of the Shahada ridge–Nandarde ridge basalts

(1) Major-element data were measured by ICP-AES at IITB. Data for KC-11 standard provide an idea of accuracy. (2) Mg No. is molecular, assuming that 85% of the total iron is in the FeO form; thus Mg No. = wt.% MgO/[MgO + 0.85FeO(T)] × 100. (3) LOI is percentage loss in weight of sample powder on ignition at 900°C for ~ 2 h. (4) Trace elements were measured by ICP-MS at UH. Data for the USGS standard BHVO-1 provide an idea of accuracy. The reference values for KC-11 are those recommended by Walsh (1982), and the BHVO-1 reference values are from a literature-based compilation (mainly Govindaraju, 1989).

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Table 3
Isotope dilution trace-element abundances and Nd–Sr–Pb isotopic data

(1) Rb, Nd, Sm, Pb and Sr abundances were measured by isotope dilution. Analytical uncertainty on Nd and Sm abundances is < 0.2%, on Sr < 0.5%, on Rb ~ 1%, and on Pb < 1%. Small acid-washed chips of the samples were used for this (as part of the procedure for isotope ratio determinations; e.g., see Peng and Mahoney, 1995), and hence, the isotope dilution abundance values are not strictly representative of the bulk rocks, although they are close to the bulk rock values.

(2) $\varepsilon_{Nd}(t)$ and ($^{87}\text{Sr}/^{86}\text{Sr}$), are the initial ratios age-corrected to 66 Ma. Pb isotopic ratios are present-day values.

(3) Analytical uncertainty on $\varepsilon_{Nd}$ is better than ±0.2 units; on $^{87}\text{Sr}/^{86}\text{Sr}$ better than 0.00002; on $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ better than ±0.012, and on $^{208}\text{Pb}/^{204}\text{Pb}$ better than ±0.038.

(4) Data are reported relative to the following standard values: for NBS981 Pb, to the values of Todt et al. (1984); for NBS987 Sr, $^{87}\text{Sr}/^{86}\text{Sr}$ = 0.71024 ± 0.00002; for La Jolla Nd, $^{143}\text{Nd}/^{144}\text{Nd}$ = 0.511845 ± 0.000010.

On the other hand, isotopic data points for the flows SH44, SH45 and SH52 GPB all fall within the Poladpur Fm. field (Figs. 3 and 4). The dike SH49, which intrudes a lower, unanalyzed flow SH48, Fig. 2c has $\varepsilon_{Nd}(t)$ = -20.2 and a corresponding ($^{87}\text{Sr}/^{86}\text{Sr}$) = 0.72315; these values are the lowest and highest, respectively, yet known for any Deccan rock. The Bushe Fm. of the Western Ghats is the most crustally contaminated formation known in the Deccan, and the dike SH49 has a strong Bushe Fm. affinity, but has Nd–Sr isotopic values even more extreme than known Bushe Fm. lavas. Interestingly, this dike has the highest Mg No. (62) of all samples in this study; the combination of high Mg No. and high Sr isotopic ratios has been noted previously among lavas of the Bushe Fm. (e.g., Mahoney et al., 1982; Cox and Hawkesworth, 1984, 1985; Lightfoot and Hawkesworth, 1988; Lightfoot et al., 1990), and has been explained on the premise that more primitive (and thus hotter) mantle magmas can experience greater amounts of crustal contamination during ascent than do more evolved, cooler magmas (e.g., O’Harra, 1978; Patchett, 1980; Huppert and Sparks, 1985; Mahoney, 1988). Significant crustal contamination has thus probably caused the highly radiogenic Sr isotopic and unradiogenic Nd isotopic composition of this dike (note also its relatively high SiO$_2$ with very low TiO$_2$ and FeO(T), features typical of Bushe lavas and of many other crustally contaminated basalts). Huppert and Sparks (1985) modelled magma ascent in dikes, and noted that at low flow rates in narrow dikes, flow conditions should be laminar, and hence, magma should solidify against dike walls, preventing subsequent batches from contamination. However, basaltic magmas can ascend turbulently if flow rates are sufficiently high, and under turbulent conditions, the products of partial melting of the country rocks are continuously swept away by the magma, thus allowing further contamination to continue. The dike width above which magma flow is expected to be turbulent is ~ 3 m. Note that the outcrop width of the SH49 dike in the field is ~ 15 m. This E–W-trending dike, and the flow it intrudes (SH48), are found 4 km south of Boradi (Fig. 2a), just to the eastern side of the Shirpur–Boradi road. They are not seen at the Nandarde ridge itself.

Fig. 5 shows the primitive-mantle-normalized trace element patterns of the Shahada and Nandarde ridge flows and dikes. The patterns of the isotope-
Fig. 3. (a) Nd–Sr and (b) Nd–Pb isotopic plots for the Shahada and Nandarde ridge flows and dikes. Formation fields are after Peng et al. (1994).

cally Mahabaleshwar-like dikes SH41 and SH51 have modest Pb and Ba peaks and are enriched in the light rare-earth elements relative to the heavy ones, with small negative Eu anomalies resulting from plagioclase fractionation (Fig. 5a). The pattern for the isotopically Bushe-like dike SH49 shows large peaks at Pb, Th and U, and a large trough at Nb–Ta, as expected from crustal contamination, and is light
rare-earth-enriched with a negative Eu anomaly (Fig. 5a). The patterns for the flows (Fig. 5b) have peaks at Pb, Rb and Ba, troughs at Nb–Ta, and light rare-earth enrichment with very small Eu troughs. These flows appear to have been contaminated to intermediate degrees, just like the Poladpur Fm. lavas of the Western Ghats.

6. A regional perspective

To briefly restate our main results, most dikes of the Shahada and Nandarde ridges are isotopically and chemically similar to lavas of the Mahabaleshwar Fm. of the Western Ghats (southwestern Deccan), and the flows to the Poladpur Fm. The whole assemblage of rocks is therefore similar to the Wai Subgroup. The presence of Wai Subgroup lavas, dominantly belonging to the Poladpur Fm., has also been reported in the Buldana and Lonar areas of the central Deccan (Fig. 1), 150–200 km SSE of our area, (Subbarao et al., 1994, 1996, 1998; Peng, 1998).

Lavas isotopically and chemically indistinguishable from the Ambenali Fm. constitute the top parts of sequences south of Jabalpur and north of Chikaldara in the northeastern Deccan (Fig. 1). They are underlain by flows chemically resembling the Poladpur Fm., and at Chikaldara, several flows similar to the Khandala Fm. Lavas with broadly Poladpur- and Khandala-like elemental compositions are also abundant in a thick section to the south of Mhow, and thus appear to be widespread across the northeastern Deccan (Peng, 1998; Peng et al., 1998). However, most of the northeastern Poladpur- and Khandala-like basalts are different from the chemically similar southwestern basalts in having consistently higher $^{206}\text{Pb}/^{204}\text{Pb}$. As the general stratigraphic order in the Chikaldara and Jabalpur areas is crudely the same as that in the southwestern Deccan (i.e., Ambenali-like lavas overlying chemically Poladpur-like lavas, which in turn overlie chemically Khandala-like lavas), Peng et al. (1998) argued that they are petrogenetically related to the southwestern Deccan basalts but erupted from different feeder vents; that is, the northeastern basalts are not just far-travelled lavas erupted from the same dikes as the southwestern ones. The locations of the feeder dikes for the northeastern flows are unknown; many may be relatively near the sections studied. Thus, overall, Wai Subgroup-like lavas seem to be widespread over the central and northern Deccan, and are by no means confined to the southern region of the Western Ghats.

However, with regards to the basalts of our study area, their chemical and isotopic similarities with the Wai Subgroup basalts do not necessarily mean that the entire Wai Subgroup (as defined from the Western Ghats) physically extends into our area. This statement derives from the following observations. (1) Several GPBs are present in our area (our unpublished data; SH47 and SH52 are only two examples; Sheth, 1998). In the Western Ghats, GPBs are confined to the oldest (Kalubai) subgroup only, and are conspicuously absent from the younger (Lonavala and Wai) subgroups (Hooper et al., 1988). Therefore, the widespread occurrence of GPBs in the Wai Subgroup-like sequences in the Shahada–Nandarde region strongly suggests that this region has had an evolutionary history at least partly independent of the Western Ghats. Highly plagioclase-phyric flows and GPBs are thought to have had relatively local eruptive vents because of their expected high viscosity (e.g., Mahoney, 1988). (2) The relatively dike-rich Narmada–Satpura–Tapi region could have been an important source area for the Deccan eruptions, noting the important role of rifting and lithospheric extension (e.g., Sheth and Chandrasekhar, 1997a,b). (3) A few cases of dikes and sills passing into flows have actually been demonstrated or inferred for the Narmada–Satpura region, based on field, geochemical, palaeomagnetic and geochronometric studies (e.g., Crookshank, 1936; Subbarao et al., 1988; Bhattacharji et al., 1994; Sen and Cohen, 1994).

The present study, supplemented by some recent studies (Deshmukh et al., 1996; Yedekar et al., 1996; Peng et al., 1998), strongly suggests that some of the common magma types in the Deccan are much more widespread than generally believed previously, and our findings extend the outcrop areas of these geographically widespread and volumetrically abundant magma types substantially. However, the Ambenali Fm., which separates the Poladpur and Mahabaleshwar Fms. in the Western Ghats, is completely absent in our study area, and around Mhow, but Ambenali-
type lavas form the top parts of more distant sections in the northeastern Deccan, and may have flowed consistently in a northeastern direction (Peng et al., 1998).

**7. Conclusions**

Flows and dikes of the Shahada–Shirpur region of the Tapi rift in the Deccan flood basalt province are closely similar to the Wai Subgroup of the Western Ghats, in terms of their elemental and isotopic chemistry. Wai Subgroup-like lavas are previously known from the central, northern and northeastern Deccan, and many have been thought to be far-travelled flows erupted along the Western Ghats. On the other hand, at least the dikes, and probably also the GPB flows of our study area have been emplaced from relatively local feeders distributed along this rift zone. However, our new data extend
the known outcrop area of the many widespread Deccan magma types substantially, and these magma types indeed appear to have a nearly province-wide distribution.

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References


