Chemical evolution, petrogenesis, and regional chemical correlations of the flood basalt sequence in the central Deccan Traps, India

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The lava sequence of the central-western Deccan Traps (from Jalgaon towards Mumbai) is formed by basalts and basaltic andesites having a significant variation in TiO₂ (from 1.2 to 3.3 wt%), Zr (from 84 to 253 ppm), Nb (from 5 to 16 ppm) and Ba (from 63 to 407 ppm), at MgO ranging from 10 to 4.2 wt%. Most of these basalts follow a liquid line of descent dominated by low pressure fractionation of clinopyroxene, plagioclase and olivine, starting from the most mafic compositions, in a temperature range from 1220° to 1125°C. These rocks resemble those belonging to the lowermost formations of the Deccan Traps in the Western Ghats (Jawhar, Igatpuri and Thakurvadi) as well as those of the Poladpur formation. Samples analyzed for ⁸⁷Sr/⁸⁶Sr give a range of initial ratios from 0.70558 to 0.70621. A group of flows of the Dhule area has low TiO₂ (1.2–1.5 wt%) and Zr (84–105 ppm) at moderate MgO (5.2–6.2 wt%), matching the composition of low-Ti basalts of Gujarat, low-Ti dykes of the Tapti swarm and Toranmal basalts, just north of the study area. This allows chemical correlations between the lavas of central Deccan, the Tapti dykes and the north-western outcrops. The mildly enriched high field strength element contents of the samples with TiO₂ > 1.5 wt% make them products of mantle sources broadly similar to those which generated the Ambenali basalts, but their high La/Nb and Ba/Nb, negative Nb anomalies in the mantle normalized diagrams, and relatively high ⁸⁷Sr/⁸⁶Sr, make evident a crustal input with crustally derived materials at less differentiated stages than those represented in this sample set, or even within the sub-Indian lithospheric mantle.

1. Introduction

The Deccan Traps of Western India are one of the best known flood basalt provinces in the world. They form a huge lava field, with associated dyke swarms and intrusive complexes, which cover large parts of peninsular India (figure 1). The rocks were emplaced in a time span from 69 to 63 Ma, straddling the Cretaceous-Paleogene boundary, with the most intense volcanic pulse at 66.9 ± 0.2 Ma (Sen 2001; Mahoney *et al* 2002; cf. Pande 2002, references therein and subsequent comments). Its

reconstructed stratigraphy includes some 2500 m of mafic lava flows, grouped into eleven formations and three subgroups (the lowermost Kalsubai subgroup, comprising the Igatpuri, Jawhar, Neral, Thakurvadi, and Bhimashankar formations, the Lonavala subgroup, comprising the Khandala and Bushe formations, and the uppermost Wai subgroup, comprising the Poladpur, Ambenali, Mahabaleshwar, and Panhala formations; cf. Mahoney 1988; Peng *et al* 1994). The stratigraphy of the Deccan has been first defined in the Western Ghats sections (cf. Najafi *et al* 1981; Cox and Hawkesworth

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Figure 1. Geological map of central Deccan with location of the samples. The inset shows outcrops of the Deccan Traps. Filled circles: samples with TiO₂ > 1.5 wt%; open circles: samples with TiO₂ < 1.5 wt%.

1985; Subbarao and Hooper 1988). Several other papers attempted to recognize the known formations elsewhere in the province, often using multi-elemental statistics (e.g., Mitchell and Widdowson 1991; Peng *et al* 1998; Khadri *et al* 1999a, 1999b). Mahoney *et al* (2000) demonstrated that the lava flows in the northern part of the Deccan, though having generally similar geochemical features with respect to some cropping out in the Western Ghats, crop out with a different stratigraphic sequence (Bushe Fm. upwards, Ambenali and Poladpur intercalated, and downwards Bushe Fm. again; cf. also figure 11 of Widdowson *et al* 2000, for a general overview). This means that the chemical formations cannot be used as chronostratigraphic markers throughout the province. They could have been erupted from different feeding systems at different times, not resolvable with current radiometric techniques (Peng *et al* 1998; Hooper 1999; Mahoney *et al* 2000, 2002).

Further interest to the knowledge of the genesis and the evolution of the Deccan Traps derives from the possibility of correlation between the chemistry of the lava flows cropping out in the

Narmada-Tapti regions and the dyke swarm still extensively exposed (e.g., Melluso *et al* 1999; Chandrasekharam *et al* 1999; Mahoney *et al* 2000; Sheth *et al* 2004), which may be the source of at least some northern Deccan basalts. The chemical characteristics of the lava flows in the central Deccan, and the relationships between these lavas and the other parts of the Deccan is also an open argument. The lava sequence around Aurangabad is, curiously, poorly known, one of the few published papers being Subbarao *et al* (1994). This paper is a petrological and geochemical study of an extensive sampling of basalts of central-western Deccan. Particular emphasis will be given to the chemical correlations between the lavas of this area of Deccan and the Tapti dykes, the lavas of Tapti-Satpuras and Gujarat.

The Deccan Traps lava flows, though being tholeiitic basalts for the most part, have very heterogeneous geochemical characteristics. The Ambenali basalts have probably the weakest evidence of interaction with continental crust or lithospheric mantle, given their transitional mid-ocean-ridge basalt (T-MORB)-like chemical

features (e.g., Lightfoot *et al* 1990). The enriched basalts of Gujarat have most chemical and isotopic features almost identical to the present-day la Reunion basalts (Melluso *et al* 1995; Peng and Mahoney 1995; J J Mahoney and L Melluso, unpublished data). On the other hand, several formations from the Western Ghats and elsewhere show chemical evidence of interaction with continental crust or lithospheric mantle, from the Bushe Fm. extreme (the lavas of this formation have some of the highest initial $^{87}\text{Sr}/^{86}\text{Sr}$ (up to 0.7200) and present-day $^{206}\text{Pb}/^{204}\text{Pb}$ (up to 22.46) and the lowest initial $^{143}\text{Nd}/^{144}\text{Nd}$ (down to 0.5118) ratios, coupled with low Nb, Ti and Zr contents) to the lowermost formations (Peng *et al* 1994). Peng *et al* (1994) modelled the crustal inprint with at least two different steps of contamination, characterized by different crustal end-members, which mixed in variable amounts to Ambenali-like mantle-derived magmas. It is worth remembering that major chemical types found in the Deccan have no obvious equivalents in the Western Ghats lava pile. Notable are the highly enriched, and sometimes potassium-rich, basalts cropping out in the Kathiawar peninsula, at Pavagadh, and in the Narmada valley (Krishnamurthy and Cox 1977, 1980; Mahoney *et al* 1985; Melluso *et al* 1995), and the highly incompatible element-depleted tholeiites of Gujarat (Melluso *et al* 1995).

The role of partial melting and mantle source heterogeneity in the petrogenesis of the Deccan Trap basalts, as opposed to the crustal influx, is still very poorly constrained. The magmatic evolution, as well as the petrogenesis of highly evolved rocks like rhyolites, are also an argument open to future modern modelling and debate.

2. Sampling locations and geological setting

The samples pertinent to this study have been sampled in road sections from an area comprised within Bhir, Jalgaon, Dhule, the Gujarat state and Mumbai (figure 1). In the area just south of Bhir, flows belonging to Bhimashankar, Khandala, Poladpur, Ambenali and, less frequently, Mahableshwar Fm. have been found (L Melluso, unpublished data; Khadri *et al* 1999a). Talusani (2001) recently described alkali basalt flows in the area of Bhir. The lava flows have been sampled at different heights, ranging from ca. 860 mt, sample D327 (northern tip of the Western Ghats), to Thana, close to the sea level, and to the samples around Dhule (ca. 300 mt a.s.l.). The samples from D328 to D330 have been collected in the Gujarat state. According to the geological map of Subbarao and Hooper (1988), the southwestern-most samples of

this study belong to the Igatpuri formation (D340 to D336, from Thana to Igatpuri), whereas the lavas around Nasik belong to the Thakurvadi and Khandala formations (D325 to D335). Subbarao *et al* (1994) argued that the area of Aurangabad is mostly formed by flows of the lowermost formations (Jawhar and Igatpuri).

3. Petrography and mineral chemistry

The sampled lava flows of central Deccan are tholeiitic basalts (72%) and basaltic andesites (28%) (figure 2; table 1), with the latter being more abundant at low MgO contents. They are variably fresh, and porphyritic for phenocrysts of plagioclase, clinopyroxene and less abundant and often altered olivine, with microcrystalline ground-mass of variable size, with plagioclase, pyroxenes and more abundant oxides. Mg-rich, olivine-phyric, basalts are not widespread (samples D333 and D325). Plagioclase phenocrysts up to 0.5 cm in size, have been observed in many samples (D283 to D288, D292 to D295, D334 to D338).

Mineral chemistry: Chemical analyses of the main mineral phases found in a sample subset are given in table 2. Ca-rich clinopyroxene belongs to the augite-ferroaugite (subcalcic ferroaugite) series. Their Mg# (atomic Mg/(Mg + Fe)) varies from 0.80 to 0.33. The TiO_2 content of Ca-rich clinopyroxene is low, and ranges from 0.42 to 1.54 wt%. Al_2O_3 is also low and ranges from 0.90 to 2.75 wt%. A few pigeonites have been analysed in sample D316 (table 2). The observed clinopyroxene trend is typical of tholeiitic series magmas. Plagioclase ranges from An_{72} to An_{34} . Olivine is present as fresh crystals only in a few samples, and ranges

Figure 2. T.A.S. classification diagram for the central Deccan samples. Symbols: open squares: samples with $\text{TiO}_2 > 1.5$ wt%; filled diamonds: samples with $\text{TiO}_2 < 1.5$ wt%.

Table 1. Major (wt%) and trace element (ppm) analyses of the samples of central Decan.

Type	smpl	h class	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Sc	V	Cr	Ni	Cu	Zn	Rb	Sr	Y	Zr	Nb	Ba
	333	620 B	49.51	1.76	12.37	12.52	0.18	10.1	10.90	1.85	0.59	0.17	33	335	543	126	52	104	15	204	24	122	6.9	176
	325	680 B	49.69	1.73	12.40	13.01	0.19	9.81	9.84	2.37	0.69	0.27	31	341	320	109	83	113	22	199	26	134	6.0	169
	300	610 B	49.40	1.60	13.37	12.75	0.16	8.96	10.78	2.08	0.65	0.26	26	285	195	94	83	92	18	283	23	118	11.8	176
	289	620 B	48.76	1.86	13.55	12.78	0.17	8.84	11.05	2.07	0.69	0.23	28	319	164	92	104	97	18	267	24	125	13.6	194
	307	520 B	50.76	1.66	13.24	11.96	0.16	8.74	9.83	2.53	0.93	0.20	32	297	372	32	18	108	25	226	27	137	7.5	244
	276	530 B	48.94	1.78	13.50	12.65	0.21	8.62	11.34	2.10	0.63	0.22	27	314	180	91	99	95	14	269	26	125	10.0	166
	301	630 B	49.48	1.62	13.57	12.19	0.15	8.35	11.56	2.23	0.63	0.20	26	315	197	91	114	97	19	274	21	121	9.0	177
	290	620 B	49.00	2.10	14.06	12.49	0.15	8.27	10.68	2.32	0.68	0.25	34	337	256	109	154	113	16	268	32	130	11.8	171
	277	480 B	51.07	1.84	13.63	11.22	0.16	7.97	11.74	2.12	0.02	0.24	38	364	356	122	136	94	3	215	30	107	7.3	73
	322	810 BA	52.59	1.64	13.01	11.65	0.15	7.93	9.58	2.41	0.81	0.23	29	287	336	133	112	109	23	266	24	137	5.6	247
	308	520 B	51.74	1.90	13.24	12.30	0.16	7.84	9.50	2.08	0.95	0.29	32	331	241	112	71	110	33	236	30	150	11.1	238
	303	580 B	50.19	1.91	13.56	12.29	0.16	7.78	10.68	2.51	0.69	0.23	36	344		110	128	104	23	250	22	120	12.6	169
	326	670 B	50.28	1.87	13.86	11.95	0.19	7.75	10.71	2.35	0.76	0.29	30	346	199	60	61	101	17	225	29	151	8.0	212
	305	600 B	50.22	1.95	13.43	12.41	0.19	7.67	11.58	2.11	0.19	0.27	39	381	350	121	148	102	6	258	23	111	7.5	124
	278	490 B	50.89	1.74	13.57	11.34	0.15	7.66	11.83	2.12	0.48	0.22	33	340	322	121	140	93	18	204	24	113	5.2	120
	306	620 B	51.05	1.87	13.46	12.33	0.16	7.63	10.60	2.00	0.65	0.25	35	345	271	112	162	106	21	242	27	119	9.9	151
	279	500 B	50.96	1.86	13.78	11.05	0.15	7.62	12.02	2.27	0.08	0.21	39	361	313	117	155	91		216	28	109	6.9	69
	327	860 B	50.56	1.76	13.86	12.06	0.18	7.54	10.77	2.33	0.71	0.23	35	358	360	84	85	104	24	195	30	112	6.4	189
	331	710 B	50.37	1.76	14.31	12.01	0.17	7.53	10.12	2.60	0.89	0.24	31	337	211	42	30	100	34	214	28	129	6.9	216
	298	415 BA	52.28	1.82	13.28	11.66	0.16	7.52	9.80	2.22	0.97	0.29	31	301	231	93	88	109	33	227	30	143	10.8	241
	340	40 B	51.26	1.68	14.41	11.50	0.16	7.50	10.10	2.54	0.57	0.28	32	300	258	89	102	104	19	299	24	125	10.0	190
	296	580 B	49.58	2.01	13.94	12.34	0.17	7.21	11.95	2.17	0.38	0.25	33	344	259	83	153	109	7	319	27	140	12.4	186
	283	590 B	50.65	2.82	12.93	13.93	0.17	7.16	9.30	2.19	0.47	0.37	34	398	113	65	236	122	8	292	35	193	14.3	292
	299	430 B	50.64	1.92	13.96	12.81	0.16	6.99	9.99	2.32	0.94	0.26	30	296	125	36	57	118	30	245	33	147	11.0	255
	281	510 B	50.43	2.09	13.80	12.46	0.18	6.98	11.34	2.26	0.18	0.26	38	393	296	95	179	110	7	226	27	115	6.5	117
	274	780 BA	52.87	2.36	12.02	14.10	0.15	6.98	7.90	1.90	1.44	0.27	38	409	88	57	148	134	47	264	34	174	10.2	407
	304	580 B	51.38	1.86	14.14	11.77	0.16	6.91	10.63	2.32	0.62	0.22	35	339	267	112	174	101	20	241	27	118	10.2	136
	302	580 B	49.08	2.24	14.27	13.39	0.20	6.85	11.53	1.96	0.23	0.25	36	393	209	98	204	112	14	194	28	139	11.5	122
	315	280 B	49.93	1.86	14.76	12.73	0.18	6.85	10.55	2.35	0.54	0.23	28	337	125	81	135	114	19	358	26	119	9.1	229
	323	750 B	51.53	2.10	13.49	12.54	0.19	6.84	9.69	2.48	0.90	0.24	29	359	246	65	98	107	17	221	34	157	10.8	264
	324	740 BA	52.15	1.92	14.12	11.88	0.18	6.57	9.85	2.25	0.82	0.26	34	341	224	59	108	107	16	278	28	158	9.7	230
	280	540 B	50.03	2.17	14.25	12.82	0.19	6.57	11.25	2.35	0.08	0.30	39	386	170	83	170	113	2	250	27	127	8.5	130
	330	270 B	49.84	2.40	13.46	13.42	0.21	6.56	11.70	2.04	0.07	0.30	36	409	208	90	176	119	5	270	31	146	13.4	103

Table 1. (Continued)

335	460 B	49.24	2.47	13.86	13.61	0.16	6.46	10.25	2.74	0.90	0.31	32	380	228	93	138	107	20	246	37	188	9.4	317
282	540 B	51.28	2.05	14.30	12.20	0.17	6.42	10.64	2.38	0.28	0.27	33	357	155	79	139	108	7	249	30	128	7.7	162
292	675 BA	52.18	2.28	13.37	12.65	0.16	6.41	9.66	2.28	0.72	0.30	36	384	167	74	132	115	22	237	33	152	9.2	196
329	360 B	50.37	2.15	14.53	12.70	0.18	6.20	11.47	2.12	0.09	0.22	34	372	175	97	179	111	4	289	29	134	12.8	88
310	660 B	49.57	3.28	13.11	14.71	0.24	6.16	10.07	2.31	0.12	0.42	37	489	147	63	269	146	2	264	44	229	15.2	196
334	530 BA	52.52	2.09	12.53	12.77	0.17	6.14	9.95	2.72	0.84	0.26	29	368	99	52	53	100	22	229	32	175	8.2	245
339	120 B	51.88	1.70	14.10	12.81	0.17	6.09	9.67	2.38	0.96	0.23	34	296	156	57	78	114	30	164	37	145	6.5	275
332	700 BA	52.08	2.04	13.67	12.59	0.19	6.07	9.77	2.54	0.71	0.36	31	354	199	76	93	112	12	299	28	148	9.0	268
295	640 B	51.37	2.10	13.66	13.36	0.15	6.06	10.08	2.60	0.33	0.29	30	342	92	62	133	117	10	331	29	154	11.4	242
293	700 B	49.05	1.65	15.83	12.39	0.14	5.85	11.89	2.45	0.52	0.22	27	285	67	66	99	91	10	318	23	120	11.5	169
297	510 B	51.85	1.99	13.98	12.71	0.16	5.74	9.84	2.44	1.01	0.28	31	323	130	47	91	111	29	260	34	161	12.8	299
294	700 B	49.97	1.74	15.71	12.23	0.16	5.43	11.36	2.58	0.60	0.22	28	299	66	59	68	106	17	312	24	120	10.4	195
288	610 B	51.89	2.70	12.77	14.06	0.19	5.23	9.27	2.54	0.96	0.40	32	412	99	54	126	130	27	241	44	221	12.4	330
284	580 B	51.85	2.91	13.07	14.05	0.18	5.22	8.83	2.57	0.93	0.39	35	434	127	60	182	128	30	241	42	219	13.0	300
275	575 BA	52.50	2.55	12.17	14.53	0.18	5.14	8.91	2.52	1.13	0.37	36	438	94	51	194	129	32	252	38	195	12.2	401
311	630 B	51.74	2.39	13.85	13.92	0.18	5.08	8.93	2.71	0.86	0.34	30	390	75	60	200	122	26	242	41	183	11.3	334
285	540 BA	52.12	2.48	13.08	13.91	0.21	5.07	9.33	2.56	0.85	0.39	33	416	72	45	164	130	23	252	37	186	10.1	307
309	710 BA	52.09	2.36	12.90	13.99	0.19	5.06	9.42	2.51	1.16	0.31	37	396	74	51	186	138	44	250	36	182	9.5	324
286	560 BA	52.16	2.35	13.99	13.62	0.20	4.56	9.37	2.78	0.64	0.32	34	398	69	45	187	128	10	257	37	178	10.5	299
312	690 BA	52.42	2.43	13.37	14.21	0.20	4.43	9.53	2.73	0.37	0.30	33	424	76	29	213	125	15	254	36	172	11.0	202
314	260 B	51.96	3.13	13.28	14.00	0.18	4.43	9.19	2.95	0.48	0.40	31	418	100	53	243	130	20	274	42	248	15.6	368
321	570 BA	52.67	2.73	12.54	14.76	0.17	4.42	8.32	2.56	1.41	0.42	33	394	73	36	101	127	43	244	37	217	14.3	377
287	580 BA	52.43	2.79	13.71	13.40	0.18	4.42	8.95	2.77	0.93	0.41	35	417	118	55	180	126	25	251	44	212	12.6	318
313	310 BA	52.63	3.19	13.36	13.45	0.19	4.29	9.05	2.81	0.59	0.43	32	435	99	56	257	134	15	262	45	253	15.5	363
336	370 BA	52.29	2.73	13.24	14.37	0.20	4.28	9.18	2.76	0.60	0.36	34	445	60	34	120	119	15	261	37	195	15.1	317
338	230 B	51.86	2.92	13.58	14.14	0.20	4.21	8.80	2.90	1.07	0.33	28	469	51	30	136	130	28	271	38	212	12.3	307
337	300 BA	52.40	2.76	13.98	13.34	0.20	4.19	8.70	2.95	1.11	0.40	30	442	50	19	110	116	30	263	36	209	15.0	342
LTi	316	280 B	51.16	1.48	15.03	13.11	5.28	11.37	2.01	0.16	0.21	43	357	54	42	153	106	4	197	31	96	8.1	144
LTi	317	290 B	51.88	1.30	15.44	12.10	5.16	11.46	2.25	0.05	0.17	41	326	53	42	140	98	5	174	26	84	8.2	128
LTi	318	? B	51.76	1.22	14.21	13.03	6.02	10.76	2.04	0.62	0.17	37	343	64	37	144	102	15	145	28	94	8.5	171
LTi	319	470 BA	53.40	1.25	14.03	12.53	5.37	10.07	2.15	0.82	0.17	42	351	59	49	153	110	29	144	29	105	9.9	202
LTi	320	510 B	51.94	1.20	14.35	12.81	6.14	10.64	2.17	0.37	0.18	43	352	62	49	152	101	12	141	28	87	10.3	182

h = approximate height above sea level.
B = basalt.
BA = basaltic andesite.

Table 2. *Representative analyses of mineral phases in the central Deccan rocks. An, Or, Ab, in mol%, Ca, Mg, Fe + Mn in mol%, ilm and ulv in mole fraction.*

PLAG		SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	Cr ₂ O ₃	NiO	Sum	An	Ab	Or
D325	l	56.15		27.08	0.86			9.61	5.56	0.53			99.8	47.3	49.6	3.1
D325	l	54.22		28.09	0.90			11.19	4.98	0.36			99.7	54.2	43.7	2.1
D325	l	51.02		30.63	0.81			13.65	3.50	0.17			99.8	67.6	31.4	1.0
D325	e	51.60		30.61	0.59			14.00	3.28	0.15			100.2	69.6	29.5	0.9
D333	l	50.26		30.08	0.63			13.85	3.24	0.21			98.3	69.4	29.4	1.3
D333	l	52.33		28.78	1.18			12.03	4.37	0.31			99.0	59.2	38.9	1.8
D316	e	48.14		32.68	0.70			15.96	2.08	0.07			99.6	80.6	19.0	0.4
D316	l	55.93		26.50	0.68			9.65	5.48	0.33			98.6	48.3	49.7	2.0
D333	l	56.98		26.78	0.78			9.52	5.49	0.04			99.6	48.8	50.9	0.2
D293	e	50.37		31.14	0.42			14.73	2.98	0.18			99.8	72.4	26.5	1.1
D293	l	56.83		26.01	0.75			8.93	5.89	0.63			99.0	43.9	52.4	3.7
D335	l	54.84		27.56	0.79			10.30	4.82	0.50			98.8	52.5	44.5	3.0
D335	l	57.57		26.02	0.92			8.42	6.11	0.64			99.7	41.6	54.6	3.8
D335	e	51.90		30.42	0.58			13.46	3.65	0.25			100.3	66.1	32.4	1.5
D335	l	59.67		24.41	0.56			6.75	6.78	0.91			99.1	33.6	61.0	5.4
PX														Ca	Fe*	Mg
D325	e	52.27	0.69	2.69	7.35	0.09	16.67	19.31	0.28		0.63		100.0	40.0	12.0	48.0
D325	l	51.75	1.12	2.47	9.64	0.22	15.43	19.18	0.22		0.29		100.3	39.7	15.9	44.4
D325	e	52.66	0.87	2.12	8.03	0.08	16.34	19.89	0.28		0.44		100.7	40.6	12.9	46.4
D325	l	51.83	0.96	1.27	13.92	0.41	14.35	16.93	0.28		0.00		100.0	35.2	23.3	41.5
D325	l	53.64	0.38	0.38	15.90	0.39	11.83	18.62	0.19		0.00		101.3	39.0	26.6	34.4
D333	l	52.49	0.68	2.18	7.37	0.29	16.29	19.86	0.21		0.30		99.7	40.9	12.3	46.7
D333	l	51.72	0.94	2.47	8.80	0.30	16.26	18.44	0.26		0.43		99.6	38.3	14.8	47.0
D316	e	52.17	0.43	2.15	8.24	0.18	16.67	18.51	0.18		0.10		98.6	38.3	13.6	48.0
D316	l	50.31	0.97	2.01	16.83	0.36	13.00	15.85	0.27		0.00		99.6	33.5	28.3	38.2
D316	l	50.75	0.68	1.13	23.22	0.62	12.37	11.24	0.18		0.00		100.2	23.9	39.6	36.6
D316	l	51.69	0.44	1.43	18.62	0.43	18.61	7.56	0.11		0.00		98.9	15.6	30.8	53.6
D316	l	53.03	0.29	0.70	20.11	0.54	21.20	3.98	0.06		0.00		99.9	8.0	32.5	59.5
D316	l	49.41	0.42	0.74	29.99	0.81	8.58	10.18	0.13		0.00		100.3	22.1	52.1	25.9
D293	l	49.98	1.37	0.93	20.38	0.64	10.28	15.75	0.27		0.00		99.6	33.9	35.3	30.8
D293	l	50.88	1.24	1.93	11.75	0.33	14.72	18.56	0.23		0.00		99.6	38.3	19.5	42.2
D293	l	51.42	1.08	2.58	10.11	0.20	14.85	19.62	0.20		0.00		100.1	40.6	16.7	42.7
D293	e	51.52	1.08	2.13	9.46	0.28	14.77	19.80	0.23		0.13		99.4	41.3	15.9	42.9
D293	l	50.02	1.54	1.35	16.57	0.50	11.01	18.04	0.29		0.00		99.3	38.6	28.5	32.8
D335	e	51.00	1.21	2.66	10.82	0.27	14.09	19.06	0.28		0.54		99.9	40.3	18.3	41.4
D335	l	51.59	1.09	2.24	9.39	0.27	14.73	19.93	0.26		0.36		99.9	41.6	15.7	42.7
D335	l	50.99	0.92	0.90	17.02	0.56	11.25	17.89	0.26		0.07		99.9	37.8	29.0	33.1
OLIV		SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	Cr ₂ O ₃	NiO		Mg#		
D325	l	34.27			41.76	1.14	22.69	0.36				0.09	100.3	0.49		
D325	l	36.29			32.21	0.85	30.32	0.25				0.13	100.1	0.62		
D333	e	38.66			16.50	0.53	42.53	0.36				0.14	98.7	0.82		
D333	l	37.27			25.88	0.63	34.90	0.30				0.10	99.1	0.70		
D333	l	34.28			39.25	0.96	23.20	0.36				0.08	98.1	0.51		
D335	l	34.07			44.14	1.16	19.36	0.62				0.05	99.4	0.43		
D335	l	33.51			47.94	1.40	16.58	0.38				0.03	99.8	0.37		
D335	e	37.11			29.60	0.78	32.39	0.37				0.14	100.4	0.66		
D335	e	36.75			32.38	0.70	30.22	0.32				0.21	100.6	0.62		
D293	l	34.10			42.71	1.09	21.28	0.42				0.06	99.7	0.46		
D293	l	32.74			49.64	1.43	14.72	0.47				0.08	99.1	0.34		
D293	l	36.30			33.07	0.85	29.26	0.40				0.12	100.0	0.61		

Table 2. (Continued).

SPIN											Ulv		
D325	l		11.72	1.27	80.06	0.17	0.42			0.35	94.0	0.33	
D333	e		1.61	18.19	27.55	0.25	9.52			40.68	97.8	0.06	
D333	l		15.19	1.71	74.49	0.87	0.37			0.14	92.8	0.38	
D316	l		25.78	2.12	61.32	0.97	0.46			0.00	90.7	0.46	
D293	l		34.51	1.05	57.68	0.77	1.35			0.07	95.4		
D293	l		28.77	1.06	63.04	1.77	0.49			0.00	95.1	0.48	
D293	l		22.82	1.81	67.42	0.97	0.55			0.07	93.6	0.44	
D335	l		26.23	1.71	64.90	1.40	0.09			0.29	94.6	0.46	
ILM											Ilm		
D325	l		49.57	0.00	47.91	0.56	1.06			0.17	99.3	0.94	
D325	l		49.09	0.05	47.50	0.40	1.33			0.22	98.6	0.93	
D325	l		50.95	0.16	46.31	0.38	2.07			0.11	100.0	0.95	
D333	l		48.89	0.03	47.42	0.44	1.26			0.08	98.1	0.93	
D293	l		50.92	0.25	42.23	0.57	1.16			0.13	95.3	1.00	
AMPH											F	Cl	
D325	l	48.82	1.21	4.67	14.88	0.13	14.45	10.58	2.09	0.80	0.15	2.78	100.6
D325	l	49.01	1.01	4.79	14.65	0.24	14.70	10.38	1.91	0.67	0.28	2.54	100.2

Mg# = atomic Mg*/100/(Mg+Fe).
e = early.
l = late.

in composition from Fo₈₂ (cores of sample D333) to Fo₃₄ (sample D293). It is often included in plagioclase; more rarely the reverse is observed. The relatively Fe-rich nature of the analyses is remarked. Spinels are chromiferous when included in Mg-olivine (Cr₂O₃ up to 40.7 wt.% in D333). Ground-mass titanomagnetites are Al-poor (0.35–2.12 wt% as oxide). Ilmenites are Mn-poor (0.38–0.57 wt% as MnO). Rare Fe-hornblende has been found in the interstices of sample D325.

4. Geochemistry of the lava flows

The lava flows of the central-western Deccan have a wide range of MgO (from 10 to 4.2 wt%), TiO₂ (from 1.2 to 3.3 wt%) at SiO₂ from 48 to 53 wt%. Their Mg/(Mg + Fe²⁺) ratio ranges from 0.65 to 0.40. The sample D333 has characteristics similar to primitive magmas, and also its most forsterite-rich olivine we have found (Fo₈₂) is close to that expected from chemical equilibrium with the host rock (Fo₈₅) (cf. also Beane and Hooper 1988, for further discussion on Mg-rich samples of this area of the Western Ghats). The concentration of incompatible trace elements is widely variable (e.g., Zr from 84 to 250 ppm; Y from 23 to 45 ppm; Nb from 6 to 16 ppm). K₂O, Rb and Ba reach values as high as 1.44 wt%, 47 ppm and 407 ppm, respectively, in basaltic andesites found north of the Bhir village (D274, D275).

Representative major and trace element diagrams, using Zr as differentiation index (Hooper 1994), are shown in figure 4. The samples show a trend of CaO, MgO, Cr and Ni decrease with increasing Zr, whereas Ba, K₂O, V, Zn, Y, Nb and TiO₂ contents increase. However, plagioclase-phyric basaltic and basaltic andesite lava flows occurring in the neighborhoods of Dhule (D316 to D320, figure 1, table 1) have peculiar chemical characteristics, with respect to the bulk of the lava flows of the central Deccan: at moderate MgO (5–6.2 wt%), they have low TiO₂ (1.2–1.5 wt%) and Zr (< 105 ppm). They have also relatively high Sc contents (37–43 ppm) and Al₂O₃ (14–15.4 wt%). These samples plot clearly outside the trends depicted from the other samples (figures 2, 4).

Figure 3. Pyroxene diagram for the central-western Deccan samples (squares). The pyroxenes of the Gujarat tholeiitic basalts (Melluso *et al* 1995) are shown in grey for comparison.

Figure 4. Representative variation diagrams using Zr as differentiation index. Rayleigh fractional crystallization modelling from sample D333 is reported in a few diagrams. Bulk-rock partition coefficients used: $D_{Zr} = 0.1$; D_{Nb} and $D_{Ba} = 0.01$; $D_{Ti} = 0.2$; $D_Y = 0.14$ (cf. Melluso *et al* 2001). Symbols as in figure 2.

The central-western Deccan samples span a moderate range of Zr/Y (3.1–5.9) and Ti/V (20–44), with the lowest values found in the samples with low TiO₂ (Zr/Y = 3.1 – 3.6 and

Ti/V = 20 – 25). The samples have relatively high Ba/Nb and La/Nb (13–40 and 1.15–2.9, respectively), and low Nb/U (7–19). There is no correlation between the value of these ratios and degree

Table 3. Rare earths and other element contents of representative central Deccan samples.

Sample	D333	D325	D331	D274	D330	D335	D339	D293	D294	D288	D313	Low-Ti D320	Low-Ti D319	Low-Ti D316
La ppm	12.54	13.43	21.82	22.56	15.42	18.63	18.46	13.68	15.88	25.27	27.73	12.40	16.32	11.90
Ce	27.95	30.24	49.31	50.03	34.69	41.62	39.65	31.55	36.85	58.94	63.99	24.71	33.03	25.46
Pr	3.74	4.18	6.60	6.65	4.61	5.41	5.21	4.14	5.01	8.06	8.65	3.05	4.12	3.18
Nd	17.09	18.09	27.73	29.54	19.23	24.23	21.24	17.93	23.51	35.19	37.14	13.92	15.20	13.39
Sm	4.21	4.74	7.17	7.29	4.68	6.37	5.26	4.32	5.59	8.67	8.79	3.62	3.83	3.48
Eu	1.48	1.38	2.00	2.23	1.54	2.13	1.54	1.51	1.68	2.46	2.49	1.14	1.18	1.13
Gd	4.98	5.12	7.75	7.18	5.02	6.57	6.02	4.21	4.97	8.98	9.04	3.58	4.82	3.92
Tb	0.74	0.86	1.35	1.14	0.79	1.02	1.07	0.63	0.82	1.46	1.45	0.62	0.82	0.69
Dy	4.18	5.33	8.01	7.05	4.64	5.78	6.65	3.84	5.11	8.85	8.67	4.34	5.02	4.69
Ho	0.80	1.08	1.49	1.43	0.91	1.16	1.38	0.80	1.01	1.75	1.75	1.03	1.09	1.07
Er	2.01	2.82	3.82	3.71	2.43	2.93	3.57	1.94	2.59	4.56	4.50	2.75	2.98	2.62
Tm	0.30	0.40	0.51	0.50	0.33	0.44	0.53	0.28	0.33	0.63	0.63	0.39	0.46	0.41
Yb	1.90	2.50	3.43	2.99	2.02	2.60	3.56	1.74	2.06	3.90	3.97	2.16	3.03	2.68
Lu	0.28	0.35	0.53	0.42	0.30	0.41	0.54	0.27	0.29	0.56	0.55	0.31	0.42	0.46
Hf	3.26	4.55	5.21	4.76	4.34	4.74	4.64	2.82	4.40	5.36	5.53	3.98	4.15	2.49
Ta	0.55	0.42		0.54	0.63	0.75	0.57	0.79	0.71	0.76	0.91	0.39	0.48	0.61
Pb	2.04					3.04		1.73						2.23
Th	3.24	2.05	6.29	3.02	2.18	2.27	4.04	2.07	2.07	3.27	3.98	3.76	3.64	2.18
U	0.73	0.53	1.14	0.55	0.56	0.42	0.93	0.51	0.55	0.71	0.90	0.83	0.78	0.54
La/Yb	4.5	3.6	4.3	5.1	5.1	4.8	3.5	5.3	5.2	4.4	4.7	3.9	3.6	3.0
La/Nd	1.42	1.44	1.52	1.48	1.55	1.49	1.68	1.48	1.31	1.39	1.45	1.72	2.08	1.72
La/Sm	1.87	1.78	1.92	1.95	2.07	1.84	2.21	1.99	1.79	1.83	1.99	2.15	2.68	2.15
Eu/Eu*	0.98	0.85	0.82	0.93	0.96	1.00	0.83	1.07	0.97	0.85	0.85	0.96	0.83	0.93

Ratios are chondrite normalised.

Eu/Eu* = Eu_n/(√Gd_n*Sm_n).

of differentiation (e.g., with decreasing MgO or increasing Zr contents).

The samples D277 and D279 have low Zr/Y (3.5–3.8) at TiO₂ = 1.84–1.86 wt%, and have also low Ba/Y (2.4). They seem to be quite similar to samples of the Ambenali Fm., which is characterized by similar range of these oxides and ratios (cf. Lightfoot *et al* 1990). The samples D327 and D339 have low Zr/Y (3.7–3.9), with high TiO₂ (1.70–1.76 wt%) and Ba/Y (6.3–7.5). From their stratigraphic position and chemistry, they should belong to the Thakurvadi or Khandala Fms.

The lanthanide rare earth element (REE) contents more than double from the least to the most evolved compositions (ΣREE = 82 ppm in D333; ΣREE = 179 ppm in D313; table 3 and figure 5). The low-Ti samples have some of the lowest REE contents (ΣREE = 74–92 ppm), taking into account their evolved nature. The samples are moderately light rare earth element-enriched ((La/Yb)_n from 3.0 to 5.1; the subscript *n* means normalized to chondritic values). The heavy rare earth element patterns are substantially flat ((Tb/Yb)_n from 1.1 to 1.7), with the lowest values found in the low-Ti basalts

((Tb/Yb)_n = 1.1–1.3). Small negative europium anomalies are noted in the evolved samples (Eu/Eu* = 0.85–0.83, where Eu is normalized europium and Eu* is europium interpolated between normalized samarium and gadolinium).

5. Sr-isotopes

Fourteen samples of basalts and basaltic andesites were analyzed for Sr-isotopic composition (table 4). The values recalculated at 66 Ma range from 0.70558 to 0.70618. The data thus show minor variation, when compared to the very wide range observed in the Deccan Trap lava flows (0.7038 to 0.72315; e.g. Peng *et al* 1994; Chandrasekharam *et al* 1999). Nevertheless, these data are significantly higher than typical Ambenali basalts (⁸⁷Sr/⁸⁶Sr = 0.70383–0.70558) and also higher than the lowest values of Pavagadh/drillhole samples of Gujarat (⁸⁷Sr/⁸⁶Sr = 0.70414–0.70457; Peng and Mahoney 1995), testifying input of different source components or the effects of increasing ⁸⁷Sr/⁸⁶Sr due to crustal contamination. The data on the other hand, are similar to those obtained

Figure 5. Chondrite normalized rare earth element diagrams for central western Deccan samples. E-MORB composition from Sun and McDonough (1989). Other samples from Melluso *et al* (1995) or L Melluso (unpublished data). Normalization values of Boynton (1984).

Table 4. *Sr isotopic composition of samples from central Deccan.*

	$(^{87}\text{Sr}/^{86}\text{Sr})_{\text{i}}$		$(^{87}\text{Sr}/^{86}\text{Sr})_{\text{meas}}$		$^{87}\text{Rb}/^{86}\text{Sr}$	
	Rb	Sr	Rb/Sr			
M284	0.70621	30 241	0.70655	0.124	0.360	
M286	0.70593	10 257	0.70604	0.039	0.113	
M287	0.70596	25 251	0.70645	0.100	0.288	
M299	0.70558	30 245	0.70591	0.122	0.354	
M300	0.70605	30 263	0.70662	0.114	0.330	
M304	0.70618	20 241	0.70641	0.083	0.240	
M306	0.70611	21 242	0.70635	0.087	0.251	
M307	0.70562	25 226	0.70592	0.111	0.320	
M308	0.70581	33 236	0.70619	0.140	0.405	
M314	0.70613	20 274	0.70633	0.073	0.211	
M324	0.70601	16 278	0.70617	0.058	0.166	
M331	0.70600	34 214	0.70643	0.159	0.460	
M332	0.70593	12 299	0.70604	0.040	0.116	
M339	0.70600	4 289	0.70604	0.014	0.040	

in most basalts of the Toranmal section, northwest of the study area ($^{87}\text{Sr}/^{86}\text{Sr} = 0.70467 - 0.70675$; Mahoney *et al* 2000), and to the Poladpur Fm basalts (0.70573 – 0.70856; Lightfoot *et al* 1990), which seem to be widespread in the northern Deccan (cf. Mahoney *et al* 2000).

6. Magmatic evolution

The major and trace element variations observed in the central-western Deccan samples with more than 1.5 wt% TiO_2 (figure 4) seem to be generally compatible with crystal fractionation processes starting from chemically similar parental magmas. Major element mass balance calculations indeed indicate that the transition from the most primitive basalts (D331, D325) to evolved basaltic andesites (D313, D310) can be obtained after fractionation (roughly 40–55%) of olivine, plagioclase, clinopyroxene and minor oxides (table 5). Modelling of some elements incompatible with these phases (figure 4) also confirm that moderate degrees of fractionation (ca. 55%) are needed in the transition from the most primitive basalt D333 to the most evolved basaltic andesites. It is worth noting that modelling was successful for both contamination- (and alteration) sensitive (e.g., Ba, K_2O) and insensitive (Zr, Nb, Y, TiO_2) elements and oxides, testifying that the fractionation stage recorded in these lavas occurred not too far from a closed system. The position of the samples in the pseudoternary diagram Forsterite-Diopside-Silica indicates that the evolution occurred at low pressure (close to the surface), and that the samples with pigeonite plot close or at the invariant point with olivine,

Table 5. *Mass balance calculations. Two sets of partition coefficients were calculated: $D(\text{Nb})$ assume $D\text{Nb} = 0$, and hence $f = \text{Nb0}/\text{Nb}$; $D(\text{MB})$ assume f (degree of residual liquid) of the mass balance calculations.*

	From D333	To D313	$f(\text{Nb})$ 0.44 D(Nb)	$f(\text{MB})$ 0.48 D(MB)
TiO_2	1.76	2.43	0.60	0.56
P_2O_5	0.17	0.30	0.31	0.23
Sc	33	32	1.05	1.05
V	335	435	0.68	0.64
Cr	543	99	3.09	3.32
Ni	126	56	2.00	2.11
Zn	104	134	0.69	0.66
Sr	204	262	0.69	0.66
Y	24	45	0.23	0.15
Zr	122	253	0.10	0.00
Nb	7	16	0.00	−0.11
Ba	176	363	0.11	0.02
La	12.54	27.73	0.03	−0.08
Ce	27.95	63.99	−0.02	−0.13
Pr	3.74	8.65	−0.03	−0.14
Nd	17.09	37.14	0.05	−0.06
Sm	4.21	8.79	0.10	0.00
Eu	1.48	2.49	0.36	0.29
Gd	4.98	9.04	0.27	0.19
Tb	0.74	1.45	0.18	0.09
Dy	4.18	8.67	0.10	0.00
Ho	0.80	1.75	0.03	−0.07
Er	2.01	4.50	0.01	−0.10
Tm	0.30	0.63	0.08	−0.02
Yb	1.90	3.97	0.09	−0.01
Lu	0.28	0.55	0.15	0.05

The transition between D333 and D313 was obtained through fractionation of 28.8% olivine, 38.3% cpx and 33% plagioclase.

plagioclase, clinopyroxene, pigeonite and liquid. Empirical whole-rock thermometers suitable for anhydrous tholeiitic compositions (e.g. Eggins 1992; Toplis and Carroll 1995) span temperatures from 1233–1227°C (D333 and D325) to 1125–1123°C, the latter obtained for the evolved basaltic andesites plotting close to or at the reaction point (D337 and D313; figure 6). Sano *et al* (2001) performed crystallization experiments on a composition very similar to the most primitive sample of this study (IG-02; $\text{MgO} = 9 \text{ wt\%}$; $\text{TiO}_2 = 1.7 \text{ wt\%}$) and found olivine on the liquidus at 1220°C, followed by augite at 1190°C, plagioclase at 1170°C, opaque oxides at $T < 1180^\circ\text{C}$ (depending on the oxygen buffer used in the experiments), and pigeonite at 1134°C. The upper and lower temperature values closely match our empirical estimates.

Figure 6. One atmosphere pseudoternary diagram Forsite-Diopside-Silica diagram (Grove *et al* 1982), with the rocks of central-western Deccan. The two temperatures shown in the diagram have been calculated for samples D333 and D313 using the T-MgO relationship of Eggins (1992). Symbols as in figure 2.

7. Chemical correlations and petrogenesis

The low-Ti lava flows from the surroundings of Dhule are chemically unrelated with the other central-western Deccan lava flows. On the other hand, they have very marked chemical similarities with:

- the low-Ti basalts and basaltic andesites widely cropping out in the Kathiawar peninsula, Gujarat (cf. Melluso *et al* 1995);
- the low-Ti dykes of the Tapti dyke swarm (Melluso *et al* 1999);
- the low-Ti basalt lavas cropping out at the Toranmal section (figure 8a; Mahoney *et al* 2000; Chandrasekharam *et al* 1999);
- the Bushe basalts (figure 8b).

The Dhule flows can be considered as the southernmost expressions of the Kathiawar low-Ti types. The low-Ti basalts and basaltic andesites, though being chemically evolved samples, have the lowest incompatible element contents. The pattern of the least incompatible elements and Nb is very similar to average enriched MORB (Sun and McDonough 1989), excluding the selective enrichment in Rb, Ba, K and light rare earth elements. The same is observed from the comparison of the rare earth element patterns (figure 5). This is an indication of their provenance from moderately incompatible element-poor mantle, similarly to the low-Ti basalts of Gujarat and the Tapti dykes (Melluso *et al* 1995, 1999). The flat heavy rare earth element patterns of these rocks indicate their ulti-

mate provenance from sources located within the spinel stability field. The data also indicate that crustal contamination during the ascent to the surface, that may be the cause of the low strength element enrichment over Nb, did not influence the heavy rare earth element contents appreciably. We finally note that contamination processes acting on these samples did not modify their normal low-pressure magmatic evolution, leaving them with compositions plotting on the low-pressure cotectics.

In the mantle normalized diagrams (figure 7), the central-western Deccan basalts have negative Nb, Sr and P troughs. This feature makes these rocks more similar to lavas of lowermost formations of the Western Ghats (Khandala, Thakurvadi and Jawhar), to some of the Poladpur Fm. lava flows, and some high-Ti dykes of Tapti (Melluso *et al* 1999, and unpublished data) rather than typical Ambenali and Mahabaleshwar basalts (cf. figures 5 and 7) and highly enriched basalts of Kathiawar, Pavagadh and Rajpipla (Melluso *et al* 1995; Peng and Mahoney 1995).

The diagrams Zr/Y vs. TiO₂ (figure 8b) indicate that the samples with TiO₂ > 1.5 wt% plot in the same field of the Jawhar-Igatpuri Fm. and still broadly within the very scattered compositions of the Thakurvadi Fm. The Poladpur samples, at broadly the same TiO₂, plot at slightly lower Zr/Y, but this may be the result of different analytical techniques involved. It is worth noting that, on the basis of radiogenic isotope data and multi-elemental statistics, basalts ascribed to the Poladpur Fm. have been found in the Toranmal section (Mahoney *et al* 2000).

The high values of the ratios between large ion lithophile elements and Nb, together with the relatively high ⁸⁷Sr/⁸⁶Sr ratios, are evidence of a crustal input in all the central-western Deccan samples. We note that this feature is already present in the most mafic samples, and there is no evidence of increase of these ratios with increasing degree of fractionation. Therefore, this relative enrichment occurred in a very early stage of evolution (picrite basalt level, not represented in our sample set), or directly in the mantle source.

Concerning the chemical characteristics of mantle-derived magmas which generated the central-western Deccan sequence, from the range of Zr/Y and TiO₂ of primitive tholeiitic magmas (with MgO > 9 wt%) found throughout the province, the composition of the basalts of the central-western area, and fractionation models starting from different parental magmas (figure 8b), we note some features:

- The mafic parental magmas of the Deccan have a large range of variation of Zr/Y and TiO₂, with

Figure 7. Primitive mantle-normalized incompatible (PMN) element diagrams for mafic rocks of southwestern Deccan, and Gujarat. Reference data are taken from Melluso *et al* 1995, 1999, and unpublished data. Primitive mantle values and E-MORB values of Sun and McDonough (1989).

the least enriched end-members being the low-Ti picrite basalts of Gujarat, and the most enriched end-members being the high-Ti picrite basalts of Pavagadh, and drillholes in Gujarat (Melluso *et al* 1995; Peng and Mahoney 1995; Krishnamurthy and Cox 1977).

- Fractional crystallization cannot be the cause of the range of Zr/Y observed in the Deccan basalts and picrite basalts, thus implicating strong parental magma heterogeneity.
- The rocks of central-western Deccan with $\text{TiO}_2 > 1.5 \text{ wt.}\%$ appear to have been generated by fractional crystallization starting from mildly enriched mafic precursors, whereas the low-Ti basalts may have had incompatible

element-depleted primitive precursors, such as the picrite basalts of Gujarat (Melluso *et al* 1995). These latter resemble mid-ocean ridge basalts when high field strength elements are considered.

- A mixing curve between the low-Ti and high-Ti basalts of Gujarat is roughly able to account for HFSE variations of the likely mantle-derived magmas throughout the Deccan. This can indicate that both high field strength element-depleted and -enriched sources were involved, to variable mixing proportions, in the melting processes of the mantle beneath the province. This has to be verified on a larger data set.

Figure 8(a and b). Chemical correlation diagrams between the central western Deccan basalts and other Deccan samples. The chemical data on the Toranmal section are from Mahoney *et al* (2000); the chemical data on the Tapti dykes are taken from Melluso *et al* (1999), and for the Gujarat basalts are taken from Melluso *et al* (1995). Main references for other basalt data are: Bodas *et al* 1988; Khadri *et al* 1988; Cox and Hawkesworth 1985; Lightfoot and Hawkesworth 1988; Lightfoot *et al* 1990, Peng *et al* 1994 and other references therein.

8. Concluding remarks

This study on the flood basalt sequence of central-western Deccan has the following implications for the knowledge of this province:

- The most mafic lava flows of this area have been found in the Western Ghats slopes (close to Igatpuri), whereas the most evolved flows have been mostly found in the eastern-most areas. This may be the result of a temporal change of

Figure 8(b). (Continued)

chemistry of the erupted magmas (more mafic liquids erupted earlier, evolved liquids later and upward sequence, and preserved only far from this sector of the province).

- Most samples have major and trace element compositional trends typical of low-pressure liquid lines of descent of tholeiitic magmas, caused by olivine, clinopyroxene and plagioclase fractionation, starting from the most mafic liquids of this study.

- The incompatible element contents and ratios of the most mafic rocks and the Sr-isotope composition of the central Deccan samples indicate a crustal input. However, the evolution from basalt to basaltic andesite most likely took place in a substantially closed system.
- The lava flows have a strong resemblance to some chemical types of the lowermost formations of the Deccan, and probably also with the Poladpur basalts. The Dhule lava flows with low-Ti

affinity are close analogues of the low-Ti rocks widespread in the Kathiawar peninsula and in the Tapti swarm (cf. Melluso *et al* 1995, 1999; Mahoney *et al* 2000), and should be referred to as a discrete magma type, unlike the low-Ti rocks of the Bushe Fm. This magma type can also be distributed as a chemical type in the lowermost formations.

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Appendix: Analytical techniques

Mineral compositions were obtained on polished thin sections using a CAMECA electron microprobe at CNR-C.S.Q.E.A. Rome. Silicates and oxides were used as standards. The data were reduced utilizing the CAMECA's PAP correction method.

Sample chips, obtained from a steel jaw crusher, were first washed in distilled water and then ground in a low-blank agate mortar. Major and trace elements were analysed at Napoli (CISAG) with a Philips PW1400 X-Ray fluorescence (XRF) spectrometer (more details in Melluso *et al* 1995, 2001). Precision is estimated to be within 1% for SiO₂, TiO₂, Al₂O₃, Fe₂O_{3t} and CaO, better than 6% for K₂O, ± 0.03 wt% for MnO and P₂O₅, generally better than 5–10% for Sc, V, Cr, Ni, Cu, Ba, Zn, Sr, Y and Zr in the observed compositional ranges, and ± 1 ppm for Rb and Nb below 10 ppm. Na and Mg were analysed by atomic absorption spectrophotometry (AAS) at Napoli. Typical precision is better than 2% for Mg and better than 6% for Na.

In order to fully compare XRF data from different laboratories, cross-checking of samples analysed at Naples and Washington State University (courtesy of Peter Hooper) was performed. Bias has been observed for some P determinations and for Ba, though the significance is uncertain, whereas absolutely comparable values have been obtained for the other elemental determinations, in particular for the key incompatible elements Zr, Y,

Nb and Ti. Therefore, major emphasis was given to the elements with comparable analytical uncertainty and accuracy, in order to make all the inferences useful to general readership.

Rare earth elements, U, Th, Pb, Ta and Hf were analysed for a subset of samples by inductively coupled plasma-mass spectrometry (ICP-MS) at C.R.P.G. Nancy (France) (samples D293, D316, D333, D335), and Ferrara University (Italy) (samples D274, D288, D294, D313, D319, D320, D325, D330, D331, D339; table 3). Uncertainty in the measurements are typically within 5–10% relative for most elements in the observed compositional ranges.

Strontium isotopic compositions have been analyzed at Rome University, using a VG54E mass spectrometer. Full details of the analytical procedures are described in Comin-Chiaramonti *et al* (1997).

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