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Petrogenesis of Fractionated Basaltic Lava Flows of Poladpur-Mahabaleshwar Formation around Mahabaleshwar, Western Ghats, India

BABITA R. CHOUDHARY and GAJANANRAO N. JADHAV
Deapartment of Earth Sciences, Indian Institute of Technology Bombay, Powai, Mumbai - 400 076
Email: jadhav@iitb.ac.in

Abstract: Geochemical investigations of Wai sub-group volcanic flows (in and around Mahabaleshwar) have been undertaken to determine the petrogenetic processes involved in the formation of volcanic flows. In comparison to the Ambenali Formation, Mahabaleshwar Formation flows were affected more by crustal materials, which left a signature consisting of enriched levels of K, Rb, Ba, Ti and P. Ratios of Nb/Zr and Ba/Y were sensitive to fractional crystallization; Mahabaleshwar formation flows showed the highest Nb/Zr ratios. Ba was noted as a boundary marker element between the Ambenali (47.3 to 63.9 ppm Ba) and Mahabaleshwar (83.1 to 180 ppm) formations. The general trend of incompatible element concentrations increasing from lower Poladpur to upper Mahabaleshwar flows with increasing Zr and the linear array on the plot are consistent with the fractionation of olivine and clinopyroxene. MgO ranged from 4.8 to 7.1 wt%, TiO_2 from 1.8 to 4.6 wt%, SiO_2 from 47 to 52 wt% and Al_2O_3 from 12 to15.5 wt%. The Mg number (Mg#) was much lower, ranging from 36 to 50. The K_2O/ P_2O_5 ratio showed the role of assimilation in the basaltic flows. TiO_2, Y, Zr, Nb and Mg# were used to determine fractional crystallization, whereas Ba, Rb, K_2O and SiO_2 were used for monitoring the fractional crystallization effects of crustal contamination. The range of Zr/Y and $TiO_2 > 1.8$ wt% appears to have been generated by fractional crystallization starting from enriched mafic precursors.

Keywords: Deccan basaltic flow; Volcanism; Magmatic evolution; Crustal contamination; Geochemistry, Maharashtra.

INTRODUCTION

The Deccan volcanic province (DVP) in western India represents one of the largest accumulations of continental lava flows on earth. The DVP hosts the Deccan traps, a thick sequence of nearly horizontal basalt flows, that erupted at the Cretaceous - Tertiary boundary. Extensive petrological and geochemical studies have produced a well-defined chemical stratigraphy for the DVP (Mahoney et al. 1982; Cox and Hawkesworth 1985; Devey and Lightfoot 1986; Beane et al. 1986; Hooper et al. 1988; Lightfoot et al. 1990; Melluso et al. 1995; Greenough et al. 1998; Mahoney et al. 2000; Melluso et al. 2002; Higgins and Chandrasekharam 2007).

The focus of this work is the part of the DVP (Fig 1a) in and around Mahabaleshwar, in SW Maharashtra, India, which stratigraphically falls in the Wai sub-group (the uppermost sub-group of the DVP). The present study includes a field-petrography and geochemical investigation of the study area. The main aims of the paper are (i) to geochemically characterize the Wai subgroup, flow by flow (Poladpur - Mahabaleshwar) and (ii) to correlate it with the already established observed spectrum of variation in analyzed samples from the study area.

SAMPLING LOCATIONS AND GEOLOGICAL SETTING

For this study representative samples were collected from the road sections of an area within the Wai sub-group. The lava flows have been sampled at different heights within the three formations of the Wai sub-group (Fig 1b) using the geological map (Subbarao and Hooper, 1988). During the excursion, a vertical profile of the different flows was prepared. The studied section, located in the SW part of Maharashtra state in the Satara district, lies 17° 55’ N and 73° 40’ E. The three formations of the Wai sub-group have a combined thickness of 1200 m at Mahabaleshwar and numerous flow exposures have been characterized in the study area (e.g., Najafi et al. 1981; Mahoney et al. 1982; Cox and Hawkesworth, 984, 1985). The present field excursion has identified 46 flows. The Wai sub-group actually consists of five formations: Poladpur, Ambenali,

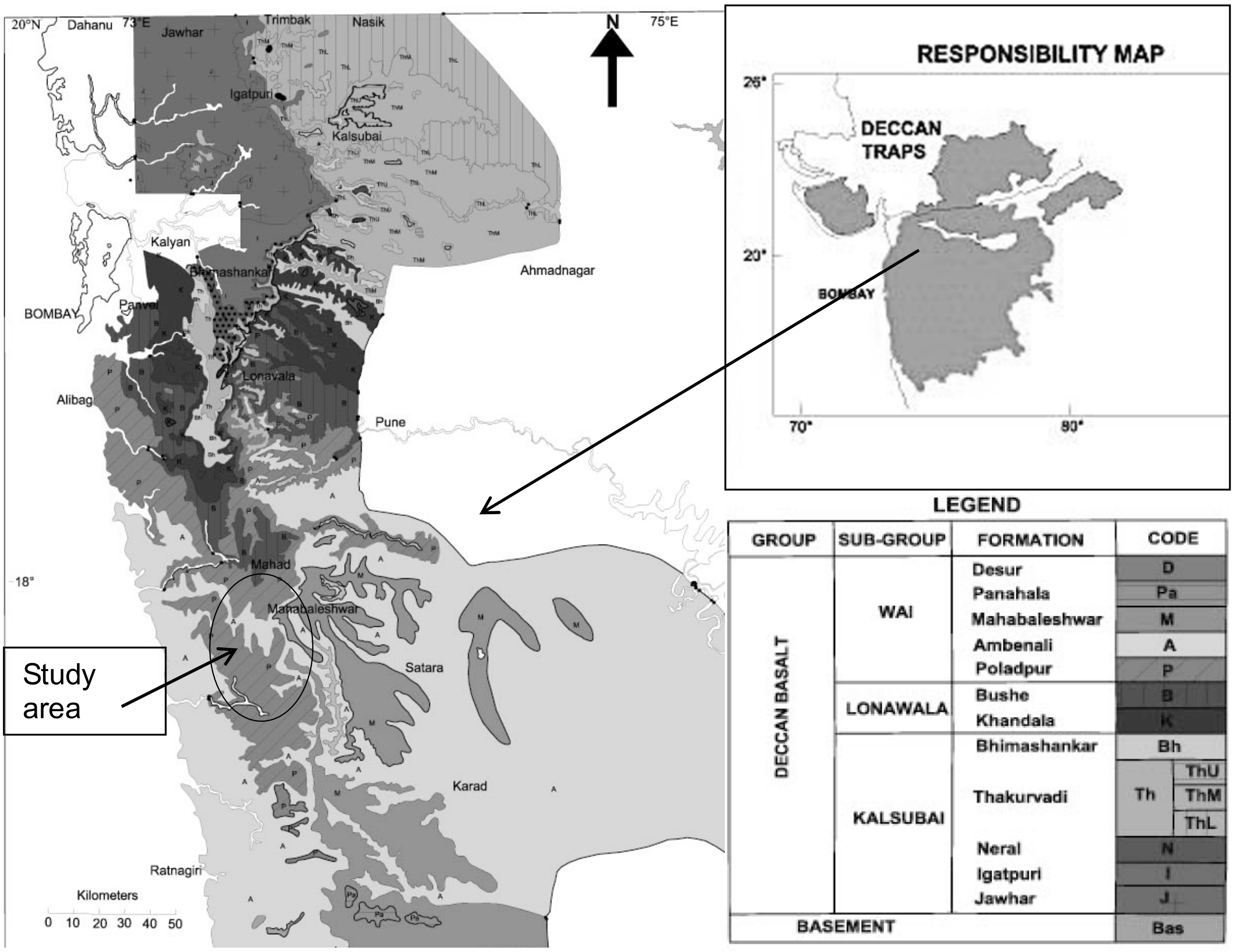

Fig.1. (a) Map showing the major geological subgroups of the Deccan Basalt Group in Western Ghat section , based on Subbarao and Hooper (1988)

Mahabaleshwar, Panhala and Desur, but only the Poladpur, Ambenali and Mahabaleshwar formations are considered in the present study because the two upper formations are weathered or eroded here. The sub-group is composed of both simple and compound flows that are separated by boles that represent pauses in volcanic activity between the flows. Structurally, the flows are approximately horizontal, although in some places they are undulatory in nature (particularly in the Mahabaleshwar Formation). Columnar jointing is commonly observed in thick flows.

PETROGRAPHY

Most of the field samples consist of about 10–20% phenocrysts (plagioclase, clinopyroxene and less-abundant often-altered olivine) and 80-90% microcrystalline groundmass. Iron oxides are abundant. The mostly fractured plagioclase phenocrysts range in size from 1 to 9 mm, whereas, the pyroxene phenocrysts are 2 mm in diameter and have reabsorbed margins (Fig.2). In general, the Ambenali-Mahabaleshwar flows are more porphyritic than the Poladpur flows. Although pyroxene occur as micro-phenocrysts in the samples, it was actually part of the groundmass phase in most of the samples. Olivine occurs mainly in the younger flows of the Ambenali and Mahabaleshwar formations and usually showed varying degrees of alteration. Large plagioclase crystals frequently exhibit zoning (Fig.2a). Glomeroporphyric clusters made up of plagioclase and augite were common in more porphyritic flows (Fig.2b). However, ophitic or sub-ophitic textures were also observed. The groundmass constituents also contained Fe–Ti oxide minerals in addition, to glass.

ANALYTICAL METHODS

Variations in plagioclase, pyroxene, olivine and Fe–Ti oxide mineral content were investigated using SEM-EDX at the Institute of Experimental Mineralogy and Petrology,

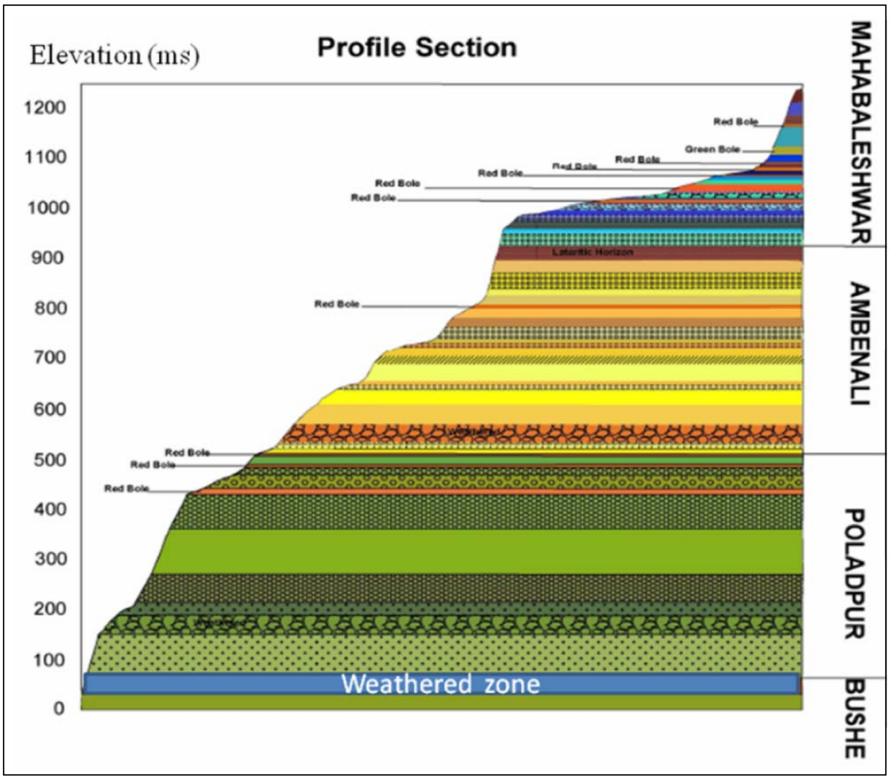

Fig.1b. Vertical profile section along the Poladpur-Mahabaleshwar road section showing flow by flow stratigraphy and redbole distribution in the Wai subgroup basalt

Russian Academy of Sciences, Chernogolovka, Moscow. For the whole rock analyses, whole rock powder was prepared by crushing chips of selected samples in a tungsten carbide ball mill. Bulk rock was analyzed at the Institute of Microelectronics and High Purity Materials, Russian Academy of Sciences, Chernogolovka, Moscow. International standards were used in the calibration. The contents of the major components (Na, Mg, Al, P, S, K, Ca, Ti, Mn, and Fe) and several minor components (Li, V, Cr, Mn, Ni, Cu, Zn, Sr, and Ba) were determined by ICP-AES. Integration time of the spectrum during measurement was 5 s. The determination of the element content in aqueous solutions was carried out quantitatively using calibration solutions (High Purity Standards) of 0.5 and 10 mg/L of each element (Choudhary 2012). Elemental content in the probe was determined using spectrometer software (Thermo SPEC, version 4.1). The same procedure was followed to determine the content of rare earth elements and trace elements by ICP-MS with an X-7 Spectrometer (Thermo Electron, USA). Indium was used as an internal standard in all measurements. Loss on ignition (LOI) for samples was determined after heating at 1000°C for 1 h.

Mineral Chemistry

Chemical analyses obtained from SEM-EDX for the main mineral phases show that calcium-rich pyroxene is predominant in the studied samples (Figs 3a and 3b; Table 1). Ca-rich clinopyroxene belongs to the augite-ferroaugite series. The TiO_2 content in the clinopyroxene is generally low, ranging from 0.79 to 1.74 wt% except for one analysis which has zoned pyroxene phenocryst, where a high value of 3.33 wt% was measured. Al_2O_3 is also low, ranging from 2.08 to 2.91 wt%. The observed clinopyroxene trend is typical of a tholeiitic series magma. In the Ambenali Frmation (sample 18/8; Fig. 3b), a zoned pyroxene crystal shows variation in

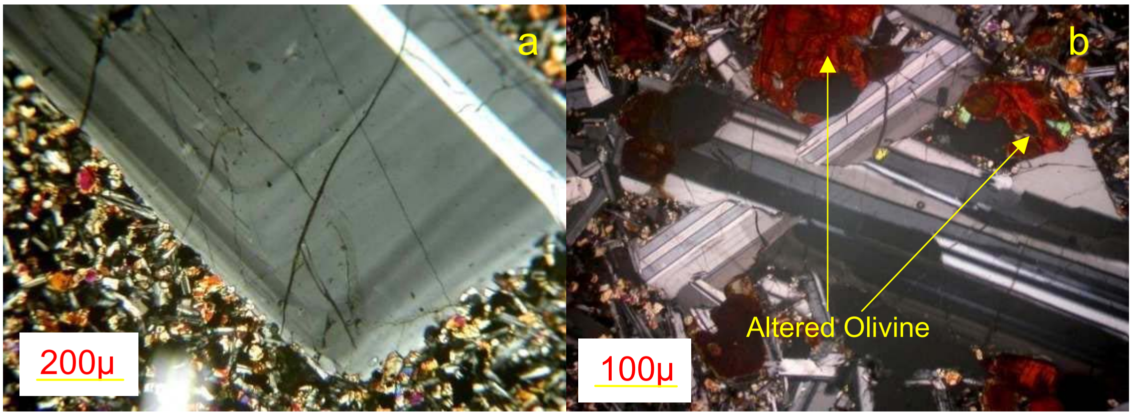

Fig.2. (a) Zoned plagioclase into the Ambenali rock (sample No-19/6 , 10X, XPL). **(b)** Twinned laths of plagioclse and altered olivines in the Mahabaleshwar formation rock (Sample No-33/1, 5X, XPL)

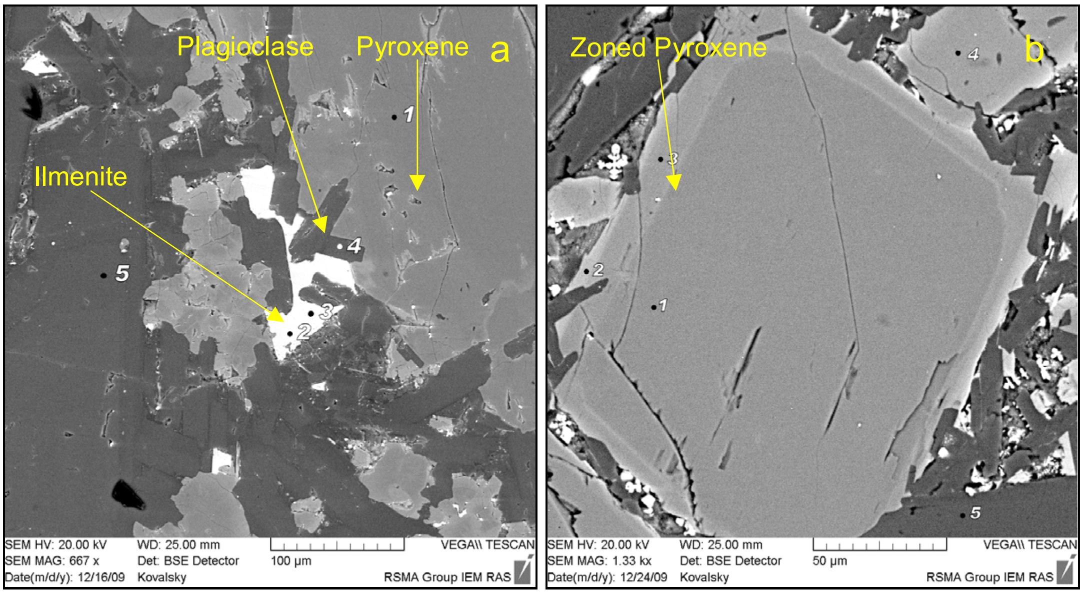

Fig 3 (a) BSE images of Poladpur Formation Sample no. 13/4 different minerals pyroxene, ilmenite, titanomagnetite in the ground mass **(b)** Sample 18/8 from Ambenali Formation showed zoned pyroxene crystal and ground mass feldspar minerals, point analysis results are given in Table 1.

composition from core to rim (Table 1). Samples 13/4 (Poladpur) and 18/8 (Ambenali) have low-calcium pyroxene (pigeonite). Fragments of quartz were found in one sample (19/2) giving visible evidence of crustal contamination (Choudhary 2012). Groundmass titanomagnetite is Al-poor and ilmenite is Mn-poor (MnO).

Oxides and Elemental Geochemistry of Flows

Bulk rock composition analysis was carried out on 18 selected samples to discern petrogenetic parameters and resulting data was plotted on bivarient diagrams. On a plot of total alkali vs. SiO_2 (Fig.4a) the Wai sub-group samples lie in the tholeiitic basalt fields. The variation in MgO with respect to other major elements and magnesium number (Mg#) for samples from the Wai sub-group are shown in Figs.4b to 4i; and analytical data are summarized in Table 2. The analyzed samples from the Mahabaleshwar flows are enriched in K, Rb, Ba, Ti and P, which reflects a crustal signature (Cox and Hawkesworth, 1984) indicating assimilation of crustal material. On the other hand, samples from Ambenali Formation are relatively less contaminated (Table 2).

The MgO in the whole rock ranges from 4.8 to 7.1 wt%, TiO_2 from 1.8 to 4.6 wt%, SiO_2 from 47 to 52 wt% and Al_2O_3 from 12 to 15.5 wt% (Table 2a). Figs. 4b to 4g show chemical variation of MgO with respect to important oxides. Mg# has been plotted against MgO wt% (Fig. 4h) and the plot shows a decreasing trend in MgO content with decrease in Mg#. Low magnesium numbers suggest that the magma was unlikely to have been in equilibrium and also show that the basalt magma was derivative in nature (Cox, 1980). TiO_2, Y and Mg# are used to determine the fractional crystallization and Ba, Rb, K_2O and SiO_2 contents are used for monitoring the fractional crystallization effects of crustal contamination. The Mg# [$Mg\#=100\times Mg/(Mg+Fe2^+)$] estimated for primitive mantle-derived basaltic magmas is 70 (Basaltic Volcanism Study Project, 1981). The Mg#s determined in these samples are much lower, ranging from 36 to 50. The low Mg#, Ni (60-122 ppm), Cr (75-447 ppm) and MgO (4.8–7.1 wt%) contents of the Wai sub-group basalt indicate the evolved nature of the lava. Therefore, they must have been modified significantly by fractional crystallization and/or crustal assimilation processes during ascent (DePaolo, 1981). Thus, it seems that the Wai Formation basalt correspond to evolved Deccan basalt composition, which represents an evolved original partial melt derived from the mantle. Whole rock analysis shows that plagioclases are more consistent in composition (Fig. 4i); in these samples there is a decrease in Al_2O_3 as Mg# decreases, which indicates plagioclase fractionation.

Trace Element Chemistry

The concentrations of incompatible trace elements vary widely (Table 2b). Selected major and trace elements are plotted against Zr in Fig. 5 (a to p). Zr is one of the most incompatible trace elements in a partial melt or crystal fractionation process in basalt. Zr has been chosen as an index of evolution because: (1) it shows large variations,

Table 1. Major oxides of mineral and ground mass from the flows of Wai Subgroup formation

	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	Cr_2O_3	P_2O_5	V_2O_5	SO_3	Cl	Total
Poladpur Formation: 13/4 Ground mass minerals (Fig 3a)															
Pyx	51.5	0.79	2.13	8.68	0.23	15.74	20.15	0.33	0.08	-	0.11	-	-	-	99.74
Ilme	-	53.03	-	45.52	0.53	0.67	0.13	-	-	-	0.12	-	-	-	100
Ilme	0.32	14.2	4.46	77.87	0.3	0.42	-	0.02	0.04	0.04	-	1.28	0.01	-	98
Plag	57.3	0.23	20.43	6.93	0.36	2.16	9.41	5.38	0.54	0.06	0.12	0.01	-	0.01	103
Plag	51.21	-	29.35	0.77	0.17	0.21	12.7	4.06	0.13	-	-	0.03	-	0.03	98.6
Poladpur Formation: 13/4 Ground mass minerals															
Pyx	50.7	0.97	2.27	13.03	0.4	15.12	17.64	0.18	-	-	0.09	-	-	0.05	100.4
Oli	49	0.35	0.65	28.5	0.74	13.2	5.9	0.2	0.02	-	-	0.04	0.2	-	98.82
Plag	52.67	0.003	28.83	0.84	-	0.2	12.36	4.57	0.31	-	-	-	0.09	0.05	99.78
Ilme	0.1	52.04	0.03	44.48	0.43	1.02	0.19	0.08	-	-	0.15	0.34	-	-	98.52
Ambenali Formation: 18/8 Zoned mineral (Fig 3b)															
Pyx	51.66	0.79	2.91	9.75	0.3	15.96	19.39	0.57	-	0.33	-	-	0.01	-	101.7
Pyx	47.83	3.33	3.61	19.82	0.51	9.3	18.18	0.31	-	-	0.02	0.18	0.11	0.08	102.89
Pyx	50.92	1.13	2.79	12.82	0.27	15.92	17.44	0.17	-	0.06	0.1	0.04	-	-	101.6
Pyx	52.02	1.1	2.08	12.75	0.53	15.77	17.1	0.26	0.18	0.15	-	-	-	0.02	101.96
Plag	51.96	0.02	30.19	0.62	0.02	0.23	13.99	3.69	0.18	0.04	-	0.07	-	0.01	100.9
Ambenali Formation: 18/8 minerals															
Pyx	50.31	1.14	2.82	10.39	0.3	16.13	18.33	0.37	0.03	0.47	0.15	-	0.14	0.03	100.4
Pyx	51.5	1.16	2.22	13.1	0.32	15.3	16.9	0.48	0.07	0.02	-	-	-	-	100.66
Pyx	51.18	1.61	1.41	21.17	0.43	18.33	7.74	0.01	0.05	-	-	-	0.17	-	101.94
Pyx	50.41	1.08	2.87	13.97	0.28	15.12	16.62	0.25	-	0.07	0.04	0.1	0.1	0.01	100.68
Plag	52.26	-	29.42	1.22	-	0.34	12.53	4.22	0.02	0.02	0.13	0.05	0.08	-	100.14
Plag	51.12		29.61	0.72		0.3	13.78	3.92	0.07	-	-	-	0.1	-	99.49
Mahabaleshwar Formation: 33/7 –Ground mass mineral															
Plag	54	0.1	27.6	0.78	-	0.15	11.7	4.71	0.21	0.11	-	-	0.07	-	99.37
Plag	55.37	0.01	26.74	1.29	-	0.08	10.2	5.18	0.19	0.06	0.19	-	-	0.03	99.31
Plag	55.35	0.23	28.28	0.69	0.01	0.2	11.72	4.81	0.27	-	0.27	0.06	-	0.01	101.8
Pyx	49.72	1.74	2.49	13.39	0.23	14.61	17.84	0.35	-	-	0.02	0.02	0.08	-	100.4
Pyx	50.72	1.26	2.31	13.45	0.35	14.45	18.61	0.33	-	0.02	-	0.29	0.01	0.03	100.52
Pyx	49.83	1.62	2.85	12.76	0.18	13.84	18.12	0.21	0.09	-	-	0.16	0.09	-	99.5
Ilme	0.18	43.5	0.21	55.3	0.67	0.6	0.24	0.17	-	0.08	-	0.87	0.2	0.09	100.91
Mahabaleshwar Formation: 34-2- Ground mass mineral															
Plag	51.51	0.23	30.01	0.58	-	0.17	13.56	3.95	0.22	-	-	-	0.19	0.04	100.2
Plag	53.85	0.17	27.94	1.12	0.07	0.15	11.65	5.15	0.21	0.12	-	0.08	-	0.02	100.46
Pyx	50.98	1.24	2.14	13.66	0.37	16	16.44	0.29	0.02	0.19	0.06	-	0.12	-	100.71
Pyx	51.5	0.92	2.37	8.73	0.37	16.4	19.3	0.3	0.02	0.37	-	-	0.04	0.06	100

Pyx= pyroxene, Plag= plagioclase, Oli= olivine, Ilme= Ilmenite

(2) it is one of the elements least likely to have been affected by alteration, and (3) Zr/Nb is relatively unaffected by the low-pressure fractional crystallization of a gabbroic assemblage such as plagioclase, pyroxene and olivine (Hooper et al. 1994). Lightfoot et al. (1990) proposed that the Ambenali Formation has a Zr/Nb range of 10.5–17; the data obtained from the samples studied here show a range of 9–17. The plot of Zr/Nb ratio against Ba/Y (Fig. 5a) supports the established view of Lightfoot et al. (1990), that the flows of the Wai sub-group have been derived from a source with similar Zr/Nb.

In general, samples show a broadly decreasing trend of MgO, CaO, Al_2O_3, Cr, and Ni and an increase in P_2O_5, TiO_2, Sr, Y, Nb, Ba and Sc with increasing Zr (Figs 5b to 5p); K_2O has an almost scattered trend. K_2O, Rb and Ba reach values as high as 0.59 wt%, 15.2 ppm and 180 ppm, respectively, in the samples from Mahabaleshwar Formation. The concentrations of incompatible trace elements vary widely. Zr varies in Poladpur samples from 109 to 148 ppm, in Ambenali samples from 139 to 179 ppm and in Mahabaleshwar samples from 138 to 272 ppm. Y varies in Poladpur samples from 23.7 to 28.7 ppm, in Ambenali samples from 28.3 to 35.2 ppm and in Mahabaleshwar samples from 22.2 to 45.3 ppm. Nb in Poladpur samples ranged from 6.4 to 9.8 ppm, in Ambenali samples from 10 to 11.9 ppm and in Mahabaleshwar samples from 11.6 to 28.1 ppm.

Lightfoot et al. (1990) suggested that Ba contents is a key factor for distinguishing Ambenali rocks from Poladpur

Table 2a. Major oxide distribution in Poladpur, Ambenali and Mahabaleshwar formations

	Poladpur				Ambenali				Mahabaleshwar									
Oxides (wt%)	13/4	14/9	15	17	18/8	19/2	19/6	23/6	31/1a	31/1b	32/4	32/7	33	33/5	33/7	34/2	36/6	37/3
SiO_2	48.98	50.97	48.32	49.26	50.17	49.17	48.38	47.03	47.39	47.78	50.6	50.27	48.85	49.81	51.03	51.2	49.3	50.96
TiO_2	1.72	1.99	2.17	2.75	3.09	3.19	3.21	2.78	4.46	4.6	2.4	3.58	3.52	3.5	3.02	3.21	2.55	2.34
Al_2O_3	14.83	13.96	14.4	13.44	12.97	13.16	13.45	13.42	12	11.99	14.9	12.88	13.17	12.23	13.86	13.05	14.54	14.85
Fe_2O_3	15.21	13.56	14	15.8	17.16	15.68	16.26	16.41	18.24	17.69	13	15.01	15.98	16.99	14.83	15.06	14.14	14.85
MnO	0.17	0.17	0.2	0.21	0.19	0.2	0.21	0.22	0.24	0.24	0.14	0.22	0..28	0.2	0.19	0.2	0.19	0.17
MgO	5.58	6.18	7	5.89	5.3	5.61	5.73	6.86	5.44	5.2	5.9	5.13	5.73	4.85	4.68	5.82	5.89	5.37
CaO	10.33	10.27	11.24	9.62	8.38	10.07	9.94	10.54	9.02	9.2	10.4	9.4	9.55	9.13	8.78	8.23	10.31	8.54
Na_2O	2.39	2.39	2.27	2.55	2.29	2.52	2.41	2.29	2.48	2.6	2.6	2.62	2.41	2.62	2.93	2.51	2.55	2.44
K_2O	0.32	0.33	0.21	0.26	0.2	0.15	0.16	0.24	0.34	0.32	0.45	0.57	0.2	0.35	0.37	0.4	0.31	0.25
P_2O_5	0.16	0.16	0.19	0.23	0.26	0.24	0.24	0.21	0.39	0.39	0.21	0.31	0.3	0.31	0.31	0.3	0.21	0.21
Total	99.99	99.98	100.00	100.01	100.01	99.99	99.99	100.0	100.0	100.01	100	99.99	99.99	99.99	100	99.98	99.99	99.98
LOI	2.91	2.19	2.73	2.81	1.91	2.83	1.83	2.19	1.82	1.92	1.84	2.56	1.68	1.98	2.55	1.76	2.65	1.85
Mg#	43.39	47.42	50.0	42.40	37.95	41.59	41.12	45.24	36.81	37.15	47.17	37.42	41.45	36.00	38.53	42.64	45.14	45.36

Table 2b. Trace element distribution in Wai Subgroup

Element (ppm)	13/4	14/9	15	17	18/8	19/2	19/6	23/6	31/1	31/1	32/4	32/7	33	33/5	33/7	34/2	36/6	37/3
Sc	39.4	35.6	37.3	33.4	37.3	36.6	37.9	34.5	36.5	38.1	27.9	39.0	38.7	36.6	31.3	39.4	32.6	34.1
V	338	340	356	438	454	478	432	418	464	447	290	416	403	410	369	381	354	341
Cr	391	242	408	75.4	294	441	113	127	350	338	447	401	78.2	281	344	439	305	413
Co	47.3	49.6	49.3	51.4	42.2	46.4	48	53.2	58.2	51.6	44.8	49.7	46.7	47.2	44.1	46.1	50.6	41.4
Ni	86.1	104	119	95.8	88.1	104	112	99.2	103	96.2	122	65.9	60.7	72.4	80.9	89	81.6	91.5
Rb	8.3	12.9	2.8	3.7	12.5	4.1	4.9	3.5	6.3	5.5	8.6	8.5	2.8	15.2	4.3	11.2	3.7	9.7
Sr	187	177	190	194	199	205	200	182	234	232	270	231	222	216	209	202	200	197
Y	27	23.9	23.7	28.7	35.2	32.7	32.4	28.3	45.3	38.1	22.2	37.6	33.6	36.3	39.4	34.2	27.5	29.1
Zr	109	114	112	148	179	173	169	139	272	243	138	227	204	221	208	185	158	148
Nb	6.4	8.0	8.7	9.8	11.9	11.8	11.3	10.0	28.1	27.0	14.9	21.7	20.3	21.0	19.0	15.3	13.4	11.6
Ba	75.3	51.8	53.4	57.0	47.3	63.9	63.8	61.9	141	139	176	180	115	143	136	122	115	83.1

Table 2c. Rare eath elements distribution in Wai Subgroup

Element (ppm)	13/4	14/9	15	17	18/8	19/2	19/6	23/6	31/1	31/1	32/4	32/7	33	33/5	33/7	34/2	36/6	37/3
La	10.1	8.6	8.7	9.6	12.3	11.7	12.6	9.2	26.4	24.2	16.3	22.3	19.1	22.1	20.5	17.2	14.7	13.9
Ce	23.1	21.9	22.7	24.5	31.1	30.1	30.7	23.4	61.7	55.6	37.1	52.2	47.0	51.5	46.2	41	33.5	32.4
Pr	3.6	3.2	3.3	3.8	4.7	4.4	4.8	3.4	8.7	7.4	4.7	7.1	6.3	6.9	6.3	5.8	4.6	4.5
Nd	17.1	16.2	16.6	19.2	23.8	22.4	23	17.5	38	34.3	20.0	32.2	29.8	31.5	29.0	26.2	21.6	21.6
Sm	4.7	4.7	4.8	5.6	6.6	6.5	6.5	5.2	10.1	8.9	4.9	8.0	7.5	8.0	7.3	6.9	5.5	5.6
Eu	1.7	1.5	1.5	2.1	2.4	2.0	2.3	2.0	3.1	2.5	1.8	2.4	2.2	2.3	2.6	2.3	2.0	1.9
Gd	6	5.8	5.7	6.8	8.3	7.8	8.2	6.3	11.4	10.3	5.4	9.3	8.7	9.3	8.5	8.2	6.5	6.9
Tb	1	0.95	1.0	1.1	1.3	1.3	1.3	1.0	1.8	1.6	0.84	1.5	1.3	1.5	1.3	1.3	1.0	1.1
Dy	5.2	5.5	5.6	6.1	7.6	7.2	7.5	5.8	9.7	9.1	4.7	8.4	7.7	8.3	7.8	7.8	5.9	6.3
Ho	1.1	1.1	1.2	1.2	1.4	1.5	1.5	1.1	1.9	1.8	0.91	1.7	1.6	1.7	1.5	1.4	1.2	1.3
Er	3.2	2.9	3.2	3.4	4.1	4.0	3.9	3.2	5.4	4.9	2.5	4.6	4.2	4.5	4.3	4	3.4	3.6
Tm	0.44	0.40	0.41	0.44	0.53	0.53	0.56	0.43	0.69	0.64	0.36	0.63	0.56	0.59	0.58	0.59	0.42	0.49
Yb	2.7	2.5	2.5	2.8	3.3	3.4	3.4	2.7	4.4	4.0	2.2	4.0	3.5	3.9	3.6	3.6	2.8	3.1
Lu	0.38	0.37	0.36	0.39	0.46	0.47	0.48	0.38	0.62	0.57	0.33	0.58	0.51	0.56	0.52	0.49	0.42	0.43
Hf	3.4	3.6	3.7	4.6	5.2	5.2	4.9	4.0	7.6	7.4	4.0	6.7	6.1	6.7	6.0	5.4	4.5	4.5
Ta	0.59	0.87	0.91	1.1	1	1.2	0.94	1.0	2.3	2.6	1.3	2.2	2.0	2.1	1.8	1.4	1.2	0.93
Th	1.3	1.0	1.0	1.1	1.4	1.4	1.4	1.1	3.1	2.8	2.2	3.0	2.8	3.0	2.6	2.1	1.9	1.4
U	0.33	0.26	0.25	0.29	0.37	0.37	0.37	0.26	0.77	0.68	0.48	0.76	0.65	0.72	0.55	0.5	0.34	0.33

lava samples. Ambenali Formation rocks contain < 100 ppm Ba whereas Poladpur rocks generally have >100 ppm Ba. Similarly, Sheth et al. (2004) proposed that Ba is useful in discriminating the Mahabaleshwar Formation (Ba >100 ppm) from the Ambenali Formation. Our study supports these categorizations. In the present study the Ambenali samples contain 47.3 to 63.9 ppm Ba whereas Poladpur samples show 51.8 to 75.3 ppm of Ba (i.e., Ba < 100 ppm; Choudhary, 2012). The Mahabaleshwar flows show Ba in the range of 83.1 to 180 ppm (with a majority of the samples exceeding 100 ppm). The results show a relatively high Sc content (27.9–39.4 ppm), relatively low Ba/Nb and La/Nb (4-12 and 0.9-1.57, respectively), a moderate range of Zr/Y (4–6.5) and Ti/V (31-61), and high Nb/U (19-39). There is no correlation between the value of these ratios and degree of differentiation (e.g., with decreasing MgO or increasing Zr contents). The samples are moderately enriched in light rare earth element (e.g., La/Yb from 3.4 to7.4). The heavy rare earth element patterns are flat (e.g., Tb/Yb from 0.35 to 0.40).

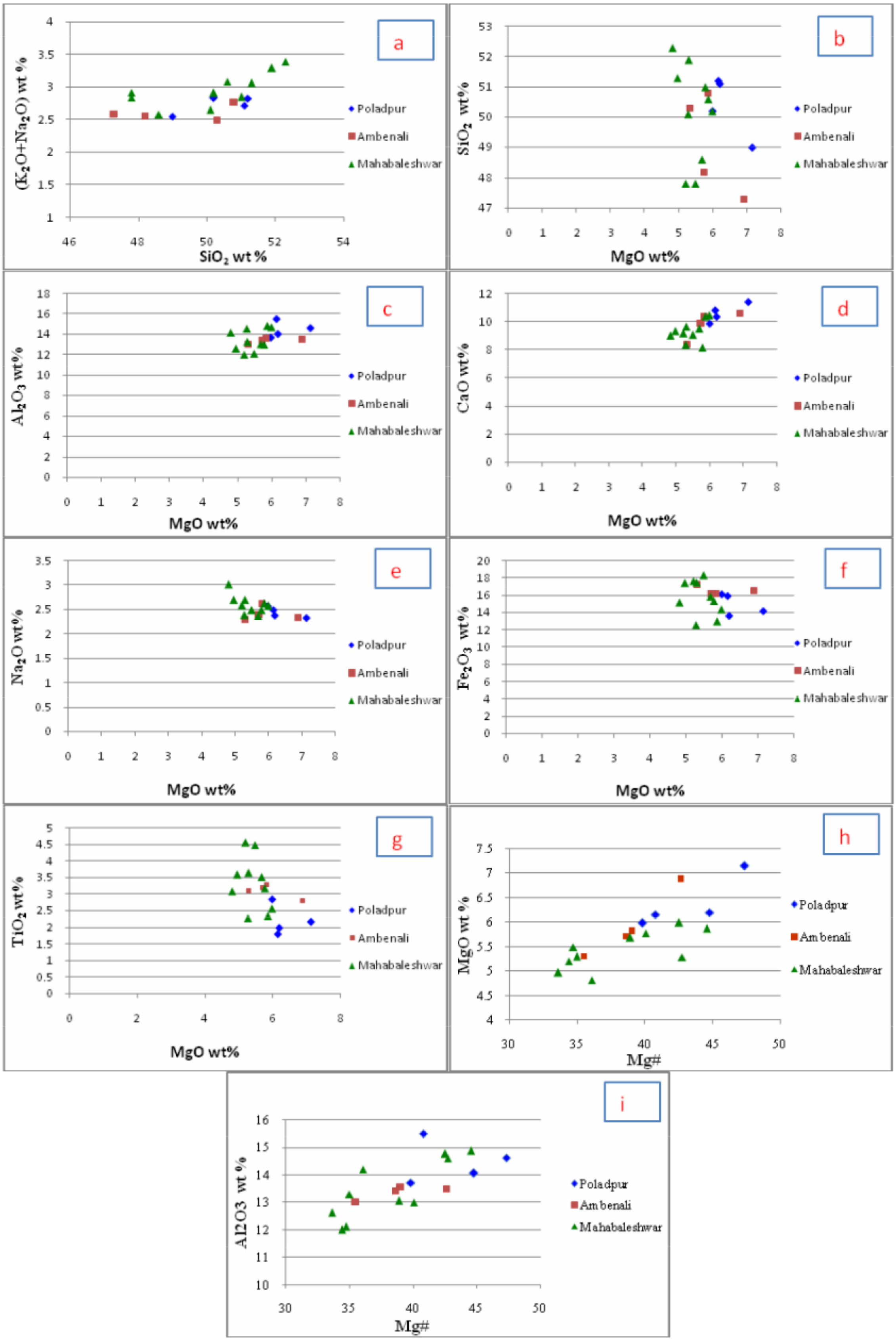

Fig.4. Variation diagram of major oxides versus MgO and Magnesium number.

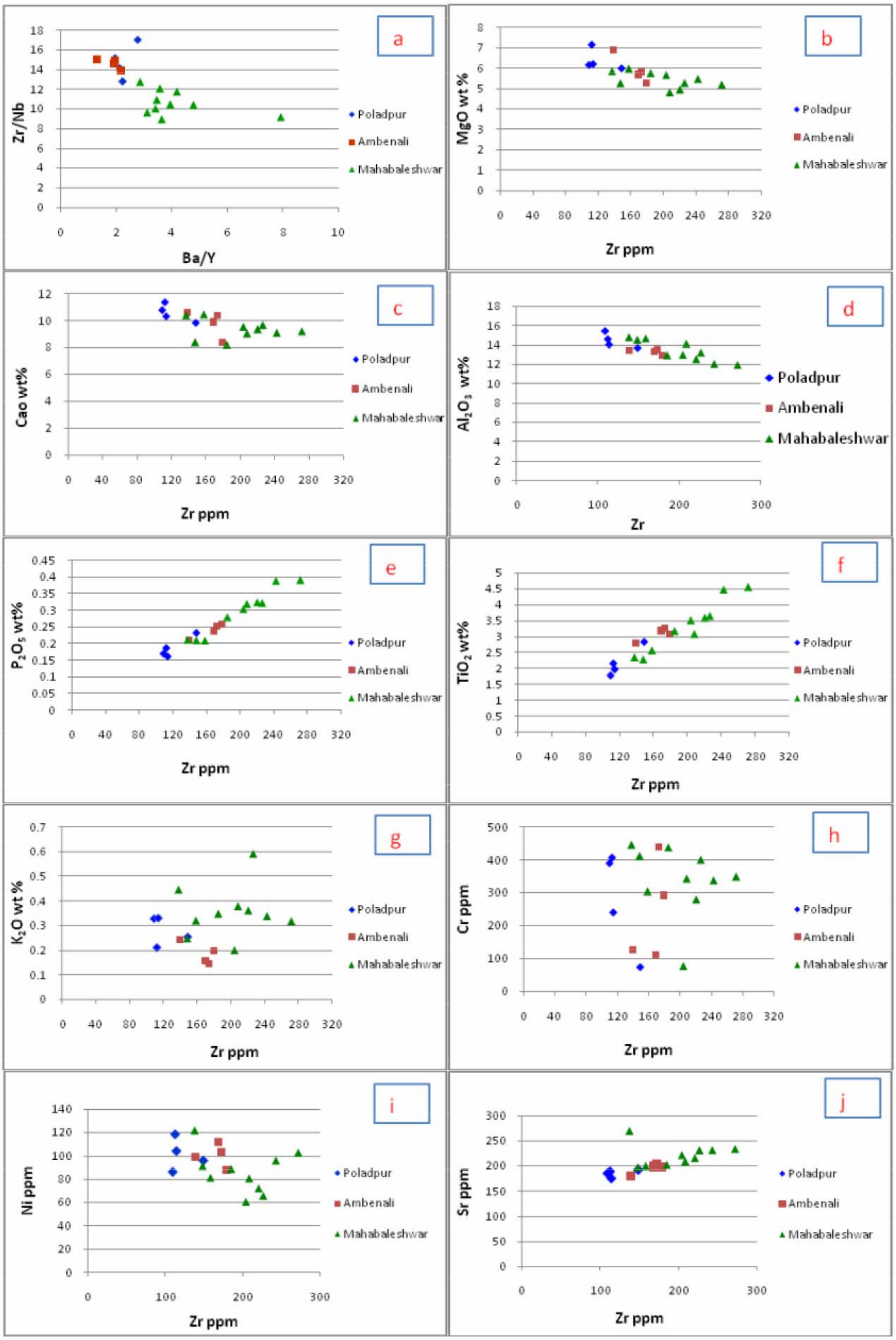

Fig.5. Variation diagram of selected major element oxides (wt.%) and trace elements (ppm) versus Zr

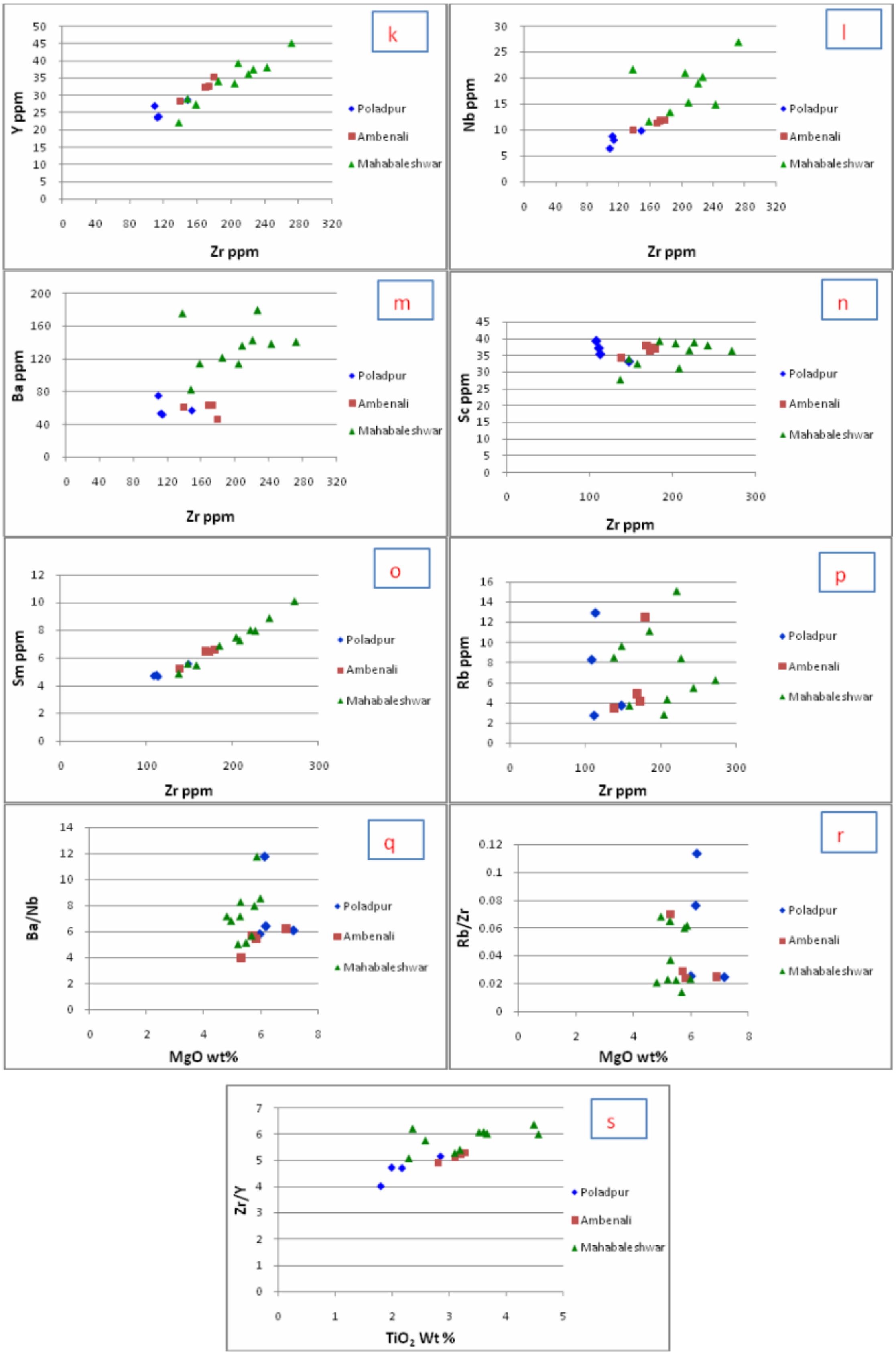
k
Y ppm
0 5 10 15 20 25 30 35 40 45 50
Zr ppm
0 40 80 120 160 200 240 280 320
l
Nb ppm
0 5 10 15 20 25 30
Zr ppm
0 40 80 120 160 200 240 280 320
m
Ba ppm
0 40 80 120 160 200
Zr ppm
0 40 80 120 160 200 240 280 320
n
Sc ppm
0 5 10 15 20 25 30 35 40 45
Zr ppm
0 100 200 300
o
Sm ppm
0 2 4 6 8 10 12
Zr ppm
0 100 200 300
p
Rb ppm
0 2 4 6 8 10 12 14 16
Zr ppm
0 100 200 300
q
Ba/Nb
0 2 4 6 8 10 12 14
MgO wt%
0 2 4 6 8
r
Rb/Zr
0 0.02 0.04 0.06 0.08 0.1 0.12
MgO wt%
0 2 4 6 8
s
Zr/Y
0 1 2 3 4 5 6 7
TiO₂ Wt %
0 1 2 3 4 5
◆ Poladpur
■ Ambenali
▲ Mahabaleshwar

Fig.5. Contd...

DISCUSSION

Crystal Fractionation

The continental flood basalt of the DVP is saturated with plagioclase, pyroxene and olivine. The successive flows generally demonstrate chemical variations that can be explained by low-pressure fractionation of these minerals. This is well supported by previous work in the region (e.g., Cox, 1980; Hooper, 1988b; Lassiter et al., 1995; Baragar et al., 1996; Hawkesworth et al., 2000). Bivariant plots of major and trace element analyses (Figs. 4 and 5) suggest that fractional crystallization played a controlling role in the wide compositional variation that occurred during the evolution of the studied basalts. The general trend of increasing concentrations of incompatible elements (e.g., Nb and Y) with increasing Zr, suggests olivine and/or clinopyroxene fractionation (Figs. 5k and l); the linear array on the plot is consistent with this fractionation hypothesis. Plagioclase and clinopyroxene fractionation are reflected in plots of Zr vs. CaO (Fig. 5c). Cr and Ni have a generally inverse correlation with Zr concentrations, which also explains the fractionation of olivine and clinopyroxene (Figs. 5h and i). The variation in TiO_2 and P_2O_5 (elements compatible with Ti oxides and apatite) shows an increase in the contents of these elements with increasing Zr concentration (Figs. 5e and f). The major and trace element variation and mineralogical evidence from the Wai sub-group basalts support open system fractionation and magma mixing processes in a shallow crustal magma chamber. The variation diagrams (Figs 4b to g) show that rocks with less than 7% MgO demonstrate that the gabbro fractionation trend matches with the characters of other continental flood basalt occurrences. An increase in Zr and P_2O_5 suggest that approximately 50% of the gabbro must be fractionated from parent basalt bodies with more than 7% MgO (Cox and Hawkesworth, 1985). Crystal fractionation processes may play a role in controlling some of these variations, but the distinct behavior of elements such as Zr, Y, Nb, La, Rb, Nd, K, P and Ti suggests that the degree of melting, inhomogeneities in the mantle source, or magma mixing should be considered.

Crustal Contamination

Past studies have documented the importance of crustal contributions in the contamination of continental basalts (e.g., DePaolo, 1981). According to Cox (1980) mafic magma injections induce crustal melting and magma mixing. The large ion lithophile elements (LILE), such as K, Rb, and Ba, and high field strength elements (HFSE), such as Zr and Nb, are incompatible in the investigated basalt samples. Ratios like those of Ba/Nb or Rb/Zr will not significantly change with simple fractional crystallization in basaltic rocks, although variations in these ratios can be related to crustal contamination resulting from the high Ba/Nb and Rb/Zr (Figs. 5q and r) of the continental crust (Taylor and Maclennan, 1985). This figure shows that most of the samples have no significant variation in Ba/Nb or Rb/Zr ratio with decreasing MgO, which explains the extent of crustal involvement. Assimilation and fractional crystallization are the possible processes when Mg#s are low (36–50). However, massive amounts of crustal contamination affect elements severely enough to mask the actual fractionation trends in the studied lava flows. The high values of the ratios between large ion lithophile elements and Nb, also focuses on the crustal input in the Wai sub-group lavas.

Mantle Source and Evolution

The bulk distribution coefficients of Zr and Sm are small and similar in both mantle melting process and fractionation of basaltic magmas (Sun and McDonough, 1989). The variation diagram of Zr versus Sm (Fig.5o) shows good correlation. As mentioned by Saunders et al. (1992), correlation between source compositions and measured ratios of incompatible elements in basalt is at best tentative and the ratios may reflect an integration of source values. The constancy of the Zr/Sm ratio in the samples studied suggests a single magmatic lineage for the mantle source, i.e., a single mantle source for the lava flows of the Wai subgroup. This is also supported by the normalized trace element pattern for primitive mantle (Fig.6) and the constancy of average incompatible element ratios: Ba/Nb=11 to 5 (except one sample having low value), Ba/La=10 to 5 (except one sample having low value), Rb/Nb=0.13 to 1.6 and La/Nb=0.89 to 1.57.

Commonly, the major and trace element variations observed in samples with more than 1.8 wt% TiO_2 seem to be compatible with crystal fractionation processes. Sensitive (Ba and K_2O) and insensitive (Zr, Nb, Y and $TiO_{2)}$ elements and oxides depict the fractionation recorded in these lavas. A comparison of the Wai sub-group basalt formation (Fig. 6) reveals differences in the degree of incompatible element enrichment and their variation that follows a trend. Incompatible elements (Zr, Y, Nb, La, Rb and Nd) are those most likely to be transported by melts and other fluids passing through the mantle. They are the elements which reflect the process of mantle enrichment and depletion and also the degree of partial melting.

Chemical Correlations and Petrogenesis

The pattern of the least incompatible elements is very

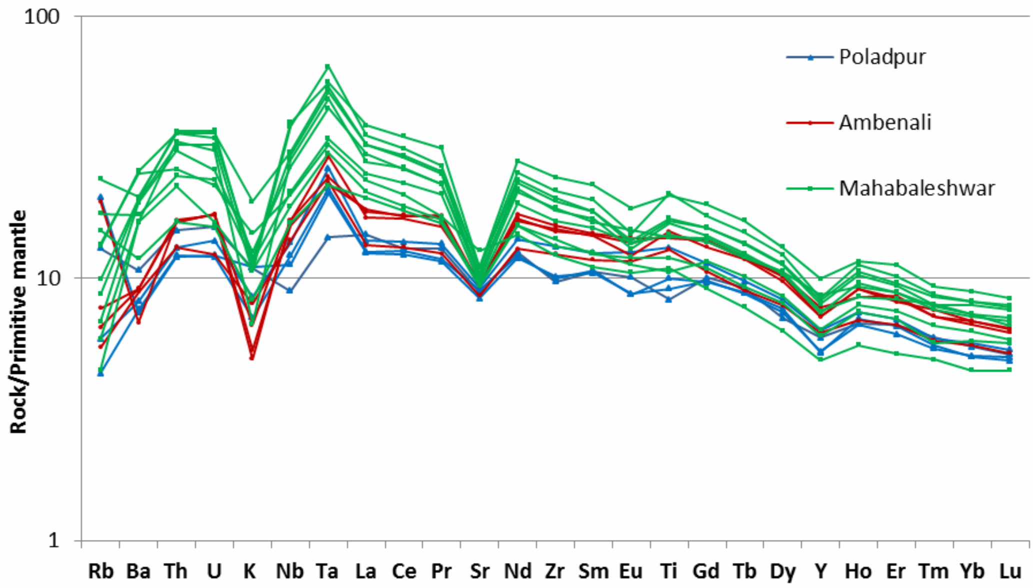

Fig.6. Primitive mantle normalized multielemental pattern of more evolved flow basalt of Wai subgroup formations (average composition pattern)

similar to average enriched mid-ocean ridge basalt (MORB). The Mahabaleshwar and Ambenali formations show similar peaks for all elements except Ba (normalized primitive-mantle multi-element pattern (Fig. 6). However, all flows of the three formation almost have the same value for Sr; the Ambenali and Poladpur formations have parallel trends for Rb up to Pr, whereas from Sr to Lu the Ambenali and Mahabaleshwar formations show similar patterns. This suggests that their origin is from a moderately incompatible element-rich mantle (Melluso et al., 1995; 1999). The data also show that crustal contamination during the ascent may have been the cause for enrichment of low-strength element over Nb and did not influence the heavy rare earth element contents appreciably.

CONCLUSIONS

- Crystal fractionation, mixing and crustal contamination of the source magma are the primary reasons for compositional variability in Wai sub-group basalts. The much lower Mg# suggests that the magma was modified significantly by fractional crystallization and crustal assimilation. Sensitive Ba and K_2O and insensitive Zr, Nb, Y and TiO_2 elements and oxides indicate fractionation. The distinct behavior of elements such as Zr, Y, Nb, La, Rb, Nd, K, P and Ti suggest variable degree of melting, inhomogeneities in the mantle source or magma mixing which are to be considered.
- Occurrences of MgO with concentrations less than 7% demonstrate that the gabbro fractionation trend which is similar to several other continental flood basalts. Zr/Y and TiO_2 >1.8 wt% appear to have been generated by fractional crystallization starting from enriched mafic precursors, suggesting an incompatible element-rich mantle. The constancy of the Zr/Sm ratio and average incompatible element ratios Ba/Nb, Ba/La, Rb/Nb and La/Nb suggest a single magmatic lineage for the mantle source.
- The primitive mantle normalized multi-element patterns show contamination by continental material. Variations in Ba/Nb and Rb/Zr ratios are related to crustal contamination since Ba/Nb and Rb/Zr are high in the continental crust. In comparison, the Ambenali Formation flows were less affected by crustal materials. The high ratios of large ion lithophile elements and Nb are evidence of a crustal input in the flows Wai sub-group.

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