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The Deccan tholeiite lavas and dykes of Ghatkopar–Powai area, Mumbai, Panvel flexure zone: Geochemistry, stratigraphic status, and tectonic significance

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ABSTRACT

Mumbai City, situated on the western Indian coast, is well known for exposures of late-stage Deccan pillow basalts and spilites, pyroclastic rocks, rhyolite lavas, and trachyte intrusions. These rock units, and a little-studied sequence of tholeiitic flows and dykes in the eastern part of Mumbai City, constitute the west-dipping limb of a regional tectonic structure called the Panvel flexure. Here we present field, petrographic, major and trace element and Sr–Nd isotopic data on these tholeiitic flows and dykes, best exposed in the Ghatkopar–Powai area. The flows closely resemble the Mahabaleshwar Formation of the thick Western Ghats sequence to the east, in Sr–Nd isotopic ratios and multielement patterns, but have other geochemical characteristics (e.g., incompatible trace element ratios) unlike the Mahabaleshwar or any other Formation. The flows may have originated from a nearby eruptive center, possibly offshore of Mumbai. Two dykes resemble the Ambenali Formation of the Western Ghats in all geochemical characteristics, though they may not represent feeders of the Ambenali Formation lavas. Most dykes are distinct from any of the Western Ghats stratigraphic units. Some show partial (e.g., Sr–Nd isotopic) similarities to the Mahabaleshwar Formation, and these include several dykes with unusual, concave-downward REE patterns suggesting residual amphibole and thus a lithospheric source. The flows and dykes are inferred to have undergone little or no contamination, by lower continental crust. Most dykes are almost vertical, suggesting emplacement after the formation of the Panvel flexure, and indicate considerable east–west lithospheric extension during this late but magmatically vigorous stage of Deccan volcanism.

1. Introduction

The Deccan Traps are a large continental flood basalt (CFB) province of Late Cretaceous to Palaeocene age, currently occupying ~500,000 km^2 in western and central India (Fig. 1a). They are best developed in the Western Ghats escarpment in the southwestern part of the province (Fig. 1a), where they have been divided into three subgroups and eleven formations with a total stratigraphic thickness of ~3.4 km over a ~500 km distance (e.g., Najafi et al., 1981; Beane et al., 1986; Lightfoot et al., 1990; Peng et al., 1994; Table 1). Several distant Deccan lava sections are broadly correlatable with the Western Ghats type section (e.g., Peng et al., 1998 and Peng et al., this volume; Mahoney et al., 2000), whereas others are stratigraphically and petrogenetically unrelated (e.g., Sheth and Melluso, 2008; Sheth et al., 2013), suggesting polycentric eruptions. Three major dyke swarms, including the ~ENE–WSW-trending Narmada–Tapi dyke swarm, the ~N–S-trending Coastal dyke swarm, and the more randomly oriented Nasik–Pune dyke swarm (Fig. 1a), have been extensively studied (e.g., Auden, 1949; Viswanathan and Chandrasekharam, 1976; Deshmukh and Sehgal, 1988; Melluso et al., 1999; Widdowson et al., 2000; Bondre et al., 2006; Ray et al., 2007; Sheth et al., 2009; Hooper et al., 2010; Vanderkluysen et al., 2011). These studies have indicated that the Narmada–Tapi dyke swarm fed some lower-and middle-level stratigraphic formations of the Western Ghats sequence, and the Coastal and Nasik–Pune swarms fed many lavas of the the middle and upper formations.

Alkalic and silicic rocks are concentrated in a few areas in the province, such as that of Mumbai City (Fig. 1a–c) on the western Indian rifted margin (e.g., Sukheswala and Poldervaart, 1958; Sukheswala, 1974; Sethna and Battiwala, 1977). Mumbai City is located in the ~150 km-long, structurally complex Panvel flexure zone, in which the volcanic pile shows significant tectonic dips

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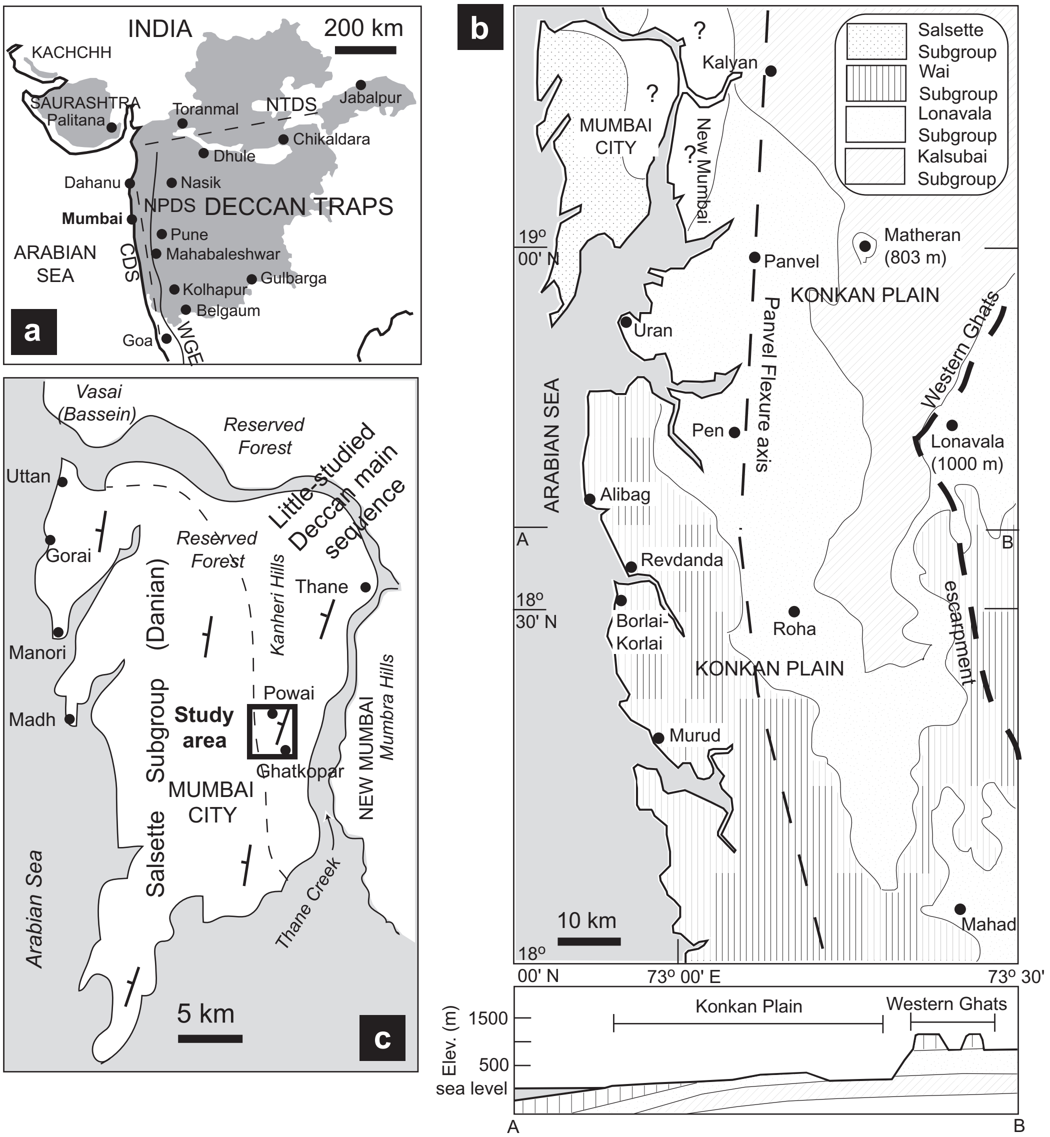


Fig. 1. Maps of the Deccan Traps (a), the western Deccan Traps (b) and Mumbai City (c), with important features and localities mentioned in the text marked. In (a), WGE is the Western Ghats escarpment, NTDS the Narmada–Tapi dyke swarm, CDS the Coastal dyke swarm, and NPDS the Nasik–Pune dyke swarm (Vanderkluysen et al., 2011 and references therein). (b) shows the map and west–east cross-section (drawn just south of Alibag) of the stratigraphic subgroups of the Western Ghats sequence (based on Hooper et al., 2010).

Table 1
Geochemical stratigraphy of the Western Ghats section, Deccan Traps.

Group	Sub-group	Formation	Magnetic polarity	$^{87}Sr/^{86}Sr_{(65Ma)}$
Deccan Basalt		Desur* (∼100 m)	N	0.7072–0.7080
		Panhala (>175 m)	N	0.7046–0.7055
	Wai	Mahabaleshwar (280 m)	N	0.7040–0.7055
		Ambenali (500 m)	R	0.7038–0.7044
		Poladpur (375 m)	R	0.7053–0.7110
	Lonavala	Bushe (325 m)	R	0.7078–0.7200
		Khandala (140 m)	R	0.7071–0.7124
	Kalsubai	Bhimashankar (140 m)	R	0.7067–0.7077
		Thakurvadi** (650 m)	R	0.7067–0.7224
		Neral (100 m)	R	0.7062–0.7104
		Jawhar-Igatpuri (>700 m)	R	0.7085–0.7128

Notes: Table based on Subbarao and Hooper (1988) and references therein, Peng et al. (1994), and Vanderkluysen et al. (2011). N = normal magnetic polarity, R = reverse magnetic polarity.
* The Desur is considered by many as a "Unit" of the Panhala Formation itself.
** The Sr-isotopic range for most of the Thakurvadi Formation lavas is 0.7067–0.7112, but a single flow in the formation (Paten Basalt) has an anomalously high, broadly Bushe-like value (0.7224).

towards the Arabian Sea (Auden, 1949; Dessai and Bertrand, 1995; Sheth, 1998). The Panvel flexure is similar to flexures in other CFB provinces on rifted continental margins, notably the Karoo, the Paraná and the East Greenland (Nielsen and Brooks, 1981; Klausen and Larsen, 2002; Klausen, 2009). The southern and western parts of Mumbai City (Fig. 1c) expose west-dipping volcanic and volcanosedimentary deposits (spilitic pillow lavas, shales, tuffs, and rhyolite lavas) as well as compositionally diverse intrusions, formed during a late, Danian phase of Deccan magmatism (Sethna and Battiwala, 1977, 1980; Sethna, 1999; Singh, 2000; Sheth et al., 2001a,b; Cripps et al., 2005; Zellmer et al., 2012). The eastern part of Mumbai City (Fig. 1c) exposes tholeiitic basalt flows intruded by tholeiitic dykes. The flows dip 17–18° west, as seen in the Ghatkopar–Powai hills (Figs. 1c and 2a). East of the Ghatkopar–Powai area and the adjacent Thane Creek (Fig. 1c), the Deccan lavas dip very gently west (2–3°) in the New Mumbai area (Mumbra hills). Further eastwards, they form isolated tablelands of essentially horizontal flows like Matheran (803 m, Fig. 1b) rising from the low-lying Konkan Plain, and still further east, these almost horizontal flows form peaks reaching $\geqslant$1 km in the Western Ghats escarpment (e.g., Beane et al., 1986; Fig. 1a and b).

Whereas the lava stratigraphy of the Western Ghats has been mapped over hundreds of kilometers in north–south and east–west directions, the tholeiitic sequence of the eastern part of Mumbai City has been studied little, with only a brief mention of ankaramite in the Powai area (Figs. 1c and 2a) by Sukheswala and Poldervaart (1958). Yet this sequence spectacularly exposes the western limb of the Panvel flexure (Fig. 3a), and is an important "connecting dot" in tracing the stratigraphic and structural framework of the western Deccan Traps. Here we present field, petrographic, and whole-rock geochemical (major and trace element and Sr–Nd isotopic) data on the tholeiitic lavas and dykes of this sequence. The data help to evaluate the relationships between the flows and the dykes and their stratigraphic positions in the Western Ghats sequence, and permit several volcanological and tectonic interpretations to be made.

2. Field geology, samples, and petrography

Development of Mumbai City, one of the most highly populated (20 million people) and densely populated (25,000 people per km^2) in the world, has destroyed most geological outcrops and left the rest highly inaccessible. We sampled lava flows and dykes in the Ghatkopar–Powai hills which reach 209 m above sea level. A considerable portion of these hills, except the part falling in the IIT Bombay campus (Figs. 2a and 3a), has been extensively quarried and replaced by buildings. Quarrying continues in parts. The higher hills (reaching 462 m) to the north of Powai are off access, being located within the Sanjay Gandhi National Park and Reserved Forest (Fig. 3a).

The Ghatkopar–Powai hills (Figs. 2a and 3a and b) expose small-scale compound pahoehoe basaltic lava flows, sometimes separated by "red bole" beds which may represent palaeosols, sedimentary interbeds, or inter-flow ash eruptions (e.g., Wilkins et al., 1994; Srivastava et al., 2012). The flows dip west-northwest at 17–18°. They are highly weathered, with much secondary zeolitization and silicification. A flow with abundant 3–5 mm diameter clinopyroxene phenocrysts forms the summit of the IIT Hill, and may be the ankaramite mentioned by Sukheswala and Poldervaart (1958). The volcanic sequence is cut by numerous dykes (Fig. 3c and d), also all of mafic composition, but relatively fresh. The dykes are up to a few meters thick, traceable along strike for up to a few tens of meters, and form low ridges. Almost all dykes are vertical or nearly so (dip 87° east) (Fig. 3c), though one (MMD7) dips east at a moderate angle (45°). All dykes are truncated by the present erosion level and none was seen to pass into a flow.

Interpretive cross-sections showing the field relationships between individual flows and dykes are given in Fig. 2b and c. Because of the severe destruction of field relationships, the lack of distinctive flows traceable from one section to another, and the possibility of faulting apparent from the regional context (see also Dessai and Bertrand, 1995; Klausen and Larsen, 2002), no composite field stratigraphic sequence can be attempted.

Phenocrysts of olivine (usually highly altered) and sometimes clinopyroxene are common in the Ghatkopar–Powai flows. The IIT Hill summit ankaramite (samples MMF6 and MMF7) shows beautiful rounded clusters, up to 5 mm in size, of twinned and radially arranged clinopyroxene phenocrysts, as well as smaller phenocrysts of olivine, in a fine-grained basaltic groundmass. The dykes have a very different appearance in thin section. They are much fresher, fine- to medium-grained and, in contrast to the flows, olivine-free to olivine-poor. Several dykes are aphyric, and porphyritic dykes have plagioclase as the main phenocryst phase, rarely with small clinopyroxene and/or olivine microphenocrysts.

3. Geochemistry

3.1. The need for geochemical correlations

Small-scale compound pahoehoe flows are characteristic of the lower five formations (Jawhar through Bhimashankar), as well as the middle Bushe Formation (e.g., Bondre et al., 2004), together constituting a >1900 m total thickness in the Western Ghats stratigraphy (Table 1). Similarly, picritic horizons occur interspersed at various levels in the Western Ghats stratigraphy (e.g., Cox and Hawkesworth, 1985; Beane et al., 1986; Beane and Hooper, 1988), and plagioclase-megacrystic flows (the so-called giant plagioclase basalts), which constitute valuable field and geochemical marker horizons in mapping of the Western Ghats stratigraphy (Beane et al., 1986; Hooper et al., 1988), are not encountered here. Most Ghatkopar–Powai flows and dykes are also petrographically undistinctive. Thus, field and textural features of these flows and dykes are not a guide to their position in the Western Ghats sequence. We therefore use geochemical data, particularly the concentrations and concentration ratios of alteration-resistant elements, as well as Sr and Nd isotopic ratios, to evaluate the correlations of the Ghatkopar–Powai flows and dykes with the Western Ghats sequence.

3.2. Geochemical analytical methods

Our sample set includes 9 flow samples (MMF1 to MMF9) and 14 dyke samples (MMD1 to MMD15, excluding MMD2 which we later realized to probably represent fallen boulders of the ankaramite flow MMF6–MMF7). Small chips of these samples were cleaned in an ultrasonic bath and ground to powders of <75 μm grain size using a Retsch PM-100 planetary ball mill and stainless steel grinding balls, at IIT Bombay. Major oxide compositions of the flows and dykes were determined by inductively coupled plasma atomic emission spectrometry (ICPAES) at the Department of Earth Sciences, IIT Bombay (instrument: Jobin Yvon Ultima-2). Loss on ignition (LOI) values were also determined at IIT Bombay. A large suite of trace elements including the rare earth elements (REE) was analyzed by inductively coupled plasma mass spectrometry (ICPMS) at National Taiwan University on dissolutions of the samples using an Agilent 7500cx spectrometer. The analytical details of the ICPAES and ICPMS analyses are as described by Sheth et al. (2013). The major oxide and LOI data are presented in Table 2, and the trace element data in Table 3.

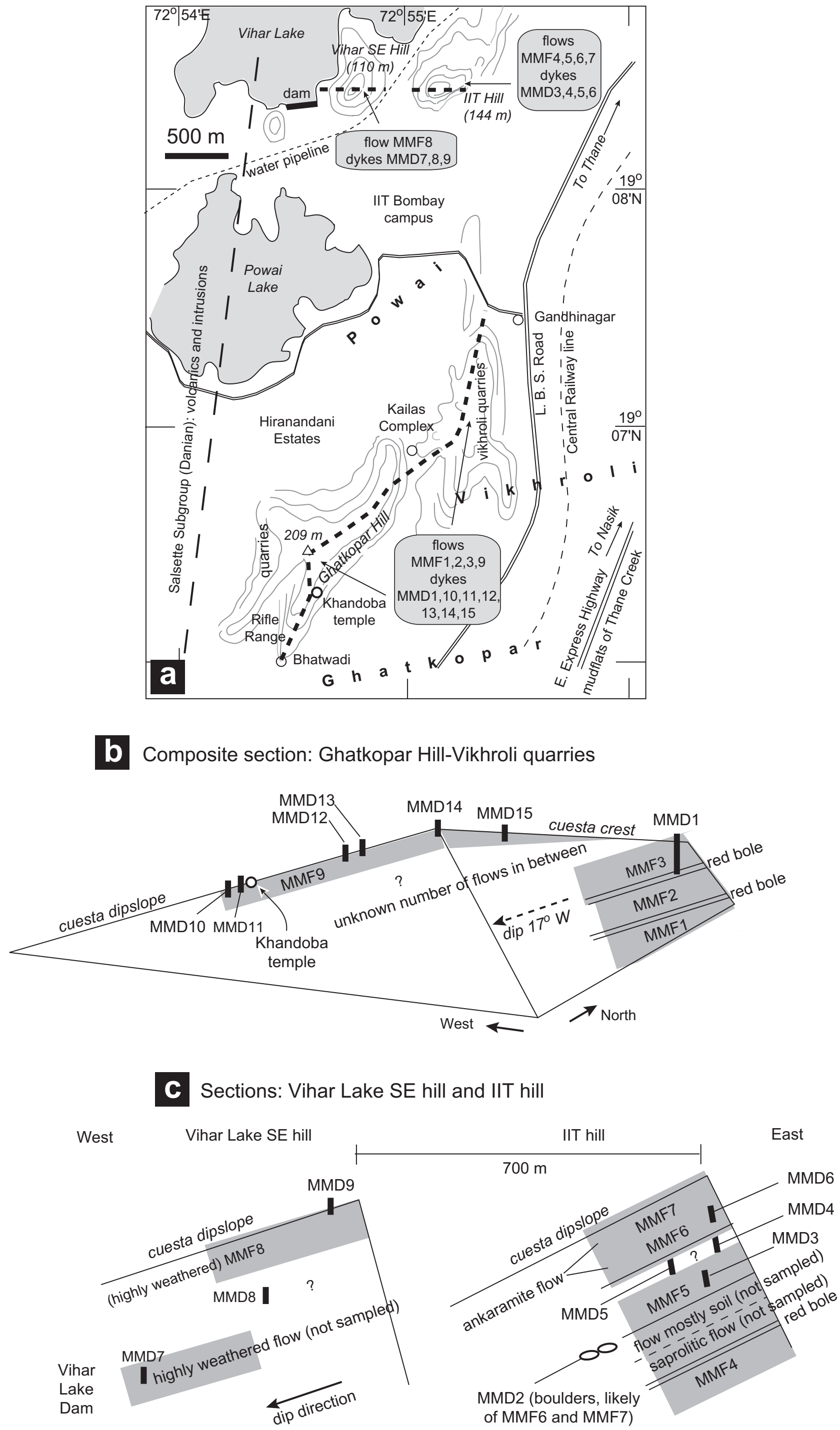


Fig. 2. (a) Map of the Ghatkopar–Powai area of Mumbai City, showing the main topographic and geological features, as well as the man-made features and landmarks. The general planform of the Ghatkopar–Powai hills is indicated by grey contours, and heavy broken lines over the hills show the field traverses. (b and c) Cross-sections of the lava flows and dykes as identified in the field, with sample numbers marked.

A large subset of the samples (5 of the 9 flows and 7 of the 14 dykes, chosen so as to cover key samples from the field stratigraphy) was analyzed for strontium and neodymium isotopic ratios at the Institute of the Earth's Crust, Siberian Branch of the Russian Academy of Sciences. The procedures followed Pin and Santos-Zalduegui (1997) for Nd and Pin et al. (1994) for Sr, with minor modifications outlined by Rasskazov et al. (2002) and Ivanov et al. (2008), respectively. Isotope ratios were measured using a Finnigan MAT 262 mass spectrometer. Accuracy of the analyses was tested by measurements of the SRM 987 (0.710263 ± 0.000011, 2σ) and JNd-1 (0.512102 ± 0.000005, 2σ) reference materials. The Sr–Nd isotopic data are presented in Table 4.

3.3. Alteration

Though material as fresh as possible was collected in the field, outcrop and petrographic observations and LOI values indicate considerable alteration in the flows. LOI values range from 2.33 wt.% to as much as 7.77 wt.% for the flows and from 0.80 wt.% to 4.07 wt.% for the dykes, though most dykes have val-

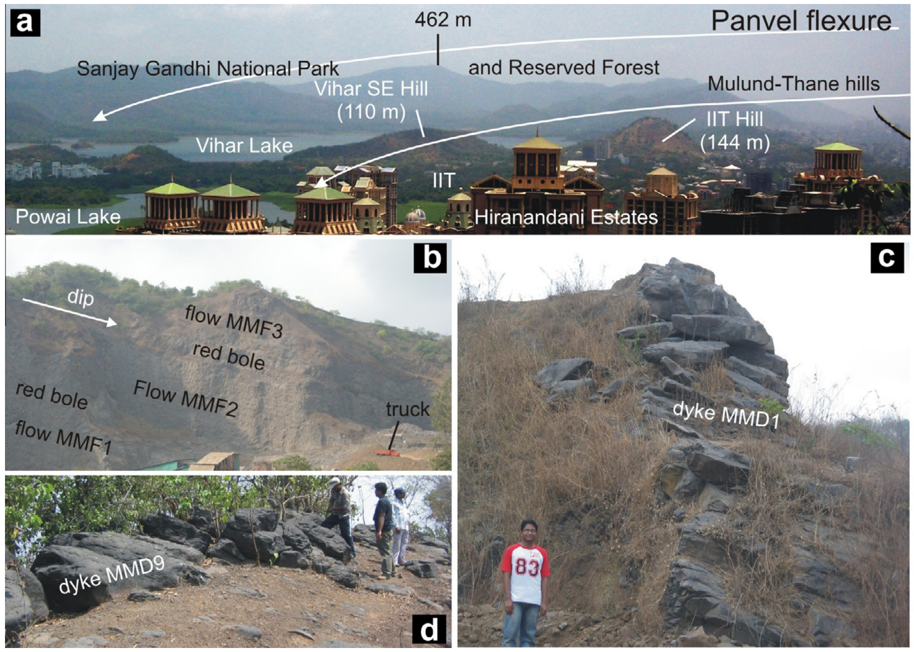


Fig. 3. Field photographs. (a) Panoramic view of the area, looking north from the top of the Ghatkopar Hill (209 m) towards Powai and beyond. The distinctly westerly dips of the lava sequence formed due to the Panvel flexure are shown by the white arrows. (b) Sequence of three basalt flows separated by two red boles, Vikhroli quarries. (c) Dyke MMD1 in abandoned quarry, Vikhroli. (d) Dyke MMD9 forming linear ridge cuttting flow MMF8, on Vihar SE Hill.

Table 2
Major element data (in wt.%) for the Ghatkopar–Powai flows (MMF) and dykes (MMD).

Trend	–	–	–	–	–	–	–	–	N40°	N335°	?
Rock name	BA	BA	B, sa	B, sa	PIC	PIC	B, sa	B, sa	BA	B, sa	B, sa
Sample	MMF2	MMF3	MMF4	MMF5	MMF6	MMF7	MMF8	MMF9	MMD1	MMD3	MMD5
SiO_2	48.52	47.89	50.62	48.67	47.80	49.26	50.21	48.82	50.45	48.74	49.35
Al_2O_3	12.15	8.32	11.92	12.50	8.76	8.54	13.00	11.82	12.93	13.95	13.08
TiO_2	1.80	0.83	1.69	1.67	1.19	1.32	1.99	2.14	0.89	2.25	1.68
Fe_2O_3T	12.8	11.49	13.11	11.74	12.63	12.17	12.90	14.65	13.95	13.40	13.75
MnO	0.17	0.16	0.18	0.14	0.18	0.18	0.16	0.18	0.21	0.19	0.17
MgO	9.14	12.13	10.24	6.37	15.46	12.53	7.61	5.28	6.21	5.40	8.04
CaO	5.98	9.17	10.42	10.95	9.57	12.35	10.13	9.65	10.35	10.30	9.47
Na_2O	2.59	0.42	1.96	3.02	1.32	1.40	2.70	3.23	1.94	2.12	2.24
K_2O	0.12	0.01	0.23	0.01	0.34	0.30	0.30	0.40	0.67	0.50	0.64
P_2O_5	0.20	0.16	0.17	0.13	0.12	0.12	0.21	0.15	0.15	0.24	0.21
LOI	6.46	7.77	2.33	7.63	3.29	2.39	3.78	5.86	1.03	2.18	1.95
Total	99.93	98.35	102.87	102.83	100.66	100.56	102.99	102.18	98.78	99.27	100.58
Mg#	64.2	72.6	64.6	55.9	74.1	70.6	58.0	45.7	52.8	48.5	57.7
Trend	?	N170°	N0°	N0°	N0°	N170°	N30°	N20°	N25°	–	–
Rock name	B, sa	B, sa	B, sa	BA	BA	BA	B, sa	B, sa	B, sa	Meas.	Ref.
Sample	MMD6	MMD7	MMD8	MMD9	MMD10	MMD11	MMD12	MMD13	MMD14	BHVO2	BHVO2
SiO_2	50.56	49.35	48.49	52.13	49.96	50.56	44.62	48.74	47.09	51.07	49.9
Al_2O_3	13.11	13.73	13.04	12.43	12.89	13.08	12.67	12.69	12.24	13.30	13.5
TiO_2	2.41	0.86	2.08	1.92	0.83	0.79	2.46	2.77	2.31	2.75	2.73
Fe_2O_3T	14.78	12.23	13.37	14.47	12.93	12.53	15.90	15.06	15.08	12.68	12.3
MnO	0.20	0.20	0.19	0.20	0.19	0.20	0.20	0.21	0.21	0.17	0.166
MgO	5.84	6.59	6.95	4.27	6.81	7.01	5.83	5.70	5.83	7.54	7.23
CaO	10.10	11.16	11.76	8.13	11.00	10.78	10.62	10.29	9.71	11.76	11.4
Na_2O	2.22	1.85	2.08	2.20	1.70	2.04	1.97	2.13	2.52	2.17	2.22
K_2O	0.28	0.32	0.19	1.05	0.32	0.54	0.01	0.03	0.05	0.45	0.52
P_2O_5	0.22	0.09	0.20	0.25	0.13	0.12	0.27	0.25	0.21	0.27	0.27
LOI	1.45	0.80	0.81	2.99	1.64	2.30	4.07	1.37	2.88		
Total	101.17	97.18	99.16	100.04	98.40	99.95	98.62	99.24	98.13	102.16	100.24
Mg#	48.0	55.7	54.8	42.6	57.0	58.5	46.1	46.9	47.5		

Notes: BA = basaltic andesite; B, sa = subalkalic basalt; PIC = picrite. MMF6 and MMF7 are ankaramites (picrites by the TAS diagram). The rock names are based on major oxide data recalculated to 100% on an anhydrous basis using the SINCLAS program. Mg# = 100 $Mg^{2+}/(Mg^{2+} + Fe^{2+})$, atomic, assuming 85% of the total Fe to be in the Fe^{2+} form. Reference values and measured values on the USGS standard BHVO2 (Wilson, 2000) provide an idea about analytical accuracy.

ues between 1 and 3 wt.% (Table 2). This alteration may have resulted in the loss (or gain) of the more mobile elements such as K, Na, Rb, Ba, Sr, and Pb (e.g., Peate et al., 2012). Indeed, compared to the common 2–5 ppm Pb concentrations in the Western Ghats and other Deccan lavas, as well as mafic dykes (e.g., Peng et al., 1994, 1998; Vanderkluysen et al., 2011), the Mumbai flows have

Pb concentrations ranging from 6 ppm (MMF5) to as much as 111 ppm (MMF7). The dykes have still higher Pb concentrations from 23 ppm (MMD9) to 398 ppm (MMD7). Pb contents do not correlate well with LOI values, but there are good positive correlations between Pb, Cu and Zn for the samples (Table 3), suggesting that hydrothermal fluids with high Pb–Cu–Zn may have affected the rocks. A similar alteration phenomenon has been reported from late-stage Deccan alkali basalt in the Mumbai area (Zellmer et al., 2012), as well as for the Palitana lava sequence and the Eastern Saurashtra dykes from the northwestern Deccan Traps (Sheth et al., 2013). Given the strong weathering, we treat the concentrations of the mobile elements with caution, and use only the alteration-resistant elements (Ti, Zr, Nb, Y, Th and the REE) and their ratios, as well as isotopic ratios (particularly of Nd) for geochemistry-based interpretations.

3.4. Nomenclature and general compositional characteristics

We used the SINCLAS program (Verma et al., 2002) to obtain the CIPW norms, Mg Numbers (Mg#) and standardized, IUGS-recommended rock names for the samples, based on LOI-free adjusted data. Total iron was divided into Fe^{2+} and Fe^{3+} varieties based on the Middlemost (1989) scheme built into the program. 12 of the 20 mafic rock samples analyzed for major elements were classified by SINCLAS as subalkalic basalt, and 6 as basaltic andesite. These two rock types constitute the overwhelming majority of Deccan "flood basalts" (e.g. Beane et al., 1986; Beane, 1988; Peng et al., 1998). The two clinopyroxene-rich samples ("ankaramites" MMF6 and MMF7) were classified as picrite.

LOI-free recalculated MgO contents of the flows range from 16.05 wt.% (MMF6) to 5.55 wt.% (MMF9), and Mg# values from 74.1 (MMF6) to 45.7 (MMF9), where Mg# = [atomic Mg/($Mg + Fe^{2+}$)]*100, assuming Fe^{2+} to be 85% of Fe_{total}. Flows MMF3 and MMF4, despite their nomenclature as basaltic andesite and subalkalic basalt respectively, are also quite primitive. The two flows have recalculated MgO contents of 13.53 wt.% and 10.30 wt.%, and Mg# values of 72.6 and 64.6, respectively, consistent with petrographic observations. In comparison, the dykes are much more evolved in composition. Recalculated MgO contents range from 8.25 wt.% (MMD5) to 4.45 wt.% (MMD9), but for most samples are between 5 and 7 wt.%. Mg# values range from 58.5 (MMD11) to 42.6 (MMD9). All dykes are quartz-normative (0.05–10.35 wt.%, though commonly 3–5 wt.%).

4. Geochemical correlations with the Western Ghats sequence

The geochemical approach has been very useful in stratigraphic correlation of widely separated lava sections in the Deccan Traps (e.g., Beane et al., 1986; Devey and Lightfoot, 1986; Lightfoot et al., 1990; Peng et al., 1998 and this volume; Mahoney et al., 2000). The same approach has been used in evaluating correlations and genetic relationships between Deccan lavas and potential fee-

Table 3
Trace element data (in ppm) for the Ghatkopar–Powai flows (MMF) and dykes (MMD).

Trend	–	–	–	–	–	–	–	–	–	N40°	N335°	N30°	?
Sample	MMF1	MMF2	MMF3	MMF4	MMF5	MMF6	MMF7	MMF8	MMF9	MMD1	MMD3	MMD4	MMD5
P	778	786	615	626	657	538	538	789	635	631	1021	633	840
Sc	24.0	29.0	23.6	25.1	25.5	32.8	43.6	30.9	28.5	47.2	31.3	46.4	25.8
Ti	9187	10,580	7353	7955	8442	6758	7707	10,970	11,280	5211	13,180	5210	9693
V	264	279	221	237	257	263	349	304	308	305	340	302	266
Cr	182	421	1248	796	285	1603	1981	386	58	312	452	220	360
Mn	1571	1208	1196	1138	888	1348	1387	1181	1129	1647	1409	1398	1218
Co	30	39	76	47	36	76	59	46	42	50	45	50	52
Ni	73	66	548	198	73	390	215	93	68	60	167	80	148
Cu	295	86.6	244	570	125	587	654	161	473	664	4843	1801	568
Zn	111	98.3	171	319	86.3	353	381	121	241	355	2322	914	326
Ga	14.9	18.1	14.4	15.0	17.1	13.6	13.9	17.7	14.3	15.3	21.9	15.6	19.0
Rb	31	0.5	2.8	4.3	1.0	7.0	6.8	5.0	5.2	8.3	9.2	12	13
Sr	173	201	198	257	115	173	176	416	241	166	223	195	288
Y	24.4	22.8	16.6	18.4	18.9	16.2	17.5	22.3	24.2	22.4	31.6	21.8	21.6
Zr	106	125	92.0	98.0	107	81.0	85.0	132	112	79.0	154	79.0	126
Nb	7.4	13	8.1	8.1	9.3	6.6	6.1	10	7.6	8.7	13	8.7	9.2
Cs	0.23	0.01	0.57	0.40	0.13	0.29	0.20	0.04	0.13	0.01	0.11	0.02	0.30
Ba	99	50	75	100	13	108	107	242	185	190	104	205	175
La	10.5	14.9	11.7	11.9	13.5	9.90	9.50	15.3	7.60	12.0	12.9	11.8	14.4
Ce	24.5	32.9	26.7	26.3	29.4	23.0	23.0	33.6	19.9	25.1	30.2	24.9	31.7
Pr	3.16	4.43	3.30	3.50	3.94	2.93	3.01	4.57	2.85	2.87	4.27	2.84	4.27
Nd	14.4	18.9	14.2	15.2	16.8	12.7	13.5	19.8	13.9	11.3	19.5	11.2	18.4
Sm	3.93	4.56	3.42	3.75	4.03	3.16	3.50	4.83	4.19	2.51	5.33	2.47	4.49
Eu	1.29	1.46	1.08	1.18	1.27	1.02	1.11	1.61	1.44	0.82	1.71	0.83	1.43
Gd	4.37	4.59	3.49	3.82	4.05	3.27	3.63	4.87	4.67	2.85	5.81	2.82	4.44
Tb	0.72	0.73	0.53	0.60	0.62	0.52	0.57	0.75	0.79	0.50	0.94	0.49	0.68
Dy	4.34	4.28	3.12	3.51	3.64	3.01	3.33	4.31	4.72	3.40	5.67	3.33	3.96
Ho	0.89	0.88	0.63	0.70	0.74	0.62	0.67	0.86	0.96	0.80	1.17	0.78	0.80
Er	2.31	2.31	1.61	1.81	1.90	1.61	1.72	2.24	2.45	2.37	3.03	2.29	2.08
Tm	0.33	0.33	0.23	0.26	0.27	0.23	0.24	0.32	0.34	0.38	0.43	0.37	0.30
Yb	1.97	2.05	1.42	1.57	1.66	1.40	1.47	1.92	2.08	2.57	2.64	2.47	1.82
Lu	0.28	0.30	0.20	0.23	0.24	0.20	0.21	0.28	0.30	0.40	0.38	0.39	0.26
Hf	2.63	3.18	2.33	2.50	2.71	2.05	2.19	3.42	2.95	1.84	3.78	1.85	3.01
Ta	0.55	0.97	0.59	0.59	0.70	0.48	0.44	0.77	0.59	0.53	0.93	0.53	0.65
W	0.15	0.27	0.27	0.28	0.17	0.24	0.26	0.22	0.14	0.29	0.36	0.24	0.31
Tl	0.10	0.02	0.02	0.05	0.01	0.05	0.06	0.03	0.05	0.06	0.13	0.08	0.08
Pb	20	8	28	82	6	68	109	15	56	123	319	149	112
Th	1.39	1.77	1.47	1.20	1.44	1.06	1.02	1.61	0.78	1.55	1.46	1.56	1.62
U	0.37	0.32	0.36	0.25	0.31	0.22	0.21	0.33	0.18	0.31	0.33	0.31	0.32

Table 3 (*continued*)

Trend Sample	? MMD6	N170° MMD7	N0° MMD8	N0° MMD9	N0° MMD10	N170° MMD11	N30° MMD12	N20° MMD13	N25° MMD14	N40° MMD15	Meas. BHVO-2	Ref. BHVO-2
P	976	582	796	1124	550	543	1033	1100	867	557	1186	1200
Sc	34.6	43.4	35.9	31.9	45.3	47.6	31.6	32.6	28.7	39.0	31.3	32
Ti	13,960	5107	12,120	10,130	4761	4771	14,250	15,830	12,180	5139	16,490	16300
V	371	290	351	349	286	288	401	425	353	263	317	317
Cr	332	390	407	68	261	260	93	390	146	394	284	280
Mn	1441	1488	1484	1337	1394	1506	1459	1521	1387	1402	1287	1290
Co	44	42	50	34	47	48	48	44	47	44	45	45
Ni	70	88	117	24	64	84	86	94	162	89	112	119
Cu	507	1348	1138	304	699	1315	712	1013	4731	2283	128	127
Zn	254	696	584	152	374	678	379	478	2263	1149	101	103
Ga	21.5	15.5	20.3	17.5	15.0	15.4	23.0	23.4	18.8	16.1	22.2	21.7
Rb	10	8.2	8.3	22	8.3	9.0	0	4.4	1.0	7.0	9.3	9.8
Sr	207	151	226	278	151	198	194	206	231	197	396	389
Y	31.5	22.8	25.4	26.2	19.6	20.1	32.7	37.3	27.3	20.9	26.4	26
Zr	153	67.0	122	127	62.0	62.0	147	171	125	66.0	174	172
Nb	13	7.7	12	16	6.8	6.8	9.8	11	8.3	7.4	18.6	18
Cs	0.09	0.00	0.09	0.03	0.01	0.03	0.00	0.02	0.01	0.00	0.09	0.1
Ba	107	194	103	303	203	267	37	63	41	165	146	130
La	12.7	10.3	10.7	22.0	9.80	10.1	9.80	11.0	8.00	11.1	15.6	15
Ce	29.9	21.4	26.1	42.6	20.9	21.2	26.1	27.3	21.4	22.5	36.8	38
Pr	4.22	2.43	3.46	5.12	2.42	2.45	3.74	4.19	3.07	2.52	5.33	5.29
Nd	19.3	9.60	15.7	19.9	9.70	9.80	18.3	20.3	14.9	9.90	24.2	25
Sm	5.34	2.19	4.28	4.20	2.19	2.20	5.46	6.08	4.51	2.25	6.21	6.2
Eu	1.74	0.75	1.44	1.41	0.76	0.78	1.79	1.97	1.51	0.82	2.03	2.07
Gd	5.83	2.65	4.62	4.44	2.51	2.52	6.10	6.78	5.04	2.63	6.18	6.3
Tb	0.96	0.48	0.76	0.70	0.44	0.44	1.01	1.13	0.84	0.46	0.94	0.9
Dy	5.79	3.33	4.54	4.38	2.99	2.97	6.04	6.70	5.05	3.18	5.26	5.31
Ho	1.19	0.79	0.94	0.96	0.70	0.70	1.23	1.37	1.03	0.745	1.02	1.04
Er	3.10	2.37	2.41	2.69	2.06	2.07	3.16	3.52	2.66	2.19	2.50	2.54
Tm	0.44	0.39	0.34	0.41	0.33	0.33	0.45	0.49	0.38	0.35	0.34	0.34
Yb	2.72	2.59	2.09	2.71	2.26	2.23	2.68	2.98	2.28	2.32	2.01	2
Lu	0.39	0.41	0.30	0.42	0.36	0.35	0.38	0.42	0.32	0.36	0.28	0.28
Hf	3.80	1.55	2.97	2.96	1.52	1.50	3.71	4.36	3.09	1.57	4.35	4.1
Ta	0.96	0.47	0.90	1.05	0.42	0.43	0.74	0.86	0.61	0.46	1.32	1.4
W	0.37	0.26	0.32	0.24	0.20	0.17	0.14	0.30	0.32	0.35	0.24	0.27
Tl	0.04	0.15	0.14	0.09	0.08	0.13	0.01	0.04	0.11	0.09	0.020	0.059
Pb	55	398	362	23	146	228	52	83	325	199	2.0	2.2
Th	1.45	1.30	1.22	2.88	1.17	1.18	1.04	1.21	0.90	1.57	1.25	1.2
U	0.33	0.25	0.29	0.57	0.24	0.24	0.25	0.31	0.21	0.29	0.42	0.42

der dykes (e.g., Bondre et al., 2006; Sheth et al., 2009, 2013; Vanderkluysen et al., 2011). As found in these studies, the most useful geochemical parameters are Sr–Nd–Pb isotopic ratios, followed by primitive mantle normalized multielement patterns, binary discrimination diagrams using alteration-resistant incompatible elements and element ratios, and finally, multivariate statistical methods (particularly discriminant function analysis). Isotopic ratios of Sr, Nd and Pb are not affected by fractional crystallization, and the Nd isotopic ratios are known not to change appreciably by moderate or even high amounts of post-eruption subaerial alteration (e.g., Faure, 1986; DePaolo, 1987), whereas Sr and especially Pb isotopic ratios are prone to such alteration (but see Lightfoot and Hawkesworth, 1988; Sheth et al., 2011, 2013). Because of the extremely high and evidently non-magmatic Pb concentrations in the Ghatkopar–Powai rocks, we have not measured Pb isotopic ratios. We examine each line of geochemical evidence below, starting with Sr–Nd isotopic ratios.

4.1. Sr- and Nd-isotopic variations

The Western Ghats sequence shows a great range in initial Sr–Nd isotopic composition (age-corrected to 65 Ma), with $\varepsilon_{Nd}(t)$ ranging from +8 to −19, and $(^{87}Sr/^{86}Sr)_t$ from <0.704 to >0.720. Several Western Ghats stratigraphic formations are well separated in Sr–Nd isotope space, particularly towards more "enriched" compositions (lower $^{143}Nd/^{144}Nd$ and higher $^{87}Sr/^{86}Sr$) (Fig. 4). Sr–Nd data for the Ghatkopar–Powai flows and dykes, as well as for tholeiitic dykes of the Coastal swarm (Vanderkluysen et al., 2011), are plotted in Fig. 4. Compared to the great Sr–Nd isotopic range covered by the Western Ghats sequence, the Ghatkopar–Powai flows and dykes have a restricted range of $\varepsilon_{Nd}(t)$ from +5.6 to −5.5 and $(^{87}Sr/^{86}Sr)_t$ from 0.704314 to 0.706483.

A striking result is that data for four of the five analyzed flow samples (MMF4, MMF7, MMF8 and MMF9) plot in the narrow Mahabaleshwar Formation field. The fifth (flow MMF2) is located between the Mahabaleshwar and the Bhimashankar fields. Data for four of the seven analyzed dykes (MMD1, MMD4, MMD9 and MMD15) plot cleanly within the Mahabaleshwar field. A fifth (MMD8) plots within the area of overlap between the Mahabaleshwar, Panhala and Ambenali fields, whereas dykes MMD13 and MMD14 are located within the Ambenali field. Notably, none of the stratigraphic formations of the Western Ghats sequence, except for the Mahabaleshwar and the Ambenali (and possibly Panhala for dyke MMD8) are represented.

Several Ghatkopar–Powai dyke compositions plot very close to those of the Coastal swarm dykes, many of which are inferred to be feeders to the Poladpur and Ambenali Formations (Hooper et al., 2010; Vanderkluysen et al., 2011; note that no Ghatkopar–Powai dykes are Poladpur type).

4.2. Primitive mantle-normalized multielement patterns

Lavas of many Western Ghats formations show distinctive primitive mantle-normalized multielement patterns (see e.g., Peng et al., 1994; Mahoney et al., 2000; Sheth et al., 2004, 2009). We tried many matches between the Ghatkopar–Powai flows and

Table 4
Sr and Nd isotopic data for the Ghatkopar–Powai flows (MMF) and dykes (MMD).

Sample	Rb/Sr	$^{87}Rb/^{86}Sr$	$(^{87}Sr/^{86}Sr)_p$	$\pm 2\sigma$	$(^{87}Sr/^{86}Sr)_t$	Sm/Nd	$^{147}Sm/^{144}Nd$	$(^{143}Nd/^{144}Nd)_p$	$\pm 2\sigma$	$(^{143}Nd/^{144}Nd)_t$	ε_{Ndt}
MMF2	0.002	0.007	0.706490	0.000010	0.706483	0.2413	0.1459	0.512408	0.000007	0.512346	−4.0
MMF4	0.017	0.049	0.705556	0.000010	0.705511	0.2467	0.1491	0.512365	0.000005	0.512302	−4.9
MMF7	0.039	0.112	0.705977	0.000009	0.705874	0.2593	0.1567	0.512339	0.000007	0.512272	−5.5
MMF8	0.012	0.035	0.705751	0.000010	0.705719	0.2439	0.1475	0.512339	0.000007	0.512276	−5.4
MMF9	0.022	0.062	0.704600	0.000010	0.704542	0.3014	0.1822	0.512894	0.000007	0.512817	5.1
MMD1	0.041	0.119	0.705918	0.000010	0.705808	0.2223	0.1344	0.512402	0.000004	0.512345	−4.1
MMD4	0.062	0.178	0.705927	0.000010	0.705763	0.2213	0.1338	0.512415	0.000005	0.512358	−3.8
MMD8	0.037	0.106	0.704630	0.000010	0.704532	0.2726	0.1648	0.512751	0.000007	0.512681	2.5
MMD9	0.080	0.231	0.705813	0.000010	0.705600	0.2111	0.1276	0.512423	0.000007	0.512369	−3.6
MMD13	0.021	0.062	0.703981	0.000010	0.703924	0.2995	0.1811	0.512918	0.000003	0.512841	5.6
MMD14	0.004	0.013	0.704326	0.000010	0.704314	0.3027	0.1830	0.512884	0.000007	0.512806	4.9
MMD15	0.036	0.103	0.705604	0.000010	0.705509	0.2273	0.1374	0.512401	0.000010	0.512343	−4.1

Notes: JNd-1 yielded a value of $^{143}Nd/^{144}Nd = 0.512102 \pm 0.000005$ (2σ), and NBS987 yielded a value of $^{87}Sr/^{86}Sr = 0.710263 \pm 0.000011$ (2σ). The isotopic measurements were on unleached samples. Isotopic ratios with subscript "p" indicate present-day (measured) values, and those with subscript "t" indicate age-corrected initial values for 65 Ma.

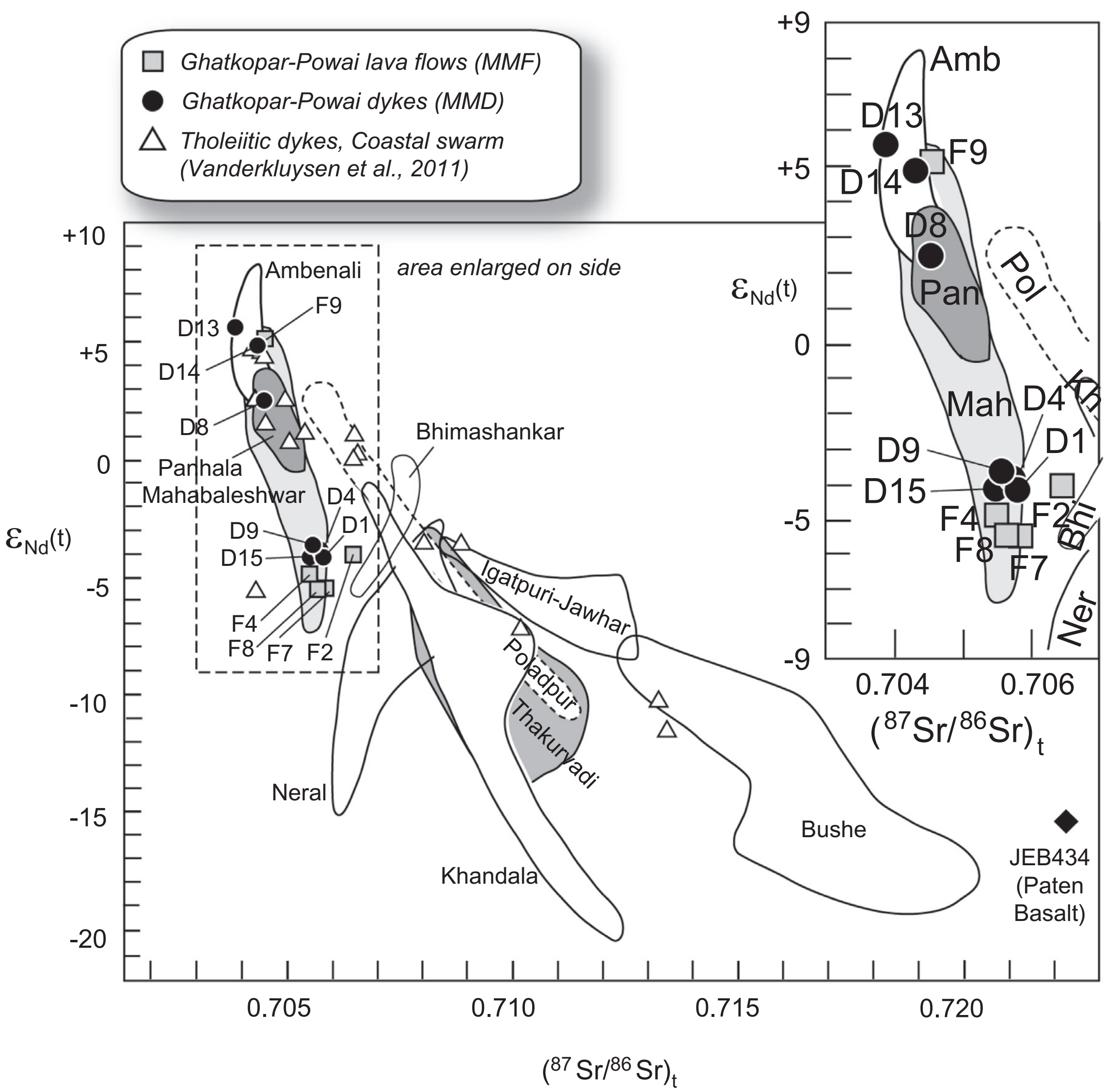


Fig. 4. Sr–Nd isotopic plot for the Ghatkopar–Powai flows and dykes, with sample numbers indicated (without the prefixes to avoid cluttering). Data are shown for the Western Ghats stratigraphic formations and the Coastal swarm dykes (Vanderkluysen et al., 2011). All data are initial values for 65 Ma.

dykes and various Western Ghats formations, their constituent members, or flows. The closest matches of the flows are shown in Fig. 5, and those of the dykes in Fig. 6. The anomalously high Pb values of our samples are not plotted.

All Ghatkopar–Powai flows, MMF1 through MMF9, closely match the Mahabaleshwar Formation pattern (Fig. 5a and b), consistent with the isotopic data. Dykes MMD3, MMD5, MMD8 and MMD9 are also matched to the Mahabaleshwar Formation

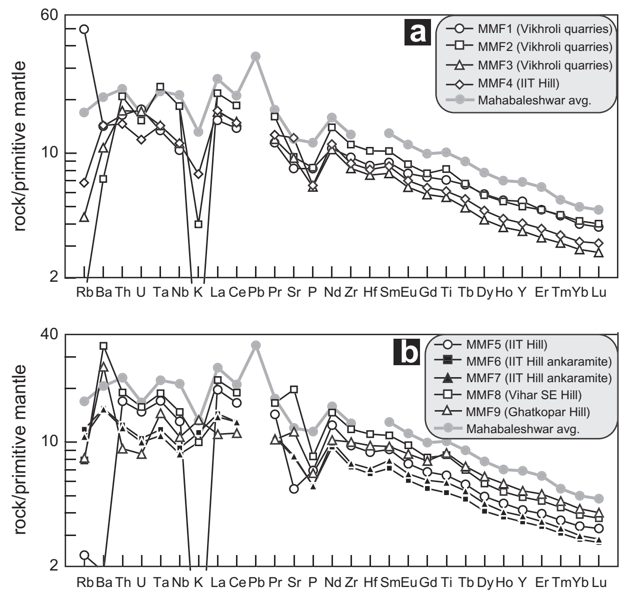


Fig. 5. (a and b) Comparison of primitive mantle-normalized multielement patterns of the Ghatkopar–Powai flows with those of selected Western Ghats lavas, members, or formation averages (main data sources are Beane et al., 1986; Beane, 1988; Vanderkluysen et al., 2011). The normalizing values are from Sun and McDonough (1989).

(Fig. 6a); the last two analyzed for isotopes provided the same match. On the other hand, dykes MMD6, MMD12, MMD13 and MMD14 are closely matched to the Ambenali Formation (Fig. 6b). The last two, analyzed for Sr–Nd isotopes, provided the same match. Intriguingly, a large number (6) of the 14 dykes analyzed have normalized multielement patterns that are strikingly different from those of any Deccan tholeiitic lavas or dykes yet analyzed (Fig. 6c). The most notable feature of these patterns is their prominent concave-upward shape between La and Lu, i.e., a concave-upward REE pattern. They also have small troughs at P and Ti. These dykes are MMD1, MMD4, MMD7, MMD10, MMD11 and MMD15. Three of these (MMD1, MMD4 and MMD9) were analyzed for Sr–Nd isotopes, and all three are located cleanly in the Mahabaleshwar Formation field (Fig. 4), suggesting that the other three may also resemble the Mahabaleshwar in isotopic ratios. However, the multielement pattern of the Mahabaleshwar Formation, also shown in Fig. 6c, shows the great chemical dissimilarity between these dykes and the Mahabaleshwar lavas. Hereafter we refer to these unusual tholeiitic dykes found in the Ghatkopar–Powai area, with Concave upward (or Convex downward) REE Patterns, as the "CREEP" dykes.

4.3. Binary geochemical plots

Compared to isotopic ratios and multielement patterns, binary plots of major and trace elements are less diagnostic for stratigraphic correlations because of the substantial overlap between the Western Ghats formations in these plots. Besides, elements such as Rb, K and Sr are highly mobile during alteration and weathering, as is Ba during advanced weathering (e.g., Mahoney et al., 2000). To compare the Ghatkopar–Powai flow and dyke data to the Western Ghats sequence, we therefore employ a plot of Ti/Y vs. Zr/Nb ratios (Fig. 7a), involving four alteration-resistant incompatible elements. The Zr/Nb ratio is unchanged even during extreme alteration (e.g., Mitchell and Widdowson, 1991; Widdowson and Cox, 1996; Sheth et al., 2011), and both ratios are insensitive to the olivine-gabbro fractionation well known for the Western Ghats sequence (e.g., Cox and Hawkesworth, 1984,

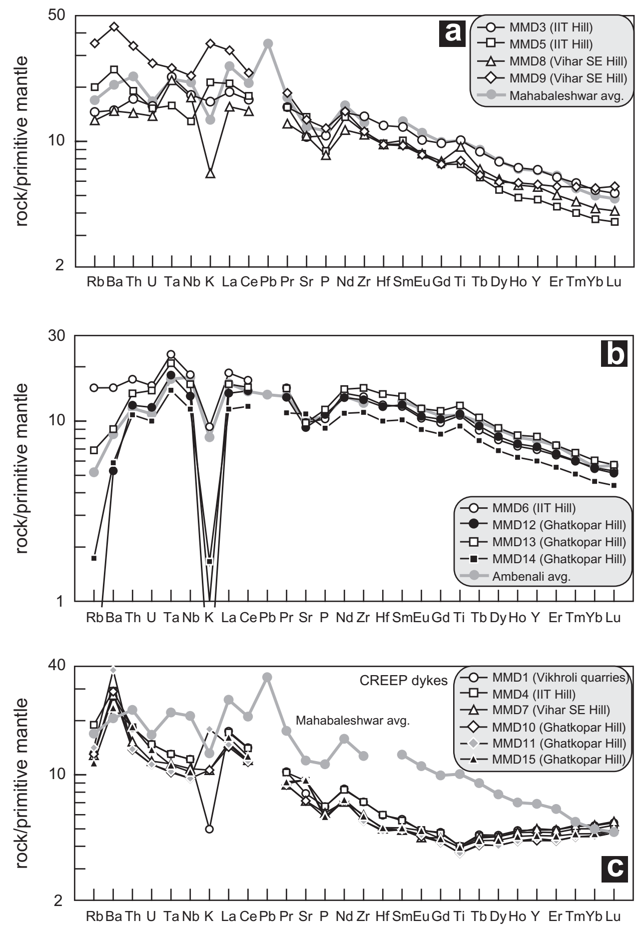
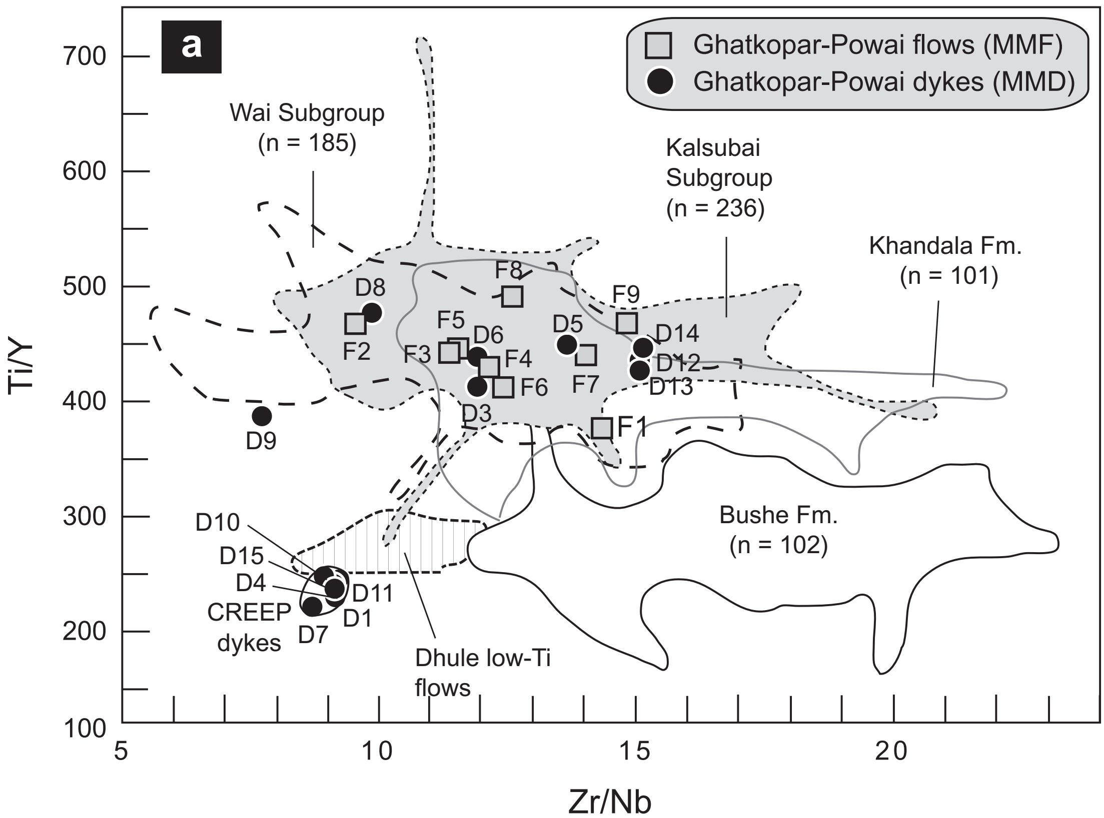


Fig. 6. (a–c) Comparison of primitive mantle-normalized multielement patterns of the Ghatkopar–Powai dykes with those of selected Western Ghats lavas, members, or formation averages (main data sources are Beane et al., 1986; Beane, 1988; Vanderkluysen et al., 2011). The normalizing values are from Sun and McDonough (1989).

1985; Devey and Cox, 1987; Lightfoot et al., 1990). The two ratios however change in opposite directions during crustal contamination.

The plot (Fig. 7a) shows that the Ghatkopar–Powai flows and many dykes are located within the large area of overlap between the Kalsubai and the Wai Subgroups of the Western Ghats sequence. Even the Khandala Formation, from the middle Lonavala Subgroup, has a substantial area of overlap with these two, whereas the Bushe field is distinct from all others, and unrepresented in the samples, consistent with the isotopic results. The six CREEP dykes have the lowest Ti/Y ratios of all and define a tight cluster touching the field of the low-Ti flows of the Dhule area (Melluso et al., 2004). However, whereas the Ghatkopar–Powai flows closely correspond to the Mahabaleshwar Formation in their isotopic composition and their normalized multielement patterns, Fig. 7a shows that all flows with the exception of MMF2 have Zr/Nb values above 10.5, thus exceeding the range for the Mahabaleshwar Formation and within the range for the Ambenali Formation (10.5–15, Table 5). Flow MMF2, though with a perfectly Mahabaleshwar-like Zr/Nb ratio (9.61), does not have Mahabaleshwar-like isotopic composition (Fig. 4). A plot of Th (another alteration-resistant incompatible element) vs. Zr (Fig. 7b) also shows that none of the Ghatkopar–Powai flow samples is located in or near the Mahabaleshwar Formation field, and most flow samples are in fact located outside any formation field.

As regards the dykes, data for dykes MMD3 and MMD6 plot very close to each other on the Ti/Y vs. Zr/Nb plot (Fig. 7a) and in



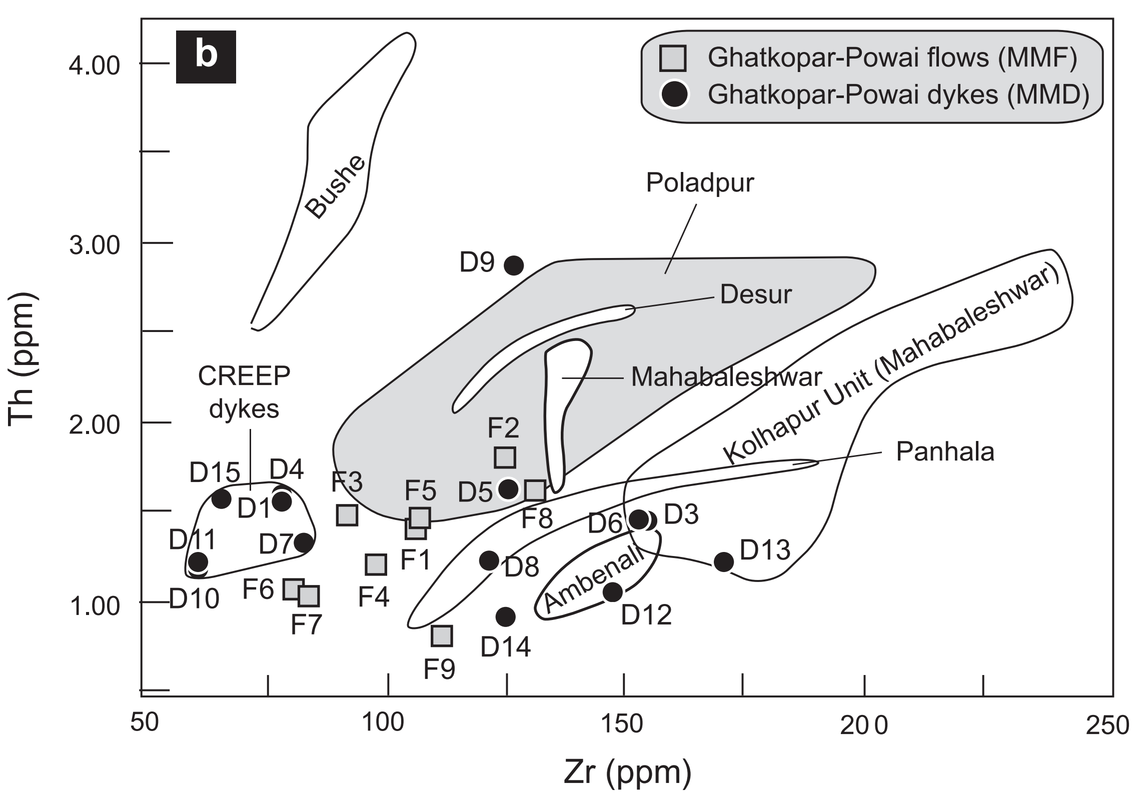


Fig. 7. (a) Plot of Ti/Y vs. Zr/Nb for various Deccan mafic lavas as well as the Ghatkopar–Powai flows and dykes. Data sources are as follows: The Kalsubai and Wai Subgroups and the Khandala and Bushe Formations of the Lonavala Subgroup (total 624 samples): Beane (1988); Dhule area low-Ti flows: Melluso et al. (2004); Ghatkopar–Powai flows and dykes: this study. The CREEP dykes are shown as a cluster. Sample numbers are marked next to these flow and dyke samples. (b) Plot of Th vs. Zr, showing the concentration ranges of the younger stratigraphic formations and constituent units of the southern Western Ghats region, and also the Bushe Formation. Based on Lightfoot et al. (1990). Also shown are the data for the Ghatkopar–Powai flows and dykes, with the CREEP dykes marked as a separate cluster.

Table 5
Geochemical criteria used to distinguish the younger stratigraphic units, Western Ghats.

Formation	Sr (ppm)	Ba (ppm)	Ba/Y	$(^{87}Sr/^{86}Sr)_t$	Zr/Nb	TiO_2 (wt.%)
Desur Unit (Panhala)	>230	>150	–	0.707–0.708	<12.5	Low (<2.25)
Panhala	<200	<90	–	0.704–0.705	>13	Low (<2.2)
Mahabaleshwar	>250	>100	>4	>0.705	<10.5	>2.0
Kolhapur Unit (Mahabaleshwar)	>200	–	–	0.704–0.705	<14.0	High (>2.25)
Ambenali	200–250	<100	<3.5	<0.705	10.5–15	<2.7
Poladpur	–	>100	>3.5	0.705–0.713	15–20	–
Bushe	–	>100	–	>0.713	>20	Very low (<1.5)

Notes: Based on Devey and Lightfoot (1986), Lightfoot et al. (1990), Mitchell and Widdowson (1991), and Jay and Widdowson (2008). The Kolhapur Unit overlies the Ambenali Formation in the southermost Deccan Traps (from Kolhapur southwards, Fig. 1a) and comprises highly fractionated flows with distinct geochemical features from the Mahabaleshwar Formation as shown. The Desur lavas are considered a Unit of the Panhala Formation by some; they overlie and are more radiogenic than the Panhala flows in the southernmost Deccan Traps, but have trace element abundances similar to the Mahabaleshwar Formation (e.g., Lightfoot et al., 1990). Dashes mean that the particular criterion is not distinctive or not defined for that particular formation or unit.

the Th–Zr plot at the edge of the Ambenali field (Fig. 7b). However, they have distinct multielement patterns, MMD3 strongly resembling the Mahabaleshwar pattern and MMD6 the Ambenali pattern. Dyke MMD8 is located within the narrow, curved Panhala field, consistent with its isotopic match. Note however that its Zr/Nb ratio (9.76) is well below the Zr/Nb >13 required of Panhala lavas (e.g., Mitchell and Widdowson, 1991; Table 5). Dyke MMD12, not analyzed for isotopes, most closely matches the Ambenali Formation pattern in multiple elements, and is located within the Ambenali field in the Th–Zr plot. Dykes MMD13 and MMD14, which are Ambenali-type both by isotopic ratios and multielement patterns, plot outside the Ambenali field in the Th–Zr plot. The six CREEP dykes have the lowest Zr contents of all and some of the lowest Th contents, and again form a small cluster distinct from any formation field.

In a plot of Th/Yb vs. Ta/Yb (Fig. 8), combining other alteration-resistant elements, data for a few Ghatkopar–Powai flow samples lie within or close to the Mahabaleshwar field, with MMF9 located at the edge of the Ambenali field, and others outside any formation field. Several dykes (MMD3, MMD5, MMD6, MMD8, MMD9) are located within or very near the Mahabaleshwar field, and dykes MMD12, MMD13 and MMD14 are located at the edge of the Ambenali field. Dyke MMD4 is located within the Poladpur field, which is otherwise unrepresented, as are the Panhala and the Bushe. The CREEP dykes again define a small and tight cluster distinct from any of the formations.

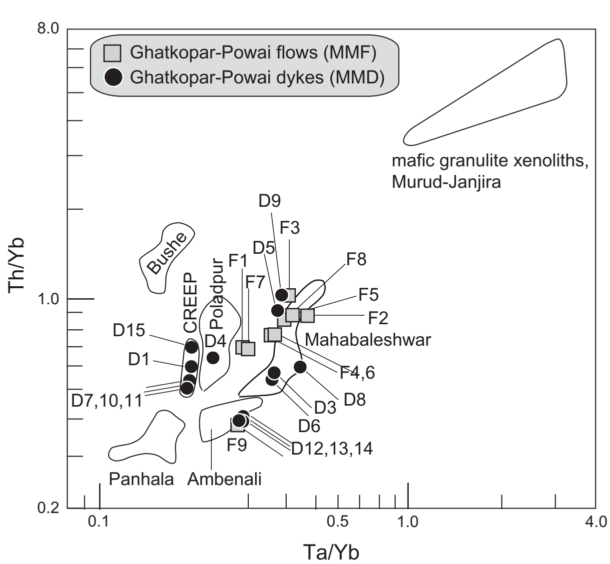


Fig. 8. Plot of Th/Yb vs. Ta/Yb for the younger formations of the Western Ghats and the Bushe Formation, from Lightfoot and Hawkesworth (1988). The Ghatkopar–Powai flow-dyke data are plotted. Also shown is a field for the mafic granulite xenoliths found at Murud-Janjira (Dessai et al., 2004).

4.4. Discriminant function analysis

We performed discriminant function analysis (DFA) using multiple alteration-resistant elements to quantitatively evaluate chemical affinities of the Ghatkopar–Powai flows and dykes to the Western Ghats sequence, using the same methodology as used by Peng et al. (1998), Sheth et al. (2004, 2009), Bondre et al. (2006), and Vanderkluysen et al. (2011), among others. As commonly observed, the closest DFA matches differ from the closest isotopic and trace element matches, and remain inconclusive.

5. Discussion

5.1. Stratigraphic and volcanological implications of the Ghatkopar–Powai flows

All isotopic and elemental evidence discussed so far shows that the Ghatkopar–Powai flows, though with close similarities to the Mahabaleshwar Formation of the Western Ghats sequence in Sr–Nd isotopic ratios and multielement patterns, cannot represent the Mahabaleshwar Formation, or indeed any other stratigraphic formation. Presently we assign the geochemically distinctive Ghatkopar–Powai lava flows, of an unknown (possibly small) areal extent and stratigraphic position, to a "Ghatkopar–Powai Unit". Future work will show if these flows are represented in the Mumbra Hills of New Mumbai to the east of the Thane Creek (Fig. 1c). From their prominent westward dips, we infer that the Ghatkopar–Powai flows predate the Panvel flexure.

The Ghatkopar–Powai dykes clearly cut the these flows, and cannot represent their feeders. Two of the Coastal swarm dykes analyzed by Vanderkluysen et al. (2011) plot near the flow MMF9 in the Sr–Nd isotopic plot (Fig. 4), but are nevertheless distinct from it. No other Coastal swarm dykes are located anywhere near the other Ghatkopar–Powai flows in this plot. The feeder dykes of the Ghatkopar–Powai Unit are unidentified. However, because of the distinctive geochemical characteristics of the Unit, we infer that it formed from a relatively nearby eruptive center. This center may be under the Arabian Sea, on the continental shelf, where a considerable extent of Deccan lavas and associated intrusions is known from geophysical exploration and drilling for oil (e.g., Chandrasekharam, 1985), and hydrothermal systems associated with such an eruptive center could also explain the very high Pb–Cu–Zn enrichments noted in the Ghatkopar–Powai flows and dykes.

5.2. Stratigraphic and volcanological implications of the Ghatkopar–Powai dykes

The Ghatkopar–Powai dykes have no exact geochemical equivalents in the Western Ghats stratigraphy. Dykes MMD6, MMD12, MMD13 and MMD14 have close similarities to the Ambenali Formation, but the correspondence is not complete for MMD6 and MMD13. Dykes MMD12 and MMD14 can be considered Ambenali-type by all plots used in this paper. The six CREEP dykes (three of them analyzed for isotopes being Mahabaleshwar-like) are distinct from anything yet analyzed from the Deccan province. It is not known if the Ghatkopar–Powai dykes fed lavas at higher stratigraphic levels than the flows studied. The sheer number of dykes observed in this small area suggests a potential eruptive center, but lavas with appropriate geochemical signatures are yet to be found.

With the exception of dyke MMD7 (dipping 45° east), the Ghatkopar–Powai dykes are all vertical or nearly so. Dykes dipping landward at angles of ~40° and outcropping close to the coastline have been described from the East Greenland flexure by Klausen and Larsen (2002). None of the Ghatkopar–Powai dykes shows dips of ~73° due east, expected for dykes originally intruded subvertically and rotated with the lava flows (which dip 17° west) due to the Panvel flexure. We interpret this as showing that these dykes postdate the Panvel flexure (see also Klausen and Larsen, 2002). As noted by Hooper et al. (2010), west-dipping lavas of the Poladpur and Ambenali Formations exposed in the Konkan area south of Mumbai have been brought to nearly sea level (from high elevations on the Western Ghats) by the Panvel flexure. The flexure must therefore postdate the lavas and feeder dykes of these formations. We think that the two Ambenali-type Ghatkopar–Powai dykes (MMD12 and MMD14) may represent rare late, post-Panvel flexure, injections of Ambenali-type magma, unrelated to the Ambenali Formation *per se*.

5.3. Tectonic implications of the dykes

The strike directions could be unambiguously measured in the field for 12 of the 14 Ghatkopar–Powai dykes (Tables 2 and 3), and show a strong preferred orientation. Thus three dykes trend N0°, two N30°, two N40°, two N170°, and one each N20°, N25°, and N335°. Vanderkluysen et al. (2011) discussed some issues faced in assigning dykes of this region to either the Coastal or the Nasik–Pune swarms. They assigned all dykes west of the Panvel flexure axis, and with trends between N20°W and N20°E, to the Coastal swarm. Dykes east of the Panvel flexure, or dykes west of the flexure but with trends outside the N20°W–N20°E interval, were assigned by them to the Nasik–Pune swarm. The Ghatkopar–Powai dykes are located 20 km west of the Panvel flexure axis (Fig. 1b), and by the definitions of Vanderkluysen et al. (2011), the six dykes MMD7 (N170°), MMD8 (N0°), MMD9 (N0°), MMD10 (N0°), MMD11 (N170°), and MMD13 (N20°) belong to the Coastal swarm, whereas the six dykes MMD1 (N40°), MMD3 (N335°), MMD4 (N30°), MMD12 (N30°), MMD14 (N25°) and MMD15 (N40°) belong to the Nasik–Pune swarm. It is interesting that the former six dykes are all located in the western part of the study area (Figs. 1c and 2a), on an essentially north–south line connecting the Vihar SE Hill to almost the summit of the Ghatkopar Hill. The other six are located east of this line.

The CREEP dykes belong to both swarms in equal numbers. CREEP dykes MMD7, MMD10 and MMD11 belong to the Coastal swarm, whereas MMD1, MMD4 and MMD15 belong to the Nasik–Pune swarm. Thus the factors governing their unusual REE composition are not structural or tectonic. Ambenali-type dykes MMD12 and MMD14, outcropping at the summit of the Ghatkopar Hill, belong to the Nasik–Pune swarm. Dykes MMD8 and MMD9 from the Vihar SE Hill, Mahabaleshwar-like by several (not all) criteria used in this paper, belong to the Coastal swarm.

The topics of lithospheric extension and tectonics of continental flood basalt eruptions, and their relative timing, have been much debated for the Deccan Traps (e.g., Hooper, 1990; Sheth, 2005; Ray et al., 2007; Hooper et al., 2010; Vanderkluysen et al. 2011). The latter two studies, based on extensive geochemical-isotopic and structural data on hundreds of Deccan dykes, representing the three major dyke swarms of the province, have concluded the following: directed lithospheric extension was an important control on the feeder dykes of the lower and middle formations of the Western Ghats sequence (see also Bondre et al., 2006), whereas the feeder dykes of the upper formations, with more random trends, were not controlled by regional directed extension. Notably, the upper formations make up ⩾50% of the Deccan lava volume and span the Cretaceous–Palaeogene boundary (Self et al., 2006).

Our new data on the Ghatkopar–Powai dykes considerably expand the temporal frame, as these dykes were intruded at a late, post-Panvel flexure stage of Deccan magmatism. This late stage was nonetheless magmatically vigorous, as inferred from the sheer number of dykes in this small area (and this number must be a minimum, noting the severe human modification of the area). Dykes are preferentially emplaced perpendicular to the maximum tensile stress or the least compressive stress (e.g., Gudmundsson and Marinoni, 2002). The structural data on the Ghatkopar–Powai dykes mean that the stress regime in the study area, particularly in its western part, had become strongly extensional in an east–west direction (cf. Ray et al., 2007) as these late-stage tholeiitic dykes were emplaced, probably as the Seychelles were about to be rifted from western India (Devey and Stephens, 1991). Future Ar–Ar dating work coupled with palaeomagnetic measurements on these dykes will elucidate the details and timings of these tectonic and magmatic events.

5.4. Petrogenesis of the flows and dykes

Given the objectives of this study, a detailed discussion of the petrogenesis of the Ghatkopar–Powai flows and dykes is beyond the scope of this paper. The Ambenali Formation magmas are considered the parental magma type of the Western Ghats tholeiitic sequence, as they show the least continental lithospheric influence and transitional MORB-like chemical characteristics with $\varepsilon_{Nd}(t)$ values up to +8 (e.g., Mahoney et al., 1982; Macdougall, 1986; Fig. 4). Most Western Ghats formations, with the exception of the Ambenali and Mahabaleshwar, contain lavas highly contaminated by continental crust (e.g. Lightfoot and Hawkesworth, 1988; Lightfoot et al., 1990; Peng et al., 1994). The elongated fields defined by these formations in Fig. 4 have been interpreted as mixing arrays between Ambenali magmas and continental lithospheric materials of various types.

Compared to the great Sr–Nd isotopic range covered by the Western Ghats sequence, the Ghatkopar–Powai flows and dykes have $\varepsilon_{Nd}(t)$ ranging from +5.6 to −5.5 and $(^{87}Sr/^{86}Sr)_t$ from 0.704314 to 0.706483, i.e., compositions relatively uncontaminated by continental lithosphere. The Mahabaleshwar Formation magmas have been interpreted as indicating contamination of Ambenali-type magmas by low-ε_{Nd}, but low $^{87}Sr/^{86}Sr$, lithospheric materials, either lithospheric mantle (Lightfoot and Hawkesworth, 1988; Lightfoot et al., 1990) or lower crust (Mahoney et al., 1982; Bhattacharya et al., 2013). We infer that the isotopically Ambenali-, Panhala-, and Mahabaleshwar-type Ghatkopar–Powai flows and dykes represent magmas little contaminated by lower crust. Xenoliths of mafic and felsic granulites representing such crust, along with crust-mantle-transitional pyroxenites and websterites, are found in the Murud lamprophyres (Fig. 1b, Dessai et al., 2004). Isotopic data are not yet available on these xenoliths, but the Mahabaleshwar Formation field in Fig. 8 extends from the Ambenali field towards these xenolithic granulites, broadly consistent with a lower crustal contaminant.

It is of interest that trachyte intrusions from Mumbai dated at 60–61 Ma and containing alkali basalt enclaves (Sheth et al., 2001a; Zellmer et al., 2012) also have Mahabaleshwar- and Panhala-like Sr–Nd–Pb isotopic compositions, and have been interpreted as partial melts of earlier Deccan basalt lavas or related gabbroic rocks in intracrustal sill complexes (Lightfoot et al., 1987). Since partial melting does not change these isotopic ratios, it is likely that the mafic protoliths of these trachytes were the intrusions related to the Ghatkopar–Powai tholeiitic rocks of this study. The Danian Mumbai rhyolite lavas also have similar Nd- and Pb-isotopic ratios to the trachytes, but higher Sr isotopic ratios (op. cit.). Thus, Deccan magmatism in Mumbai as a whole, from the Ghatkopar–Powai tholeiitic sequence studied here to the youngest differentiated intrusions, appear to have involved isotopically Mahabaleshwar-type magmas, sources, or contaminants.

The CREEP dykes are also isotopically Mahabaleshwar-like, but very distinctive in their REE patterns. We speculate that the concave upward REE patterns of these tholeiitic dykes are caused by the preferential retention of the middle REE during partial melting, in a residual phase such as amphibole (e.g., Davidson et al., 2007). This would thus be a lithospheric, rather than asthenospheric, source, but a detailed exploration of this hypothesis must be attempted elsewhere.

6. Conclusions

We have studied the geochemistry of tholeiitic flows and dykes exposed in the Ghatkopar–Powai area of Mumbai City, situated in the Panvel flexure zone, western Deccan Traps. The flows are pre-Panvel flexure, whereas the dykes are post-Panvel flexure. The geochemical signatures of most flows and dykes are unrepresented in the Western Ghats sequence. The flows are closely similar to the Mahabaleshwar Formation of the Western Ghats sequence in Sr–Nd isotopic ratios and multielement patterns, but have other geochemical characteristics (e.g., incompatible trace element ratios) unlike the Mahabaleshwar or any other Formation. Two of the dykes resemble the Ambenali Formation of the Western Ghats in all geochemical characteristics, though they are unlikely to be feeders of the Ambenali Formation lavas. Ten other dykes are distinct from any of the Western Ghats stratigraphic units. A few show partial (e.g., Sr–Nd isotopic) similarities to the Mahabaleshwar Formation. Six of the fourteen dykes analyzed have unusual, concave-downward REE patterns, which may indicate residual amphibole and thus a lithospheric source. Three of them analyzed for Sr–Nd isotopic ratios are identical with the Mahabaleshwar Formation. Overall, the geochemical signatures of the Ghatkopar–Powai flows and dykes are unrepresented in the Western Ghats stratigraphy, and the flows probably had their eruptive center relatively nearby. The flows and dykes are inferred to have undergone no or little contamination by lower continental crust. The structural trends of the dykes indicate considerable east–west lithospheric extension during this late, though still magmatically vigorous, stage of Deccan volcanism.

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