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The Feeder System of the Deccan Traps (India): Insights from Dike Geochemistry

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Three large dike systems are exposed in the Deccan Traps flood basalt province of India: the dominantly north–south-trending west coast swarm, the east–west-trending Narmada–Tapi swarm in the north-central Deccan, and the Nasik–Pune swarm in the central western Deccan. Combined major and trace element and Sr–Nd–Pb isotope data reveal that probable feeder dikes for the three main lava formations in the upper part of the lava pile (Poladpur, Ambenali and Mahabaleshwar Formations) are abundantly represented in the Nasik–Pune and coastal swarms. As a group, these dikes have no clear preferred trend. Among the highly oriented dikes of the Narmada–Tapi and west coastal areas, some have affinities with the lower part of the lava pile (Jawhar, Igatpuri, Thakurvadi and Bushe Formations) and these appear to have been intruded under the influence of regional north–south and east–west extension, respectively. Other dikes in the Narmada–Tapi swarm have the high-$^{206}Pb/^{204}Pb$ characteristic of flows in the far north-eastern Deccan. These data suggest that Deccan lava flows could have reached as much as 700 km in length. Directed lithospheric extension appears to have been an important control on the emplacement of feeder dikes for the lower and middle formations. In contrast, emplacement of the voluminous upper formations, which span the Cretaceous–Tertiary boundary and 29R–N magnetic reversal and are estimated to make up $\geq$50% of Deccan lava volume, was not controlled by directed regional extension. This conclusion contradicts predictions of rifting-based models for Deccan volcanism. Finally, isotopically distinct, north–south-trending dikes cut upper-formation flows and dikes along the coast; these dikes represent minor magmatism linked to early Paleocene east–west extension following the main phase of volcanism, in association with rifting of the Seychelles Bank from India.

KEY WORDS: *Deccan Traps; dike swarms; feeder dikes; flood basalts; geochemical correlations; large igneous provinces*

INTRODUCTION

The Deccan Traps are a flood basalt province covering 500,000 km^2 of India (Fig. 1). With an original lava volume estimated at (1–3) $\times 10^6$ km^3 (Wadia, 1975; Sen, 2001; Jay *et al.*, 2009), they are mainly composed of nearly flat-lying tholeiitic flows, many of which are laterally extensive (e.g. West, 1959; Raja Rao *et al.*, 1978), although their eruptive vents have not been found. Because flood basalts are the products of dike-fed fissure eruptions, the study of Deccan dikes as potential feeders to the Deccan flows is crucial for determining the eruptive source area(s), the lengths of lava flows, and the architecture of the flood basalt field and its evolution during the flood basalt event. In turn, these factors bear on models of the environmental impact of Deccan volcanism (e.g. Self *et al.*, 2006; Chenet *et al.*, 2008), which is of particular importance given that the Deccan event straddled the Cretaceous–Tertiary boundary (65·96 ± 0·04 Ma; Kuiper *et al.*, 2008) and early Paleocene 29R–N magnetic reversal (Vandamme *et al.*, 1991; Jay *et al.*, 2009), and hence the associated end-Cretaceous mass extinction (e.g. Courtillot *et al.*, 2000, and references therein).

Here, we report major and trace element and Sr–Nd–Pb isotopic compositions of dikes sampled from the three principal dike systems in the province. We compare dike compositions with those of major stratigraphically defined

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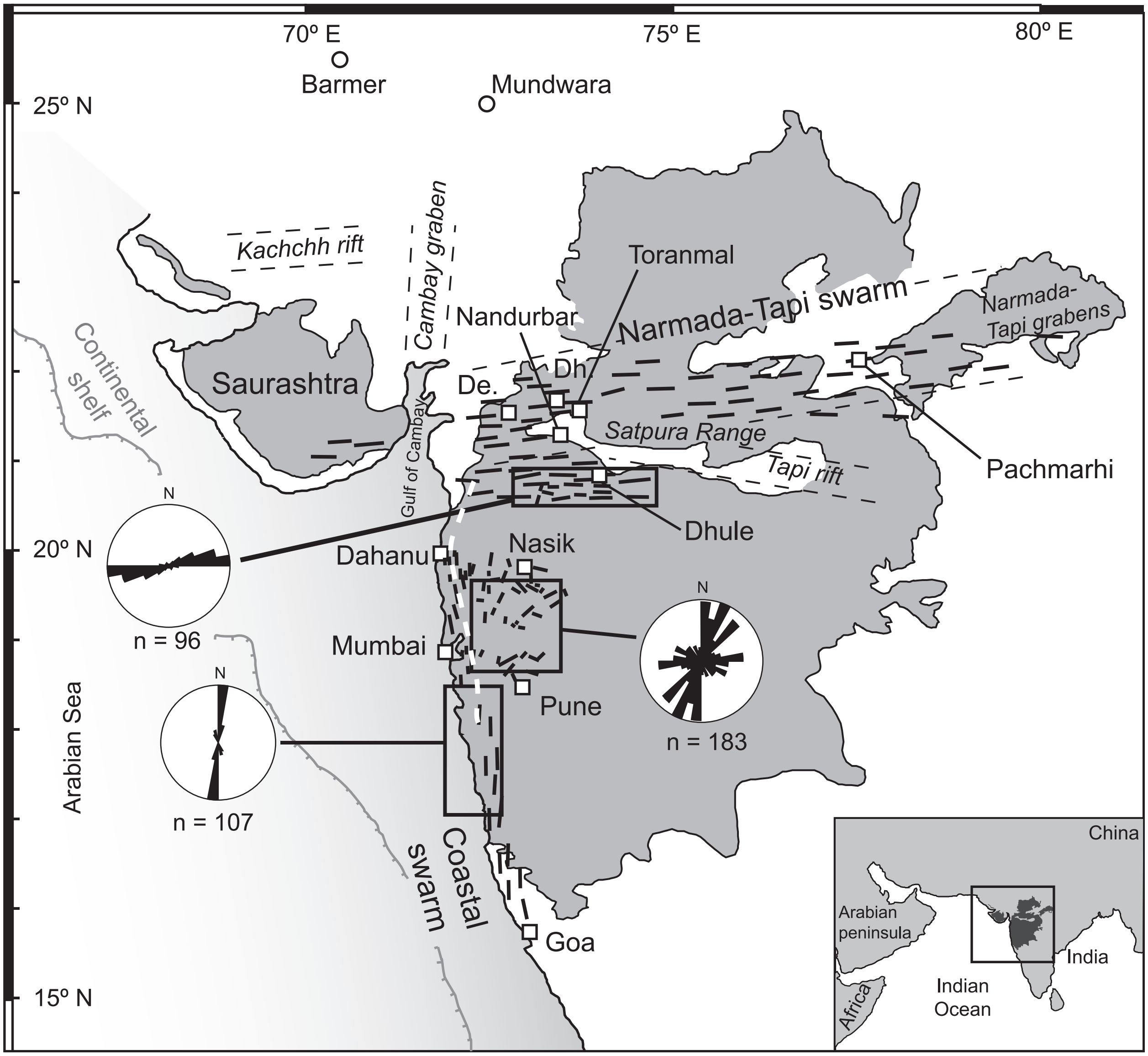

Fig. 1. Map of the Deccan Traps (gray), important localities mentioned in the text (white squares), intrusions of Mundwara and Barmer (white circles), and the three major dike swarms (shown schematically). Rectangles delimit the areas of each swarm for which we made substantial numbers (indicated by *n*) of dike-strike measurements, summarized in the rose diagrams. The white dashed line near the west coast represents the Panvel flexure (after Subrahmanya, 1998). Dh., Dhadgaon; De., Dediapada.

lava packages (formations), with the goal of determining the main areas of feeder dikes. Combining the geochemical results with data on dike trends, we explore the changes and migrations of the feeder system with time and implications for models of the origin of the Deccan Traps.

Background

Previous researchers have divided the lava flow stratigraphy in the southwestern part of the province into 11 flow formations (Table 1) on the basis of major and trace elements and Sr, Nd, and Pb isotope ratios (e.g. Cox & Hawkesworth, 1985; Beane *et al.*, 1986; Lightfoot *et al.*, 1990; Peng *et al.*, 1994; Subbarao *et al.*, 1994). These studies have mostly focused on the stratigraphically ~3400 m thick lava pile exposed in the type-sections of the Western Ghats (Fig. 2), an escarpment that separates the western coastal plain (Konkan) from the Deccan Plateau (Fig. 2a). Several of these formations have been shown to extend far to the SE, east, and/or NE. Although their chemical and isotopic variability in distant locations is somewhat greater than seen in the Western Ghats (e.g. Mitchell & Widdowson, 1991; Peng *et al.*, 1998; Mahoney *et al.*, 2000; Jay & Widdowson, 2008), their relative stratigraphic position is constant. The 11 formations are

Table 1: Stratigraphic nomenclature and maximum thickness of the western Deccan basalt formations (after Peng et al., 1994, and references therein)

Formation (max. thickness)	Member or chemical type	$(^{87}Sr/^{86}Sr)_t$	Av. Mg-no.	TiO_2 (wt %)	Av. Zr/Nb	Samples (this study)
Wai subgroup						
Panhala (>175 m)	Desur	0·7072–0·7080	48	1·6–1·9	11·4	
	Panhala	0·7046–0·7055	52	1·6–2·3	14·8	
Mahabaleshwar (280 m)		0·7040–0·7055	47	2·5–4·3	11·4	
Ambenali (500 m)	Ambenali CT	0·7038–0·7044	49	1·9–3·1	14·4	
Poladpur (375 m)	Upper	0·7061–0·7083	52	1·8–2·3	12·7	
	Lower	0·7053–0·7110	56	1·5–2·0	14·0	
	Sambarkada	**0·7075**	43	2·2–2·3	12·6	JEB-300
	Valvhan	0·7068	42	2·5–2·6	12·3	
	Ambavne	**0·7056**	45	2·0–2·1	14·0	BEL-13
Lonavala subgroup						
Bushe (325 m)	Pingalvadi	**0·7127**	61	1·1–1·2	17·2	JEB-353
	Bushe CT	0·713–0·720	55	1·0–1·3	15·3	
	Shingi Hill	0·718–**0·7181**	49	1·3–1·4	16·2	JEB-211
	Harishchandragad	0·7078–0·7079	46	2·0–2·1	12·9	
	Karla Caves	0·7147–0·7150	68	1·1–1·2	19·7	JEB-136
	Bhaja	0·712–**0·7164**	58	1·3–1·5	18·2	JEB-185
Khandala (140 m)	Rajmachi	**0·7093**–0·7102	44	2·1–2·5	14·6	JEB-297
	Khandala Phyric CT	**0·7085**	41	2·4–2·8	13·6	JEB-134
	KA3	0·7107	49	1·7	12·9	
	Madh	**0·7095**	58	1·6	14·0	DDW-13
	Boyhare	0·7102	63	1·2–1·3	13·7	
	KA2	0·7124	57	1·2	13·5	
	Khandala Phyric CT	0·7077	41	2·5–2·8	13·6	
	KA1	0·7094	61	1·0–1·1	15·4	
	Dhak Dongar	0·7071–0·7072	40	2·9–3·1	13·1	BOR-4
	KCG	0·7098	48	1·4–1·6	18·7	
	Monkey Hill GPB	0·7073–0·7075	41	3·1–3·4	12·2	KOP-21
	Giravli GPB	0·7068–0·7074	45	2·8–3·1	12·1	
Kalsubai subgroup						
Bhimashankar (140 m)	Bhimashankar CT	0·7067–0·7077	47	1·9–2·6	11·7	CH-24
	Manchar GPB	**0·7075–0·7077**	42	2·9–3·1	13·2	M-12, M-13
Thakurvadi (650 m)	Thakurvadi CT	0·7073–0·7080	58	1·8–2·2	12·0	
	Water Pipe	0·7099–0·7112	59	1·4–1·6	12·3	
	Member		71	1·0–1·1	12·0	
	Paten Basalt	**0·7224**	58	1·0	15·2	JEB-434
	Thakurvadi CT	0·7067–0·7070	58	1·8–2·2	12·4	
	Ashane	0·7068	62	2·0–2·1	9·6	
	Thakurvadi CT	0·7080–0·7088	58	1·8–2·2	11·6	M-8
	Jammu Upper	0·7112	34	2·7	9·8	
	Patti Middle	0·7099	46	2·2–2·3	8·4	
	Member Lower	0·7066–0·7067	56	1·7–2·0	11·2	
Neral (100 m)	Tunnel Five GPB	0·7082–0·7083	36	3·3–3·5	10·8	
	Tembre Basalt	**0·7084**	43	2·8–3·0	10·6	Tem-04

(continued)

Table 1: Continued

Formation (max. thickness)	Member or chemical type	$(^{87}Sr/^{86}Sr)_t$	Av. Mg-no.	TiO_2 (wt %)	Av. Zr/Nb	Samples (this study)
	Neral CT	0·7062–0·7073	62	1·5–1·7	12·3	
	Ambivli Picrite	0·7104	67	1·4–1·5	18·6	
Igatpuri–	Kashele GPB	0·7102–0·7122	40	2·6–3·1	11·5	
	Mg-rich Igatpuri		59	1·4–1·9	13·3	
	Igatpuri Phyric	0·7107–0·7124	49	1·9–2·2	14·3	
Jawhar (>700 m)	Thal Ghat GPB	0·7108	36	3·6	10·7	
	HFSE-poor Jawhar		51	1·3–1·6	13·0	
	Plag. Phyric	0·7085	38	3·0	11·7	
	Mg-rich Jawhar	0·7128	59	1·4–1·9	12·7	
	Kasara Phyric	0·7091	39	2·8–3·0	10·8	

Values in bold are from this study; associated sample name is given in the far right column. CT, chemical type; GPB, giant plagioclase basalt; KCG, Khandala coarse-grained; KA, Khandala aphyric; HFSE, high field strength element.

arranged into three subgroups on the basis of field characteristics and breaks in chemical and/or isotopic characteristics; the subgroups are the Kalsubai, Lonavala and Wai, representing the lower, middle and upper formations, respectively. The Wai Subgroup is estimated to make up ≥50% of the volume of the Deccan Traps (Self *et al.*, 2006). The chemical and isotopic signatures of the formations are distinctive and their geochemical characteristics are thought to arise from variable mixing and assimilation of products from different mantle sources and/or crustal end-members (e.g. Mahoney *et al.*, 1982; Cox & Hawkesworth, 1985; Mahoney, 1988; Lightfoot & Hawkesworth, 1988; Lightfoot *et al.*, 1990; Peng *et al.*, 1994).

Data for dikes across the province (e.g. Auden, 1949; Agashe & Gupte, 1972; Agrawal & Rama, 1976; Viswanathan & Chandrasekharam, 1976; Powar, 1981; Sinha-Roy & Radhakrishna, 1983; Sreenivasa Rao *et al.*, 1985; Beane *et al.*, 1986; Deshmukh & Sehgal, 1988; Hooper, 1990; Dessai & Viegas, 1995; Bhattacharji *et al.*, 1996; Sethna *et al.*, 1996; Sheth *et al.*, 1997, 2009; Chandrasekharam *et al.*, 1999, 2000; Melluso *et al.*, 1999; Subbarao *et al.*, 1999; Mahoney *et al.*, 2000; Widdowson *et al.*, 2000; Bondre *et al.*, 2006; Ray *et al.*, 2007) have led to the recognition of three main dike systems: (1) the Narmada–Tapi swarm, in which dikes generally strike ENE–WSW, parallel to the Narmada and Tapi river valleys; (2) the coastal swarm, which is approximately parallel to the west coast and composed largely of approximately north–south-striking dikes; (3) the Nasik–Pune swarm, in which dikes exhibit a weakly expressed NNE–SSW preferred strike (Fig. 1). Tholeiitic dikes are the most abundant, and are overwhelmingly vertical to subvertical. Alkalic and tholeiitic dikes with shallower dips (10–30° from vertical) also crop out along the coast at Mumbai and north and south of it (Dessai & Bertrand, 1995; Sheth, 1998); some of these dikes may have been tilted tectonically after emplacement, because the lava pile in this area (i.e. west of the Panvel flexure) dips to the west. The Panvel flexure is a monocline that formed along the west coast as a consequence of late-stage east–west extension that culminated in the post-Deccan rifting and separation of the Seychelles microcontinent (e.g. Sheth, 1998; Hooper *et al.*, 2010). Dikes of approximately Deccan age have also been reported in the Seychelles, with chemical and isotopic compositions broadly similar to flows of the Bushe Formation (e.g. Devey & Stephens, 1991).

Despite a lack of systematic geochemical studies, the Narmada–Tapi and coastal swarms have previously been discounted as feeder systems, because many of these dikes cut flows at all levels of outcrop (e.g. Auden, 1949; Beane *et al.*, 1986; Hooper, 1990). On the basis of reconnaissance major and trace element analysis of 42 Nasik–Pune dikes, Beane *et al.* (1986) postulated that the Nasik–Pune swarm served as the principal locus of feeders for the Deccan lava pile. Hooper (1990, 1999) interpreted the lack of any strong preferred orientation among these dikes as evidence that the main phase of eruptive activity was not accompanied by significant directed extension at the regional scale. This conclusion, in turn, has been used as a key argument in favor of a plume-head origin for the Deccan Traps (e.g. Hooper, 1990; Campbell, 1998), as opposed to a rifting-controlled origin (e.g. White & McKenzie, 1989), although Sheth (2000) disputed this argument.

The topography along the Narmada–Tapi grabens and the Western Ghats escarpment exposes extensive sections through the lava pile. However, east of the Ghats large areas of the monotonous, elevated Deccan (Maharashtra) Plateau provide few opportunities to observe flow

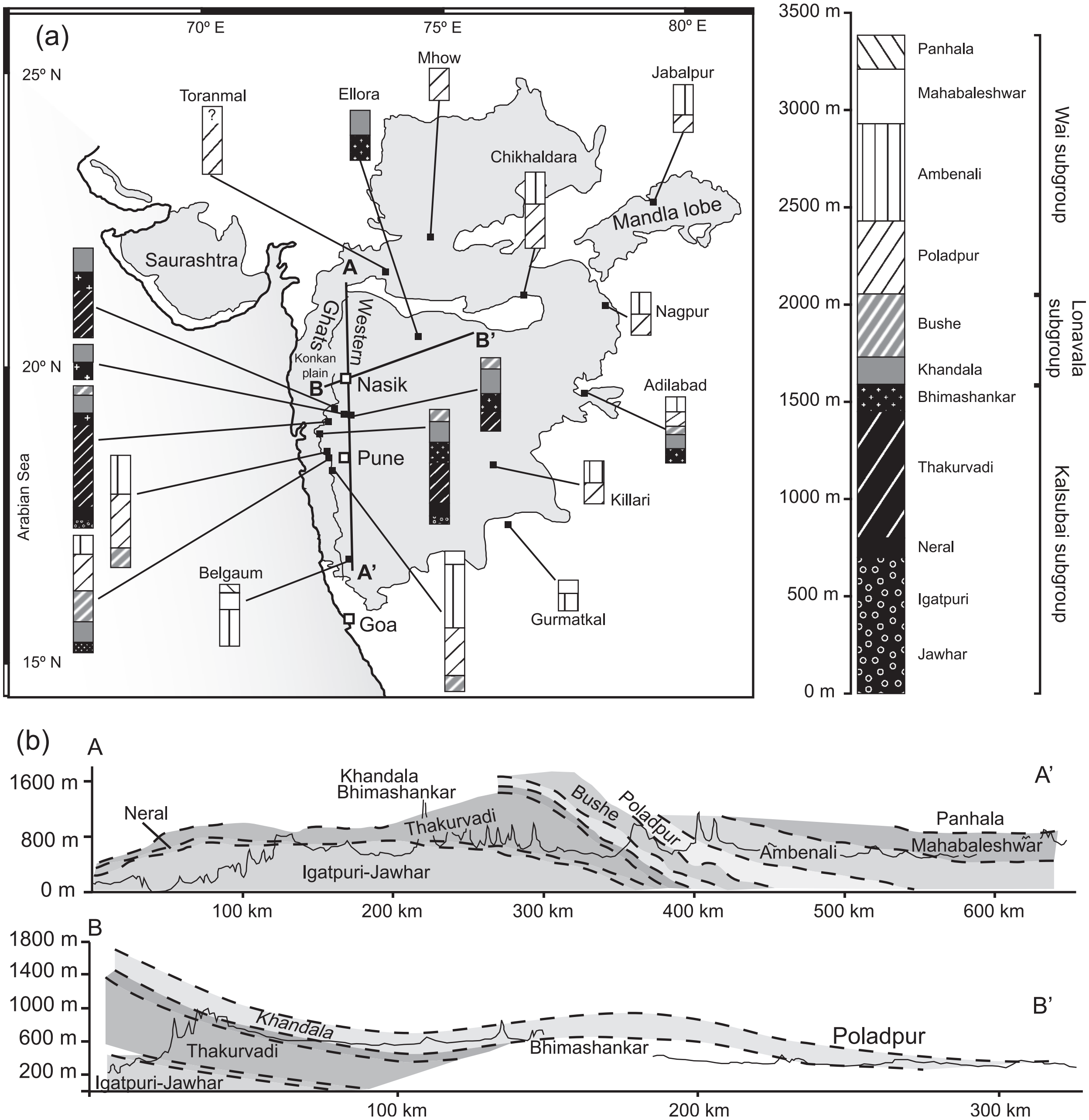

Fig. 2. (a) Sketch map of selected Deccan stratigraphic sections and simplified stratigraphic column (formation thicknesses in column are maximum observed values). Compiled from Beane *et al.* (1986), Devey & Lightfoot (1986), Mitchell & Widdowson (1991), Subbarao *et al.* (1994), Peng *et al.* (1998), Mahoney *et al.* (2000) and Jay & Widdowson (2008). (b) Schematic cross-sections of the central Deccan Traps. Modified after Kaila (1988), Mahoney (1988), Peng (1998) and Jerram & Widdowson (2005).

stratigraphy. Throughout this immense area, only the topmost flows of the local stratigraphy are exposed and, accordingly, the few outcrops of potential feeder dikes in these regions are biased toward feeders of the upper formations. Thus, to obtain a comprehensive and representative overview, we devoted particular attention to dikes in those areas where erosion offers 'windows' into the deeper parts of the stratigraphy, these being the Konkan coastal plain north and NE of Mumbai, and in the Narmada–Tapi grabens.

The timing of extension

Dike emplacement and orientation are largely controlled by local stresses and pre-existing zones of weakness within the rock (e.g. Delaney *et al.*, 1986). In a homogeneous medium, dikes form perpendicular to the minimum principal compressive stress (e.g. Ida, 1999; Ernst *et al.*, 2001; Gudmundsson & Marinoni, 2002; Jourdan *et al.*, 2006). The existence of two large swarms of well-oriented dikes in the Deccan indicates that these dikes were emplaced during regional crustal extension and/or within zones that had previously been fractured. Crustal extension is estimated to have been up to 14% in the Narmada–Tapi region and 18% along the west coast (Bhattacharji *et al.*, 1996), significantly more than can be accounted for by dike dilation, estimated at 5–11% (Deshmukh & Sehgal, 1988) and 5% (Ray *et al.*, 2007), respectively.

The Late Cretaceous–Paleocene history of western India is marked by two major rifting events: first, the break-up with Madagascar at ~88 Ma (Storey *et al.*, 1995; Pande *et al.*, 2001; Melluso *et al.*, 2009); second, the post-Deccan separation of the Seychelles Bank at ~62 Ma (e.g. Dyment, 1998; Todal & Eldholm, 1998; Collier *et al.*, 2008). Researchers have long argued that Seychelles-related rifting along the edge of the present western continental shelf of India was under way near the end of flood volcanism or very soon afterward (e.g. Hooper, 1990; Devey & Stephens, 1991; Sheth, 1998; Hooper *et al.*, 2010). However, it is not clear whether rifting had begun there earlier (Collier *et al.*, 2008), during or even before the peak of flood volcanism.

The Narmada–Son lineament, which includes the Narmada graben (Fig. 1), has been postulated to be a long-lived (i.e. beginning in the Precambrian) locus of tectonic activity (e.g. Choubey, 1971; Ravi Shanker, 1991; Acharyya & Roy, 2000). Kaila (1988) reported seismological evidence of sedimentary basins, over a kilometer in thickness, immediately under the Deccan lava pile in the Narmada–Tapi region. However, emplacement of the Narmada–Tapi dikes seems not to have simply followed pre-existing SSW–NNE structural weaknesses in the crust (Ray *et al.*, 2007). Rather, the strong preferred orientation of these dikes, their consistently vertical dips and the excess crustal extension that is not accounted by dike dilation indicate that the swarm was emplaced in an environment undergoing roughly north–south-directed extension (Ray *et al.*, 2007; Vanderkluysen, 2008; Ray, 2009).

Two other major extensional structures affect the Deccan Traps: the Cambay graben and Kachchh rift (Fig. 1). Rifting in the Cambay graben may have begun in the early Cretaceous, but became active during the late Cretaceous and entered a more pronounced phase during the Tertiary; the Kachchh rift is believed to have initiated in the late Triassic and remained active until the late Cretaceous or early Paleocene (Biswas, 1987; Sheth, 1999). In summary, there is ample evidence of directed extension and sedimentation in the Cambay and Narmada–Tapi zones shortly before the onset of Deccan volcanism, but evidence of contemporaneous extension along the west coast is lacking.

SAMPLES AND METHODS

Definition of the three dike swarms, and samples

Although the three dike swarms described here have long been recognized, their geographical distribution and boundaries have been defined only loosely. These swarms overlap in some areas (e.g. the coastal and Nasik–Pune swarms overlap in the Konkan north of Mumbai). Because it is important to clarify their relationships with respect to regional extension, we apply strict criteria to categorize each. In this study, the Narmada–Tapi swarm includes only dikes north of 20°30'N. We define the coastal swarm as comprising dikes west of the Panvel flexure that trend north–south ±20°. The Nasik–Pune swarm is defined geographically as all the dikes south of 20°30'N and east of the Panvel flexure, plus all the dikes west of the flexure that have an orientation departing from north–south by more than 20°. The potential drawback of these geographical criteria is that dikes that were emplaced as part of the Nasik–Pune swarm that strike roughly north–south and are located near the coast are considered as part of the coastal swarm. Similarly, dikes emplaced in the coastal swarm but whose orientation deviates from north–south by >20° will be classified as Nasik–Pune dikes. Inevitably, there are examples that may be classified erroneously, but we have identified only about 20 contentious cases. Given the large dataset, these are unlikely to affect overall interpretations, which depend primarily on dike geochemical signature and orientation.

Most of the samples from the coastal and Nasik–Pune swarms come from the collections of Mahoney (1984), Beane (1988), Widdowson *et al.* (2000), Hooper *et al.* (2010) and Hooper's other coworkers. Data for the major elements and a group of trace elements analyzed by X-ray fluorescence spectrometry (XRF) were already available for these samples (Mahoney, 1984; Beane, 1988; Widdowson *et al.*, 2000). Data for a wider array of trace elements, mostly measured by inductively coupled plasma mass spectrometry (ICP-MS), existed for some of them (Beane, 1988). All of these data are listed in Electronic Supplement 1 (available at http://www.petrology.oxfordjournals.org/). In addition, between 2003 and 2005, we collected samples from the western Narmada–Tapi swarm (Dediapada, Dhadgaon and Nandurbar–Dhule areas, Figs 1 and 3), Nasik–Pune swarm, and coastal swarm in the northern Konkan (Dahanu–Umbargaon area; Fig. 1). The dikes sampled in the western Narmada–Tapi swarm come from different topographic, and possibly structural, levels. Whereas the Dediapada and Nandurbar areas are about 200–250 m above sea level, Dhadgaon is several

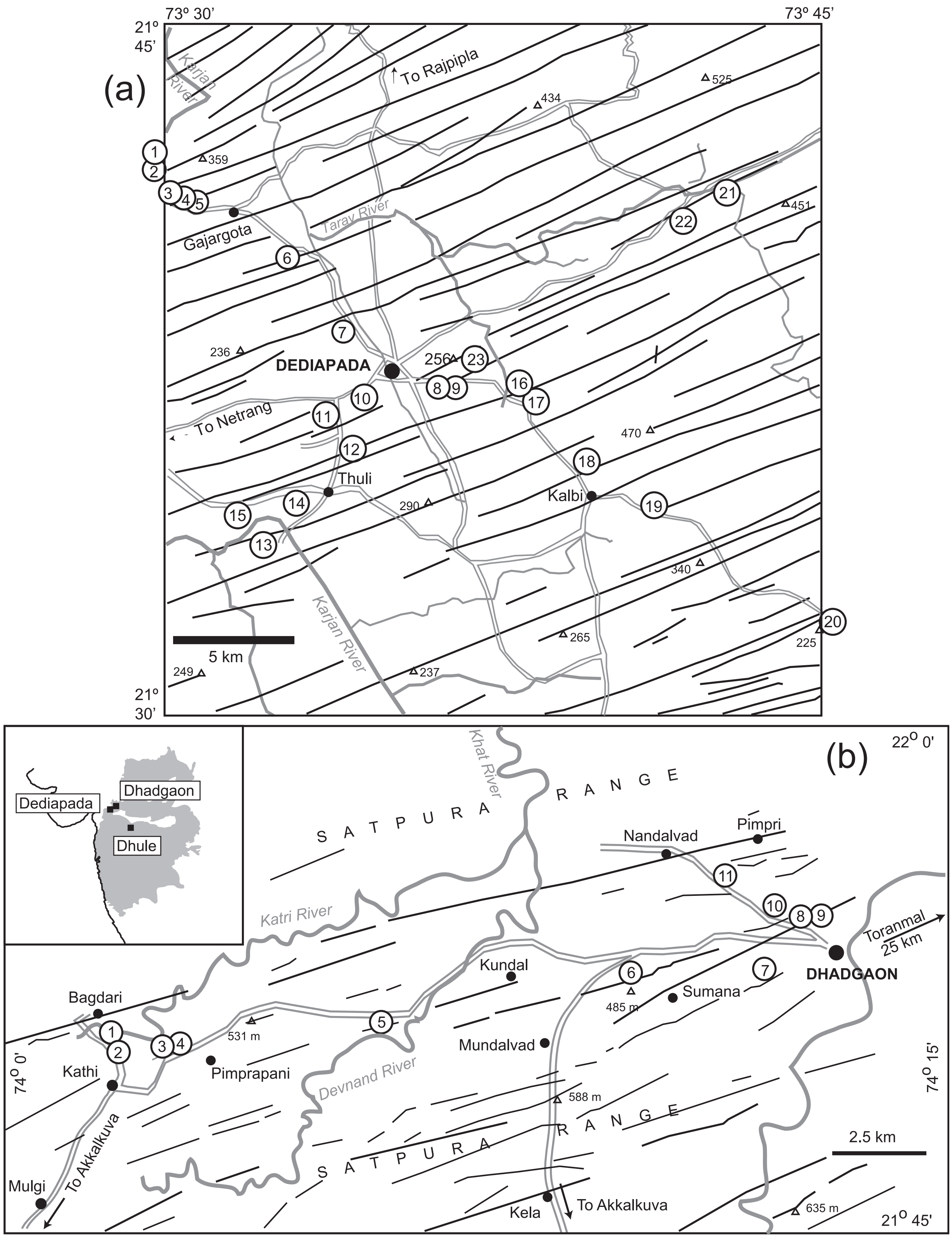

Fig. 3. Sample locations and numbers in the (a) Dediapada (DD sample prefix omitted) and (b) Dhadgaon (DHD sample prefix omitted) areas. Black lines in (a) represent recognized dikes (modified after Krishnamacharlu, 1972), whereas black lines in (b) are drawn on the basis of satellite imagery. Black dots represent villages. Sample locations for the Nandurbar–Dhule dikes are given in the map of Ray *et al.* (2007).

hundred meters higher, in the Satpura Mountain Range. Two samples from the Nandurbar area were supplied by L. Melluso (Melluso *et al.*, 1999). Particularly excellent dike exposure in the Nandurbar–Dhule area permits detailed structural analysis and tectonic interpretation (Ray *et al.*, 2007). Dikes and sills around Pachmarhi, in the eastern part of the Narmada–Tapi swarm, have been the subject of a separate study (Sheth *et al.*, 2009).

Petrographic descriptions and sample coordinates are provided in Electronic Supplement 2. Samples from all three swarms are dominantly fine- to medium-grained aphyric or sparsely phyric tholeiitic basalts and dolerites with groundmass plagioclase, clinopyroxene and Fe–Ti oxides, and millimeter-size phenocrysts of plagioclase, clinopyroxene and sometimes olivine (Ray, 2009). Rare dikes with centimeter-size plagioclase are also present, particularly in the Narmada–Tapi swarm (e.g. two dikes from Dediapada are extremely rich in plagioclase phenocrysts >2 cm across). A few of the Narmada–Tapi dikes (e.g. DHD-01, DND-07, NBD-34) exhibit interstitial clusters of tiny orthopyroxene crystals (see Chandrasekharam *et al.*, 2000). A small number of dikes are alkalic and, because they cannot represent feeders to the tholeiitic lava pile, are not discussed here (see Vanderkluysen, 2008).

Unlike the dikes, the southwestern Deccan lava flow formations are well characterized isotopically, although combined Sr–Nd–Pb isotopic data have been lacking for one or more members of several formations. To characterize these formations more fully, we measured the Sr, Nd, and Pb isotope ratios of samples of these members from the collection of Beane (1988). Samples of two other members without isotope data [the high field strength element (HFSE)-poor Member of the Jawhar Formation and the Mg-rich Member of the Igatpuri; Table 1] were either missing or contained too little remaining material for analysis. No dike in our study had chemical affinities with either of these two members.

Chemical and isotopic analyses

Major elements in our recently collected samples were measured by XRF on fused disks of bulk-rock powders at the University of Hawai'i (following Eason & Sinton, 2006), and trace elements were determined by ICP-MS (Pyle *et al.*, 1995; Neal, 2001) (Electronic Supplement 1). Sample preparation and mass spectrometry for Sr, Nd and Pb isotopic and isotope-dilution measurements (Tables 2 and 3) were carried out at the University of Hawai'i (Mahoney *et al.*, 1991). Isotopic analyses were performed on splits prepared from small (1–2 mm) rock chips that were picked to avoid alteration, and acid-cleaned prior to dissolution. Although concentrations of Pb, Sr, Nd and Sm determined by isotope-dilution are generally within 10% of those obtained by other methods for the bulk samples, the isotope-dilution values are used only for age correction (to 65 Ma) of Sr and Nd isotope ratios because these concentrations are not strictly representative of the bulk-rocks. Isotope ratios of a smaller group of samples were analyzed at the University of Alberta (Creaser *et al.*, 1997); bulk-rock powders were used for these isotopic measurements, and we used the corresponding XRF and ICP-MS concentration data for parent and daughter elements for isotopic age corrections for these samples.

Data evaluation procedures and statistical methods

Comparisons of the dikes with the flow formations were achieved using four approaches, following Peng *et al.* (1998), Mahoney *et al.* (2000), Bondre *et al.* (2006) and Sheth *et al.* (2009): (1) element vs element and element ratio vs element ratio plots (involving >850 lava flow analyses for comparison with the dike data); (2) mantle-normalized patterns of incompatible element abundances; (3) discriminant-function analysis (DFA) using a set of major and trace elements; (4) combined Sr, Nd and Pb isotope ratios.

Element plots and mantle-normalized trace element patterns are useful when studying single samples, but a statistical approach proves more practical to treat large numbers of samples in a systematic manner. DFA has proved a powerful classification tool for large datasets, particularly when determining regional lava chemostratigraphy of flood basalt provinces (e.g. Beane *et al.*, 1986; Beane, 1988; Peng *et al.*, 1998; Mahoney *et al.*, 2000). DFA is a multivariate statistical technique (e.g. Davis, 2002) that calculates discriminant functions and, in essence, computes the affinity of an unknown sample to a standard set of known or previously defined compositional groups (in the present case, the stratigraphic formations). The technique, however, has been found to be somewhat unreliable for Deccan samples with transitional chemical characteristics (such as flows near some boundaries between formations; Peng *et al.*, 1998). Also, processes such as alteration and, particularly, variable fractional crystallization or flowage differentiation in both flows and dikes can substantially affect the results of a classification. The effects of these processes can be reduced greatly by careful selection of the variables used in the DFA (Peng *et al.*, 1998). Combined Sr–Nd–Pb isotope ratios provide the ultimate test for comparing Deccan dike samples with flow formations because overlap between the isotopic fields for most of the formations is limited, and because these isotope ratios are little affected by crystal fractionation or subaerial alteration. However, many more chemical data are available for the Deccan basalts than are Sr–Nd–Pb isotopic data.

DFA was conducted using the SPSS 11.0.4 software for Macintosh (SPSS, Inc.), following the procedure detailed by Peng *et al.* (1998) and using an updated 624 sample standard set of major and trace element data for the stratigraphic formations (Electronic Supplement 3). Elements

Table 2: Isotopic and isotope-dilution data for flow members of the Western Ghats previously not characterized isotopically

Sample	Formation	Member	$(^{87}Sr/^{86}Sr)_0$	$(^{87}Sr/^{86}Sr)_t$	$(^{143}Nd/^{144}Nd)_0$	$(^{143}Nd/^{144}Nd)_t$	$\epsilon_{Nd}(t)$	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
Tem-04	Neral	Tembre Basalt	0·70858	0·70844	0·512265	0·512199	−7·0	18·923	15·553	39·261
M-8	Thakurvadi	Thakurvadi CT	0·70903	0·70881	0·512066	0·512004	−10·8	18·299	15·425	39·295
JEB-434	Thakurvadi	Paten Basalt	0·72267	0·72236	0·511829	0·511766	−15·4	20·938	16·080	40·372
M-12	Bhimashankar	Manchar	0·70777	0·70768	0·512591	0·512518	−0·7	19·707	15·749	40·417
M-13	Bhimashankar	Manchar	0·70753	0·70746	0·512607	0·512539	−0·3	19·863	15·746	40·291
CH-24	Bhimashankar	Bhimashankar CT	0·70774	0·70768	0·512506	0·512439	−2·3	20·851	15·922	41·407
KOP-21	Khandala	Monkey Hill	0·70754	0·70751	0·512383	0·512324	−4·5	18·041	15·479	38·647
BOR-4	Khandala	Dhak Dongar	0·70732	0·70710	0·512462	0·512390	−3·2	18·263	15·517	38·968
DDW-13	Khandala	Madh	0·70967	0·70946	0·511981	0·511920	−12·4	17·076	15·439	38·550
JEB-134	Khandala	Khandala Phyric	0·70864	0·70850	0·512290	0·512216	−6·6	17·497	15·460	38·586
JEB-297	Khandala	Rajmachi	0·70948	0·70925	0·512289	0·512238	−6·2	18·015	15·545	39·281
JEB-136	Bushe	Karla Caves	0·71556	0·71496	0·512157	0·512088	−9·1	22·807	16·169	41·407
JEB-185	Bushe	Bhaja CT	0·71659	0·71636	0·512099	0·512032	−10·2	21·663	16·055	40·034
JEB-211	Bushe	Shingi Hill	0·71869	0·71813	0·511646	0·511590	−18·9	18·949	15·682	40·899
JEB-353	Bushe	Pingalvadi	0·71304	0·71268	0·512223	0·512150	−7·9	19·915	15·806	39·547
BEL-13	Poladpur	Ambavne	0·70571	0·70564	0·512742	0·512668	+2·2	18·890	15·637	39·195
JEB-300	Poladpur	Sambarkada	0·70769	0·70749	0·512463	0·512396	−3·1	18·837	15·632	39·004

Sample	Pb	Sr	Rb	Nd	Sm	$^{147}Sm/^{144}Nd$	$^{87}Rb/^{86}Sr$
Tem-04	2·51	231·4	12·52	13·14	3·359	0·1545	0·1565
M-8		232·8	19·11	20·20	4·890	0·1464	0·2375
JEB-434	7·55	154·5	18·35	15·67	3·823	0·1474	0·3441
M-12		258·4	8·26	13·87	3·915	0·1706	0·0925
M-13		226·6	6·01	15·29	4·036	0·1596	0·0767
CH-24		244·7	5·96	19·65	5·087	0·1570	0·0702
KOP-21		267·1	3·23	21·70	5·007	0·1395	0·0350
BOR-4		261·0	21·89	16·68	4·640	0·1682	0·2426
DDW-13	3·87	262·7	20·64	19·21	4·526	0·1424	0·2273
JEB-134		260·5	13·46	15·34	4·416	0·1740	0·1495
JEB-297		349·0	39·51	21·74	4·310	0·1199	0·2447
JEB-136	3·12	136·6	31·35	16·38	4·399	0·1623	0·6624
JEB-185	4·65	166·2	14·46	15·44	4·032	0·1578	0·2519
JEB-211	5·86	210·4	44·19	22·92	5·017	0·1323	0·6084
JEB-353	2·76	120·3	16·14	10·89	3·081	0·1709	0·3882
BEL-13	1·75	208·4	6·07	15·18	4·389	0·1748	0·0842
JEB-300	3·62	172·2	12·81	14·57	3·805	0·1579	0·2151

The ϵ_{Nd} and $^{87}Sr/^{86}Sr$ values have been age-corrected to $t = 65$ Ma. Pb isotope ratios are present-day values, as commonly reported in Deccan literature. Data are reported relative to values of $^{87}Sr/^{86}Sr = 0{\cdot}710238 \pm 0{\cdot}000016$ (2σ; $n = 39$) for standard NBS 987 Sr, $^{143}Nd/^{144}Nd = 0{\cdot}511843 \pm 0{\cdot}000009$ ($n = 28$; 0·2 ϵ_{Nd} units) for La Jolla Nd, and the Pb isotopic values of Todt *et al.* (1996) for NBS 981 Pb; the 2σ range measured for NBS 981 Pb ($n = 44$) was $\pm 0{\cdot}009$ for $^{206}Pb/^{204}Pb$, $\pm 0{\cdot}011$ for $^{207}Pb/^{204}Pb$ and $\pm 0{\cdot}028$ for $^{208}Pb/^{204}Pb$. Within-run errors on the isotopic data are less than or equal to the external uncertainties on the standards. Isotope-dilution concentrations (in ppm) have uncertainties of 0·2% for Sm and Nd, 0·4% for Sr and 1% for Pb and Rb. Total procedural blanks were typically $\leq$25 pg for Pb, $<$35 pg for Sr, and $\leq$10 pg for Nd. Present-day $\epsilon_{Nd} = 0$ corresponds to $^{143}Nd/^{144}Nd = 0{\cdot}512640$; $\epsilon_{Nd}(t) = 0$ at 65 Ma corresponds to $^{143}Nd/^{144}Nd = 0{\cdot}512556$. All data were acquired at the University of Hawai'i.

Table 3: Isotopic and isotope-dilution data for dikes

Sample	Lab	Swarm	$(^{87}Sr/^{86}Sr)_0$	$(^{87}Sr/^{86}Sr)_t$	$(^{143}Nd/^{144}Nd)_0$	$(^{143}Nd/^{144}Nd)_t$	$\epsilon_{Nd}(t)$	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Pb	Sr	Rb	Nd	Sm
AL82-12	SIO	Coast		0·70444		0·512794	+4·6					195·5	5·64	16·81	4·95
DDH-011	UA	Coast	0·70439	0·70434	0·512337	0·512269	−5·6	16·342	15·149	36·793					
DDH-030	UH	Coast	0·70506	0·70505	0·512668	0·512600	+0·8	17·267	15·335	38·035	2·21	180·7	0·81	22·45	5·955
DDH-034	UH	Coast	0·70669	0·70665	0·512642	0·512567	+0·2	18·941	15·637	40·003	0·97	148·0	2·23	11·13	3·239
DDH-036	UH	Coast	0·71366	0·71327	0·512105	0·512036	−10·2	19·389	15·752	39·617	3·26	143·9	20·7	12·60	3·399
DDH-039	UH	Coast	0·70480	0·70455	0·512706	0·512638	+1·6	17·451	15·378	38·139	2·66	191·6	18·1	29·48	7·817
DDH-040	UH	Coast	0·70458	0·70437	0·512758	0·512690	+2·6	17·617	15·389	38·117	2·23	210·5	16·2	27·15	7·207
DDH-095	UH	Coast	0·70677	0·70650	0·512629	0·512561	+0·1	19·754	15·741	40·148	2·47	195·6	19·9	24·49	6·481
DDH-116	UH	Coast	0·70429	0·70423	0·512873	0·512798	+4·7	18·421	15·536	38·822	1·19	205·9	4·33	18·07	5·257
IND-005	UH	Coast	0·70560	0·70542	0·512684	0·512614	+1·1	18·526	15·594	39·012	1·87	176·1	11·8	19·39	5·282
JH-35	UH	Coast	0·70459	0·70452	0·512864	0·512783	+4·4	18·404	15·557	38·891	0·90	111·7	2·98	10·83	3·400
JH-40	UH	Coast	0·70665	0·70647	0·512688	0·512614	+1·1	18·861	15·638	39·104	2·95	152·8	10·7	17·93	5·168
JH-48	UH	Coast	0·70829	0·70803	0·512437	0·512371	−3·6	18·907	15·622	39·656	2·97	215·2	23·4	21·28	5·506
JH-72	UH	Coast	0·71059	0·71018	0·512254	0·512186	−7·2	19·902	15·835	40·598	2·58	113·5	17·3	12·42	3·270
JW-32	UH	Coast	0·70936	0·70886	0·512439	0·512376	−3·5	19·297	15·727	40·259	3·62	223·1	39·7	30·14	7·433
ORL-5	UH	Coast	0·70499	0·70496	0·512766	0·512691	+2·6	17·551	15·398	38·297	0·72	106·3	1·82	8·380	2·436
AM-2	UH	N–P	0·70414	0·70407	0·512861	0·512788	+4·5	18·142	15·467	38·509	0·91	203·4	4·75	18·35	5·214
AM-30	UA	N–P	0·70938	0·70920	0·512243	0·512164	−7·6	17·677	15·600	38·631					
BOR-13	UH	N–P	0·70486	0·70467	0·512713	0·512647	+1·8	17·898	15·446	38·335	2·65	228·9	16·4	30·38	7·799
BOR-14	UA	N–P	0·70489	0·70479	0·512704	0·512630	+1·4	17·898	15·454	38·369					
BOR-20	UA	N–P	0·70466	0·70452	0·512747	0·512671	+2·2	18·031	15·471	38·520					
BOR-29	UH	N–P	0·70620	0·70614	0·512669	0·512599	+0·8	18·528	15·59	39·218	2·13	226·9	4·6	22·80	6·198
DDH-5	UA	N–P	0·70435	0·70421	0·512828	0·512747	+3·7	18·000	15·465	38·502					
DDH-13	UH	N–P	0·70454	0·70451	0·512841	0·512767	+4·1	18·332	15·567	38·693	1·19	194·1	2·66	15·67	4·603
DDH-081	UH	N–P	0·70616	0·70608	0·512671	0·512601	+0·9	18·499	15·565	39·143	2·18	241·2	6·89	22·99	6·276
DDH-089	UH	N–P	0·70556	0·70550	0·512726	0·512655	+1·9	19·779	15·710	39·925	0·88	173·2	3·56	12·26	3·383
IGA-6	UH	N–P	0·70865	0·70854	0·512429	0·512364	−3·8	19·281	15·719	40·227	3·35	249·2	10·4	29·61	7·463
IGA-13	UH	N–P	0·70657	0·70647	0·512577	0·512508	−0·9	19·517	15·723	40·033	2·00	232·4	8·39	21·22	5·666
IGA-19	UA	N–P	0·71215	0·71204	0·511870	0·511804	−14·7	18·951	15·547	38·793					
JEB-008	UA	N–P	0·70480	0·70470	0·512681	0·512604	+0·9	17·152	15·314	37·785					
JEB-016	UA	N–P	0·70752	0·70728	0·512370	0·512297	−5·1	17·517	15·466	38·515					
JEB-182	UA	N–P	0·70516	0·70508	0·512693	0·512620	+1·2	18·007	15·470	38·372					
JEB-284	UA	N–P	0·70751	0·70729	0·512368	0·512295	−5·1	17·528	15·462	38·517					
JEB-327	UA	N–P	0·70759	0·70733	0·513675	0·513603	+20·4	17·521	15·475	38·591					
JEB-332	UA	N–P	0·70624	0·70608	0·512657	0·512579	+0·4	18·485	15·558	39·094					
JEB-333	UA	N–P	0·70914	0·70903	0·512005	0·511930	−12·2	16·580	15·405	37·911					
JEB-393	UA	N–P	0·70699	0·70668	0·512619	0·512544	−0·2	20·448	15·844	40·947					
JEB-396	UA	N–P	0·70490	0·70474	0·512668	0·512593	+0·7	17·775	15·344	38·075					
JEB-397	UH	N–P	0·70524	0·70514	0·512633	0·512572	+0·3	17·781	15·453	38·576	2·29	321·1	12·2	26·35	6·268
JEB-426	UH	N–P	0·70509	0·70496	0·512694	0·512632	+1·5	18·217	15·489	38·692	2·82	305·7	14·4	33·48	8·031
JEB-438	UH	N–P	0·70688	0·70665	0·512637	0·512570	+0·3	20·499	15·834	40·458	2·59	184·4	16·1	25·83	6·765
JEB-442	UH	N–P	0·70578	0·70565	0·512660	0·512591	+0·7	19·226	15·653	39·461	1·43	239·3	11·9	17·75	4·786
JEB-453	UA	N–P	0·70835	0·70809	0·512251	0·512181	−7·3	19·025	15·551	39·175					
JEB-455	UA	N–P	0·70642	0·70642	0·512662	0·512584	+0·5	18·493	15·576	39·163					
JH-20	UH	N–P	0·70821	0·70752	0·512562	0·512497	−1·2	20·683	15·893	41·129	4·20	203·1	52·0	40·46	10·225
JH-22	UH	N–P	0·70632	0·70612	0·512659	0·512589	+0·6	18·489	15·575	39·144	2·52	231·0	17·7	23·82	6·497

(continued)

Table 3: Continued

Sample	Lab	Swarm	$(^{87}Sr/^{86}Sr)_0$	$(^{87}Sr/^{86}Sr)_t$	$(^{143}Nd/^{144}Nd)_0$	$(^{143}Nd/^{144}Nd)_t$	$\epsilon_{Nd}(t)$	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Pb	Sr	Rb	Nd	Sm
JH-25	UH	N–P	0·71166	0·71148	0·512217	0·512155	−7·8	18·893	15·722	40·272	3·81	247·1	16·6	24·08	5·844
JH-28	UH	N–P	0·70435	0·70432	0·512849	0·512774	+4·2	18·041	15·473	38·454	1·19	171·3	2·34	15·39	4·514
TRM-59	UH	N–P	0·70574	0·70566	0·512355	0·512292	−5·2	17·754	15·343	37·939	2·29	306·3	9·07	21·49	5·256
UDD-9	UH	N–P	0·71712	0·71691	0·512030	0·511960	−11·6	19·323	15·732	38·794	6·79	97·22	7·74	10·08	2·749
DD-1	UH	N–T	0·71606	0·71537	0·512047	0·511990	−11·1	22·066	16·113	43·612	4·64	163·6	42·0	20·53	4·580
DD-10	UH	N–T	0·70892	0·70870	0·512504	0·512438	−2·3	21·233	15·930	41·487	1·81	252·6	20·0	19·65	5·057
DD-14	UH	N–T	0·70941	0·70912	0·512260	0·512204	−6·9	19·260	15·759	40·224	2·54	250·5	12·2	19·94	4·352
DD-15	UH	N–T	0·71101	0·71064	0·512293	0·512224	−6·5	19·301	15·764	40·071	3·96	115·7	16·2	14·29	3·862
DD-23	UH	N–T	0·70642	0·70638	0·512670	0·512557	0·0	19·836	15·775	40·103	2·44	149·7	2·72	20·63	5·480
DHD-8	UH	N–T	0·70460	0·70454	0·512801	0·512729	+3·4	17·698	15·410	38·241	1·25	192·4	3·65	15·72	4·394
DHD-9	UH	N–T	0·70454	0·70448	0·512798	0·512727	+3·3	17·791	15·438	38·376	1·44	174·5	3·86	17·85	4·964
DHD-11	UH	N–T	0·70642	0·70630	0·512681	0·512611	+1·1	19·177	15·670	39·635		211·9	10·0	20·27	5·502
DND-2	UH	N–T	0·70954	0·70937	0·512297	0·512232	−6·3	18·168	15·563	39·529	3·32	240·3	15·1	20·30	5·158
NBD-1	UH	N–T	0·71526	0·71495	0·511859	0·511802	−14·7	18·883	15·800	39·090	5·11	159·8	18·3	15·06	3·340
NBD-4	UH	N–T	0·71007	0·70960	0·512310	0·512242	−6·1	20·031	15·863	40·640	2·60	118·6	20·9	12·07	3·176
NBD-10	UH	N–T	0·71119	0·71093	0·512360	0·512297	−5·1	22·360	16·085	43·163	2·81	255·9	24·3	28·01	6·884
TAP-001	UH	N–T	0·70639	0·70592	0·512682	0·512619	+1·2	17·637	15·556	37·639	7·38	181·7	32·0	21·80	5·325
TAP-002	UH	N–T	0·70473	0·70461	0·512748	0·512679	+2·4	17·764	15·415	38·411	2·03	209·7	9·56	20·19	5·434

N–P, Nasik–Pune; N–T, Narmada–Tapi. Most dike samples were analyzed in lab UH (University of Hawai'i); standard values and errors are as in Table 2. Analyses in lab UA were performed at the University of Alberta. Age-corrections for these samples use parent–daughter ratios determined from XRF and ICP-MS concentration values. Errors (2σ) on UA sample measurements are $\pm0{\cdot}00002$ for $^{87}Sr/^{86}Sr$, $\pm0{\cdot}000009$ ($0{\cdot}2\ \epsilon_{Nd}$ units) for $^{143}Nd/^{144}Nd$, $\pm0{\cdot}011$ for $^{206}Pb/^{204}Pb$, $\pm0{\cdot}012$ for $^{207}Pb/^{204}Pb$ and $\pm0{\cdot}012$ for $^{208}Pb/^{204}Pb$. SIO indicates a sample analyzed at the Scripps Institution of Oceanography (Mahoney, 1984); errors for this sample are $\pm0{\cdot}00003$ for $^{87}Sr/^{86}Sr$ and $\pm0{\cdot}000015$ for $^{143}Nd/^{144}Nd$ ($0{\cdot}3\ \epsilon_{Nd}$ units).

used as variables included the same suite employed by Mahoney *et al.* (2000); that is, SiO_2, Al_2O_3, TiO_2, CaO, K_2O, P_2O_5, Ni, Ba, Sr, Zr, Y and Nb. Flow samples known to be from specific formations, when treated as unknowns, were correctly predicted (i.e. assigned to the correct formation) 87.8% of the time. For the dike samples, Electronic Supplement 1 reports the closest formation match if the squared Mahalanobis distance to the group centroid is $\leq$25 (conditional probability greater than 1%). Samples with no match listed are considered to be 'unclassified' because the large Mahalanobis distance indicates an unreliable statistical match.

In this study, the DFA standard set was divided into nine groups. Each group represents a different stratigraphic formation, with the exception of the lowermost two formations (i.e. Jawhar and Igatpuri Formations), which were merged because of their substantial geochemical similarities (see Peng *et al.*, 1998). Data for the Panhala Formation were not included in the standard set because analyses are too few to be statistically significant in the DFA. However, dike samples whose closest match was with the Ambenali, Poladpur or Mahabaleshwar Formation (with which the Panhala has the most chemical affinity) were checked individually for compatibility with the Panhala (e.g. Ba $<$ 90 ppm, Sr $<$ 200 ppm, Zr $<$ 130 ppm, Ba/Y $<$ 3, Nb/Zr $<$ 0·08; Lightfoot & Hawkesworth, 1988). Samples of several formation members known to be anomalous within their formation (e.g. the Harishchandragad Member of the Bushe Formation and the Paten Basalt Member of the Thakurvadi Formation; e.g. Beane *et al.*, 1986) were excluded from the DFA standard set.

RESULTS

Isotopic compositions of Western Ghats flow members

Lavas of the upper five formations in the Western Ghats (Bushe, Poladpur, Ambenali, Mahabaleshwar and Panhala) have been the subject of several isotopic investigations (e.g. Mahoney *et al.* 1982; Cox & Hawkesworth, 1985; Lightfoot & Hawkesworth, 1988; Lightfoot *et al.*, 1990; Peng *et al.*, 1994). However, four members of the Bushe and two members of the Poladpur have not previously been analyzed for isotopes. Isotopic data have likewise been lacking for several members of the lower six formations (Jawhar, Igatpuri, Neral, Thakurvadi, Bhimashankar and Khandala Formations).

Our new data for the two isotopically uncharacterized members of the Poladpur Formation lie within the previously defined Poladpur field, whereas our results for Neral and Khandala Formation samples extend the boundaries of these fields slightly (Fig. 4). The Bhimashankar field, previously represented by samples from only one of the formation's two members or chemical types, is extended to higher $\varepsilon_{Nd}(t)$ (where *t* indicates the age-corrected value) and slightly lower $^{206}Pb/^{204}Pb$. The new Bushe data extend the Bushe field significantly, with the Pingalvadi Member displaying the highest $\varepsilon_{Nd}(t)$ measured for the formation (−7·9) and the Shingi Hill Member the lowest (−18·9). The Paten Basalt (thought to be a single flow; Beane, 1988) of the Thakurvadi Formation displays a chemical signature uncharacteristic of other Thakurvadi basalts. In many ways, the Paten Basalt is more typical of the Bushe Formation (Beane, 1988); for instance, it has $TiO_2 < 1$ wt % and $Zr/Y < 4{\cdot}3$, whereas values between 1·3 and 2·7 wt % and 4·3 and 6·7, respectively, characterize other members of the Thakurvadi Formation. Thus, we expected that this member also might be isotopically distinct, and indeed the isotopic ratios of the Paten Basalt sample (JEB-434) differ considerably from those of other Thakurvadi basalts. They broadly resemble Bushe Formation values, with $^{206}Pb/^{204}Pb = 20{\cdot}938$, $\varepsilon_{Nd}(t) = -15{\cdot}4$, and even higher $(^{87}Sr/^{86}Sr)_t$, 0·72235, than found for the Bushe. To our knowledge, this $(^{87}Sr/^{86}Sr)_t$ ratio is the highest reported for any Deccan Traps lava flow [although a dike in the Tapi valley has an even higher $(^{87}Sr/^{86}Sr)_t$ ratio, 0·72315; Chandrasekharam *et al.*, 1999]. The intercalation of this anomalous Bushe-like flow within an older formation is reminiscent of the anomalously Poladpur-like Harishchandragad Member within the Bushe itself (Beane, 1988; Peng *et al.*, 1994). Such flows, although rare, pose special challenges in terms of petrogenetic models and stratigraphic correlations.

Within-dike chemical variation

Although the majority of dikes appear homogeneous at the centimeter to meter scale, a few display some macroscopic heterogeneity, most commonly in the form of vertical layering caused by varying amounts of plagioclase (see Melluso *et al.*, 1999). In a single case (the dike from which sample DND-3 came), metamorphic basement xenoliths were observed, distributed unevenly along and across strike (Ray *et al.*, 2008). Several of the studied dikes are several tens of kilometers long at the current level of exposure, and we investigated along-strike chemical variation in four examples. Sample NBD-1B was taken 15 km east of NBD-1 and displays nearly identical chemical and mineralogical composition (e.g. Fig. 5a); both represent a single >54 km long dike in the vicinity of Nandurbar (see Ray *et al.*, 2007, figs 1 and 2a). Samples NBD-3 and NBD-3B were taken 10 km apart; they are from another dike near Nandurbar that is more than 30 km long. These two samples have similar major element concentrations and similar incompatible element patterns, although absolute concentrations are slightly different (Fig. 5b) and differences in MgO, Cr and Ni are larger. The longest known dike in the Deccan, the 79 km long Sakri–Dhule–Parola dike (see Ray *et al.*, 2007, figs 1 and 2 h), was also sampled at more than one location. Sample SDPD-2 was taken from this dike 38 km east of SDPD-1, yet the two have nearly identical chemical signatures. Likewise, samples UDD-7 and UDD-7B come from the same dike in the Umbargaon–Dahanu area, but from 3 km apart; again, the two samples are almost indistinguishable. Within-dike isotopic homogeneity can similarly be demonstrated. For instance, dike samples SH43 and SH50, collected 35 km apart in the Nandurbar region, have similar $(^{87}Sr/^{86}Sr)_t$ of 0·70481 and 0·70474, $\varepsilon_{Nd}(t)$ of +1·4 and +1·5 and $^{206}Pb/^{204}Pb$ of 17·483 and 17·578, respectively (Sheth *et al.*, 1997; Chandrasekharam *et al.*, 1999). Several of the thicker dikes show evidence of multiple injections of magma in paired chilled zones. Samples NBD-37 and NBD-38 were taken from two adjacent, markedly different (in texture, grain size and crystal content) sections of such a dike, and exhibit significant chemical differences (Fig. 5c) that require two different magmas to have been injected into the dike. Nevertheless, the above results demonstrate that many Deccan dikes are chemically homogeneous over considerable distances.

The coastal dike swarm

Elemental signatures and DFA

The great majority of the coastal dike samples (85 of 117) have major and trace element compositions consistent with the compositional range of the Western Ghats eruptive succession (e.g. Fig. 6a). DFA results (e.g. Fig. 7a) show that 42% of these dikes have a strong chemical affinity with one of three formations: the Poladpur, Ambenali or Thakurvadi; only 3% are classified as Mahabaleshwar. As Hooper *et al.* (2010) noted, the Thakurvadi-like dikes cross-cut dikes with Poladpur-, Ambenali- and Mahabaleshwar-type chemical signatures, and also cut through flows of the Poladpur Formation. Because the Thakurvadi Formation lies deeper in the lava stratigraphy than the Poladpur, Ambenali and Mahabaleshwar Formations, these Thakurvadi-like dikes (which make up about 15% of the coastal sample set) cannot be feeders to the Thakurvadi Formation (Hooper *et al.*, 2010). Instead, they must represent a post-Mahabaleshwar Formation phase of magmatism. Hereafter, we term them 'pseudo-Thakurvadi'.

Excluding the pseudo-Thakurvadi dikes, the DFA also shows that 27% of the coastal swarm dikes have affinities with the lower or middle formations. These dikes crop out

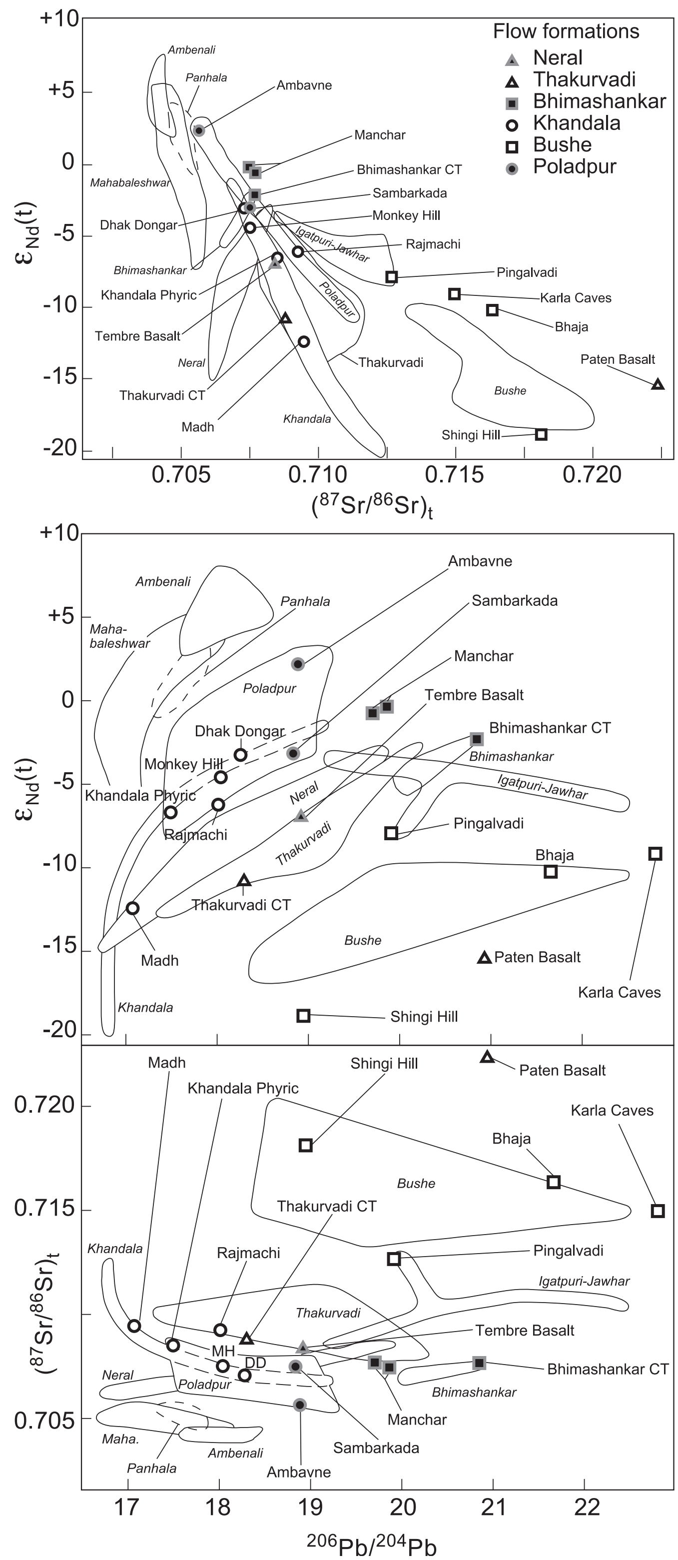

Fig. 4. Isotopic data for previously unanalyzed members and chemical types (CT) of the Western Ghats flow formations. Fields enclose previous data (formation names in italics); modified after Mahoney *et al.* (2000), with the field for the Panhala Formation after Lightfoot & Hawkesworth (1988). In the $(^{87}Sr/^{86}Sr)_t$ vs $^{206}Pb/^{204}Pb$ panel, MH stands for the Monkey Hill and DD for the Dhak Dongar Members of the Khandala Formation.

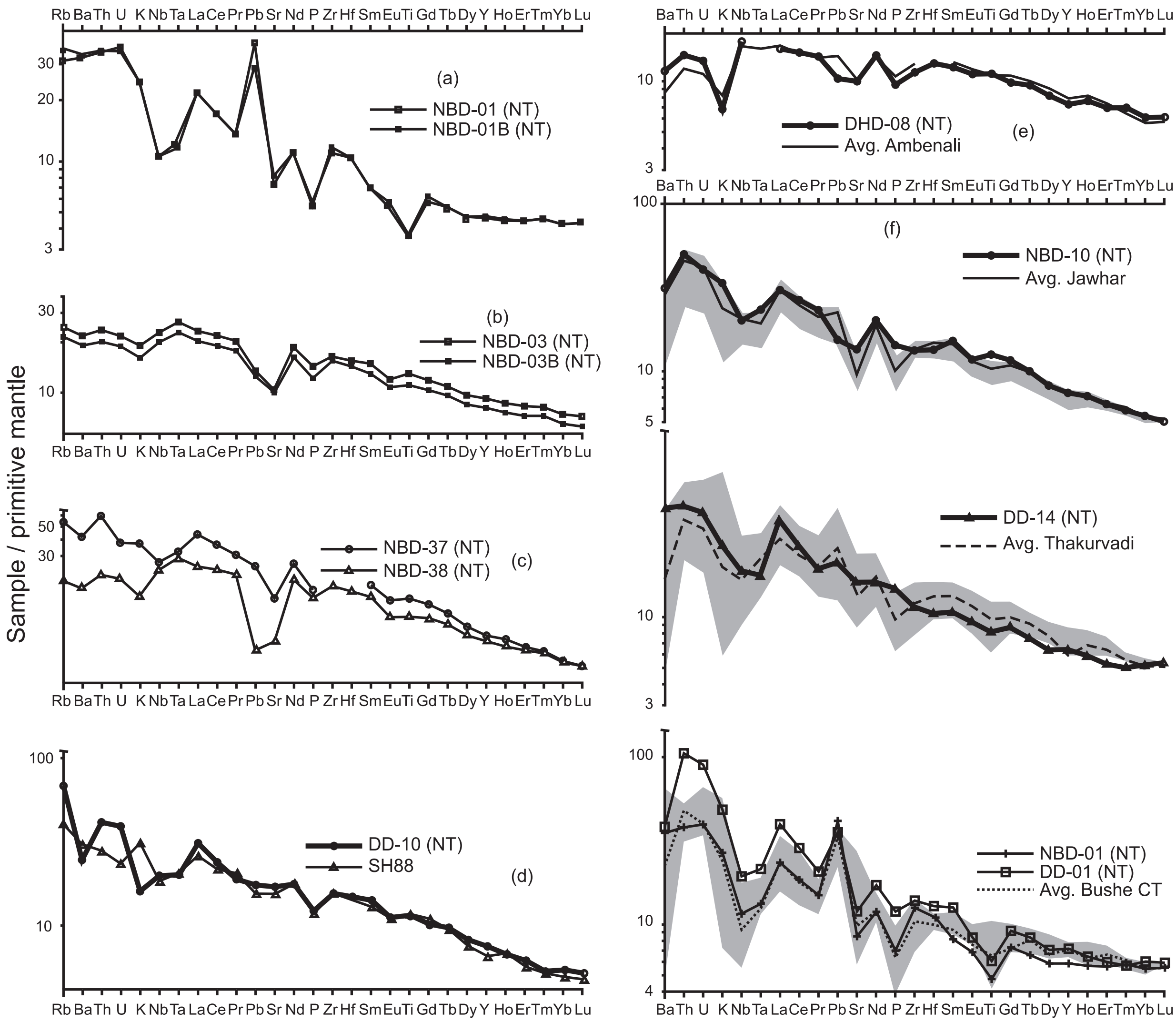

Fig. 5. Selected primitive mantle normalized trace element patterns. Formation and member averages are from the data of Beane (1988), Beane *et al.* (1986) and Peng *et al.* (1994), with the total observed range represented by the gray field. Dike swarm is indicated in parentheses, with NT standing for Narmada–Tapi. (a, b) Comparison of two samples collected along the same dike. (c) Comparison of two injections in the same dike, normalized to the same Lu value. (d) Comparison between the patterns of Narmada–Tapi dike sample DD-10 and Toranmal flow sample SH88 (Mahoney *et al.*, 2000), taken >100 km from DD-10. (e) Comparison between dike DHD-08, which has an Ambenali-type isotopic signature, and the Ambenali Formation average. (f) Patterns of Narmada–Tapi dikes with lower- and middle-formation-like isotopic signatures are compared with the average pattern of the isotopically similar formation. Formation averages are normalized to the same Lu value as the samples for comparison. Normalizing values are from Sun & McDonough (1989).

mainly north and NE of Mumbai, where the lowest levels of the flow stratigraphy are exposed (Beane *et al.*, 1986; Bodas *et al.*, 1988). By contrast, most of the upper-formation-like dikes occur along the coast south of Mumbai. The remaining ~27% of coastal swarm dikes have Mahalanobis distances >25 in the DFA.

Isotopic signatures

Fifteen tholeiitic samples from the coastal swarm were selected for isotopic analysis (Fig. 8). Two from dikes near Goa, ~70 km to the SW of the present boundary of the flood basalts, were chosen to test Widdowson *et al.*'s (2000) hypothesis that some of these dikes might represent feeders of the upper lava formations. One, IND-005, is chemically similar to both the Ambenali and Poladpur Formations, which overlap in a number of major and trace element characteristics (Ba, TiO_2 and MgO contents are closer to average Poladpur values, but Ba/Y and Nb/Zr are closer to average Ambenali values). Its isotope ratios, however, are unequivocally Poladpur-type. The other sample, ORL-005, has low Sr, Ba and Zr concentrations rarely observed in Deccan flows except in the Panhala

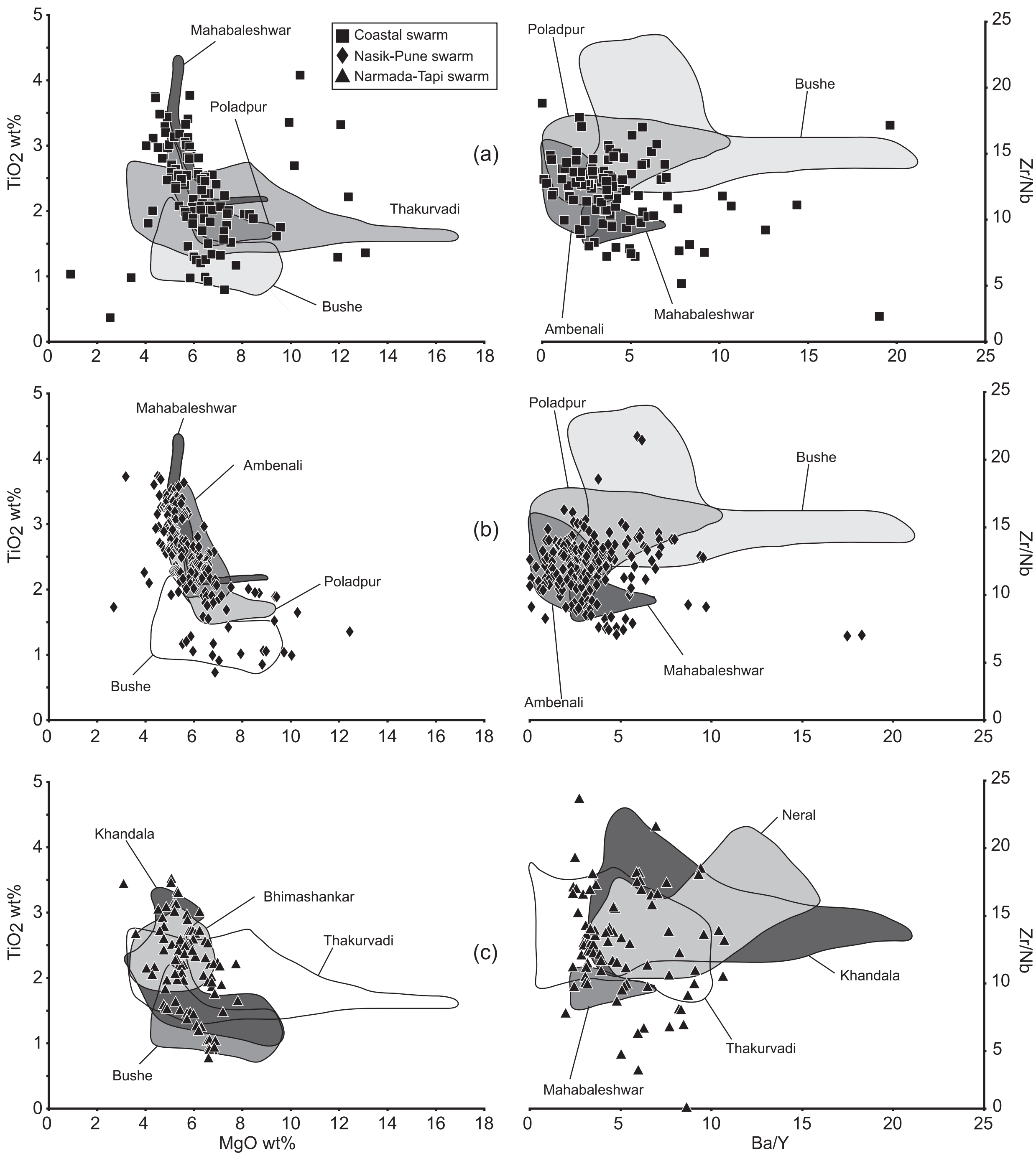

Fig. 6. Variation in four major and trace element parameters commonly used (e.g. Beane *et al.*, 1986; Lightfoot & Hawkesworth, 1988) to help discriminate between flow formations in the Western Ghats. Fields enclose data for the formations (Cox & Hawkesworth, 1985; Beane *et al.*, 1986; Beane, 1988; Lightfoot & Hawkesworth, 1988; Lightfoot *et al.*, 1990; Peng *et al.*, 1994). (a) Coastal swarm dikes (117 samples). (b) Nasik–Pune swarm dikes (186 samples). (c) Narmada–Tapi swarm dikes (97 samples). Some fields are omitted for clarity.

Formation (Lightfoot & Hawkesworth, 1988; Lightfoot *et al.*, 1990). Isotope ratios for this sample (Fig. 8) fall within the Panhala field (see dashed field in Fig. 4). Lavas of the Panhala Formation are found only in the extreme southwestern Deccan, relatively near (within ~135 km of) the Goa-area dikes. From these two results, it is probable that dikes near Goa indeed acted as feeders to some Poladpur and Panhala flows.

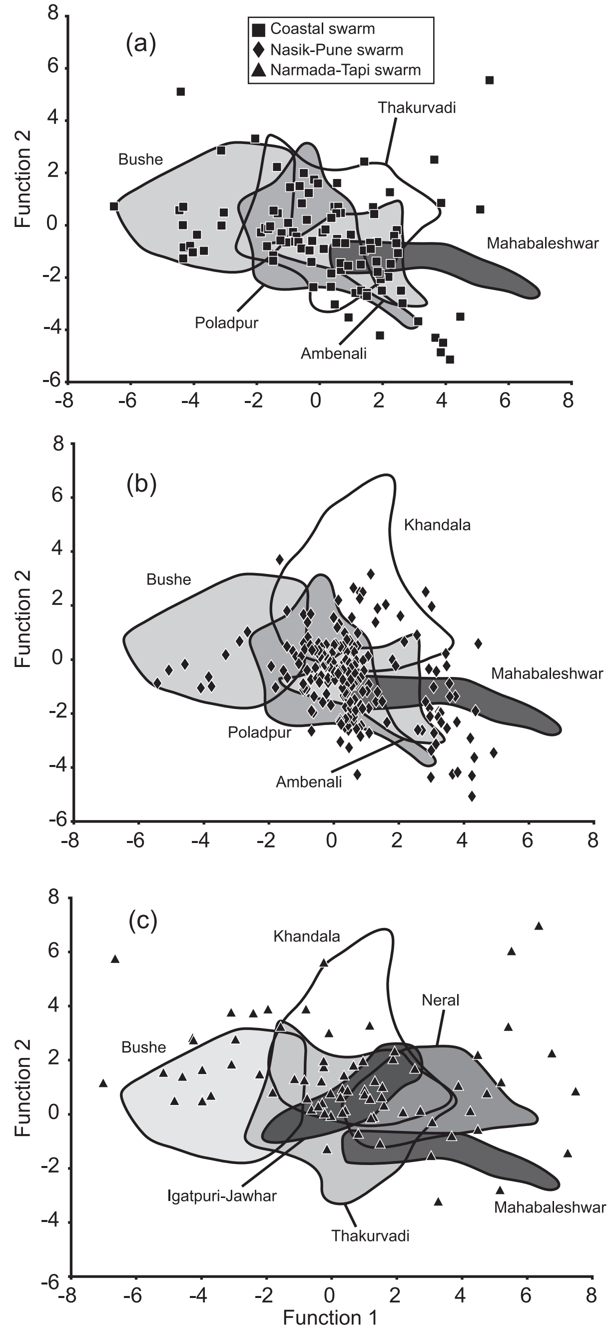

Fig. 7. Values of the first two of the eight canonical discriminant functions for Deccan dikes are compared with fields for the Western Ghats lava formations (some fields are omitted for clarity). The first two canonical functions represent 84% of the total variation in the selected elements. (a) Coastal swarm; (b) Nasik–Pune swarm; (c) Narmada–Tapi swarm. Function $1 = -0{\cdot}48SiO_2 - 0{\cdot}155Al_2O_3 + 1{\cdot}289TiO_2 + 0{\cdot}157CaO + 0{\cdot}097K_2O + 1{\cdot}397P_2O_5 - 0{\cdot}048Ni + 0{\cdot}462Ba + 0{\cdot}301Sr - 1{\cdot}707Zr - 0{\cdot}744Y - 0{\cdot}002Nb$. Function $2 = 0{\cdot}145SiO_2 + 0{\cdot}135Al_2O_3 - 0{\cdot}141TiO_2 - 0{\cdot}251CaO - 0{\cdot}286K_2O + 0{\cdot}439P_2O_5 + 0{\cdot}058Ni + 0{\cdot}953Ba - 0{\cdot}247Sr + 0{\cdot}815Zr + 0{\cdot}039Y - 1{\cdot}215Nb$.

Eight of the remaining coastal-swarm dikes can be matched isotopically with the three main upper formations (three with Poladpur, two with Ambenali, three with Mahabaleshwar), in good agreement with their major and trace element characteristics (e.g. DDH-116, Mahalanobis distance from the Ambenali centroid is only 1·71; Electronic Supplement 1). These dikes are located north, NE, and south of Mumbai (DDH-030, DDH-034, DDH-039, DDH-040, DDH-116, JH-35, JH-40, JH-48). We interpret them as probable feeders for some of the flows of these formations.

One coastal-swarm dike sampled north of Mumbai (JW-32), has an isotopic signature closely resembling that of the Plagioclase Phyric Member of the lowermost formation, the Jawhar. Another (DDH-036) has unmistakeable Bushe-type isotope ratios (Fig. 8) and major and trace element compositions. These two dikes are part of a suite sampled in this area that have major and trace element affinities with the lower and middle formations, particularly the Igatpuri–Jawhar, Thakurvadi and Bushe (DDH-036, DDH-038, JH-55, JH-57, JH-67, JW-06, JW-07, JW-29, JW-30, JW-32).

Finally, three dikes with major and trace element characteristics matching those of the Thakurvadi, Bushe and Poladpur Formations (DDH-11, JH-72 and DDH-095, respectively) have isotope ratios unlike those of any formation. The chemically Thakurvadi-like dike (DDH-11; Fig. 8) belongs to the late-stage, pseudo-Thakurvadi group.

Nasik–Pune dike swarm

Elemental signatures and DFA

In contrast to the coastal and Narmada–Tapi swarms, which contain both tholeiitic and alkalic dikes, the dikes sampled in the Nasik–Pune swarm are all tholeiitic. The great majority (89% of 194 samples) have major and trace element signatures similar to those of lavas of the Western Ghats formations (e.g. Figs 6b, 7b and 9), as also found by Beane *et al.* (1986) in their reconnaissance study. The Nasik–Pune swarm also displays the smallest proportion (~11%) of cases unclassified by DFA. Over 55% of the classified cases are matched with the upper formations (Wai Subgroup; see Fig. 10). The remainder are matched with the middle and lower formations (Lonavala and Kalsubai Subgroups); of these, Thakurvadi- and Khandala-like signatures are well represented.

Beane *et al.* (1986) and Hooper (1990) noted that, as a group, the Nasik–Pune swarm dikes lack a strongly preferred strike or trend, although Deshmukh & Sehgal (1988) and Bondre *et al.* (2006) pointed out that some portions of the swarm exhibit well-defined local preferred orientations. Our results confirm Beane *et al.*'s (1986) and Hooper's (1990) observations (Fig. 11b and g), but reveal an important difference in dike orientation with dike composition. As a group, dikes with Wai-Subgroup-like

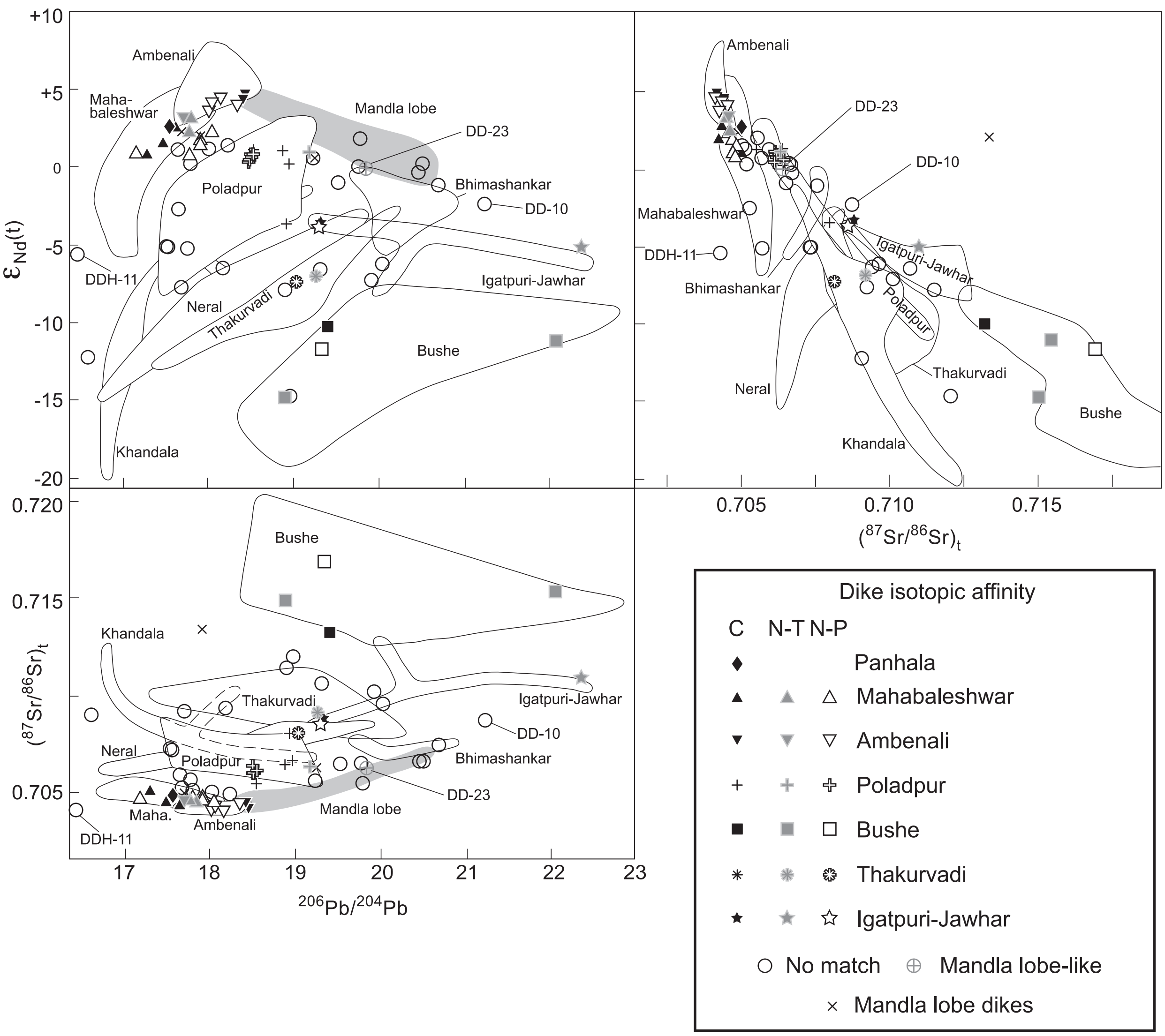

Fig. 8. Isotopic data for 64 Deccan dikes. Fields for the Deccan flow formations have been modified by addition of the data in Fig. 4. Black symbols, coastal swarm (C); gray symbols, Narmada–Tapi swarm (N-T); open symbols, Nasik–Pune swarm (N-P). The gray-shaded field encompasses data for the Mandla lobe (Peng *et al.*, 1998). Data for Mandla lobe dikes (crosses) are from J. Mahoney (unpublished data).

(i.e. Poladpur-, Ambenali- and Mahabaleshwar-like) chemical signatures display two or three dominant orientations (Fig. 11d). However, when only dikes matched by DFA to the Ambenali and Mahabaleshwar Formations are considered, the directional pattern is approximately random (Fig. 11e and g). By contrast, the Poladpur-like dikes show two preferred orientations, roughly east–west and NE–SW (unlike the approximately north–south trends of the Poladpur-like dikes in the coastal swarm). The Kalsubai-Subgroup-like dikes, on the other hand, display a strong north–south orientation (Fig. 11f).

Isotopic signatures

We analyzed the Sr, Nd and Pb isotope ratios of 34 samples from the Nasik–Pune swarm. Data for 14 samples fall within the isotopic fields of the three main upper formations: Poladpur (BOR-29, DDH-081, JEB-332, JEB-455, JH-22), Ambenali (AM-02, DDH-005, DDH-013), Mahabaleshwar (BOR-13, BOR-14, BOR-20, JEB-008, JEB-396), and one sample (JH-28) with values in the zone where the Mahabaleshwar and Ambenali fields overlap (Fig. 8). These isotopic matches are generally in good agreement with the samples' elemental affinities (e.g. Fig. 9a and b). Two chemically borderline cases, BOR-013 and BOR-014, share many characteristics with the Mahabaleshwar Formation but also diverge from it somewhat (Sr <250 ppm and Ba/Y <3·5, whereas most Mahabaleshwar flows have Sr >250 ppm and Ba/Y >4); their isotopic signatures are distinctly Mahabaleshwar-like. In only three cases (JEB-182, JEB-393 and JEB-438)

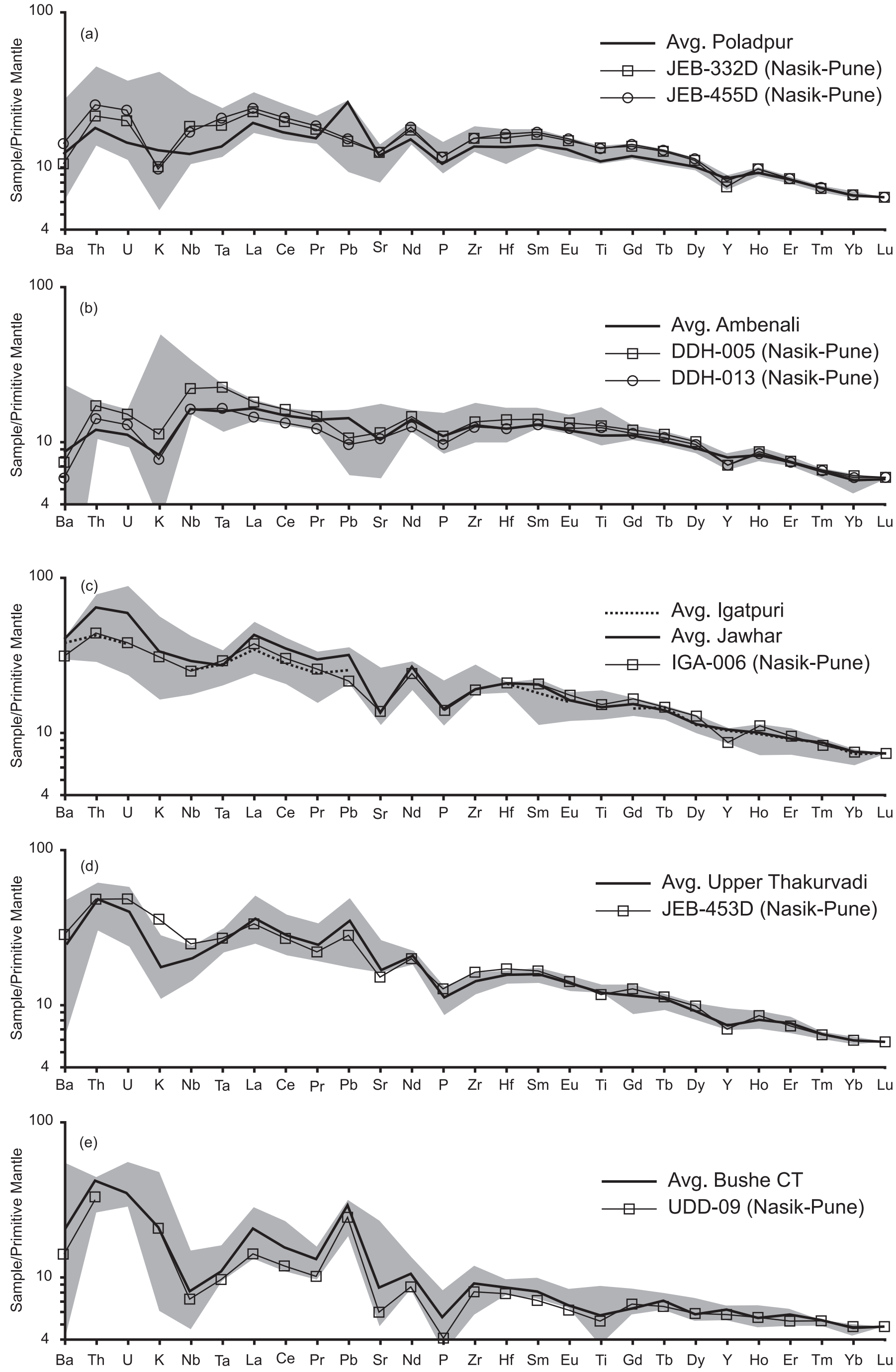

Fig. 9. Primitive mantle normalized trace element patterns for dike samples that are isotopically similar to a lava formation, compared with average patterns for the respective lava formation. Dike swarm is indicated in parentheses next to the sample number. Formation averages and sample data are normalized to the same Lu value for comparison. Data and fields are defined as in Fig. 5. 'Upper Thakurvadi' is defined as the upper two Thakurvadi chemical types and the Thakurvadi Water Pipe Member (see Table 1).

did samples matched with an upper formation by DFA not also yield an isotopic match to an upper formation. Accordingly, we conclude that many of the analyzed Nasik–Pune dikes could have been feeders for the upper formations. Furthermore, given the good correspondence of the chemical and isotopic results, we are confident that many isotopically uncharacterized Nasik–Pune swarm dikes with upper-formation chemical affinities also represent probable feeders to these formations.

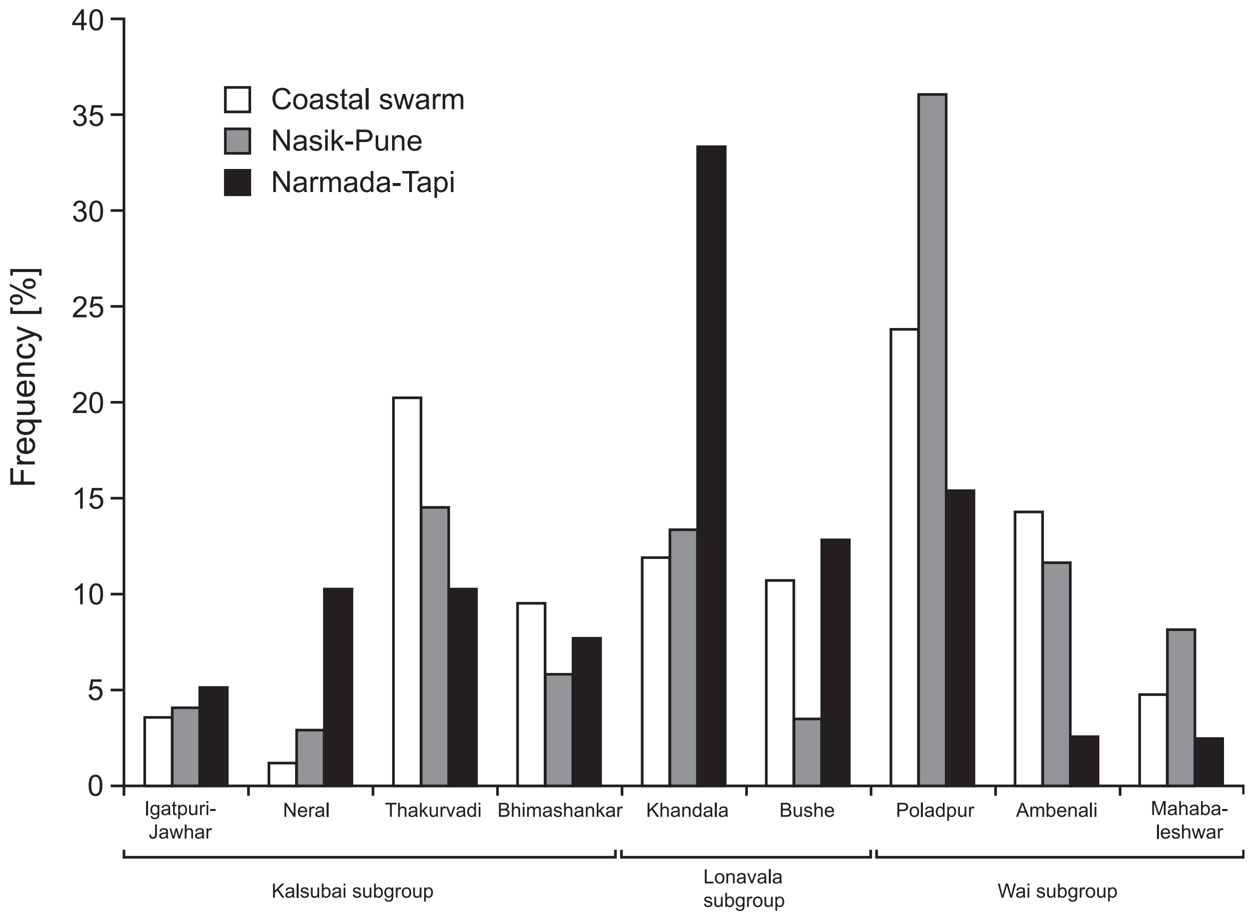

Fig. 10. Histogram of formational matches for dikes by DFA. Unclassified cases are not included.

Fourteen of the 17 remaining samples analyzed isotopically exhibit a chemical resemblance (ranging from close to distant) to formations of the Kalsubai or Lonavala Subgroups. As with the pseudo-Thakurvadi coastal dikes, the isotopic characteristics of these dikes generally do not match those of any of the known lava formations (AM-30, DDH-089, IGA-013, IGA-019, JEB-016, JEB-284, JEB-327, JEB-333, JEB-442, JH-20, JH-25). There are only three exceptions, for which both isotopic and elemental characteristics are in agreement: one dike has an Igatpuri–Jawhar-type signature (IGA-006, Fig. 9c; it is isotopically closest to the Plagioclase Phyric Member of the Jawhar Formation), one a Thakurvadi-type signature (JEB-453D; Fig. 9d), and one a Bushe-type signature (UDD-09; Fig. 9e). We infer that some probable lower- and middle-formation feeders are present in the Nasik–Pune swarm, but that most of the dikes having chemical similarities to these formations are, on the basis of poor isotopic matches, unlikely to be feeders for them. Some of these dikes may have fed flows that have been eroded, or else have not yet been sampled; others may represent arrested dikes that did not result in eruptions. The same is true of the remaining three samples analyzed isotopically, which are not matched consistently to any flow formation by either their chemical or isotopic characteristics (JEB-397, JEB-426, TRM-59).

The Narmada–Tapi dike swarm

Elemental signatures and DFA

The Narmada–Tapi swarm shows greater chemical variability than observed for the other two swarms. This chemical variability results in part from the fairly evolved nature of some of the dikes (e.g. DD-05, NBD-30; see Melluso *et al.*, 1999). It is also expressed in the wide range of observed TiO_2 concentrations. Dikes with TiO_2 <1·5 wt %, for instance, are three times more common in the Narmada–Tapi swarm than in the Nasik–Pune swarm. These low TiO_2 values are typical of the Bushe Formation and some members of the Khandala and Neral Formations, but also of low-Ti flows in Saurashtra that do not resemble any of the Western Ghats formations (Melluso *et al.*, 2006). Alkalic dikes are also common in this swarm. Even excluding the alkalic dikes, Narmada–Tapi dike chemical compositions compare rather poorly

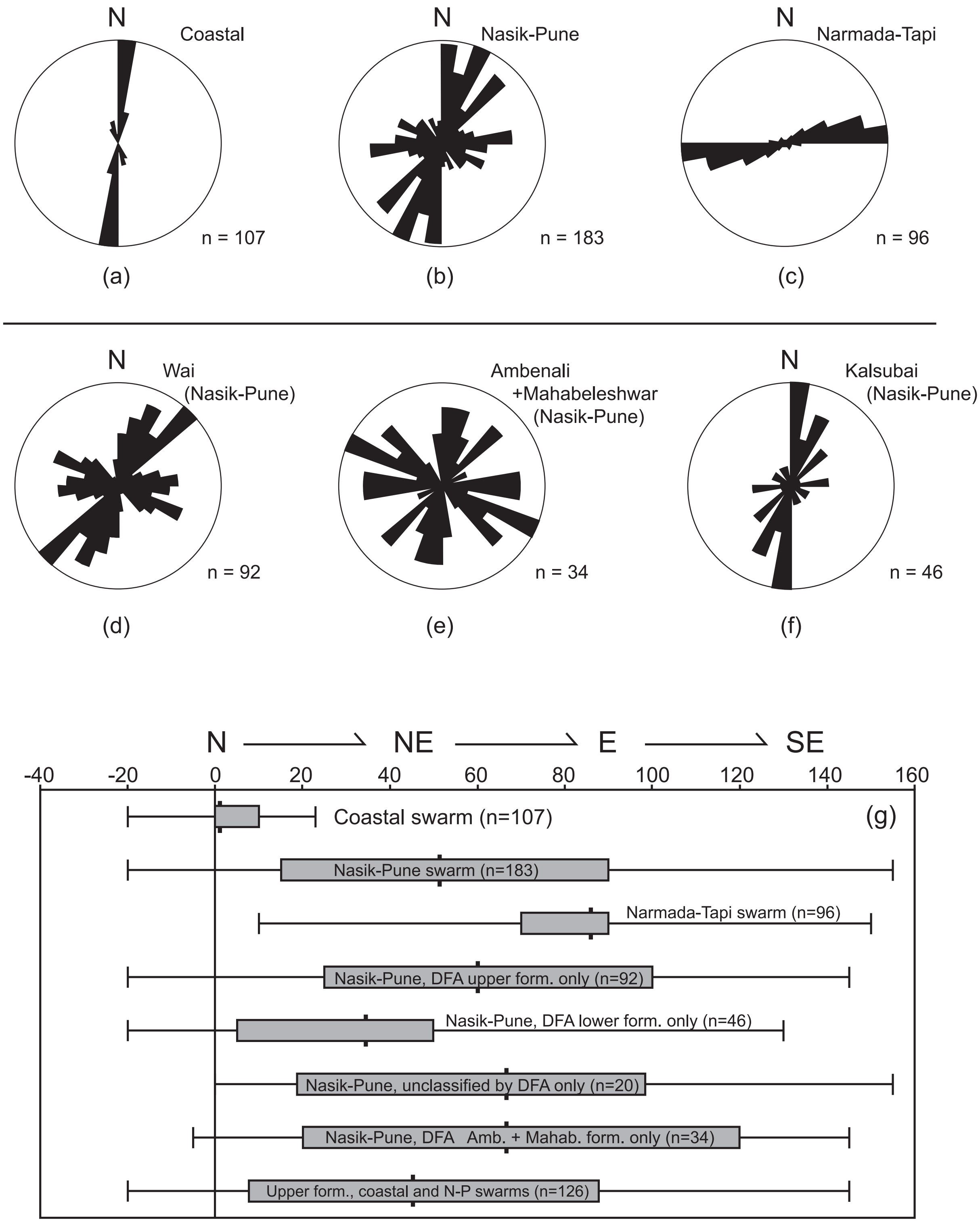

Fig. 11. (a–f) Rose histograms of dike trends (*n*, number of samples). Strike data could not be collected for 21 dikes sampled in our study. (a) Coastal swarm. (b) Nasik–Pune swarm. (c) Narmada–Tapi swarm. (d) Nasik–Pune swarm dikes that are matched by DFA to formations of the Wai Subgroup (Poladpur, Ambenali, Mahabaleshwar). (e) Nasik–Pune swarm dikes matched by DFA to the Ambenali and Mahabaleshwar Formations. (f) Nasik–Pune swarm dikes matched by DFA to formations of the Kalsubai Subgroup (Jawhar, Igatpuri, Neral, Thakurvadi, Bhimashankar). (g) 'Box and whiskers' diagram of dike trends. All data are included between the short vertical lines, which represent the minimum and maximum values observed (whiskers), whereas the gray boxes encompass data within the 25th and 75th percentiles (i.e. each box represents the median percentages of the dataset). Thick tick marks represent the averages. In the scale at the top, zero indicates due north, corresponding to dikes trending north–south. Data are grouped by swarm and DFA affinity. From top to bottom: coastal swarm; Nasik–Pune swarm; Narmada–Tapi swarm; Nasik–Pune swarm dikes matched by DFA with Wai Subgroup formations; Nasik–Pune swarm dikes matched by DFA with Kalsubai Subgroup formations; Nasik–Pune swarm dikes not classified by DFA; Nasik–Pune swarm dikes matched to the Ambenali and Mahabaleshwar Formations by DFA; coastal and Nasik–Pune (N-P) swarm dikes matched to Wai Subgroup formations by DFA.

as a group with those of the Western Ghats formations. For example, the results of our DFA show that 56% of cases have Mahalanobis distances >25 from the statistically closest formation match.

The remaining 44% (39 out of 89) can be matched principally with the lower and middle formations (from Jawhar to Bushe) (Fig. 10); such dikes outnumber those matched with the upper formations by 4:1. This result is in sharp contrast to the coastal and Nasik–Pune swarms, for which most DFA matches are with the three main upper formations (Poladpur, Ambenali and Mahabaleshwar). Also, twice as many Narmada–Tapi samples are assigned to the Khandala Formation as to any other. One dike with a Bhimashankar-like signature (sample DD-10) closely matches a northern Deccan flow in the Toranmal area (Mahoney *et al.*, 2000) in its major element composition and in the trace elements from Nb to Lu in Fig. 5d.

Isotopic signatures

Isotope ratios were measured for 14 Narmada–Tapi samples (Fig. 8). Four (DD-01, DD-14, NBD-01, NBD-10) can be matched isotopically to one of the lower or middle formations (one to the Igatpuri–Jawhar, one to the Thakurvadi, two to the Bushe), and have trace element patterns that broadly support the match (Fig. 5f). However, DFA did not match them with any formation, mostly because Ba (and Zr, to a lesser degree) concentrations are high in these four samples compared with Western Ghats flows of otherwise similar composition. Four samples (DHD-8, DHD-9, DHD-11, TAP-002) having chemical similarities to the upper formations also have Poladpur-, Ambenali-, or Mahabaleshwar-type isotope ratios. Sample DHD-8, in particular, represents a convincing match to the Ambenali Formation (Fig. 5e). Data for the six other samples (DD-10, DD-15, DD-23, DND-02, NBD-04, TAP-001) fall outside the isotopic fields defined by the Western Ghats formations, although one, DD-23, has an isotopic signature within the field for lavas of the northeastern Deccan (Mandla lobe in Fig. 8) that are Poladpur-like in major elements, trace elements, and Nd and Sr isotope ratios, but have higher $^{206}Pb/^{204}Pb$ than the Western Ghats Poladpur basalts (Peng *et al.*, 1998).

Interestingly, even though DFA indicated that the Khandala might be the formation represented most abundantly in the Narmada–Tapi swarm, none of the samples analyzed is isotopically equivalent to Khandala compositions. We suspect that these dikes may be analogous to the late-stage pseudo-Thakurvadi dikes in the coastal swarm.

Putting the above results together, we infer that the Narmada–Tapi swarm could have fed some flows of the lower, middle, and upper formations, as well as some flows cropping out in the northern and northeastern regions of the province. However, most of the dikes we sampled could not have been feeders for any known lavas.

DISCUSSION

Our results, combined with previous studies, allow the reconstruction of a multi-stage history for the dike swarms and other intrusions of the Deccan province. This may be summarized chronologically as follows.

(1) Mafic alkalic rocks were emplaced near Mundwara and Barmer at 68·5 Ma (Fig. 1; Basu *et al.*, 1993; Simonetti *et al.*, 1995) and in Pakistan around 73–70 Ma (e.g. Mahoney *et al.*, 2002; Kerr *et al.*, 2010).

(2) Dikes that, from their chemical and isotopic compositions, may be feeders of the lower and middle formations, from the Jawhar to Bushe, were emplaced in what is now the northern Konkan plain between Mumbai and Dahanu (i.e. coastal and western Nasik–Pune swarms) and possibly in the Narmada–Tapi region (Fig. 12). Although relatively few have been identified thus far, they typically strike approximately north–south in the Konkan and east–west in the Narmada–Tapi swarm.

(3) Dikes isotopically and chemically similar to the three main upper formations, the Poladpur, Ambenali and Mahabaleshwar, were predominantly emplaced in an area bordered by Nasik and Pune to the north and south (20°N and 18°28'N, respectively), and by the coast and Sangamner to the west and east (72°50'E to 74°13'E; Figs 12b and 13b, d). Many of these dikes are probably feeders to these upper formations. The Ambenali- and Mahabaleshwar-like dikes, in particular, show no specific regional preferred orientation (Figs 11 and 13d). Upper-formation-like dikes also include the coastal dikes of Goa, some 350 km south of Pune (Fig. 12b and c), although the timing of emplacement of the Goan dikes is uncertain relative to that of the geochemically similar lavas of the Western Ghats (Widdowson *et al.*, 2000). Some Narmada–Tapi dikes may have fed the high-$^{206}Pb/^{204}Pb$ Poladpur-like flows that are abundant in the northern and northeastern Deccan.

(4) Dikes chemically similar to members of the Thakurvadi Formation, but with distinctly different isotopic characteristics (i.e. pseudo-Thakurvadi type), were emplaced as part of all three dike systems. In the coastal and Nasik–Pune swarms, these dikes show a strong preferred north–south orientation (Fig. 13c and e). In the coastal area, they cut flows and inferred feeder dikes of the upper formations (Dessai & Viegas, 1995; Hooper *et al.*, 2010). Corresponding lava flows have not been found, suggesting that the dikes (a) did not generate lava flows (e.g. Auden, 1949) or (b) fed flows higher up in the stratigraphy that have since been eroded [although Widdowson & Cox (1996) argued against large amounts of erosion from the top of the Western Ghats

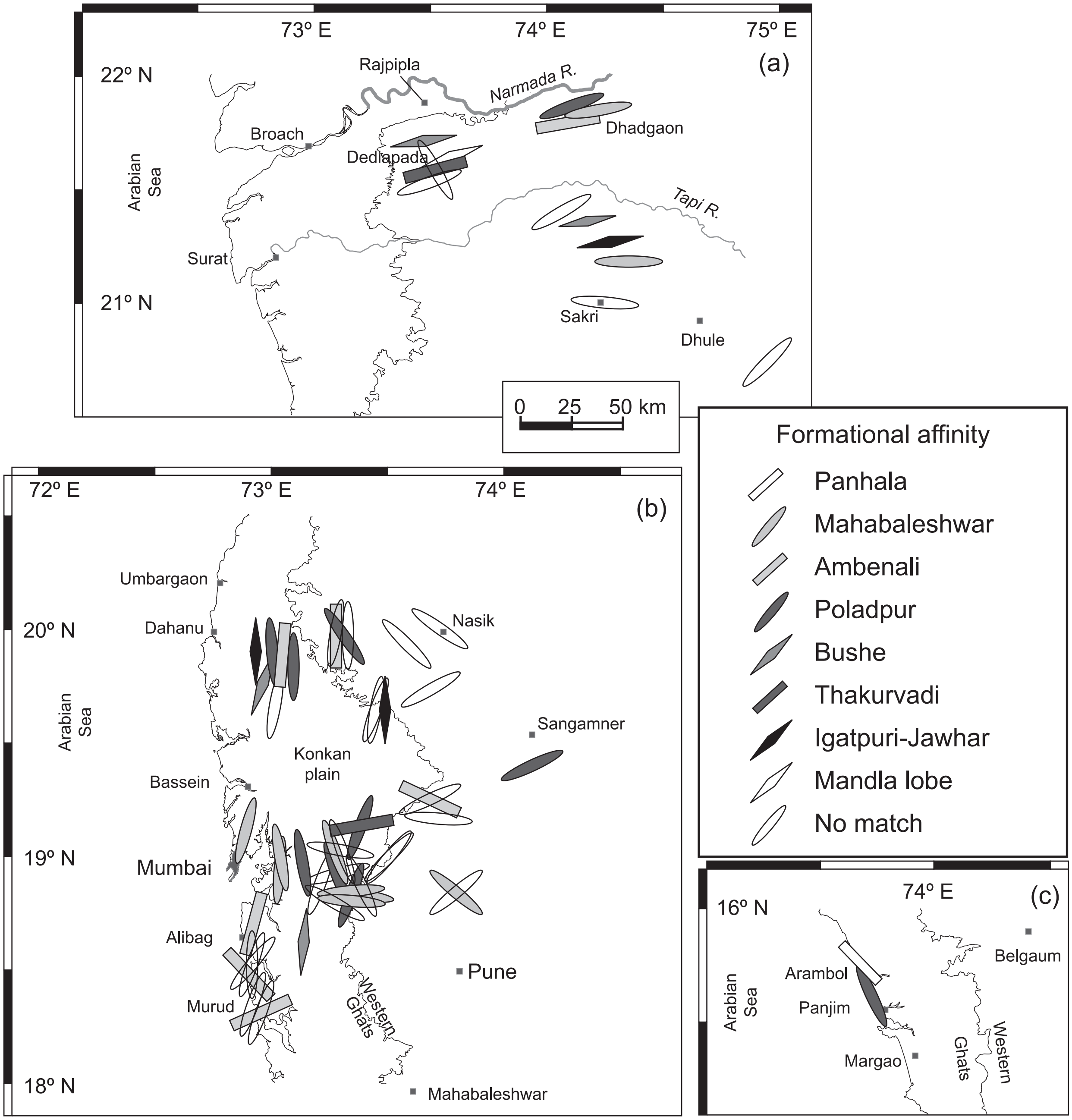

Fig. 12. Location and strike of dikes for which we measured isotopic ratios. Formational affinity indicated by combined isotopic and chemical properties is shown.

lava pile] or else (c) fed late lavas that flowed to the west and are now beneath the Arabian Sea.

(5) In the late stages of magmatism, north–south-striking alkalic dikes, including lamprophyres in some areas, were emplaced in the coastal swarm from at least as far north as Umbargaon to at least as far south as Murud (Figs 12b and 13c, 13e) (e.g. Dessai & Viegas, 1995; Vanderkluysen, 2008; Hooper *et al.*, 2010). East–west striking counterparts are also present in the Narmada–Tapi swarm. Some of the late dikes may be associated with scattered late alkalic complexes and flows, such as those in the Rajpipla area (e.g. Krishnamurthy & Cox, 1980; Mahoney *et al.*, 1985; Gwalani *et al.*, 1993; Sethna *et al.*, 1996; Simonetti *et al.*, 1998) and around Mumbai (e.g. Sethna & D'Sa, 1991; Melluso *et al.*, 2002). Lamprophyres south of Mumbai have been dated at 63–64 Ma (Knight *et al.*, 2000; Sahu *et al.*, 2003).

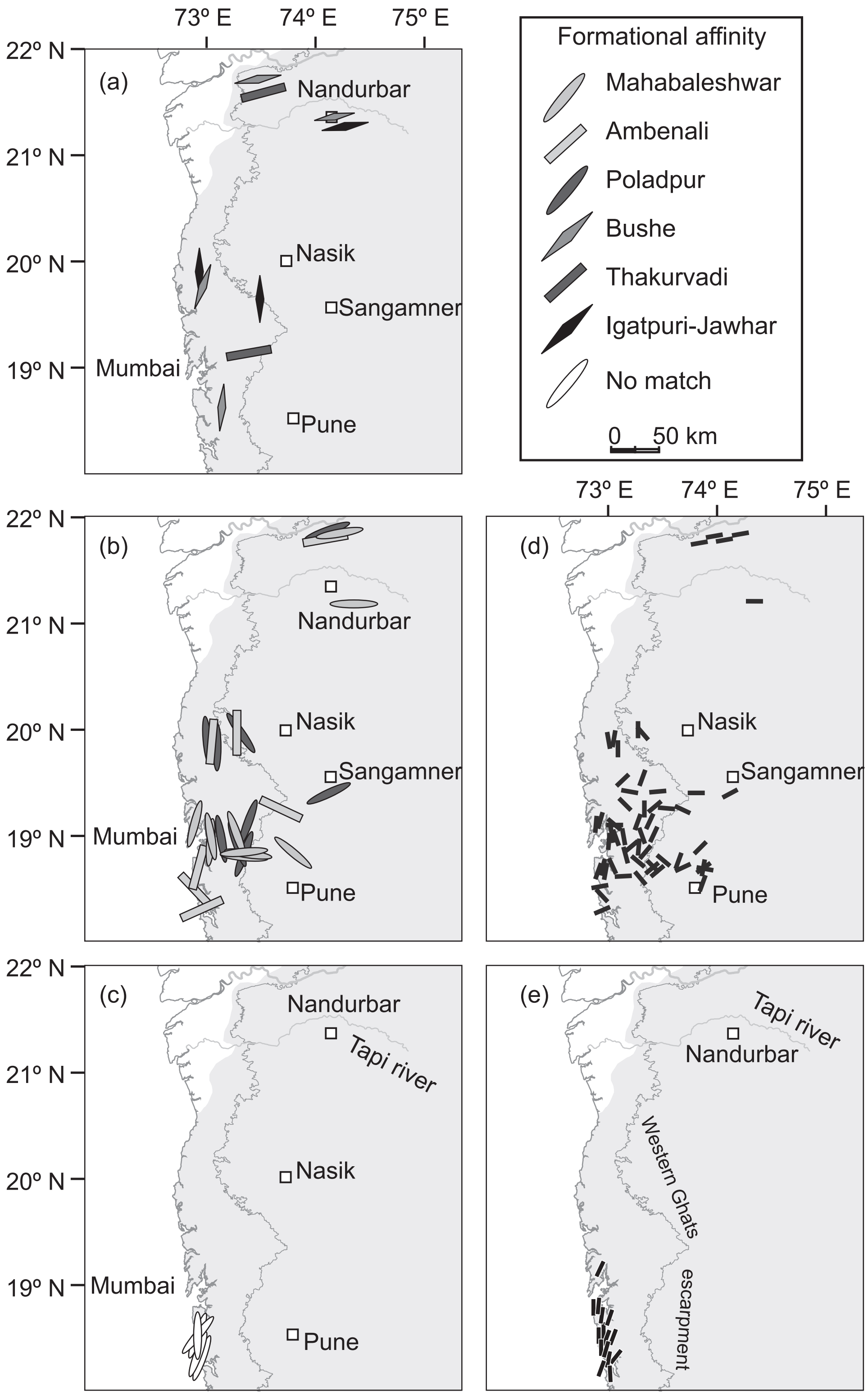

Fig. 13. Probable feeder dikes of the Deccan Traps. (a–c) Dikes for which isotopic data are available: (a) inferred feeders for the lower and middle formations; (b) upper formations; (c) post-upper-formation dikes. (d) Feeders for the upper formations inferred from chemical composition only. (e) Post-upper-formation dikes inferred from chemical composition only.

The combined results indicate that broadly north–south extension was prevalent in the Narmada–Tapi region before and/or during the period of Deccan volcanism. The results are also consistent with east–west extension in the Konkan region during eruption of the lower and middle formations. However, signs of directed regional extension during emplacement of the upper formations are lacking from the coast to at least as far inland as Sangamner. Shortly after eruption of the upper formation lavas, east–west extension appears to have resumed along what would become the west coast, leading to emplacement of the north–south-striking pseudo-Thakurvadi dikes and the subsequent alkalic dikes (see Hooper *et al.*, 2010). This well-expressed phase of east–west extension eventually led to the splitting of the Seychelles Bank from Greater India, which was followed by full-fledged seafloor spreading by ~62 Ma (Dyment, 1998; Todal & Eldholm, 1998; Collier *et al.*, 2008).

The exact time interval over which steps (2)–(4) above took place remains a matter of debate. One body of geochronological work argues that eruption of most of the flood basalts occurred in a million years or less around 65–66 Ma (e.g. Courtillot *et al.*, 1988; Duncan & Pyle, 1988; Vandamme *et al.*, 1991; Hofmann *et al.*, 2000; Sen, 2001; Chenet *et al.*, 2007). Other workers hold that the flood basalts erupted over at least several million years (e.g. Venkatesan *et al.*, 1996; Baksi, 1994, 2007; Widdowson *et al.*, 2000; Pande, 2002). Chenet *et al.* (2008, 2009), from a study of paleomagnetic secular variation, suggested that most of the stratigraphic sequence in the Western Ghats may have been emplaced in only a few hundred thousand years in several brief eruptive events, each lasting but a few decades or centuries.

Our results also have implications for the length of Deccan lava flows. If Panhala flows were fed at least in part from fissures in the Goa area, the flows would have traveled ~100 km to reach the location of the nearest remaining Panhala outcrops. Similarly, the probable feeders of the upper formations are dominantly located west of Sangamner (Fig. 13), suggesting that flows of these formations would have had to travel at least 450–550 km to reach outcrops along the eastern edge of the province. In the most extreme cases, if we assume that some lavas of the Mandla lobe were fed from dikes in the Dediapada area where the geochemically similar DD-23 sample was collected, or from Ambenali-like dikes of the Nasik–Pune swarm, these flows would have had to travel 550–700 km. These results are on a par with lava flow lengths of as much as 600 km estimated in the Columbia River flood basalt province (Hooper, 1997), but short of the proposed ~1000 km travelled by two valley-confined Deccan lava flows of the Rajahmundry Traps on India's east coast, assumed to have originated from vents either in the Mumbai coastal area or the Nasik–Sangamner region (e.g. Baksi, 2001; Self *et al.*, 2008; Jay & Widdowson, 2008; see also Sheth *et al.*, 2009).

Several models have been proposed to explain the production of the large volumes of magma necessary for the formation of continental flood basalt provinces such as the Deccan Traps. These models fall in three main categories: (1) models that invoke a mantle starting-plume head (e.g. Richards *et al.*, 1989; Campbell & Griffiths, 1990; Campbell, 1998) impinging upon the base of the lithosphere; (2) models invoking rifting above a pre-existing plume (e.g. Courtney & White, 1986; White & McKenzie, 1989; Kent, 1991) whose relatively small head spreads and grows ('incubates') at the base of the lithosphere for as much as 50 Myr before rifting triggers the flood basalt event; (3) non-plume models (e.g. Smith, 1993; Anderson, 1994; King & Anderson, 1995; Smith & Lewis, 1999; Sheth, 1999, 2005), born of the need to address shortcomings of plume-based models and what the researchers have perceived as the indiscriminate application of a single class of models to a disparate worldwide set of provinces. Because proponents of these various models have presented their arguments in detail (e.g. Campbell & Kerr, 2007; Foulger & Jurdy, 2007), we confine our discussion here to those aspects of our research that have direct implications for models of Deccan Traps origin and emplacement.

The Wai Subgroup appears to make up the volumetrically largest proportion of the Deccan succession (e.g. Widdowson *et al.*, 2000; Self *et al.*, 2006); as such, it probably represents a phase of maximum eruptive output. Our observation that the probable feeder dikes of the principal Wai Subgroup formations (Poladpur, Ambenali and Mahabaleshwar) lack any single well-defined trend runs counter to predictions of rifting-based models, both coupled rift–plume models and non-plume models. All such models rely on decompression driven by directed extension to trigger and sustain mantle melting on a large scale. Rifting-based models can explain the presence of the well-oriented lower- and middle-formation-type dikes in the Konkan and Narmada–Tapi areas (and the precursory magmatism at Mundwara in the Cambay graben, where extension was active before flood volcanism). However, rifting-based models fail to explain (1) why upper-formation magmas, estimated to make up $\geq$50% of Deccan lava volume (Self *et al.*, 2006), were erupted from a region unaffected by unidirectional extensional stresses, and (2) why the principal rifting event, culminating with the break-off of the Seychelles microcontinent, occurred after the peak of volcanism (Hooper *et al.*, 2010) and produced only comparatively tiny volumes of lava (at least onshore).

CONCLUSIONS

Combined chemical and isotopic signatures in the three principal Deccan Traps dike swarms allow us to correlate a substantial number of dikes with the known lava flow formations that make up much of the province. The results place bounds on the location, geometry, and evolution of the major feeder systems and upon the relative timing of dike emplacement with respect to regional-scale directed lithospheric extension. The main conclusions deriving from these observations are as follows.

(1) Erosion in the Konkan and Narmada regions has exposed 'windows' into the deeper levels of Deccan stratigraphy and hence the plumbing system of the feeder dike complex. Inferred feeders of the three main upper formations (Poladpur, Ambenali, and Mahabaleshwar) are found in the Nasik–Pune and coastal swarms. Their greatest concentration is in a region bounded by Nasik and Pune to the north and south and by the coast and Sangamner to the west and east, respectively. These dikes, particularly the Ambenali- and Mahabaleshwar-type dikes, do not show any marked preferred single orientation.
(2) Some dikes possessing chemical affinities with the lower and middle formations are present in the east–west-oriented Narmada–Tapi swarm. This area appears to have been the site of active north–south extension during the flood basalt episode. Some lower- and middle-formation-type dikes also are found in the coastal and Nasik–Pune swarms, where they display an overall preferred north–south strike. The relative scarcity of such dikes is in all probability a result of sampling bias resulting from unfavorable access to the lower stratigraphic levels and poor to nonexistent exposure in key areas.
(3) Dikes with chemical affinities to the Thakurvadi Formation cut flows and dikes of stratigraphically higher formations, but have isotopic signatures different from those observed in the Thakurvadi Formation or, indeed, other formations. These dikes, termed here the pseudo-Thakurvadi dikes, strike east–west in the Narmada–Tapi swarm and north–south everywhere else, and do not seem to have generated significant volumes of lava. Along the west coast, these dikes appear to be contemporaneous with late-stage rifting, which eventually led to the break-up of the Seychelles Bank from India.
(4) A later phase of volumetrically minor, syn- or post-rifting magmatism is recognized in lamprophyric and other alkalic dikes and small intrusions in the coastal swarm. This phase may have persisted until after break-up, as reflected in 60–61 Ma trachyte and basalt magmatism in Mumbai (Sheth *et al.*, 2001).
(5) Dike-formation correlations suggest that some of the major Deccan flows could have reached lengths of a few hundred kilometers (i.e. from a dike to the margins of a mappable flow unit), and perhaps as much as 550 km in the east–central Deccan. Moreover, similarities between several dikes of the Narmada–Tapi swarm and lavas of the Mandla lobe (Fig. 2) suggest that this swarm may have fed some flows that spread to the northern and northeastern reaches of the province. If so, these flows could have reached lengths of ~700 km.

Rifting-based models for the Deccan Traps fail to account for (1) the overall lack of preferred orientation of abundant dikes possessing isotopic and chemical characteristics consistent with feeders of the upper formations (Wai Subgroup, estimated to make up ≥50% of Deccan lava flow volume; Self *et al.*, 2006) and (2) the fact that the main phase of volcanism preceded the main phase of rifting, which led to continental break-up between India and the Seychelles Bank along the Indian west coast. Rift-related precursory magmatic events and directed-extension-controlled emplacement of lower- and middle-formation-type dikes are consistent with predictions of rifting-based models, but do not discount a plume-head model, as some rifting had been occurring for millions of years prior to the onset of significant volcanism. Although the possibility that rifting triggered flood volcanism cannot be ruled out, it appears that another mechanism is required to account for the voluminous upper formations.

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SUPPLEMENTARY DATA

Supplementary data for this paper are available at *Journal of Petrology* online.

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