Geology and Geochemistry of the Sangamner Mafic Dike Swarm, Western Deccan Volcanic Province, India: Implications for Regional Stratigraphy

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ABSTRACT

Numerous large, NE-SW- to E-W-trending mafic dikes outcrop around Sangamner in the western Deccan Volcanic Province. This area is part of a broader region postulated to be a shieldlike feature and a major eruption center. A combination of field, geochemical, and isotopic (Sr and Nd) characteristics is used here to understand the relationship of this dike swarm with the associated lava flows and their position in the established Deccan stratigraphy. Many dikes are compositionally similar to the Khandala and Poladpur formations belonging to the Lonavala and Wai subgroups, respectively, while one dike is similar to the Ambenali Formation. One dike has a composition distinct from all other dikes in this area as well as from most stratigraphic units, although there are many similarities in composition with the Bushe Formation as well as the Boyhare Member of the Khandala Formation. While several dikes are geochemically similar to specific flows/members within certain formations, their isotopic composition is often different, sometimes significantly so. This implies either that there is a greater range in isotopic composition for those members than previously realized or that magmas with different isotopic compositions underwent broadly similar petrogenetic evolution leading to similarities in elemental composition. NE-SW-trending Poladpur- and/or Khandala-like dikes are concentrated in the central part of the area; these dikes appear to represent a vent system that could have fed southern, western, or eastern exposures of these younger formations. It is also possible, however, that some or many of the dikes along this system were simply late-stage intrusions of magmas representing the younger formations.

Online enhancement: table.

Introduction

The intrusive component of continental flood basalt provinces is often a significant part of the total magmatism (e.g., Walker 1993). This includes sills, dikes, and plugs occurring at all levels within the crust. Dikes form an important part of the magmatic plumbing system and can also be related to the prevalent tectonic stresses. Lavas constituting individual flow fields in such provinces often erupt from discrete fissure systems, exposed subsequently as dike swarms. Linear vent systems, represented by dike swarms and accumulation of near-vent deposits, have been identified for several stratigraphic units of the Columbia River Basalt Province (e.g., Swanson et al. 1975). This not only has aided stratigraphic work but also has had a bearing on physical volcanological studies involving magmatic output and long-distance transport.

With a currently exposed area of more than 500,000 km^2 and straddling the latest Cretaceous–Early Tertiary time period, the Deccan Volcanic Province (DVP) of India is a major flood basalt province. Detailed geochemical (including isotopic) and paleomagnetic studies by numerous research groups over the past two decades have led to the establishment of a geochemical stratigraphy for the southwestern DVP (table 1), and its extension to q1 the northern and eastern parts of the province has also been attempted (e.g., Cox and Hawkesworth 1984, 1985; Beane et al. 1986; Khadri et al. 1988; Lightfoot et al. 1990; Peng et al. 1998; Mahoney et

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Table 1. Stratigraphic Classification of the Southwestern Deccan Volcanic Province and Sr Isotopic Values (at 66 Ma) for Each of the Constituent Formations

Subgroup, formation	$^{87}Sr/^{86}Sr_{66\ Ma}$
Wai:	
Desur	.7072–.7080
Panhala	.7046–.7055
Mahabaleshwar	.7040–.7055
Ambenali	.7038–.7044
Poladpur	.7053–.7110
Lonavala:[a]	
Bushe	.7078–.7200
Khandala	.7071–.7124
Kalsubai:	
Bhimashankar	.7067–.7076
Thakurvadi	.7067–.7112
Neral	.7062–.7104
Igatpuri-Jawhar	.7085–.7128

Note. Stratigraphic classification follows Subbarao and Hooper (1988), and Sr isotopic values follow Sheth (2005).
[a] Subgroup of the Deccan Basalt Group.

al. 2000; Sheth et al. 2004). While much of the previous work pertains to lava flows, a few workers (e.g., Deshmukh and Sehgal 1988; Bhattacharji et al. 1996; Melluso et al. 1999; Subbarao et al. 1999) have also studied the two principal dike swarms in this province, where dikes occur with a high frequency. The West Coast Dike Swarm (*WCDS*, fig. 1), trending N-S to NNW-SSE, consists of dikes with both tholeiitic and alkaline compositions (e.g., Melluso et al. 2002). The Narmada-Tapi Dike Swarm (*NTDS*, fig. 1) also contains tholeiitic as well as alkaline dikes and has a predominant ENE-WSW trend (e.g., Sheth 1998; Melluso et al. 1999). In the WCDS south of Mumbai (Bombay), dikes are reported to intrude flows of the youngest (Wai) subgroup (Hooper 1990) and thus cannot have fed the bulk of the Deccan lavas. However, basaltic dikes that outcrop farther south, in Goa, have been argued to be the feeder dikes of some of the younger formations (Widdowson et al. 2000). On the basis of the common occurrence of alkaline dikes in the two principal swarms and their wider span of ages, Hooper (1990) argued against these being the principal vents for the Deccan eruptions and ascribed this role to the dikes outcropping in the Western Ghats region, roughly between Nasik and Pune (fig. 1). On the contrary, Bhattacharji et al. (1996), using geochemistry and K-Ar dates for several tholeiitic dikes from both of these swarms and their associated lava flows, argued that these dikes were feed-
q2 ers to the lavas.

The frequency of dikes in the Mumbai-Nasik-Pune region, the third important zone of dikes, is quite variable, in both a lateral and a vertical sense. These dikes do not display the strong preferred orientation typical of the other two swarms. Beane et al. (1986) observed that their compositions are similar to those of the associated flows. In conjunction with the specific disposition of the chemostratigraphic formations, they suggested that such random orientation is more probably associated with development of a central shield-type volcanic edifice rather than with true fissure eruption, as exemplified by the Columbia River Basalts (CRBs). Bhattacharji et al. (1996) considered the random ori- q3
entation to be the result of a stress regime dictated by large crustal magma chambers. Sheth (2000) argued that true feeder dikes in central volcanoes usually have a radial, not random, arrangement.

To the south and southeast of Pune, dikes are virtually absent, and no dikes are observed even in areas, such as Mahabaleshwar (fig. 1), with excellent vertical exposures. This paucity of dikes in the region dominated by the thick Wai Subgroup (south and southeast of Pune) is perplexing. Lavas along the southeastern fringe of the DVP are well over 200 km away from the nearest exposed dikes. Irrespective of which of the three principal dike swarm regions was the eruptive focus, it seems highly likely that some Deccan lavas flowed distances comparable to flows from the CRBs, i.e., several hundred kilometers.

Objectives of this study. In spite of consider-

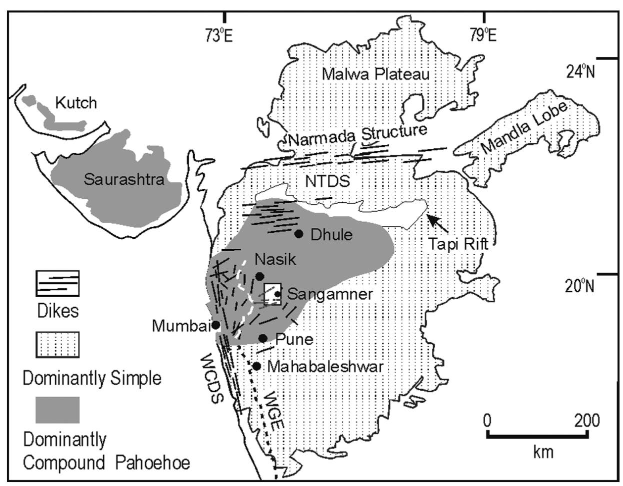

Figure 1. Map depicting some important features of the Deccan Volcanic Province (DVP). The areas dominated by "simple" and "compound pahoehoe" lava flows and the principal areas of dike concentration are shown. The study area is marked with the white box. *NTDS* = Narmada-Tapi Dike Swarm; *WCDS* = West Coast Dike Swarm; *WGE* = Western Ghats Escarpment. The Narmada-Tapi region is an ancient zone of weakness that has been reactivated at various times in the geological past.

able previous work, many questions regarding the nature of the Deccan magmatic episode remain to be satisfactorily answered; some of these were raised by Peng et al. (1998) and Mahoney et al. q4 (2000). First, what were the principal vent areas for the various formations of the Deccan stratigraphy? Second, were the eruptions of individual flows of the different formations largely monocentric (feeder dikes concentrated in a particular region) or polycentric (feeder dikes more widely distributed)? Third, how, if at all, did eruptive and intrusive activity fluctuate through space and time? In order to attempt to answer these questions, an integration of several kinds of information is required. Such information includes the distribution of dikes representing various chemical types and field evidence of feeder dikes, in addition to details of the thickness and distribution of various chemostratigraphic units. Most previous studies have looked at dikes from the DVP only on a broad, regional scale. Although valuable in many respects, they cannot provide the information and insights that a focused field and geochemical investigation of a specific, subregional dike swarm can. This study is one such focused investigation that documents the field relations and major-, trace-, rare earth–element and Sr and Nd isotope geochemistry of the dikes around Sangamner (fig. 1). These data are used to evaluate these dikes in a stratigraphic context.

Field Geology and Petrography

Figure 2 is a geological map of the study area, which is situated close to the Western Ghats Escarpment (*WGE*, fig. 1). This area has moderate relief and is drained by tributaries of the Pravara and Mula rivers (fig. 2). The basalt flows are nearly flat-lying (the sequence has a regional southerly dip of 0.5°–1°) and mainly belong to the Thakurvadi Formation (Fm.) of the Kalsubai Subgroup (Khadri et al. 1988; Subbarao and Hooper 1988). Some isolated, high peaks in the westernmost part of the area are formed by basalt lavas of the overlying Bhimashankar Fm. The flows are intruded by a minimum of 25 basaltic dikes. Extensive colluvio-alluvial deposits (locally up to 30 m thick) of the late Quaternary Pravara Fm. (Bondre 1999) overlie the basalts along the Pravara River and its tributaries. Patches of these sediments are also found along the Mula River. The basalt flows are classic compound pahoehoe, ranging in thickness from few tens of meters to well over 50 m, and are made up of individual flow lobes ranging in thickness from a few cm to 20 m (Bondre et al. 2000, 2004). The Thakurvadi Fm. is characterized by a wide range of MgO contents (3.5–17 wt%); however, flows with MgO contents of 6%–8% are most common (Khadri et al. 1988).

The southwestern and northwestern parts of the map area are remote, rugged, and highly vegetated; dikes are harder to spot in these regions. Exposure is also poor in the region dominated by the alluvium. However, extensive fieldwork aided by multispectral satellite data (from the Indian Remote Sensing Satellite IRS-1B) helped in identifying a majority of the dikes. These typically form positive relief features, such as prominent humps or spines, owing to their resistance to erosion. Only two dikes display negative relief. The dikes range in width from 1 to 18 m, with a mean width of 7.5 m and a mode of 6 m. Most dikes are simple and have a chilled margin on either side. Four dikes, however, appear to be multiple intrusions. For example, dikes Ch20 and Ch25 show more than two chilled margins. Many of these dikes can be traced over several kilometers. They form aligned, discontinuous humps, and their outcrop width shows significant variation along strike. Offshoots and apophyses are very common and indicate opportunistic exploitation of fractures by the intruding magma. There is a curious tendency for dikes to occur in pairs (fig. 2). The two dikes forming each pair are separated by a few to a few tens of meters. As discussed below, closely spaced dikes do not necessarily have identical chemical compositions. Many dikes display well-developed columnar jointing, the disposition of which helps identify their dips; most dikes are not vertical and dip at angles of 70°–80°. Two dikes show evidence of deformation during cooling in the form of twisted columns, although this might also be a result of the disturbance of geotherms by seepage of water, something that is commonly observed in lava flows. At one q5 locality, dike Ch12 shows near-vertical columns and appears to have spread out locally as a sill. A distinct NE-SW trend for most dikes, with a subsidiary E-W trend, is quite apparent from the geological map and the rosette diagram (fig. 2). Field evidence for feeder dikes is quite limited in the DVP; however, excellent evidence of near-vent material (stratified spatter and breccia) was observed at one location (fig. 2) in the area.

Plagioclase, olivine, clinopyroxene, and iron oxides are the principal mineral phases in the dikes. Most dikes are distinctly porphyritic, and plagioclase is the only phenocryst phase in many. Plagioclase glomerocrysts 1–5 mm in size are extremely common, while one dike has plagioclase megaphenocrysts (>2 cm). Microscopic observations indicate that almost all plagioclase pheno-

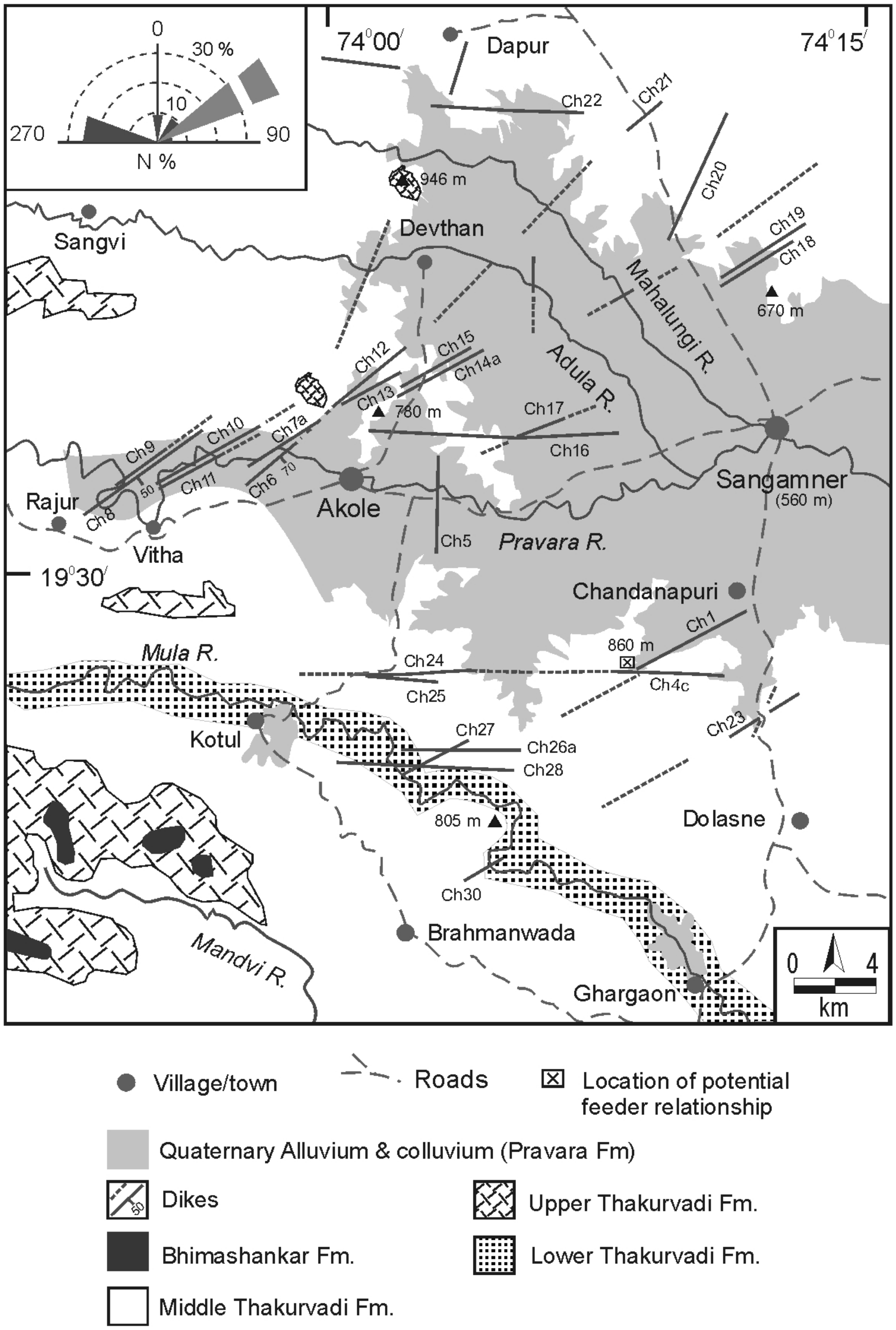

Figure 2. Geological map of the study area showing the distribution of dikes identified in this study. Dashed lines indicate dikes/dike extensions inferred from satellite imagery and topographical data. Numbers next to dikes refer to sample numbers discussed in the text. Dike dips are shown where significant. The extent of various chemostratigraphic units is from Subbarao and Hooper (1988) and Khadri et al. (1988). The inset (upper left corner of the map) is a rosette diagram of dike orientations. *N*% refers to the number of dikes trending in a given direction.

crysts show zoning, sometimes in complex patterns. Some of the more magnesian dikes have olivine phenocrysts as well as infrequent glomerocrysts consisting of olivine and clinopyroxene (optically determined to be subcalcic augite, in most cases, and rarely pigeonite). While the groundmass of some dikes is markedly inequigranular, with intergranular or intersertal textures, it is holocrystalline and equigranular in others, with plagioclase and clinopyroxene in a subophitic relationship. Iron oxides are abundant, particularly in the more evolved dikes, which also show an interstitial late-stage residuum or devitrified glass. The margins of most dikes show a much finer texture than the central regions, with plagioclase phenocrysts more abundant in the central parts.

Geochemical and Isotopic Characteristics

Analytical Methods. Fresh, texturally diverse samples were selected for analysis. Most dikes in the area appear to be quite fresh, with no or little evidence of alteration in hand samples. The more mafic dikes have undergone some alteration, as evidenced by discolored patches and iddingsitization of olivine. However, some relatively fresh olivine cores can be observed even in these. Concentrations of major elements in all dike samples were measured by direct current argon plasma atomic emission spectroscopy (DCP-AES) at Miami University, following the procedures of Katoh et al. (1999). Trace elements were determined by x-ray fluorescence (XRF) techniques at Franklin and Marshall College, following the methods of Boyd and
q6 Mertzman (1987). Errors are <2% for most major elements (~1% for SiO_2, 5% for K_2O, and 10% for P_2O_5) and 1%–5% for most trace elements measured by XRF. The accuracy of the XRF Pb data at the low concentrations measured in this study must be considered. For example, the measured value for USGS standard BHVO-2 is 4 ppm, while the accepted value is 3 ppm. Samples from this study that show more or less identical concentrations of other trace elements (e.g., Ch11 and Ch22) show a difference in their Pb values (5 and 7 ppm, respectively; table 2, available in the online edition or from the *Journal of Geology* office). Since a difference in Pb values of 1 ppm can make a significant difference in the form of primitive mantle–normalized plots, interpretations involving the presence or absence of Pb anomalies in such diagrams must be treated with caution.

Selected rare earth elements (REEs) were analyzed by inductively coupled argon plasma mass
q7 spectrometry (ICP-MS) at Miami University. Sample dissolution was achieved using 100 mg of sample powder thoroughly mixed with 300 mg of Li metaborate flux. This mix was placed in a graphite crucible and fused in a furnace at 950°C for 20 min. The resultant molten bead was dissolved in 50 mL of 5% HNO_3, and the solution was loaded onto a 1-cm-diameter quartz glass column containing 22 g of AG50W-X8 cation exchange resin. The non-REE fraction of the sample was removed by using 210 mL of a mixed (0.1 M oxalic acid and 2 M HNO_3) acid. After this step, 250 mL of quartz-distilled water was passed through the column, and REEs were collected in Teflon beakers using 200 mL of 5 M HNO_3. After drying down on a hot plate at low heat, the REE fraction was redissolved in 1 mL of 5 M HNO_3 and 5 mL quartz-distilled water, transferred to 20-mL Teflon beakers, and dried down again. The residue was dissolved in 18 mL of 1% HNO_3, and the weight of this solution was recorded. The REEs were analyzed from this solution using a Varian ICP mass spectrometer (plasma power of 1.37 kW and pump rate of 5 rpm). Measurements for each sample include five replicates, with 40 scans per replicate. Calibration curves (linear regressions) for each element were generated from three standard solutions with known concentrations (5, 160, and 500 ppb, respectively) and an acid blank that were run along with the unknowns. Concentrations of unknown samples were calculated from these curves, with ^{115}In serving as the internal standard to monitor and correct for instrumental drift. Two additional blank solutions and a 500-ppb solution were also run as unknowns. Measured concentrations for the 500-ppb solution were within 3% of this value. Concentrations for each element were corrected using the average blank values; however, the blank concentrations were quite low, and these corrections did not make a significant difference to the values.

Whole-rock Sr and Nd isotopic compositions of nine dikes (covering the spread in elemental compositions) and one lava flow were measured in static mode using a Thermo-Finnigan Triton multicollector thermal ionization mass spectrometer at
Miami University. Separation of Sr and a bulk light- q8
REE (LREE) fraction was achieved using methods similar to those described by Walker et al. (1989) and Snyder (2005). Sr isotopic ratios were corrected for fractionation using $^{86}Sr/^{88}Sr = 0.1194$. A 2-SD (standard deviation) external reproducibility of 1.4×10^{-5} based on 68 measurements of standard NBS 987, which resulted in an average $^{87}Sr/^{86}Sr = 0.710236$, is quoted for all ratios. Nd was separated from the remaining LREEs using an EiChrom Ln-Spec resin, following methods similar to those of Pin and Zalduegui (1997). Nd isotopic ratios were corrected for fractionation using $^{143}Nd/^{144}Nd = 0.7219$. A 2-SD external reproducibility of 7×10^{-6} based on 61 measurements of the La Jolla standard, which resulted in an average $^{143}Nd/^{144}Nd = 0.511846$, is quoted for all ratios. The isotopic analysis (including column separation) was repeated for sample Ch1 in order to check

the reproducibility of the obtained values. The fractionation-corrected measured ratios were age-corrected using whole-rock Rb and Sr (XRF) and Sm and Nd (ICP-MS) concentrations.

It is appropriate at this stage to demonstrate that changes to Rb and Sr concentrations well outside the analytical errors make only a small difference to the age-corrected Sr isotopic ratios. For example, the present-day Sr isotopic ratio of Ch1 is 0.70684 (table 3). Based on the Sr and Rb concentrations of 212 and 35, respectively, the age-corrected ratio is 0.70641 (for 66 Ma). Changing the Rb concentration to 25 changes the corrected ratio to 0.70653. Changing the Sr concentration to 180 changes the corrected ratio to 0.70634. These changes are very small as compared to the spread in values for any given formation in the Deccan, and hence the age-corrected isotopic data can be considered to be quite robust.

Results. Geochemical data for the samples and some derived parameters, such as magnesium number (Mg#), are listed in table 2, while REE and Sr and Nd isotopic data are given in table 3. Low values (<1.0 wt% of loss on ignition for all samples
q9 except one (table 1) suggest that the dikes have suffered only low levels of alteration and that their elemental abundances thus reflect primary values. Previous studies in the Deccan (e.g., Mahoney et al. 1985, 2000; Beane et al. 1986) have indicated that K and Rb can be affected even at modest levels of alteration, while at higher levels, Ba can also be mobile. Rb values for widely separated dikes that show very similar concentrations of other trace elements (e.g., Ch11 and Ch22) are also similar, suggesting that this element might not have been very mobile in most samples. Uncertainties in K_2O measurements by DCP-AES at the concentrations present in the dikes are relatively high, and it is difficult to discriminate alteration-related effects from those related to instrumental precision. Hence, K_2O has not been used as a discriminant for stratigraphic correlation in this study (except as one of the many variables in one run of the discriminant function analysis). The repeat analysis of sample Ch1 yielded $^{87}Sr/^{86}Sr = 0.706850$ and $^{143}Nd/^{144}Nd = 0.512610$, within the quoted 2-SD external reproducibility mentioned above.

Although the range in composition of the dikes is not large, discrete groups can nevertheless be identified on the basis of many major and trace elements and their ratios. The propensity of dikes to occur in a particular group does not seem to display a clear relationship to their location. Two dikes separated by several kilometers may show virtually the same composition (e.g., Ch11 and Ch22; fig. 2; table 2). On the other hand, dike Ch10, which is just a few meters away from Ch11 and is parallel to it, shows a markedly different texture and a somewhat different composition (table 2). The highly evolved compositions of some dikes and their high iron contents indicate that they were derived from a more fractionated magma (e.g., Ch1, Ch26a).

Table 3. Rare Earth Element (ppm) and Isotopic Data for the Deccan Samples

Sample	La	Ce	Nd	Sm	Eu	Gd	Dy	Er	Yb	Lu	$^{87}Sr/^{86}Sr_{(T)}$	$^{143}Nd/^{144}Nd_{(T)}$	$\varepsilon Nd_{(T)}$
AGV-2	39.2	72.6	32.4	5.03	1.41	4.76	3.51	1.93	1.67	.25			
AGV-2 (E)[a]	38.0	68.0	30.0	5.70	1.54	4.69	3.60	1.79	1.60	.25			
Ch1	21.6	50.7	30.9	7.47	2.32	8.41	8.34	4.78	3.91	.57	.70641 (.70684)	.512548 (.512613)	−.1
Ch4b[b]	9.10	22.5	15.1	4.23	1.50	4.79	4.72	2.66	2.13	.30	.70552 (.70563)	.512640 (.512716)	+1.7
Ch4c	10.4	26.5	18.0	5.09	1.78	5.86	6.00	3.41	2.79	.40	.70451 (.70463)	.512707 (.512784)	+3.0
Ch6	14.5	34.2	22.3	5.59	1.96	6.15	6.07	3.41	2.69	.39	.70627 (.70644)	.512511 (.512579)	−.8
Ch7a	16.7	39.4	23.4	5.5	1.82	5.73	5.50	3.10	2.45	.35			
Ch9	14.4	35.7	23.5	5.93	2.05	6.85	6.50	3.72	2.98	.42			
Ch10	18.5	42.6	25.7	6.18	2.02	6.81	6.35	3.51	2.87	.40			
Ch11	21.1	48.9	29.7	7.03	2.29	7.66	7.42	4.19	3.30	.47	.70644 (.70687)	.512497 (.512561)	−1.1
Ch13	16.2	39.7	26.2	6.66	2.29	7.46	7.57	4.23	3.35	.48	.70609 (.70621)	.512599 (.512668)	+.9
Ch16	16.4	37.5	21.4	5.24	1.71	5.76	5.61	3.19	2.65	.38	.70851 (.70877)	.512318 (.512385)	−4.5
Ch17	14.1	30.9	15.7	3.51	1.17	3.57	3.36	1.99	1.54	.22	.71162 (.71193)	.511862 (.511923)	−13.4
Ch18	21.2	46.9	27.1	6.35	2.08	7.00	6.95	4.00	3.18	.46	.70938 (.70971)	.512231 (.512295)	−6.2
Ch20	9.20	22.1	14.6	4.03	1.48	4.63	4.54	2.57	2.02	.29	.70541 (.70555)	.512626 (.512701)	+1.5
Ch24	10.8	27.0	18.3	4.89	1.73	5.69	5.69	3.18	2.62	.37			
Ch25	16.1	39.6	26.1	6.65	2.25	7.32	7.41	4.19	3.27	.47			

Note. $^{87}Sr/^{86}Sr_{(T)}$, $^{143}Nd/^{144}Nd_{(T)}$, and $\varepsilon Nd_{(T)}$ are age-corrected values at 66 Ma based on whole-rock Rb, Sr, Sm, and Nd concentrations. Measured values for $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ are in parentheses.

[a] Expected values for USGS standard AGV-2 (Wilson 1998).

[b] Flow sample.

Chemostratigraphic Affinities

Previous studies of lava piles exposed in parts of the DVP lacking an established stratigraphy have employed several tools in order to aid comparisons with the southwestern Deccan formations (Peng et al. 1998; Mahoney et al. 2000; Sheth et al. 2004). These tools include binary discriminant diagrams using elements or isotopes, normalized multielement patterns, and statistical methods such as discriminant function analysis (DFA). As this multipronged approach has proved to be reasonably or very successful for chemostratigraphic correlation, this investigation has also adopted the same general approach. It must be borne in mind that intrusives present some unique problems in stratigraphic correlation. Just like geochemical and magnetic polarity data, relative position in a vertical section is both helpful and critical in correlating flows from two widely spaced areas. Such relationships can often be difficult to ascertain for dikes and sills. In the present case, the only certainty in terms of stratigraphic position is that the dikes are younger than or similar in age to the Thakurvadi Fm., which they intrude. Cross-cutting dikes can sometimes be recognized, but poor exposure in regions of low to moderate relief often hampers this. Any attempt at correlating dikes with established stratigraphic units must therefore keep this limitation in mind.

Binary Diagrams. Figure 3 shows plots constructed using concentrations and ratios of some key elements that have been used by previous workers (e.g., Mahoney et al. 2000; Sheth et al. 2004) to discriminate between various formations. Although there is some diversity within the composition of the dikes (table 2), they define a relatively tight cluster against the backdrop of fields for the southwestern Deccan formations, as seen in figure 3. This figure shows that many dikes fall well within the fields of younger formations, notably the Khandala, Bushe, Poladpur, and Ambenali. It is apparent that there is substantial overlap in the compositional characteristics of several formations. Therefore, such plots by themselves are insufficient to discriminate between them. However, it is certainly possible to eliminate from consideration formations that do not show significant overlap, such as the Mahabaleshwar. While some dikes plot within the Ambenali field in these plots, only a few of them exhibit other geochemical characteristics that are quite distinctive of the Ambenali, such as low Ba concentrations (typically <100 ppm; Cox and Hawkesworth 1984, 1985; Beane et al. 1986), thus potentially ruling out an Ambenali affinity for the majority. Similarly, the affinity of most dikes with the Bushe Fm. can be ruled out because of the lack of distinctive characteristics, such as low TiO_2 contents (typically <1.5 wt%). Thus, on the basis of these simple plots and some general characteristics, most dikes seem to correlate with the Khandala and Poladpur formations. The more magnesian dikes (samples Ch5 and Ch20) remain problematic. The low TiO_2 and Zr values for dike Ch17, coupled with high Rb and K_2O, hint at a Bushe or Boyhare (a member of the Khandala Fm.) affinity for this dike, although some aspects of its composition are unlike any other stratigraphic unit.

Discriminant Function Analysis. Discriminant function analysis (DFA) was performed in order to quantitatively evaluate chemical affinities of the Sangamner dikes to individual southwestern Deccan formations. For this purpose, a data set consisting of 623 samples from all the southwestern formations except the Panhala was processed using the SPSS 7.5 for Windows (student version) software. The methodology utilized is essentially the same as followed by earlier workers (Peng et al. 1998; Mahoney et al. 2000; Sheth et al. 2004). No derived variables (Zr/Y ratio, Mg number, etc.) were used. Few Pb-Th-U-REE data exist for the southwestern Deccan basalts, and therefore these elements were not used as discriminating variables. Cr was not used because of contamination problems with some of the southwestern Deccan Cr data, and Na_2O and MnO were not used because of their limited range of variation in the southwestern data set, their low precision, and their variable analytical quality, in addition to alteration effects. q10

The southwestern Deccan and Sangamner data were first transformed to standardized values (Z scores). The Z score for a sample for any element is the number of standard deviations it is from the mean. The program calculated the F statistic (essentially, the ratio of the between-group variability to the within-group variability) for each variable and also the discriminant functions, group centroids, and Mahalanobis distance of each sample from the nearest formation centroid. A lower value for the Mahalanobis distance indicates a greater probability of a sample belonging to a particular formation. For the southwestern Deccan data set, eight canonical discriminant functions were obtained. These functions, from 1 through 8, account for progressively decreasing percentages of the total variance in the southwestern Deccan data set. This means that function 1 is a more effective discriminator between the groups (i.e., stratigraphic formations) than function 2, which is better than function 3, and so on. It is the two most effective discriminant functions (1 and 2) that are used in this article (fig. 4).

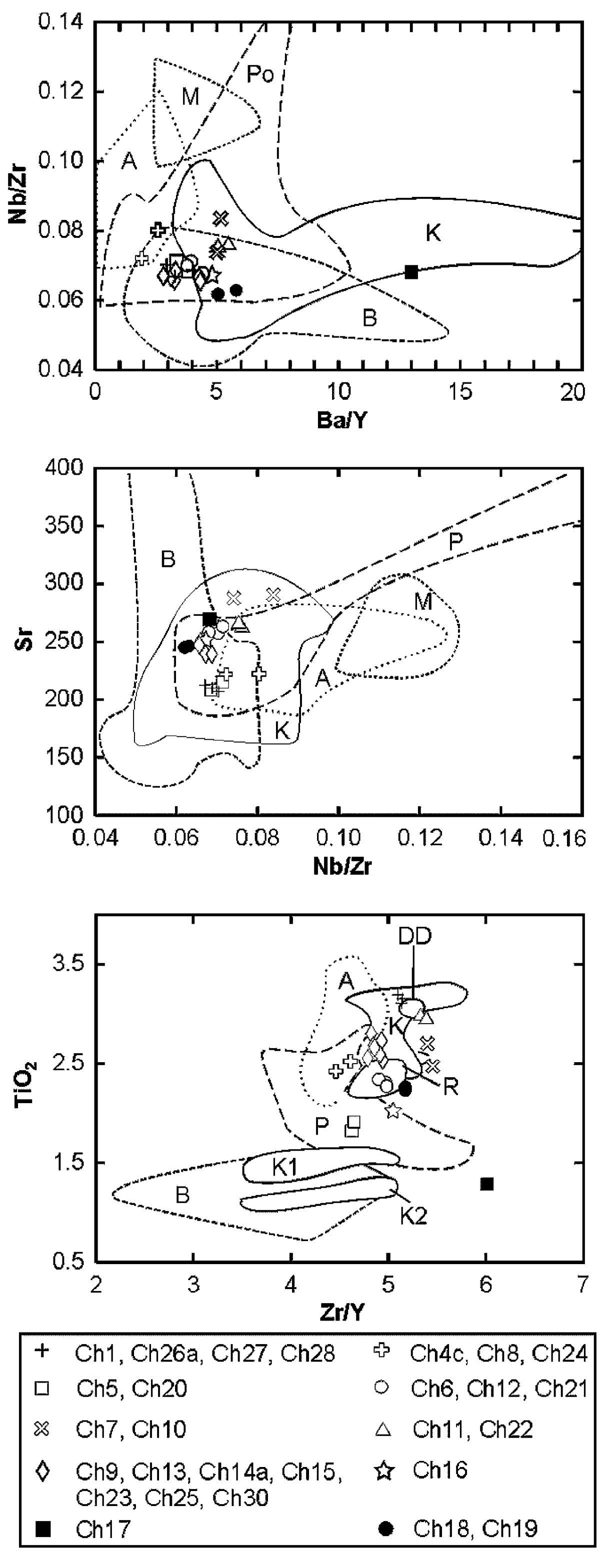

Figure 3. Plots of (*top*) Nb/Zr vs. Ba/Y, (*middle*) Sr vs. Nb/Zr, and (*bottom*) TiO_2 vs. Zr/Y for the Sangamner dike samples. Fields for relevant southwestern Deccan formations are from Sheth et al. (2004) and Peng et al. (1998) and are based on data from Beane et al. (1986) and Beane (1988). *A* = Ambenali Fm.; *B* = Bushe Fm.; *DD* = Dhak Dongar Member of the Khandala Fm.; *K*, *K*1, *K*2 = Khandala Fm.; *P* = Poladpur Fm.; *R* = Rajmachi Member of the Khandala Fm. Note the significant overlap between the fields for many of the formations.

Table 4 and figure 4 show the results of two different runs of the DFA, one using major (excluding Na_2O and MnO) as well as trace elements (Ni, Sc, V, Ba, Rb, Sr, Zr, Y, and Nb) and another using only trace elements. In the first run, 84.6% of original q11 grouped cases were correctly classified, and functions 1 and 2 (of the eight calculated by the program) accounted for 69.4% (50% and 19.4%, respectively) of the total variance in the southwestern Deccan data set. Most samples were matched with the Igatpuri and Jawhar formations. Progressive exclusion of K_2O, then K_2O, MgO, and Ni, and finally K_2O, MgO, Ni, and $Fe_2O_3{}^*$ did not make any significant difference to the result. This result is obviously in- q12 correct because the dikes intrude the Thakurvadi Fm., which overlies the Igatpuri and Jawhar formations (table 1). There is substantial overlap in the major-element composition of all southwestern Deccan formations that might have contributed to this anomalous result. In other words, major elements did not prove to be useful discriminants. Significantly different results were obtained, however, when DFA was performed using only the trace elements. In this run, 68.4% of original grouped cases were correctly classified, and functions 1 and 2 together accounted for 69.4% (42.3% and 27.1%, respectively) of the total variance in the southwestern Deccan data set. None of the samples was now matched with the Igatpuri and Jawhar formations; instead, many samples were classified with the Thakurvadi, Bhimashankar, and Khandala formations. Ch4b, a stubby flow associated with dike Ch4c, was matched with the Thakurvadi Fm. Results of this run attest to the much greater variation in the southwestern Deccan lavas in terms of trace elements, as compared to major elements. Previous q13 experience (e.g., Sheth et al. 2004) suggests that DFA by itself is insufficient for correlation and must be used in conjunction with other types of evidence (such as isotopic data and normalized multielement patterns) to aid correlation.

Normalized Multielement Patterns and Isotopic Composition. Comparisons using binary diagrams and DFA provided preliminary matches of the dikes to various formations. In order to further evaluate their

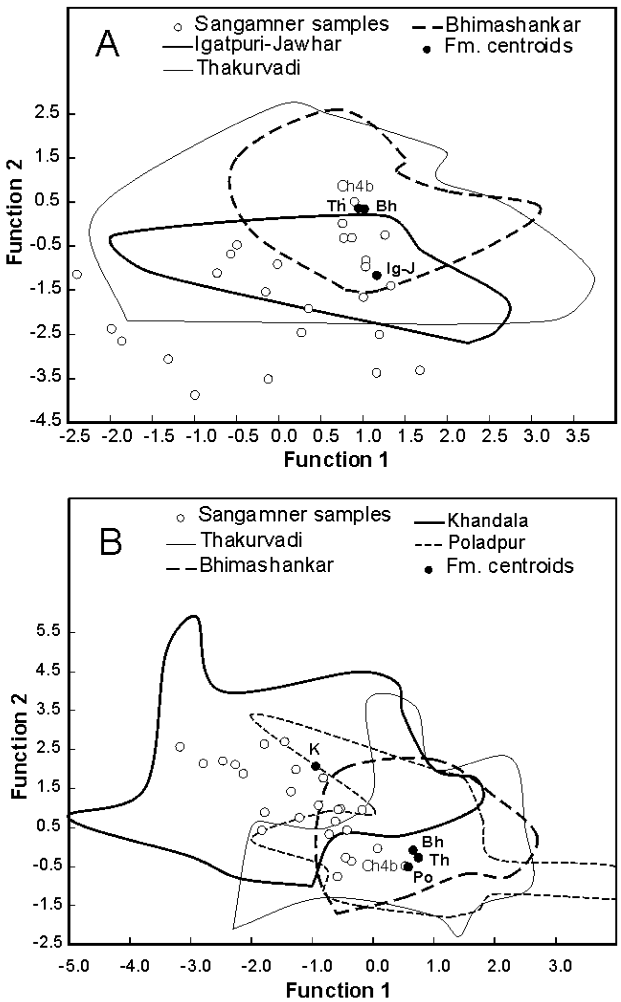

Figure 4. Values of the first two canonical discriminant functions for the Sangamner samples, with fields and centroids of their closest southwestern Deccan formations for the two runs discussed in the text. *A* shows results of the first run (table 4), where function 1 = $-0.492SiO_2 - 0.147Al_2O_3 + 1.387TiO_2 + 0.167CaO + 0.107MgO + 1.375P_2O_5 - 0.116Ni + 0.042Sc - 0.093V + 0.464Ba + 0.180Rb + 0.314Sr - 1.680Zr - 0.747Y - 0.015Nb$ and function 2 = $0.120SiO_2 + 0.029Al_2O_3 - 0.385TiO_2 + 0.048CaO - 0.289MgO - 0.315P_2O_5 + 0.268Ni + 0.035Sc + 0.764V - 0.804Ba + 0.047Rb + 0.235Sr - 0.945Zr + 0.069Y + 1.174Nb$. *B* shows results of the second run (table 4), where function 1 = $-0.294Ba + 0.963Nb + 0.335Ni - 0.045Rb + 0.188Sc + 0.473Sr + 0.854V - 0.619Y - 0.367Zr$ and function 2 = $0.798Ba - 0.715Nb + 0.324Ni - 0.277Rb + 0.100Sc + 0.048Sr + 0.086V - 0.436Y + 1.524Zr$. The elemental abundances in these equations are *Z* score–standardized values (see Sheth et al. 2004 and references therein). Formation centroids (*filled circles*) for the first run have the following function scores: Igatpuri-Jawhar (*Ig-J*) 1.165, −1.160; Thakurvadi (*Th*) 0.947, 0.356; Bhimashankar (*Bh*) 1.018, 0.342. For the second run: Thakurvadi (*Th*) 0.746, −0.274; Bhimashankar (*Bh*) 0.657, −0.081; Khandala (*Kh*) −0.942, 2.072; Poladpur (*Po*) 0.580, −0.508.

stratigraphic affinities, selected dikes were compared with individual flows or members from various southwestern Deccan formations using primitive mantle–normalized multielement patterns, chondrite-normalized REE patterns, and Sr and Nd isotopic data (figs. 5, 6, and 7, respectively). At places q14 in this section, differences in patterns based on the behavior of Pb are recognized. However, because of the generally low Pb concentrations as measured by XRF, we favor using the shape of the overall pattern, rather than individual features such as Pb peaks, in the ensuing correlations. Few previous studies have used REE patterns specifically for the purpose of chemostratigraphic correlation, as has also been pointed out by Widdowson et al. (2000). One of the reasons for this is that REE data for the Deccan are relatively few. However, as shown by Widdowson et al. (2000), these can prove to be quite useful in discrimination and are therefore used here as supporting evidence for inferences drawn from other multielement patterns.

Ch1 and Ch11 (and dikes similar to them) appear to be similar to the Dhak Dongar (DD) Member of the Khandala Fm., on the basis of their multielement and REE patterns (fig. 5*C*). The Sr concentration of Ch1, however, is much lower than typical DD values. In terms of their Sr and Nd isotopic compositions, these two dikes also plot in the Poladpur field, somewhat away from the DD Member, as seen in figure 7. The patterns for Ch18 resemble that of the Rajmachi Member of the Khandala Fm. (figs. 5*A*, 6*C*). The Rajmachi Member shows an isotopic composition distinct from those of other members of the Khandala Fm. (e.g., Peng et al. 1994) and actually plots in the Poladpur field. Ch18 also plots within the Poladpur field in figure 7 but away from the Rajmachi Member. In light of the excellent matches of multielement patterns of Ch1, Ch11, and Ch18 with the respective members, this discrepancy in isotopic composition could indicate that these members of the Khandala Fm. have a wider range in isotopic composition than previously documented. Nevertheless, on the basis of the isotopic compositions and some aspects of the elemental compositions, a Poladpur affinity cannot be discounted.

Dike Ch17 has a multielement pattern quite similar to the Bushe chemical type of the Bushe Fm.

Table 4. Results of Two Separate Runs of the Discriminant Function Analysis Discussed in the Text

	Run 1					Run 2				
Sample	Best match	*p*	M dist.	Function 1	Function 2	Best match	*p*	M dist.	Function 1	Function 2
Ch1	Ig-J	.113	13.0	−.125	−3.514	Kha(?)	.000	30.2	−2.792	2.147
Ch4b	Tha	.851	4.07	.899	.510	Tha	.967	2.39	.531	−.484
Ch4c	Bhi	.376	8.61	.758	.017	Pol	.545	6.92	−.584	−.756
Ch5	Tha	.414	8.20	1.261	−.247	Tha	.551	6.86	.072	−.039
Ch6	Bhi	.771	4.87	1.034	−.821	Bhi	.888	3.65	−.427	.441
Ch7a	Ig-J	.529	7.07	1.328	−1.396	Bhi	.679	5.71	−.535	.985
Ch10	Ig-J	.112	13.0	1.193	−2.499	Kha	.094	13.5	−1.269	1.989
Ch11	Ig-J	.251	10.2	1.678	−3.321	Kha	.297	9.56	−1.454	2.706
Ch12	Bhi	.458	7.75	1.006	−1.659	Bhi	.615	6.29	−1.213	.758
Ch13	Ig-J	.293	9.62	−.157	−1.539	Kha	.828	4.32	−.818	1.773
Ch14a	Ig-J	.040	16.2	−.734	−1.108	Kha	.291	9.64	−.894	1.072
Ch15	Ig-J	.067	14.6	−.570	−.676	Bhi	.483	7.51	−.618	.664
Ch16	Ig-J	.010	20.0	−2.397	−1.136	Bhi	.238	10.4	−1.829	.435
Ch17	Tha	.019	18.3	.268	−2.457	Ner	.077	14.2	−1.781	.892
Ch18	Ig-J	.014	19.2	−1.866	−2.649	Kha	.472	7.61	−2.264	2.119
Ch19	Ig-J	.021	18.0	−1.988	−2.373	Kha	.350	8.91	−2.132	1.882
Ch20	Tha	.686	5.65	.869	−.311	Tha	.532	7.04	−.352	−.364
Ch21	Bhi	.327	9.18	1.030	−.963	Bhi	.528	7.08	−.719	.335
Ch22	Ig-J	.101	13.3	1.160	−3.373	Kha	.021	18.0	−1.788	2.643
Ch23	Ig-J	.343	9.00	.352	−1.913	Kha	.605	6.38	−1.351	1.423
Ch24	Ig-J	.957	2.60	.772	−.316	Bhi	.849	4.09	−.452	−.273
Ch25	Ig-J	.213	10.8	−.495	−.467	Pol	.583	6.57	−.181	.955
Ch26a	Ig-J	.023	17.7	−1.313	−3.059	Kha(?)	.000	31.1	−2.470	2.208
Ch28	Ig-J(?)	.002	24.7	−.997	−3.877	Kha(?)	.000	28.5	−3.173	2.575
Ch30	Ig-J	.401	8.34	−.015	−.904	Kha	.663	5.86	−.573	.959

Note. See fig. 4 for functions 1 and 2. *p* = probability; M dist. = Mahalanobis distance. Formations: Ig-J = Igatpuri-Jawhar; Tha = Thakurvadi; Bhi = Bhimashankar; Kha = Khandala; Pol = Poladpur; N = Neral. Samples with question marks are those with Mahalanobis distance > 24, approaching a conditional probability of 0.

(fig. 5*B*); however, it differs in having a pronounced depletion in the heavy REEs, as seen in comparison of REE patterns (fig. 6*B*). The high Rb and K_2O and low TiO_2 of Ch17 are strikingly similar to the Bushe Fm. values. Ch17 is also similar in many ways to the Boyhare Member of the Khandala Fm., which bears several similarities to lavas from the Bushe Fm. Figure 6*B* reveals that the slope of the REE pattern for Ch17 is more similar to that of the Boyhare Member, as compared to the Bushe chemical type. Isotopically, this dike plots between the fields defined by the Khandala and Bushe formations. (fig. 7). Its $^{87}Sr/^{86}Sr_{(T)} = 0.7116$ is slightly lower than typical values of the Bushe Fm. (>0.7120, except for the distinctive Hari Member; Beane 1988; Lightfoot et al. 1990; Peng et al. 1994) and slightly higher than the reported value for the Boyhare Member (0.7102; Peng et al. 1994). The exact affinity of Ch17, therefore, is difficult to determine, and Ch17 could also represent a hitherto unsampled composition from the Deccan. Multielement patterns of dikes Ch6 and Ch16 are very similar (not shown), and these were compared with that of a flow from the Bhimashankar Fm. (sample JEB 366 from Beane 1988) based on their DFA match. The match is not very close for elements such as the large-ion lithophile elements. Their REE patterns are, however, almost identical to that of the Bhimashankar sample (fig. 6*A*). Both dikes plot in the Poladpur field in figure 7 and well away from the Bhimashankar field. Once again, there is disparity between affinities inferred from elemental composition and those inferred from isotopic composition. q15

Dike Ch13 was classified with the Khandala Fm. by DFA. It may be noted, however, that dike Ch25, which is compositionally quite similar to Ch13, was matched with the Poladpur Fm. by DFA. The multielement patterns for Ch13 and Ch25 are very similar and seem to agree reasonably well with that of the Kusgaon Member of the Poladpur Fm. (fig. 5*E*). Ch13 also plots in the Poladpur field in figure 7, which strongly suggests that a group of dikes similar to Ch13 (Ch9, Ch14a, Ch15, Ch23, Ch25, and Ch30) belong to the Poladpur Fm. Dike Ch4c also has a multielement pattern similar to that of the Kusgaon Member (fig. 6*E*). Ch4c has $^{87}Sr/^{86}Sr_{(T)} = 0.7045$, lowest among all dikes analyzed during this study, which puts it at the upper end of the range exhibited by the Ambenali Fm. (fig. 7) and within that for the Mahabaleshwar Fm.

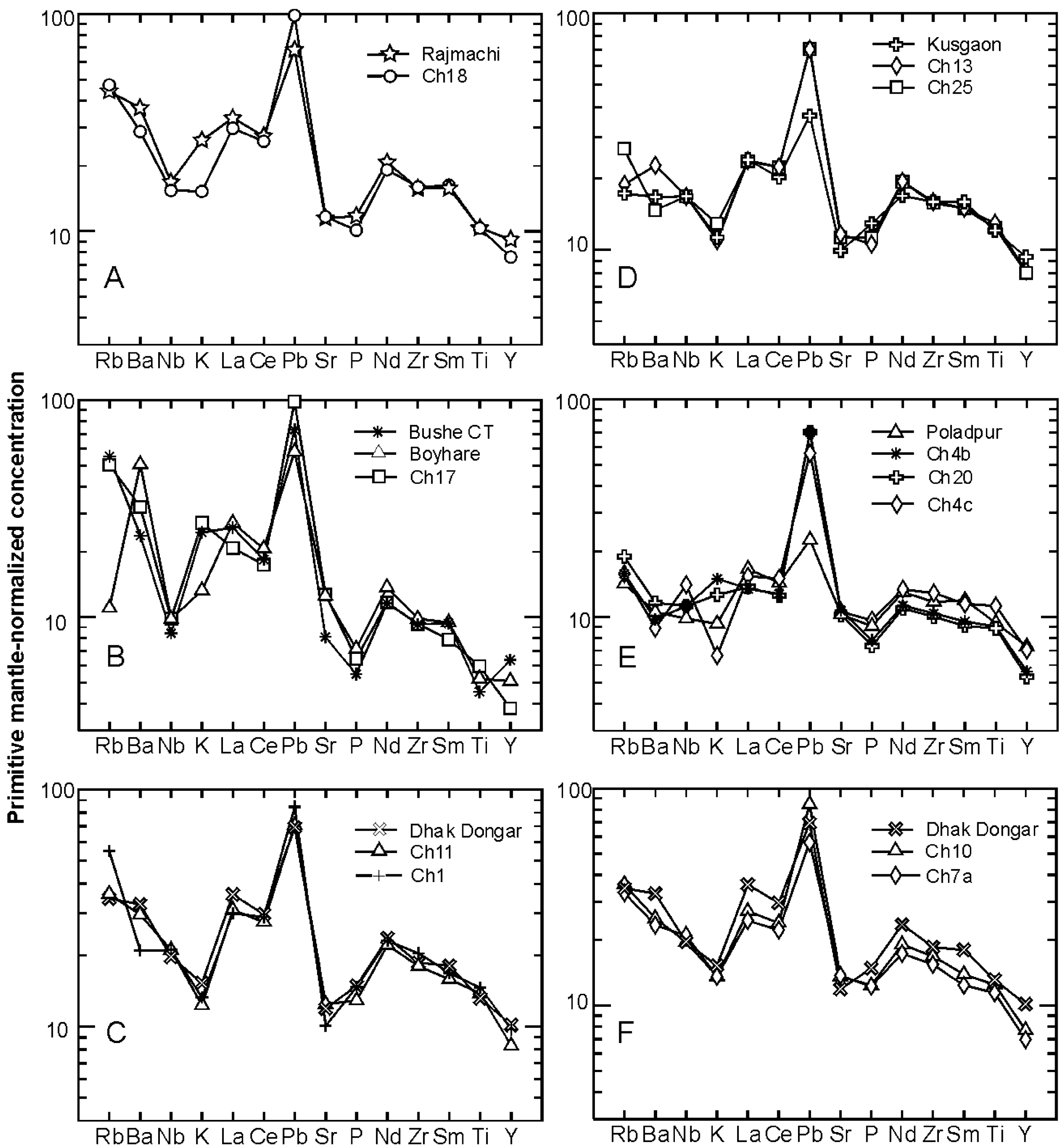

Figure 5. Comparison of multielement patterns for some Sangamner samples with those of selected formations/members of the Deccan stratigraphy. Concentrations have been normalized to the primitive-mantle values (after Sun and McDonough 1989).

Its rather low Ba concentration of ~62, however, favors a match with the Ambenali Fm. or the Poladpur Fm. (Cox and Hawkesworth 1984, 1985; Beane et al. 1986). However, the prominent Pb peak in its multielement pattern is quite unlike the typical Ambenali patterns, which have no Pb peak at all. Its affinity is provisionally determined to be Poladpur or Ambenali.

Interestingly, flow Ch4b, which shows field evidence of being fed by dike Ch4c, has a multielement pattern identical to that of dike Ch20 (fig. 5*E*). Ch4b and Ch20 have virtually identical Sr and

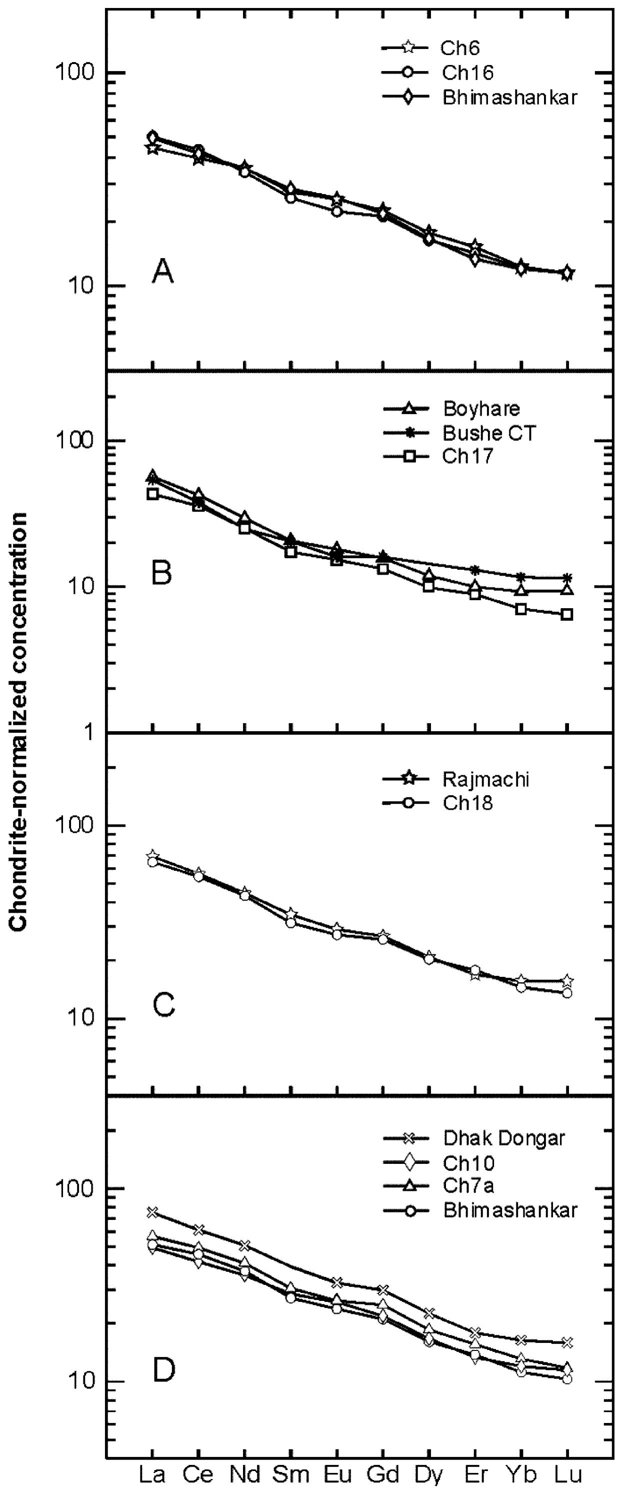

Figure 6. Comparison of rare earth element (REE) patterns for some Sangamner samples with those of selected formations/members of the Deccan stratigraphy. Concentrations have been normalized to chondritic values (after Nakamura 1974). REE data for the stratigraphic units are from Peng et al. (1994) and references therein.

Nd isotopic composition (fig. 7), which is not surprising, given their very similar multielement patterns. These patterns are similar to those for dike Ch4c and the Kusgaon Member but are depleted in REEs and elements such as Ti, Zr, and Y. There is excellent field evidence for near-vent explosive activity around dike Ch4c, and the base of Ch4b is welded to the spatter, suggesting emplacement when the spatter was hot. In this context, the discordance in isotopic composition between the dike (Ch4c) and the flow (Ch4b) creates a situation difficult to explain. A possible explanation for this discrepancy between field and elemental data and the isotopic data might be that the dike is multiply intrusive. The same dike fracture was probably used by two magmas that were compositionally somewhat different. Material belonging to only one of the pulses was sampled in the field, while the other pulse/pulses presumably remain unsampled at that location. The other pulse appears to have had a composition similar to that of dike Ch20, which is strikingly similar to that of Ch4b, although geographically not close to it. In the absence of other data or explanations, this seems to be a reasonable working hypothesis.

The moderate TiO_2 contents of Ch20 and Ch5 (~2 wt%), along with their high MgO (>8.5 wt%), hinted at a correlation with the Thakurvadi Fm. that seemed to have been confirmed by DFA. However, the $^{87}Sr/^{86}Sr_{(T)} = 0.7054$ of Ch20 is significantly lower than typical values reported for the Thakurvadi Fm. (e.g., Peng et al. 1994) and closer to that of the Poladpur and Mahabaleshwar formations. These dikes do not plot anywhere close to the Mahabaleshwar field in any of the binary diagrams used (fig. 3). Ch20 fringes the Poladpur as well as the Mahabaleshwar field in figure 7. Most Poladpur Fm. lavas are less magnesian (MgO ~ 6 wt% than these dikes; however, a picrite horizon within the upper Poladpur Fm. has been reported by Cox and Hawkesworth (1985). It is possible that Ch5 and Ch20 represent a more primitive chemical type from the Poladpur Fm.

Dikes Ch7a and Ch10 have nearly identical multielement patterns (fig. 5*F*). While these have the same general form as the pattern for the Dhak Dongar Member, they are somewhat depleted in REEs as compared to that member (fig. 6*D*). The patterns for these dikes were also compared with the Bhimashankar Fm.; the match is relatively poor for Rb, Ba, and Pb. The REE patterns for these dikes, however, are virtually identical to that of the Bhimashankar sample JEB 366 (Beane 1988; fig. 6*D*). Ch7a was correlated with the Bhimashankar Fm. by DFA, while Ch10 was correlated with the Khandala Fm.

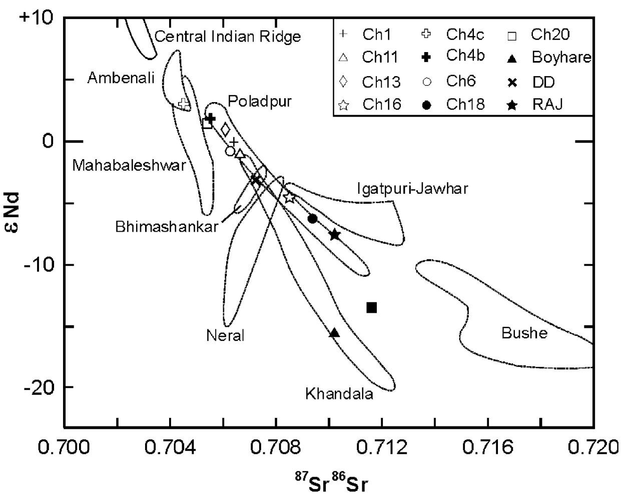

Figure 7. Sr and Nd isotopic data for the Sangamner samples. Also shown are fields for the southwestern Deccan formations (after Peng et al. 1994 and references therein). *DD* = Dhak Dongar Member; *RAJ* = Rajmachi Member.

In light of the contrasting information provided by the various techniques, the exact affinities of Ch7a and Ch10 remain uncertain.

Discussion

In the DVP, information on aspects such as the spatial distribution, number, and frequency of dikes representing various chemical types in the areas of principal dike exposure is scant. This study is one of the few attempts to present such details. This makes it possible to evaluate these dikes from a chemostratigraphic perspective and to improve our understanding of potential source areas for the Deccan lavas. An integration of several lines of geochemical evidence allows comparisons of the Sangamner dikes with certain southwestern Deccan formations and, in some cases, to particular members within these formations. Comparisons with the regional stratigraphy are not perfect, however. Isotopic ratios for certain dikes are outside the range typically exhibited by the formation or member to which they can be correlated based on elemental characteristics. This observation is not new; flows from the central and eastern DVP that are geochemically similar to southwestern Deccan formations have been shown to have systematically different isotopic compositions (e.g., Peng et al. 1998). Unlike those flows, however, intrusives from this study occur in a region where elemental and isotopic ranges were originally established for units in the Deccan stratigraphy. A recent study by Vanderkluysen et al. (2004) also reports that some dikes from the Nasik-Pune region and the WCDS are similar to some established chemostratigraphic units in terms of their major- and trace-elemental composition but have differing isotopic compositions. The Sangamner dikes are compositionally similar to several southwestern Deccan formations, although most of them can be best related to either the Poladpur Fm. or the Khandala Fm. In terms of their Sr and Nd isotopic composition, almost all analyzed dikes, with the exception of two, show an affinity with the Poladpur Fm. (fig. 7). Interestingly, these dikes encompass a large range of Poladpur isotopic compositions. Such dikes trend almost exclusively NE-SW and are concentrated in a band in the central part of the area (fig. 2), hinting at the possible manifestation of what could have been an eruptive fissure system. The nearest exposures of the Khandala Fm. are to the southeast, not too far (~10 km) from the southeastern corner of the study area, while the nearest Poladpur exposures are about 50 km to the southeast. Details of the spatial distribution of different geochemical types for dikes south and southeast of the study area are not available. Nevertheless, the Sangamner area could have been an important vent area for lavas of these two formations. This hints at the possibility that the eruption of different chemical types in the DVP was not entirely random in space and in time. Dike Ch4c shows elemental characters and Sr isotopic composition similar to those of the Ambenali Fm., except for the prominent Pb peak. This formation is exposed dominantly in the region south and southeast of Pune, about 150 km from the location of this dike. If Ch4c indeed represents this formation, this suggests that magmas (of an unknown volume) with Ambenali-type composition were intruded and/or erupted much farther north of present-day exposures. Ambenali-like flows are quite common in the eastern and northeastern DVP (e.g., Peng et al. 1998), attesting to either the originally extensive nature of this formation or polycentric eruptions of this magma type. q16

It is interesting to note the paucity of dikes in this area with a composition similar to the Thakurvadi and Bushe formations. No dike in the area was correlated with the Thakurvadi Fm. (two dikes are similar in terms of elemental characteristics but are isotopically more primitive). This suggests that feeders of the Thakurvadi might occur farther east, north, and northeast, in the areas currently exposing the older Igatpuri and Jawhar formations (see Bhattacharji et al. 1996). Dikes with compositions similar to that of the Thakurvadi Fm. have also been reported from the Tapi region by Melluso et al. (1999). Only one dike from Sangamner, Ch17, possibly correlates with the Bushe Fm. The Bushe Fm. lies between the Khandala and Poladpur formations, and the significance of the scarcity of dikes compositionally similar to it is unclear. This is particularly surprising, given that dikes chemically/isotopically similar to the latter two formations are quite abundant. This could suggest that significant volumes of Bushe magmas were not supplied to this region. Bushe-like dikes and flows have been found in the central DVP (Sheth 1998; Chandrasekharam et al. 1999; Mahoney et al. 2000), although the flows are not necessarily in the same stratigraphic order as in the southwestern Deccan.

Previous studies (Beane et al. 1986; Hooper 1990) have emphasized the randomness in dike orientations in the broader Mumbai-Nasik-Pune region. This study shows that the orientations of dikes in the Sangamner area (which is part of this broader region) are clearly not random (fig. 2). On the other hand, of 10 dikes around Igatpuri (south of Nasik, northwest of our study area), five dikes trend NNW-SSE, while the other dikes show varying orientations (V. M. Phadnis, unpublished data). There is an urgent need for detailed data on dike distribution, frequency, and orientation from this part of the DVP. This will help ascertain whether the "randomness" of orientations applies throughout this region (and so is real, not just apparent) or the discrete areas within this region tend to show consistent orientations. Pending such data, any statements regarding dike orientations and the stress regime associated with these dike swarms remain speculative.

Most dikes around Sangamner trend NE-SW, but a few also trend E-W. Do these two distinct trends have any temporal significance? The geochemistry of the dikes offers some clues in this regard. Ch11 and Ch22 are compositionally and texturally identical, but while the former trends NE-SW, the latter trends almost E-W (fig. 2; table 2). This is also the case for dikes Ch1 and Ch26a, suggesting that at least some dikes emplaced along both of these trends were of the same chemical types and thus likely contemporaneous. While dike composition in this area is not necessarily correlated with location, certain compositions do seem to be concentrated in certain regions. Four of the dikes (Ch1, Ch26a, Ch27, and Ch28) are distinctive in that they are geochemically the most evolved in this area, with the highest concentrations of incompatible elements (Rb, Zr), and the lowest MgO contents (<5 wt%). All of these dikes occur in the southern part of the study area, relatively close to each other (fig. 2), suggesting that that particular magma type was probably supplied to a restricted area.

Conclusions

Dikes of the broad Mumbai-Nasik-Pune region of the DVP have been previously postulated to be major eruptive vents for the associated lava pile. However, there have been few, if any, systematic attempts before this study to correlate these dikes to individual flows/formations that make up this lava pile. Similarly, published data for dike orientation and thickness on a local/subregional level are few, although these could illuminate several important issues such as the likelihood of this region having been an important eruptive zone and the nature of the prevalent lithospheric stress. This study reports detailed field and geochemical data for a swarm of basaltic dikes occurring around Sangamner. The data allow the comparison of the dikes to various units within the existing Deccan chemostratigraphy and the evaluation of their role as feeders. The geochemical characteristics of dikes, combined with their widths, lengths, and frequency, indicate that many dikes in the Sangamner area could have fed flows of the Poladpur and/or Khandala formations. One dike is compositionally similar to the Bushe Fm., while one is similar to the Ambenali Fm. The implications of this are not entirely clear, but it could suggest that minor volumes of magma types other than the Khandala and Poladpur were being episodically supplied to this area. By analogy with studies of dikes and flows from other basaltic provinces (e.g., Swanson et al. 1975; Martin 1989; Reidel 2005), it appears that the Sangamner dike q17 swarm would have had the potential to feed flood basalt flows of a significant extent.

This study also sheds light on some potential complications that may arise when intrusives from the DVP are correlated with established stratigraphic units. The implicit assumption in such a correlation is that the intrusives will display compositions that fall within the range defined by flows within the stratigraphy. This is, however, clearly not the case. Dikes around Sangamner are very similar to certain units in the Deccan lava stratigraphy in their elemental composition, but some of them differ subtly or significantly from their chemically similar counterparts in their isotopic composition. Similar observations have also been reported in other studies attempting to place flows from other parts of the DVP within the established stratigraphic framework of the southwestern DVP (e.g., Peng et al. 1998; Mahoney et al. 2000). Studies that seek to evaluate geochemical data within a framework of physical volcanology are in their infancy in the DVP. As a result, products of individual eruptive episodes (flow fields, volcanostratigraphic units) have not been unambiguously identified, complicating attempts to understand how magmatic activity within the province varied in space and time. Focused physical volcanological and geochemical investigations of both lavas and dike swarms on a local/subregional scale, similar to this one, have the potential to address several important questions regarding the magmatic evolution of the DVP.

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REFERENCES CITED

Beane, J. E. 1988. Flow stratigraphy, chemical variation and petrogenesis of Deccan flood basalts from the Western Ghats, India. PhD dissertation, Washington State University, Pullman.

Beane, J. E.; Turner, C. A.; Hooper, P. R.; Subbarao, K. V.; and Walsh, J. N. 1986. Stratigraphy, composition and form of the Deccan basalts, Western Ghats, India. Bull. Volcanol. 48:61–83.

Bhattacharji, S.; Chatterjee, N.; Wampler, J. M.; Nayak, P. N.; and Deshmukh, S. S. 1996. Indian intraplate and continental margin rifting, lithospheric extension, and mantle upwelling in Deccan flood basalt volcanism near the K/T boundary: evidence from mafic dike swarms. J. Geol. 104:379–398.

Bondre, N. R. 1999. Geology of the area around Akole, Maharashtra (using remote sensing techniques). MSc thesis, University of Pune.

Bondre, N. R.; Dole, G.; Phadnis, V. M.; Duraiswami, R. A.; and Kale, V. S. 2000. Inflated pahoehoe lavas from the Sangamner area of the western Deccan Volcanic Province. Curr. Sci. 78:1004–1007.

Bondre, N. R.; Duraiswami, R. A.; and Dole, G. 2004. Morphology and emplacement of flows from the Deccan Volcanic Province. Bull. Volcanol. 66:29–45.

Boyd, F. R., and Mertzman, S. A. 1987. Composition and structure of the Kaapvaal lithosphere, southern Africa. *In* Mysen, B. O., ed. Magmatic processes: physicochemical principles. Geochem. Soc. Spec. Publ. 1:13–24.

Chandrasekharam, D.; Mahoney, J. J.; Sheth, H. C.; and Duncan, R. A. 1999. Elemental and Nd-Sr-Pb isotope geochemistry of flows and dikes from the Tapi rift, Deccan flood basalt province, India. J. Volcanol. Geotherm. Res. 93:111–123.

Cox, K. G., and Hawkesworth, C. J. 1984. Relative contribution of crust and mantle to flood basalt magmatism, Mahabaleshwar area, Deccan Traps. Philos. Trans. R. Soc. Lond. A 310:627–641.

———. 1985. Geochemical stratigraphy of the Deccan Traps at Mahabaleshwar, Western Ghats, India, with implications for open system magmatic processes. J. Petrol. 26:355–377.

Deshmukh, S. S., and Sehgal, M. N. 1988. Mafic dyke swarms in Deccan Volcanic Province of Madhya Pradesh and Maharashtra. *In* Subbarao, K. V., ed. Deccan flood basalts. Geol. Soc. India Mem. 10:323–340.

Hooper, P. R. 1990. The timing of crustal extension and the eruption of continental flood basalts. Nature 345: 246–249.

Katoh, S.; Danhara, T.; Hart, W. K.; and WoldeGabriel, G. 1999. Use of sodium polytungstate solution in the purification of volcanic glass shards for bulk chemical analysis. Nat. Hum. Act. 4:45–54.

Khadri, S. F. R.; Subbarao, K. V.; Hooper, P. R.; and Walsh, J. N. 1988. Stratigraphy of Thakurvadi Formation, western Deccan Basalt Province, India. *In* Subbarao, K. V., ed. Deccan flood basalts. Geol. Soc. India Mem. 10:281–304.

Lightfoot, P. C.; Hawkesworth, C. J.; Devey, C. W.; Rogers, N. W.; and Van Calsteren, W. C. 1990. Source and differentiation of Deccan Trap lavas: implications of geochemical and mineral chemical variations. J. Petrol. 31:1165–1200.

Mahoney, J. J.; Macdougall, J. D.; Lugmair, G. W.; Gopalan, K.; and 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. 73:39–53.

Mahoney, J. J.; Sheth, H. C.; Chandrasekharam, D.; and Peng, Z. X. 2000. Geochemistry of flood basalts of the Toranmal section, northern Deccan Traps, India: implications for regional Deccan stratigraphy. J. Petrol. 41:1099–1120.

Martin, B. S. 1989. The Roza Member, Columbia River Basalt Group: chemical stratigraphy and flow distribution. *In* Reidel, S. P., and Hooper, P. R., eds. Volcanism and tectonism in the Columbia River Flood-

Basalt Province. Geol. Soc. Am. Spec. Pap. 239:85–104.

Melluso, L.; Sethna, S. F.; D'Antonio, M.; Javeri, P.; and Bennio, L. 2002. Geochemistry and petrogenesis of sodic and potassic mafic alkaline rocks in the Deccan volcanic province, Mumbai area (India). Mineral. Petrol. 74:323–342.

Melluso, L.; Sethna, S. F.; Morra, V.; Khateeb, A.; and Javeri, P. 1999. Petrology of the mafic dyke swarm of the Tapti River in the Nandurbar area (Deccan Volcanic Province). *In* Subbarao, K. V., ed. Deccan Volcanic Province. Geol. Soc. India Mem. 43:735–755.

Middlemost, E. A. K. 1989. Iron oxidation ratios, norms and the classification of volcanic rocks. Chem. Geol. 77:19–26.

Nakamura, N. 1974. Determination of REE, Ba, Fe, Mg, Na and K in carbonaceous and ordinary chondrites. Geochim. Cosmochim. Acta 38:757–775.

Peng, Z. X.; Mahoney, J. J.; Hooper, P. R.; Harris, C.; and Beane, J. E. 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.

Peng, Z. X.; Mahoney, J. J.; Hooper, P. R.; Macdougall, J. D.; and Krishnamurthy, P. 1998. Basalts of the northeastern Deccan Traps, India: isotopic and elemental geochemistry and relation to southwestern stratigraphy. J. Geophys. Res. 103:29,843–29,865.

Pin, C., and Zalduegui, J. F. 1997. Sequential separation of light-rare-earth elements, thorium and uranium by miniaturized extraction chromatography: application to isotopic analysis of silicate rocks. Anal. Chim. Acta 339:79–89.

Sheth, H. C. 1998. Geochemistry, petrogenesis, stratigraphy and structure of Deccan flood basalts of the western Satpura-Tapi region, India. PhD dissertation, Indian Institute of Technology, Bombay.

———. 2000. The timing of crustal extension, diking, and eruption of the Deccan flood basalts. Int. Geol. Rev. 42:1007–1016.

———. 2005. Were the Deccan Flood Basalts derived in part from ancient oceanic crust within the Indian continental lithosphere? Gondwana Res. 8:109–127.

Sheth, H. C.; Mahoney, J. J.; and Chandrasekharam, D. 2004. Geochemical stratigraphy of Deccan flood basalts of the Bijasan Ghat section, Satpura Range, India. J. Asian Earth Sci. 23:127–139.

Snyder, D. C. 2005. Processes and time scales of differentiation in silicic magma chambers: chemical and isotopic investigations. PhD dissertation, Miami University, Oxford, OH.

Subbarao, K. V.; Dayal, A. M.; Gopalan, K.; Hooper, P. R.; and Walsh, J. N. 1999. Narmada dykes. *In* Subbarao, K. V., ed. Deccan Volcanic Province. Geol. Soc. India Mem. 43:891–902.

Subbarao, K. V., and Hooper, P. R. 1988. Reconnaissance map of the Deccan Basalt Group in the Western Ghats, India. *In* Subbarao, K. V., ed. Deccan Flood Basalts. Geol. Soc. India Mem. 10 (enclosure).

Sun, S. S., and McDonough, W. F. 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. *In* Saunders, A. D., and Norry, M. J., eds. Magmatism in ocean basins. Geol. Soc. Lond. Spec. Publ. 42:313–345.

Swanson, D. A.; Wright, R. L; and Helz, R. T. 1975. Linear vent systems and estimated rates of magma production and eruption for the Yakima Basalt on the Columbia Plateau. Am. J. Sci. 275:877–905.

Tolan, T.; Reidel, S. P.; Beeson, M. H.; Anderson, J. L.; Fecht, K. R.; and Swanson, D. A. 1989. Revisions to the estimates of the areal extent and volume of the Columbia River Basalt Group. *In* Reidel, S. P., and Hooper, P. R., eds. Volcanism and tectonism in the Columbia River Flood-Basalt Province. Geol. Soc. Am. Spec. Pap. 239:1–20. q18

Vanderkluysen, L.; Mahoney, J. J.; and Hooper, P. R. 2004. Implications for the emplacement of the Deccan Traps (India) from isotopic and elemental signatures of dikes. EOS: Trans. Am. Geophys. Union 85 (47), Fall Meet. Suppl., Abstr. V51B-0561.

Walker, G. P. L. 1993. Basaltic-volcano systems. *In* Prichard, H. M.; Alabaster, T.; Harris, N. B. W.; and Neary, C. R. eds. Magmatic processes and plate tectonics. Geol. Soc. Spec. Publ. 76:3–38.

Walker, R. J.; Carlson, R. W.; Shirey, S. B.; and Boyd, S. B. 1989. Os, Sr, Nd and Pb isotope systematics of southern African peridotite xenoliths: implications for the chemical evolution of subcontinental mantle. Geochim. Cosmochim. Acta 53:1583–1595.

Widdowson, M.; Pringle, M. S.; and Fernandez, O. A. 2000. A post K-T Boundary (early Palaeocene) age for Deccan-type feeder dykes, Goa, India. J. Petrol. 41:1177–1194.

Wilson, S. A. 1998. Data compilation and statistical analysis of intralaboratory results for AGV-2. U.S. Geol. Surv. Open-File Rep. (in progress).

QUERIES TO THE AUTHOR

1 Table 1 has been revised to conform to *JG* style, in particular, to avoid blank entries in the first column. Because no group membership is designated for the Wai and Kalsubai subgroups, the group membership of the Lonavala subgroup has been placed in a footnote. Is the revised table accurate?

2 In the sentence beginning "On the contrary," it is unclear which dikes are meant in the passage "these dikes were feeders," because both dike swarms are mentioned earlier in the sentence. Please advise.

3 The abbreviation "CRBs" has been added here to define "CRB" for use below. Is this the correct interpretation?

4 Are the questions that follow those raised by Peng et al. and Mahoney et al.?

5 In the sentence beginning "Two dikes show," "disturbed geotherms due to seepage" has been changed to "the disturbance of geotherms by seepage" for a more precise depiction of the chain of causation. Does the revised sentence express your meaning accurately?

6 Has XRF been spelled out correctly?

7 Has ICP-MS been spelled out correctly?

8 Has TIMS been spelled out correctly?

9 There are no LOI values in table 1. Should this reference be to table 2?

10 The end of the sentence beginning "Cr was not used" has been revised. Does the revised sentence express your meaning accurately?

11 What is the significance of the asterisk after Fe_2O_3? Is it the same as in the note to table 2?

12 In table 4, a sentence has been added to the table note directing readers to the figure 4 legend for a definition of functions 1 and 2. Change OK?

13 The sentence beginning "Previous experience" has been joined to the preceding paragraph to avoid having a one-sentence paragraph. Change OK?

14 In the figure 5 legend, the word "values" has been added after "primitive-mantle" for precision. Change OK, or would you prefer "patterns," as in the text?

15 Has LILE been spelled out correctly?

16 In the sentence beginning "If Ch4c," does "much farther north" mean "much more than 150 km north" or simply "far north" of the present-day exposures?

17 Reidel (2005) is not listed in "References Cited." Please provide a full reference entry.

18 Tolan et al. (1989) is not cited in this article. Please indicate where this work is to be cited; otherwise, it will be omitted from the reference list.

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