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Structures, Petrography and Geochemistry of Deccan Basalts at Anantagiri Hills, Andhra Pradesh

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Abstract: The Deccan basalts of Anantagiri hills near Vikarabad are characterized by the occurrence of a complete and continuous sequence of colonnade structures below the laterites. These structures have enabled division of flow units 2, 3, 4, 5, 6 from the bottom upwards, into three well defined zones – Lower Colonnade Zone (LCZ); Middle Entablature Zone (MEZ) and Upper Colonnade Zone (UCZ) underlying a 5-10 m thick laterite cover. These fine to medium grained basalts composed of plagioclase, clinopyroxene, ± olivine, Ti-magnetite, ilmenite, glass, cholorophaeite and zeolites commonly show intersertal, glomeroporphyritic and rare sub-ophitic and porphyritic textures. On the A-F-M ternary plot these basalts plot in the iron rich tholeiitic field. REE plots of these rocks define patterns with mild LREE enrichment and negative Eu anomaly. Their primitive mantle normalized multi-element patterns show mild positive LREE coupled with slight LILE depletion, positive Ba, Ta and Pb peaks. The TiO_2/Yb vs Nb/Yb ratios in these tholeiites suggest a slightly enriched source with an MORB affinity. The major and trace element signatures of these tholeiitic basalts occurring at Anantagiri hills and the adjacent low lying areas in south-eastern Deccan Volcanic Province, have broad affinities with the basalts of Ambenali Formation with an overlap on basalts of Poladpur Formation, though with minor variations suggesting geochemical similarity with these two type area basalt formations.

Keywords: Deccan volcanic province, Anantagiri Hills, Colonnade structures, Tholeiites, Ambenali-Poladpur Formation Basalts, E-MORB, Andhra Pradesh.

INTRODUCTION

The Cretaceous age Deccan Volcanic Province (DVP) encompasses largely western and central India, wherein the total thickness and the number of discrete flows is the greatest in the western parts, decreasing gradually towards the east and south (Mitchell and Widdowson, 1991; Mahoney et al., 2000; Jay and Widdowson, 2008). Deccan flood basalt volcanism has been suggested to be associated with extensional tectonics, related to lithospheric stretching and continental rifting (Sheth, 2005a), in contrast to the existing plume tectonic models (Basu et al., 1993; Sen and Cohen, 1994; White and McKenzie, 1995; Sheth and Chandra-sekharam, 1997). The present area of study covers the Anantagiri Hills near Vikarabad in Andhra Pradesh (Fig.1a,b), wherein according to Dutt (1971) the Deccan basalts are represented by nine well developed lava flows (Flow:1-bottom most and Flow: 9-topmost), in which the top 3 flows (flows 7,8 &9) constitute the 5-10 m thick laterite cover. A detailed field, petrographic and geochemical study is attempted in this paper to understand the geochemical affinity of the source. Though the occurrence of columnar structures is well known in the Deccan Volcanic Province, this study is mainly aimed at: (a) reporting for the first time the existence of a continuously complete sequence of colonnade structures represented by the UCZ, MEZ and LCZ at Anantagiri hills, and (b) proposing that, as these basalt flows at Anantagiri hills and the adjoining areas in south-eastern Deccan Volcanic Province, with a MORB like geochemical affinity are compositionally broadly similar to the basalts of Ambenali Formation and Poladpur Formation (both occurring in southwest of Western Deccan Volcanic Province).

GEOLOGICAL SETTING AND PRIMARY VOLCANIC STRUCTURES

Dutt (1971) and Sinha (1974) have reported the occurrence of nine lava flows in Vikarabad and adjoining areas including the Anantagiri hills. According to them, these nine flows are separated either by an intertrappean or red

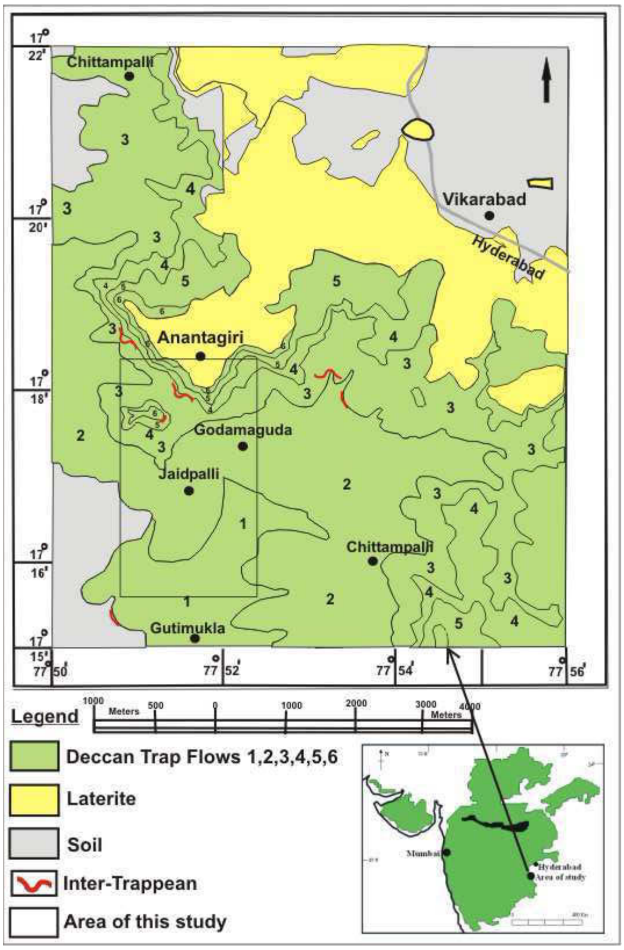

Fig.1. (a) Geology map of Anantagiri Hills and the adjacent low lying area showing Deccan Basalt Flow No's: 1, 2, 3, 4, 5 and 6 with laterite cover (Basalt Flow No's: 7, 8 ,9) (map after Dutt, 1971) . Inset map **(b)**, shows the location of the area of study in SE-Deccan Volcanic Province.

bole or an ash bed. Flows 9, 8 and 7 on the hill top are lateritised and flows 6, 5, 4 and 3 are prominently exposed over a vertical thickness of 350-400 meters on the flanks of the Anantagiri hills proper, while flow 2 and 1 are exposed in the adjacent valley and the surrounding low lying areas. Features such as vertical columnar cooling joints, horizontal fractures, vesicle rich flow top and bottom zones observed during this study, have enabled for the first time, identification of an Upper Colonnade Zone (UCZ) grading stratigraphically downwards into the Middle Entablature Zone (MEZ) which in turn is underlain by the Lower Colonnade Zone (LCZ) (Fig.2). Based on this study, it is suggested that basalt flow-6 constitutes the UCZ; basalt flow-5 defines the MEZ while basalt flows- 4, 3 and 2 make up the LCZ respectively.

The three tier classification of primary volcanic structures proposed by De (1996) has been adopted here for describing the columnar structures occurring at Anantagiri hills. The columns in the UCZ are five sided and on an average 2 m in height, with a cross-width of 1m and showing an exposed column stack thickness of 5m (Fig 3a). The cooling joints in this zone are largely vertical with minor branching. The MEZ separating the UCZ and the LCZ displays four sided inclined, intersecting and fanning columns (Figs. 3b and 3c). On an average the column height in this zone is 3m with a cross width of 0.5m and showing an exposed stack column thickness of 15 m. The underlying LEZ with a vesicular top has four to five sided vertical columns (Fig 3d), which on an average are 1m in height with a cross-width of 0.9m and an exposed column stack thickness of 10m. Similar and complete sequence of colonnade structures has been described in the Deccan Volcanic Province only from Kutch (De, 1972) and Central India (Sengupta and Ray 2006). According to Long and Wood, (1986) and Muller, (1998) consequent to the emplacement of flood basalt flows on the surface, such a pattern of colonnade structures have developed due to upward conduction of heat from the flow bottom and downward cooling from the flow top, thus leading to synchronous formation of regular vertical columns (UCZ and LCZ) along the upwardly moving cooling front and curvi-linear columns (MEZ) along the downward moving cooling front. Based on repeated core drilling and temperature measurements in the crust and melt of the Alae lava lake, Hawaaii and precise level surveys of the lake surface, Peck et al.,(1965) have suggested that there is a change in the composition of the lava with depth, decrease in temperature upwards and development of joints/cracks. According to Long and Wood (1986) multi-tiered jointing which is a significant component of the Columbia River Basalt Group (CRBG) has developed due to rapid convective cooling by ingress of water. Spry (1962) had opined that columnar prisms defining lower colonnade, central entablature and the upper colonnade structures form in a definite sequence with master joints first, mega-columns next, then normal columns and finally cross-fractures perpendicular to the isotherms due to thermal stress produced during cooling. Studies have also shown that jointing styles develop in response to isotropic thermal contractions in a lava flow, thus providing information on the state of stress during emplacement and can constrain the rate and mechanism of cooling in a lava flow and that there is viscous relaxation during cooling resulting in localized reduction in stress (Ryan and Sammis, 1978; Degraff and Aydin, 1987). According to Muller (1998) based on laboratory simulation experiments with starch and field measurements, cooling of

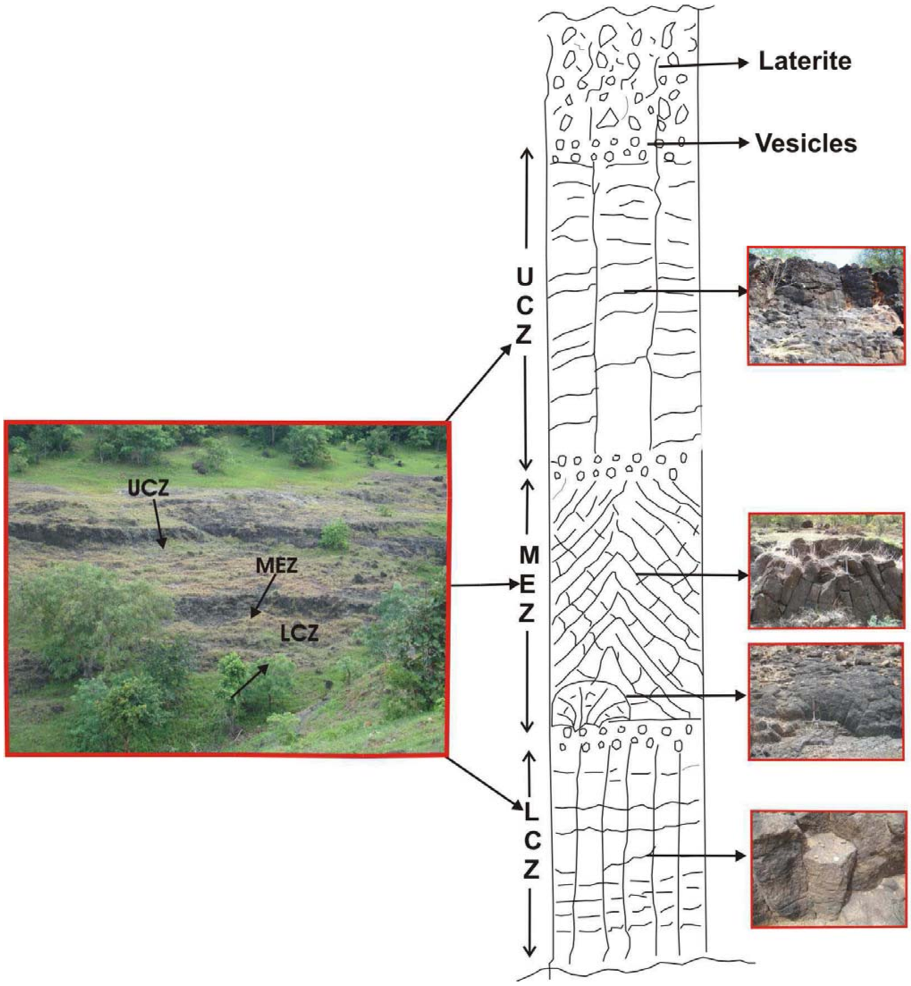

Fig.2. Inset field photos and cartoon depicting the observed stratigraphic relationship of UCZ, MEZ and LCZ, constituted by laterites (top flows 9, 8 & 7) and bottom basalt flows 6, 5 and 4 respectively. Cartoon is not to scale.

basalts is a process of thermal diffusion during which contraction stress exceeds the material strength and that column growth is dependent on differences in diffusivity. Peck and Minakami (1968) had suggested that oriented or random orthogonal cracks develop in the thin crust at temperatures in excess of 900^0C within a few minutes after the molten lava gets exposed at the surface of a ponded flow. Reiter et al (1987) had suggested that formation of columnar structures in basalt layers involves complicated boundary conditions, cooling mechanisms, stress development-release characteristics, leading to one dimensional cooling from above and below and that thermal stress parallel to the cooling surface causes vertical cracks to develop incrementally and which increase in length with cooling time. Aydin and DeGraff (1988) based on field data had suggested that the tetragonal networks of cracks at the surface of basalt flows evolve to hexagonal networks as the joints grow inwards during cooling and solidification. Saliba and Jagla (2003) had suggested that the mean width of the columns is dependent on the typical size of the irregular crack patterns at the free surface from which polygonal patterns develop as well as the termination of some cracks during advance of the cooling front which leads to thickening of the columns with depth.

PETROGRAPHY

These basalts are fine to medium grained and show intersertal, glomeroporphyritic and rare sub-ophitic and porphyritic textures. Mineralogically they are composed of plagioclase feldspar, clinopyroxene, ± olivine, Ti-magnetite, ilmenite, glass, cholorophaeite and zeolites. Plagioclase is the dominant phase with a modal abundance of 15-20% and occurring as: (a) smaller grains forming the groundmass and (b) as rare glomeroporphyritic phenocryst clusters formed by synneusis (Fig.4a). In the studied samples the phenocryst sequence observed is plagioclase – pyroxene (augite) ± olivine. The rare coarse phenocrysts of plagioclase are

Fig.3. Field photographs showing: (**a**) Upper Colonnade Zone (UCZ) with thick, five sided vertical columns; **(b and c)** Middle Entablature Zone (MEZ) with four sided, inclined and fanning columns and (**d**) Lower Colonnade Zone with four to five sided, thin vertical columns.

occasionally zoned, while the fine grained groundmass plagioclase shows not so common sub-ophitic association largely with Cpx and associated with rare olivine, as an important microcrystalline phase in these flows (Figs.4b and c). Secondary minerals like calcite, opaline silica and dark brown-yellowish brown cholorophaeite, white ameboidal aggregates of zeolites are commonly found in the vesicles (Fig.4d). Partially altered microphenocrystic olivines, showing reddish-brown iddingsite along fractures and grain boundaries, are associated with matrix plagioclase, Cpx and glass which exhibit intersertal texture (Fig.4e). Such intersertal textures observed in basalts, in association with a mixture of pale–dark brownish glass and clinopyroxene in the interstices of the fine grained plagioclase laths in the matrix, indicates near surface conditions of cooling of a basaltic melt carrying early formed silicate minerals as suggested by Nabelek and Taylor (1978) , who also opined based on dynamic crystallization experiments that intersertal texture developes by cooling of a melt containing faceted plagioclases in a melt. Ti-magnetite and/or ilmenite occur as subhedral to skeletal grains with a modal abundance of ~5%, along with fine-grained matrix of Cpx, plagioclase, cholorophaeite (Fig.4f).

GEOCHEMISTRY

Major and trace element analyses including the rare earth elements of these basalts were carried out at NGRI, Hyderabad by X-Ray Fluorescence Spectrometer (Phillips make MagiXPRO, Model PW 2440) and ICP-MS (Perkin Elmer make, model SCIEX ELAN DRC II). Samples were made into pressed pellets with a borax base in aluminum cups for major element analysis while for trace element analysis including the rare earth elements, samples were dissolved using HF-HNO3-HCLO4 acid mixture in Teflon vessels and open digestion. International Reference Materials JB2, BCR-1 and BHVO-1 were used as calibration standards for all the analyzed samples to check for the accuracy and precision during analysis. The overall precision of XRF analysis was 5% below RSD while for ICP-MS analysis it was better than 10% RSD. The detailed procedures followed for sample preparation, XRF and ICP-

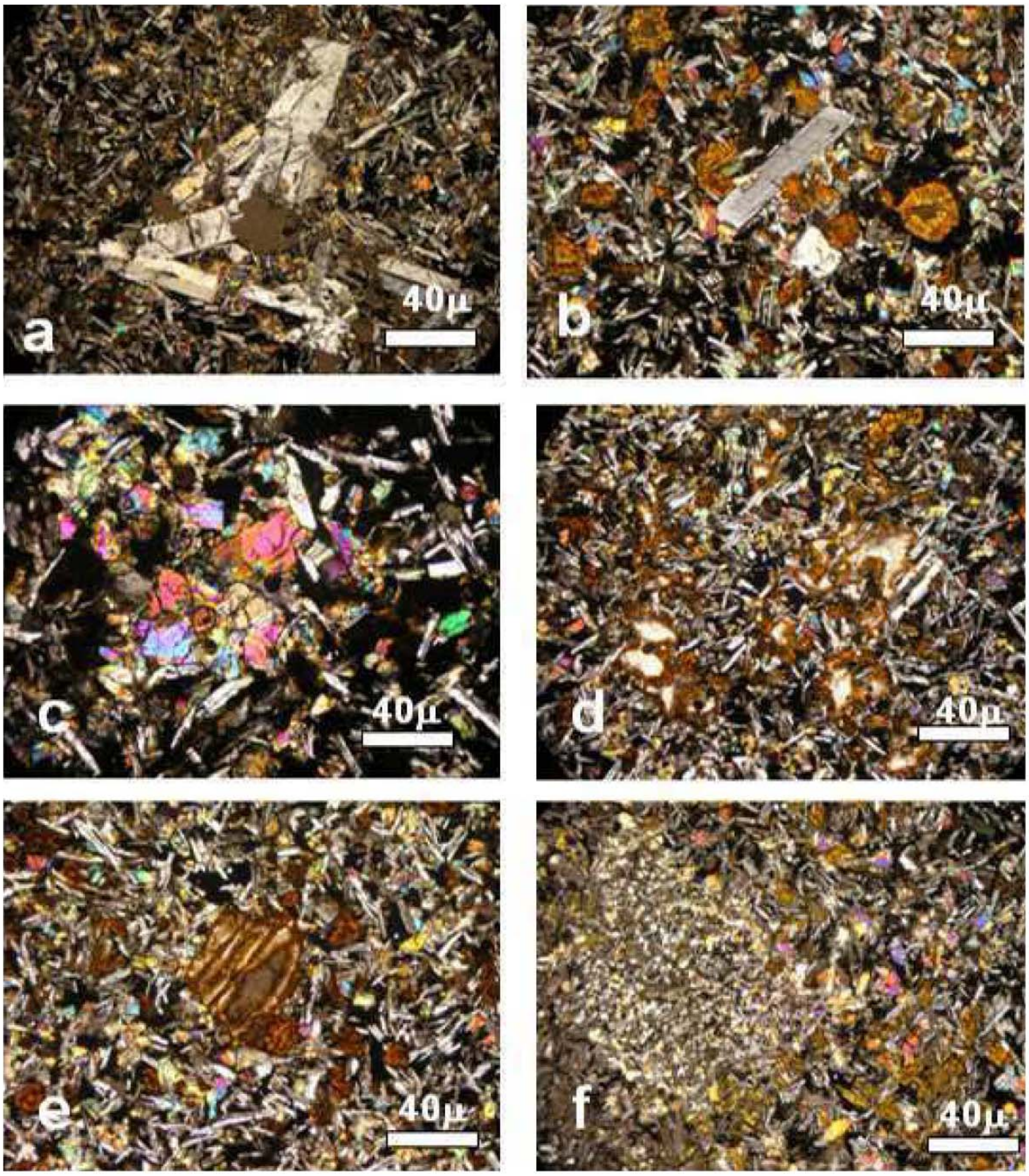

Fig:4. Photomicrographs showing: **(a)** Coarse grained glomeroporphyritic cluster of plagioclase phenocrysts due to synneusis, in a finer grained plagioclase, Cpx and opaque rich matrix in UCZ basalts; **(b)** Medium grained, zoned plagioclase phenocryst in association with fine grained plagioclase, Cpx and chlorophaeite in LCZ basalts; **(c)** Clinopyroxene defining rare sub-ophitic texture in association with plagioclase, opaques and minor olivine in UCZ basalts; **(d)** Amygdaloidal textures defined by calcite and opaline silica in vesicles in UCZ basalts; **(e)** Rare olivine phenocyst altered to iddingsite in association with fine grained plagioclase, Cpx, opaques , showing intersertal texture in LCZ basalts; **(f)** Skeletal Ti-Magnetite in association with fine grained Cpx, plagioclase ± olivine, cholorophaeite in MEZ basalts.

MS analysis have been given by Balaram and Rao, (2003) and Krishna et al. (2007) respectively.

Geochemical data of basalt flows 6, 5, 4, 3, 2 and 1 at Anantagiri hills and the adjacent areas shows that these are tholeiites having SiO_2 ranging from 47.51 to 50.06%, Al_2O_3 from 12.28 to 13.81 and MgO from 5.04 to 7.20% (Tables 1, 2). In the Fe+Ti-Al-Mg ternary AFM diagram (after Jensen, 1976) these basalts plot in iron-rich tholeiite field (Fig.5a), while the $Zr/TiO_2*10000$ vs Nb/Y plot (Fig.5b) (after Winchester and Floyd, 1977), reflects their sub-alkaline nature. SiO_2, Al_2O_3, total alkalies (K_2O and Na_2O), Ni and Cr show a slightly decreasing trend against MgO (Fig. not shown), possibly implying early crystallization of olivine and clinopyroxene which are

Table 1. Major element composition of Anantagiri basalts

	DR-1	DR-2	DR-3	DR-4	DR-5	DR-6	DR-7	DR-8	DR-9	DR-10	DR-11	DR-12
SiO_2	50.06	49.82	48.48	47.51	49.04	49.05	47.99	47.84	48.83	49.1	48.86	48.07
Al_2O_3	14.81	14	13.69	14.21	13.92	13.83	12.88	14.02	13.4	13.28	14.05	14.88
Fe_2O_3*	12.08	12.38	13.85	13.91	13.53	12.43	14.77	12.89	13.2	12.77	12.68	12.13
MnO	0.17	0.18	0.18	0.18	0.18	0.18	0.16	0.19	0.18	0.18	0.18	0.19
MgO	5.04	5.19	6.72	6.43	6.24	6.05	6.77	6.51	7.2	6.21	6.2	6.77
CaO	11.71	11.86	11.29	11.66	11.07	11.88	10.82	11.71	10.51	11.19	10.81	11.06
Na_2O	2.38	2.44	2.05	2.02	1.99	2.05	1.95	2.06	2.05	1.91	2.25	2.02
K_2O	0.38	0.39	0.15	0.16	0.15	0.18	0.18	0.2	0.3	0.17	0.21	0.15
TiO_2	1.88	1.97	2.29	2.39	2.23	2.39	2.53	2.55	2.7	2.53	2.72	2.57
P_2O_5	0.21	0.21	0.25	0.25	0.27	0.2	0.24	0.22	0.23	0.2	0.21	0.21
Total	98.72	98.45	98.96	98.71	98.61	98.22	98.29	98.69	98.89	98.03	98.68	98.05

*Total Iron as Fe_2O_3.

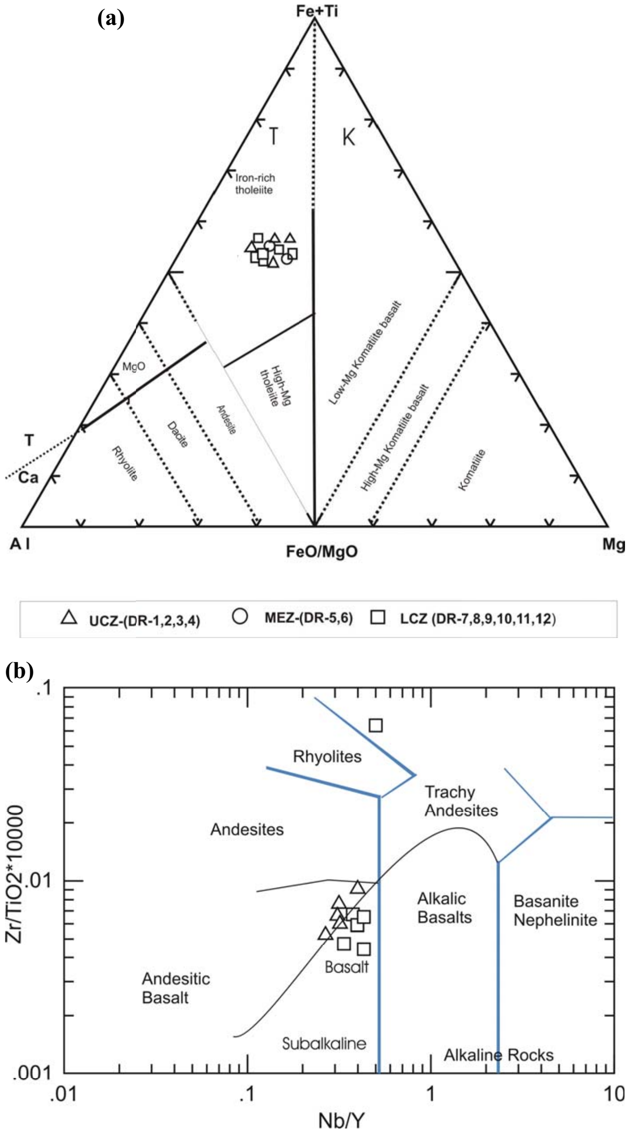

Fig.5. (a) Fe+ Ti-Al-Mg Ternary diagram show that these basalts are iron rich tholeiites in composition (figure after Jenson, 1976), **(b)** Zr/TiO_2 * 10,000 vs Nb/Y binary diagram showing the sub-alkaline nature of these basalts (after Winchester, and Floyd.1977).

observed as rare phenocrysts in these basalts. In the TiO_2 vs FeO/MgO diagram (after Melluso et al 1995), the UCZ, MEZ and the LCZ basalt samples define a trend ranging from low Ti-CFB's to high Ti-CFB's respectively (Fig.6). Melluso et al (1995, 2006) have reported the presence of near primitive picritic basalts, consisting of low-Ti, intermediate-Ti and high-Ti types from the Saurashtra region of Gujarat. They have suggested that the low-Ti type picritic basalts are geochemically similar to transistional or normal ocean ridge basalts but with significant contribution from continental crust, while the high-Ti picritic basalts are geochemically and isotopically similar to recent shield volcanoes of the Reunion hotspot. In the absence of isotope data on the studied tholeiitic basalt flows of Anantagiri hills and the surrounding areas, it is difficult to definitely conclude whether the differing Ti concentrations reflect more than one source for these basalts, though they indicate low- and high-Ti types.

The $FeO^{(T)}$/MgO ratios ranging from 1.61 to 2.16 in these basalts reflects their fractionated nature. The six basalt

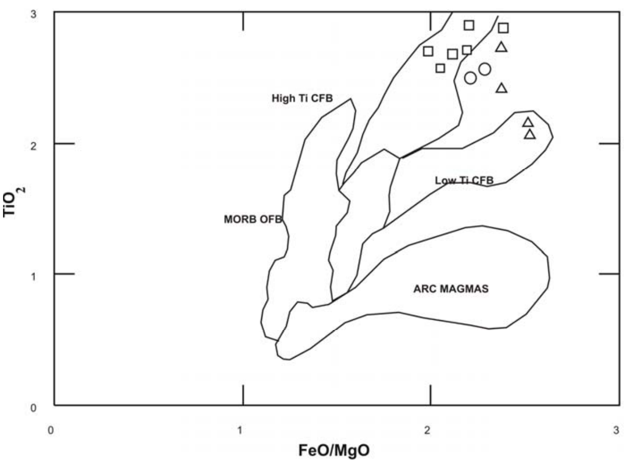

Fig.6. TiO_2 vs FeO/MgO diagram showing samples plotting in low Ti-CFB and high Ti-CFB fields (after Melluso et al. 1995). Symbols are as given in Fig.5.

Table 2 Major element composition of Anantagiri hills basalts

	DR-1	DR-2	DR-3	DR-4	DR-5	DR-6	DR-7	DR-8	DR-9	DR-10	DR-11	DR-12
SC	39.82	38.40	42.33	48.36	36.79	36.44	36.85	36.49	38.31	39.41	27.69	36.81
V	358.48	399.74	263.55	303.41	257.47	305.72	409.24	424.83	517.37	438.37	315.22	405.86
Cr	44.95	131.92	42.88	54.45	44.22	66.56	186.34	136.39	146.34	143.18	113.30	133.77
Co	51.47	51.61	55.24	64.85	54.12	50.76	52.26	52.73	52.90	54.85	38.30	52.49
Ni	22.54	51.76	22.58	29.93	22.67	24.38	66.89	37.37	38.70	40.10	30.62	38.87
Cu	205.77	201.82	241.54	279.52	227.61	220.59	229.97	232.87	254.08	252.13	184.35	238.44
Zn	135.58	107.04	157.55	190.88	164.13	154.59	122.25	151.82	165.04	171.67	121.59	163.50
Ga	21.32	22.26	20.74	25.26	20.53	21.17	22.51	23.33	23.87	24.15	17.66	22.67
Rb	6.54	8.16	1.43	3.52	1.96	4.30	2.97	4.72	3.36	3.65	3.59	3.33
Sr	207.53	209.16	194.22	242.58	200.65	213.53	213.37	227.91	235.18	242.66	171.11	223.89
Y	32.71	32.66	31.86	31.69	31.27	32.13	31.96	32.56	32.68	32.52	25.14	32.41
Zr	142.75	129.67	137.08	217.01	134.21	160.24	149.05	150.71	152.79	154.08	113.35	145.18
Nb	10.32	10.11	10.18	12.65	9.85	12.07	7.07	12.95	13.14	12.83	11.31	12.44
Cs	0.16	0.19	0.08	0.10	0.07	0.11	0.05	0.06	0.03	0.05	0.05	0.05
Ba	119.78	274.79	61.11	81.73	93.36	83.30	185.28	211.46	192.02	176.28	156.13	179.29
La	10.66	11.35	7.69	9.63	7.34	9.88	10.33	12.05	10.85	11.10	8.16	10.30
Ce	26.98	25.63	21.76	27.60	21.06	26.51	25.39	28.25	27.61	28.03	20.62	26.14
Pr	3.17	2.47	2.86	3.41	2.59	3.21	2.62	3.52	3.35	3.44	2.51	3.19
Nd	18.52	17.50	16.75	20.83	16.16	19.83	18.82	21.28	20.86	21.27	15.62	19.46
Sm	4.87	4.50	4.74	6.03	4.70	5.34	5.02	5.71	5.75	5.73	4.27	5.44
Eu	1.29	1.69	0.84	1.04	0.91	1.34	1.81	1.76	1.79	1.81	1.32	1.66
Gd	6.87	5.94	7.11	8.85	6.98	7.13	6.39	7.47	7.87	7.80	5.72	7.15
Tb	1.10	1.04	1.13	1.40	1.13	1.11	1.07	1.15	1.17	1.17	0.85	1.07
Dy	5.63	5.24	5.37	6.81	5.30	5.66	5.26	5.96	5.82	5.88	4.33	5.40
Ho	1.07	1.11	1.04	1.28	1.04	1.10	1.09	1.15	1.12	1.13	0.82	1.06
Er	3.57	3.31	3.28	4.03	3.20	3.37	3.20	3.60	3.47	3.58	2.58	3.26
Tm	0.57	0.53	0.49	0.60	0.48	0.54	0.49	0.54	0.51	0.52	0.38	0.48
Yb	2.95	2.82	2.85	3.39	2.82	2.76	2.65	2.77	2.82	2.79	2.07	2.66
Lu	0.39	0.41	0.40	0.51	0.41	0.38	0.39	0.39	0.38	0.38	0.28	0.36
Hf	3.21	3.22	3.08	4.41	2.92	3.61	3.44	3.40	3.34	3.33	2.53	3.16
Ta	1.18	1.35	0.87	0.94	0.93	1.65	1.68	2.14	1.94	1.69	1.67	2.04
Pb	3.18	1.73	2.95	2.69	3.10	3.17	1.38	0.51	0.47	0.61	0.44	0.55
Th	1.55	1.63	0.79	1.04	0.75	0.98	0.94	1.20	0.90	0.92	0.72	0.91
U	0.40	0.40	0.21	0.22	0.16	0.25	0.30	0.36	0.28	0.30	0.22	0.30
Mg#	31.7	31.78	35.04	33.93	33.88	35.09	33.74	37.8	37.74	35.08	35.21	38.27
TiO_2/Yb	0.64	0.70	0.80	0.71	0.79	0.87	0.96	0.92	0.96	0.91	1.31	0.97
Zr/TiO_2	75.93	65.82	59.86	90.8	60.18	67.05	58.91	59.1	56.59	60.9	41.67	56.49
Nb/Y	0.32	0.31	0.32	0.40	0.31	0.38	0.22	0.40	0.40	0.39	0.45	0.38
Rb/Y	0.20	0.25	0.04	0.11	0.06	0.13	0.09	0.14	0.10	0.11	0.14	0.10
Ba/Y	3.66	8.41	1.92	2.06	2.99	2.59	5.80	6.12	5.54	5.11	6.21	5.53
Ba/Nb	11.61	27.18	6.00	6.46	9.48	6.90	26.21	16.33	14.61	13.74	13.81	14.41
Zr/Nb	13.83	25.38	13.47	17.15	13.63	11.39	21.09	10.08	10.09	10.39	10.03	10.06
Nb/La	0.97	0.45	1.32	1.31	1.34	1.42	0.68	1.24	1.40	1.34	1.39	1.40
Nb/Ce	0.38	0.20	0.47	0.46	0.47	0.53	0.28	0.53	0.55	0.53	0.55	0.55
Nb/Yb	3.50	3.59	3.57	3.73	3.50	4.37	2.67	4.68	4.66	4.60	5.46	4.68
La/Nb	1.03	1.12	0.76	0.76	0.75	0.82	1.46	0.93	0.83	0.87	0.72	0.83
Pb/Nb	0.31	0.17	0.29	0.21	0.31	0.26	0.19	0.04	0.04	0.05	0.04	0.04
Th/Yb	0.53	0.58	0.28	0.31	0.27	0.35	0.36	0.43	0.32	0.33	0.35	0.34
Th/La	0.15	0.14	0.10	0.11	0.10	0.10	0.09	0.10	0.08	0.08	0.09	0.09
Nb/Zr	0.07	0.08	0.07	0.06	0.07	0.08	0.06	0.09	0.09	0.08	0.06	0.07
Ba/Zr	0.34	0.24	0.45	0.38	0.40	0.52	0.24	0.40	0.26	0.40	0.38	0.42
Ba/y	1.66	1.41	1.92	2.58	2.99	2.59	1.80	1.49	1.88	1.42	2.21	1.53
Zr/Nb	13.83	12.83	13.47	13.15	13.63	13.28	14.08	11.64	11.63	12.01	13.02	11.67
(La/Ce)N	1.01	1.14	0.91	0.89	0.89	0.96	1.04	1.09	1.01	1.02	1.02	1.01
(La/Yb)N	2.51	2.79	1.87	1.97	1.81	2.48	2.71	3.02	2.67	2.76	2.73	2.69
(La/Sm)N	1.37	1.58	1.02	1.00	0.98	1.16	1.29	1.32	1.18	1.21	1.20	1.18
(Sm/Gd)N	0.81	0.79	0.87	0.89	0.89	0.83	0.82	0.82	0.85	0.83	0.84	0.86

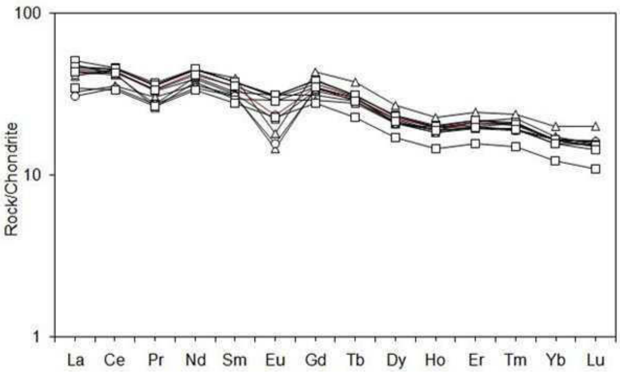

Fig.7. Chondrite normalized REE diagram for these basalts show slightly fractionated patterns, mild LREE enrichment, negative Eu anomalies and nearly flat HREE. Symbols are as given in Fig.5.

flows studied at Anantagiri hills do not have significantly different major and trace element trends and $(La/Ce)_N$, $(La/Yb)_N$, $(La/Sm)_N$, $(Sm/Nd)_N$ ratios etc, thus suggesting a genetic linkage, possibly implying their formation from a single source. REE values were normalized after Sun and McDonough, (1989) and their distribution in these basalts shows mild fractionated patterns coupled with negative Eu anomalies (Fig.7). Primitive mantle normalized incompatible element distribution patterns exhibited by these basalt flows, show slight LREE enrichment and LILE (K, Rb, Sr) and P depletion, positive Ba, Ta, Pb and Ti peaks, and a near flat pattern from Nd to Lu, similar to that of the basalts of Ambenali and Poladpur formations occurring in south-western Deccan Volcanic Province (Fig.8). The positive Pb anomaly with moderately high values of LILE elements Ba (ranging from 61 to 274 ppm) and Sr (ranging from 171 to 242 ppm); low Rb concentration (ranging from 1.4 to 8 ppm), and values of the other incompatible elements such as Zr, Nb, Hf, Th, U and Ta coupled with the low ratios of Pb/Nb (0.04 to 0.31) and La/Nb (0.72 to 1.46) of the Anantagiri hill basalts do suggest limited influence of crustal contamination or the sub-continental lithospheric mantle. In the Nb/Y vs Rb/Y, Ba/Zr vs Nb/Zr and Zr/Nb vs Ba/Y binary diagrams, the Anantagiri hills basalts, plot largely in the Ambenali Formation basalt field, a few overlapping with Poladpur Formation basalt field, possibly suggesting geochemical similarity with the Ambenali and Poladpur formation basalts (Fig.9a-c). The Ba/Y (4.18 to 6.21) and Zr/Nb ratios (10.02-10. 3) in these basalts, while being slightly higher are nearer to the ratios reported for the basalts of Ambenali and Poladpur formations by Mahoney et al, (2000). The Nb/La and Nb/Ce ratios in these tholeiites ranging from 0.450-1.42 and 0.199 to 0.552 respectively are nearer though slightly higher than the values reported for primitive mantle (1.02 and 0.4 respectively) and average crustal value of 0.69 and 0.33 respectively (Taylor and McLennan, 1985), which suggests an enriched source characteristic. The tholeiites of Anantagiri-Vikarabad area show emplacement on the quartzo-feldspathic granitic basement and the Proterozoic Bhima basin towards the east. These basalts have Pb values ranging from 0.44 to 3.18 ppm which in comparison are lower than the Pb values (ranging from 5 to 56 ppm) reported for the quartzo-felspathic gneiss-granite basement of Dharwar craton and the nearby Hyderabad quartzo-feldsapathic granites (Diwakara Rao et al., 1972; Rama Rao et al., 2001). According to Condie (1997), the average Pb values in upper and middle crust are 18 and 15.3 ppm respectively. Hence it is suggested that the positive Pb anomaly exhibited by the Anantagiri hills basalts does indicate the influence of crustal contamination or the sub-continetal lithospheric mantle in their petrogenesis.

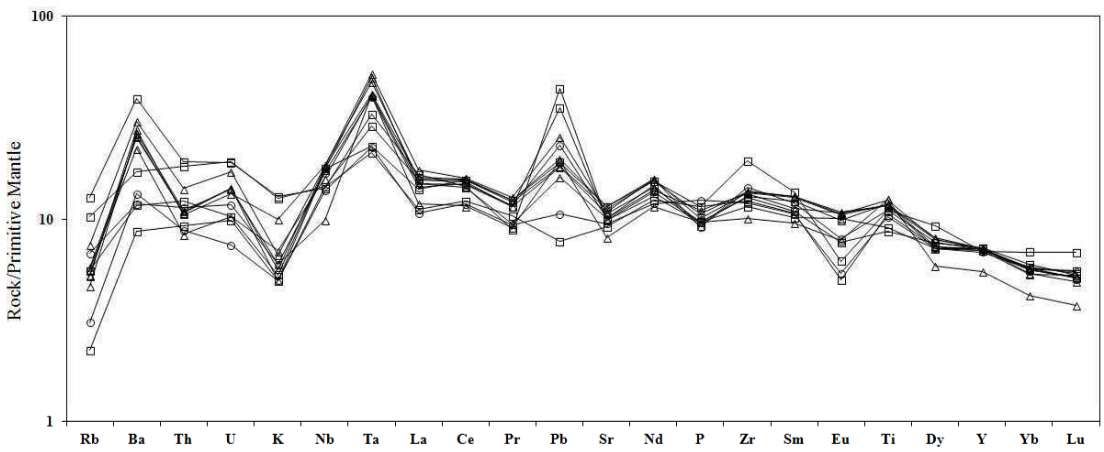

Fig.8. Primitive mantle normalized incompatible element patterns of these basalts show mildly positive peaks for Ba,Ta,Pb, Zr and Ti and lows for K and P respectively in near similarity with the Ambenali and Poladpur Formations. Symbols are as given in Fig.5.

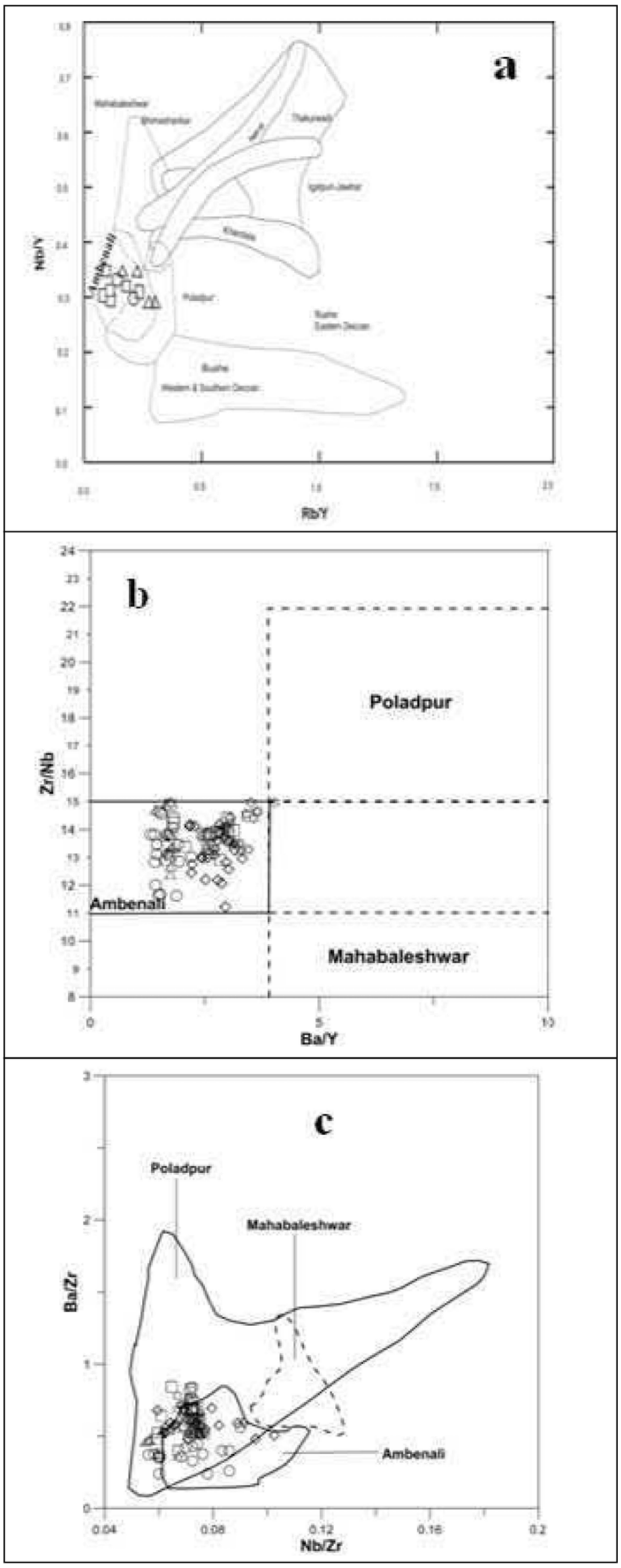

Fig.9. (a) Nb/Y vs Rb/Y, **(b)** Ba/Zr vs Nb/Zr and **(c)** Zr/Nb vs Ba/Y binary plots showing a majority of these basalts plotting in Ambenali Formation basalt field and a few in the Poladpur Formation basalt field (figure after Mahoney, et al 2000). Symbols are as given in Fig.5

The Ba/Nb= 6.0-27.2; La/Nb=0.75-1.46; Pb/Nb=0.17-0.3 ratios of these basalts represent the MORB-IOB array as suggested for the Columbia River basalts (Peng et al, 1995). Al_2O_3, Fe_2O_3,MgO, CaO, K_2O, Rb, Co, Sc, Ni, show a negative trend while TiO_2, P_2O_5, Nd, La and Nb are mildly positive with increasing Zr content in these basalts (figure not shown) and such a relationship is suggested to reflect a near primary magmatic character (Akash Kumar and Talat Ahmad, 2007). The observed relationship between Nb and Zr suggests limited influence of crustal contamination and/or sub-continental lithospheric mantle. Incompatible elemental ratios such as Zr/Nb (av.10, except for samples: DR-2, 7) and Th/La (av.0.09) in the Anantagiri hills basalts are nearly similar to MORB-Ocean Island Basalts (Zr/Nb=7-10; Th/la=0.01-0.15) implying an enriched mantle source, as suggested for the Emeishan flood volcanic province (He Bin et al, 2007 and Vadim et al, 2012). The intermediate Sr (171-242 ppm), the slightly low to elevated Ba (61-274 ppm), the low K, Rb and the Zr/Nb ratio are nearly similar to that of the basalts of Ambenali and Poladpur formations. Most of the Deccan tholeiitic basalts (5-8 wt% MgO) have been considered as evolved products derived from high Mg basaltic/picritic primary melts, showing mineralogical and major element chemical similarities with mid-ocean ridge basalt (MORB) (Furuyama et al., 2001), while in contrast Melluso et al. (1995, 2006) have proposed that their trace element geochemistry is more similar to Ocean Island Basalts (OIB). TiO_2/Yb vs Nb/Yb diagram (Fig.10; after

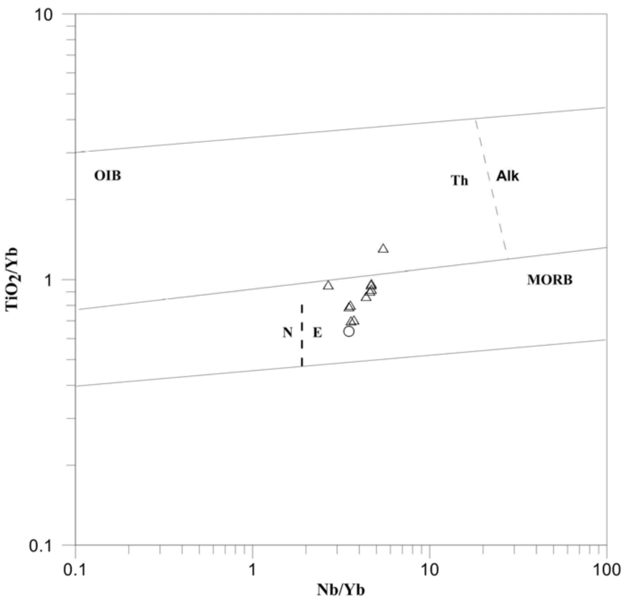

Fig.10. TiO_2/Yb vs Nb/Yb plot showing these basalts having an E-MORB affinity on the MORB-OIB array (Figure after Pearce, 2008 and Hastie et al., 2007). Symbols are as given in Fig.5.

Pearce, 2008 and Hastie et al., 2007) shows that the Anantagiri hill basalts plot in the E-MORB field within the MORB-OIB array, reflecting a mildly enriched mantle source . While on the Th/Yb vs Nb/Yb diagram these basalts plot just below the MORB-OIB array (figure not shown).

CONCLUSION

The present study has enabled identification of the Lower Colonnade Zone (basalt flow nos.4, 3, 2); the Middle Entablature Zone (basalt flow no.5) and the Upper Colonnade Zone (basalt flow no.6) at Anatagiri hills. In the Fe+Ti-Al-Mg ternary diagram these basalts plot in iron-rich tholeiite field, while in the Zr/TiO_2*10000 vs Nb/Y plot these rocks plot largely in the field of sub-alkaline basalts. The TiO_2 vs FeO/MgO relationship in these basalts defines a low Ti-CFB to high Ti-CFB trend. Primitive mantle normalized incompatible element distribution patterns exhibited by these basalts, show broad similarities with the basalts of Ambenali and Poladpur formation. The Nb/Y vs Rb/Y, Ba/Zr vs Nb/Zr and Zr/Nb vs Ba/Y binary relationship largely constrains these tholeiites within the field of basalts of Ambenali Formation with minor overlap with the Poladpur Formation, suggesting geochemical similarity of the studied basalt flows with the basalts of Ambenalli and Poladpur formations. TiO_2/Yb vs Nb/Yb ratios of these basalts suggest a mildly enriched source with an E-MORB affinity.

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