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Geochemistry of Dalma metavolcanic Suite from Proterozoic Singhbhum Mobile Belt, Eastern India: Implications for Petrogenesis and Tectonic Setting

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ABSTRACT

The Dalma metavolcanic belt is composed of ultramafics at the base, tuffs on top and basalts in-between. It extends for about 200kms east-west in the middle of the Proterozoic Singhbhum Mobile Belt. Ultramafics are chiefly composed of actinolite, hornblende, relic pyroxene and olivine. The main mineral constituents of basalts are actinolite, hornblende, chlorite, epidote, clinozoisite and plagioclase whereas; tuffs are composed of xenocrysts of biotite, quartz, k-feldspar, plagioclase and iron oxides. Ultramafic samples have high MgO (> 21 wt.%) and low SiO_2 (< 42 wt.%), Al_2O_3 (< 10 wt.%) and Na_2O+K_2O (< 1 wt.%). CaO shows large variation in these samples from 3.91 to 7.77 wt. %. In studied basalt samples SiO_2, TiO_2, Al_2O_3, MgO and alkalis (Na_2O+K_2O) show variation like (45.7-48.3 wt.%), (0.64-0.97 wt.%), (9.3-13.9 wt.%), (8.5-13.6 wt.%) and (0.95-4.64 wt.%) respectively. In studied tuffs the SiO_2, TiO_2, Al_2O_3, MgO and alkalis show variation from (48.9-49.8 wt.%), (0.7-0.8 wt.%), (13.6-13.9 wt.%), (8.4-9.1 wt.%) and (2.39-2.85 wt.%) respectively. In general, studied samples show light rare earth element depleted patterns and flat patterns for heavy rare earth elements similar to MORBs on chondrite normalized REE diagrams. The overall enrichment of LILEs (e.g., Rb, K and Th) and depletion of HFSEs (e.g., Nb-Ta trough) on primitive mantle normalized multi-element diagrams are similar to subduction zone or islamd arc basalts. Ratios like Ti/Y, Ti/Zr, Zr/Nb and Ti/V are also similar to those found in arc related volcanic suites. Sm/Yb vs La/Sm diagram indicates generation of melts from the spinel lherzolite mantle source. On tectonic setting discrimination diagrams like Zr vs Zr/Y, Zr vs Ti and Ti vs V majority of studied samples clearly show island arc tectonic affinity.

INTRODUCTION

In the eastern part of the Indian shield, an arcuate shaped basin usually referred to as Singhbhum mobile belt (SMB) occurs in between the Singhbhum granitoid complex (SGC) and Chotanagpur granite-gneiss complex (CGGC) (Fig.1). The investigated 1484±44 Ma old Dalma metavolcanic suite (Sengupta et al., 2000) is well preserved in the middle of the Proterozoic SMB. The unreliable radiometric age data of SGC and CGGC (Moorbath et al., 1986; Radhakrishna, 1989; Sengupta et al., 1991; Saha, 1994; Mahadevan, 2002; Misra, 2006) and wide differences of opinion regarding the geodynamic evolution of SMB have made the stratigraphic correlation of the Dalma metavolcanic suite difficult. According to one school of opinion, Dalma metavolcanic suite overlies unconformably the metasedimentary rocks of the SMB (Iyengar and Murthy, 1982). The other school has considered a conformable relationship of the Dalma metavolcanic suite with the metasedimentary rocks of the SMB (Bose and Chakraborti, 1981; Sarkar, 1982a and 1982b; Bose et al., 1989). Furthermore, most of the previous geochemical studies of the Dalma metavolcanic suite have utilized mainly major element chemistry without thoroughly considering the effects of post igneous alteration and metamorphism (Bhattacharyya et al., 1980; Gupta et al., 1980). As a result, the Dalma metavolcanic suite has been interpreted as an ensialic rift related suite (Sarkar and Saha 1977), a greenstone belt (Gupta et al., 1980), a volcanic arc suite (Banerjee, 1982), an ophiolite suite (Sarkar 1982a), marginal basin basalts (Chakraborti and Bose,1984) and back arc basin basalts (Bose et al., 1989). As such, geodynamic evolution of Dalma metavolcanic suite and the sequence of the geological events in the SMB are still not clear. Hence, the main aim of the present paper is to describe petrogenesis and tectonic setting of the Dalma metavolcanic suite with the help of immobile minor and trace elements including rare earth elements.

GEOLOGICAL SETTING

The Dalma metavolcanic suite forms an arcuate shape belt of about 200km length and about 2500m thick within the SMB (Verma et al., 1978) (Fig. 1). It has been dated 1484 ± 44 Ma by Rb/Sr method (Sengupta et al., 2000). Dhalbhum Formation (>4000m) and Chaibasa Formation (>8000m thick) exists in the north and south of this suite respectively (Saha, 1994). The Dalma metavolcanic suite represents an explosive volcanism comprising sub-aerial basaltic flows mixed with tuff and agglomerate that unconformably overlies the Dhalbhum Formation (Sarkar and Saha, 1963). The Dalma metavolcanic rocks comprise four major lithological varieties namely, (a) fragmental mafic metavolcanic rocks, (b) non-fragmental metavolcanic rocks, (c) metagabbro to metadolerite and (d) altered ultramafic rocks. Fragmental mafic metavolcanic rocks, also described as agglomerate and breccia by earlier workers, preponderate especially for more than 25 km to the west of Dalma peak where the fragmental material makes up frequently a greater proportion of the total rock. From the Dalma peak westwards up to Sonapet village its contacts with the metasedimentary rocks to the north and south appear to be faulted (Banerjee, 1982). In non-fragmental metavolcanic rocks primary magmatic features are obscure. Neither the top, bottom of the flows, nor the direction of the flows can be decided from the outcrops. Metagabbro and associated metadoleritic rocks are well exposed in the Sonapet and Hesadi area. At many places, the metagabbroic bands are interlayered with metabasalt and tuffaceous rocks. The ultramafic rocks are extensively exposed in the Sonapet and Dulmi area over a strike length of more than 10 km. However, no continuous ultramafic band is traceable on a regional scale. Singh et al. (2001) reported the occurrence of acid agglomerates along the northern flank of the folded

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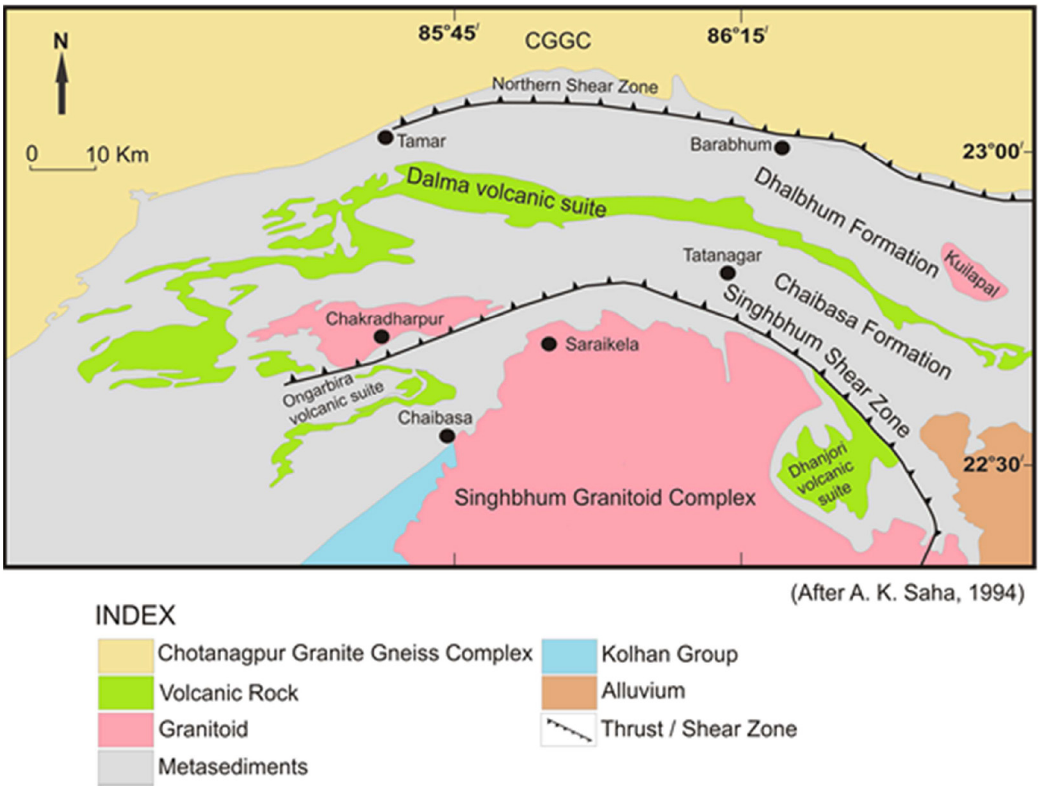

Fig.1. Simplified geological map of the Singhbhum Mobile Belt (after Saha, 1994) showing major stratigraphic units.

Dalma volcanics. The exposures of vitric, lithic or crystal lithic tuffs are occurring interbedded with mafic and ultramafic rocks along the Subarnarekha River (Ray et al., 1991).

PETROGRAPHY

Based on the mineralogy, the studied Dalma metavolcanic rocks are categorized as ultramafics, basalts (mafics) and tuffs. The detailed petrographical characteristics including mineralogy and texture of these rock types are discussed below:

Ultramafics

The primary minerals such as olivine and pyroxene are usually altered to secondary low temperature mineral assemblage e.g., serpentine, actinolite, hornblende, chlorite, however, relics of primary pyroxene and olivine have been sometimes preserved (Fig. 2a). Petrographically, these rocks are characterized by pseudomorphic textures after olivine and pyroxene, besides the presence of the accessory amounts of epidote, chlorite, tremolite, quartz and fine grained magnetite. The olivine pseudomorphs are anhedral, measuring from 0.2 to 0.5 mm and exhibit radial extinction. Pyroxene is usually pale brownish and commonly occurs as large porphyro-clasts up to centimeter in size. Many pyroxene porphyroclasts show undulose extinction with chlorite and amphibole alteration and have lobate grain boundaries.

Basalts

Basalts or mafic metavolcanic samples are dominantly composed of secondary mineral assemblage e.g., actinolite, hornblende, chlorite, epidote and clinozoisite besides, plagioclase with subordinate amounts of quartz, biotite, sphene and opaques (Fig. 2b). These rock types are essentially fine to medium grained and exhibit sub-ophitic to intergranular/intersertal textures. The plagioclase mostly occurs as un-zoned laths however, some grains of plagioclase exhibit albite twinning. At places plagioclase grains are partly altered to albite, partially enclosed in secondary amphibole giving rise to sub-ophitic textures. The presence of secondary amphibole i.e., actinolite and hornblende probably replacing pyroxene reflects amphibolite grade of metamorphism experienced by the studied rock types. Also the small amount of fine grained magnetite is widely disseminated in the groundmass.

Tuffs

Tuffs are essentially fine grained and are light to dark grey in colour. These rock types are mainly composed of xenocrysts of biotite, quartz, k-feldspar and plagioclase. Besides, minor amounts of iron oxides and often garnet are set in a very fine grained matrix of quartz, sericite, chlorite, k-feldspar, plagioclase and epidote (Fig. 2c).

GEOCHEMISTRY

Analytical Procedure

All the major elements and selected trace elements (Cr, Ni, V, Sr, Ba, Nb, Y and Zr) of the representative samples from the Dalma metavolcanic suite were determined by X-ray fluorescence spectrometer at Wadia Institute of Himalayan Geology, Dehradun, India. For this purpose, fused glass beads and pressed powder pellets were used respectively for major and trace elements. For all major elements analytical precision is substantially better than ± 1% and for trace elements generally better than 5%. Loss on ignition (LOI) is calculated as percent weight loss of a reweighed sample on heating to 1000°C. Representative samples were also analyzed for Sc, Nb, Th, Ta, Hf and REE at National Geophysical Research Institute, Hyderabad, India by ICP-MS, following a procedure by Balaram et al., (1990). All the samples analyzed by the ICP-MS technique are precise within ± 7%. Representative chemical compositions are given in Table 1.

Geochemical Characteristics

The spatial distribution of the mineral assemblages in the Dalma metavolcanic suite, suggest that there is a general gradational rise from

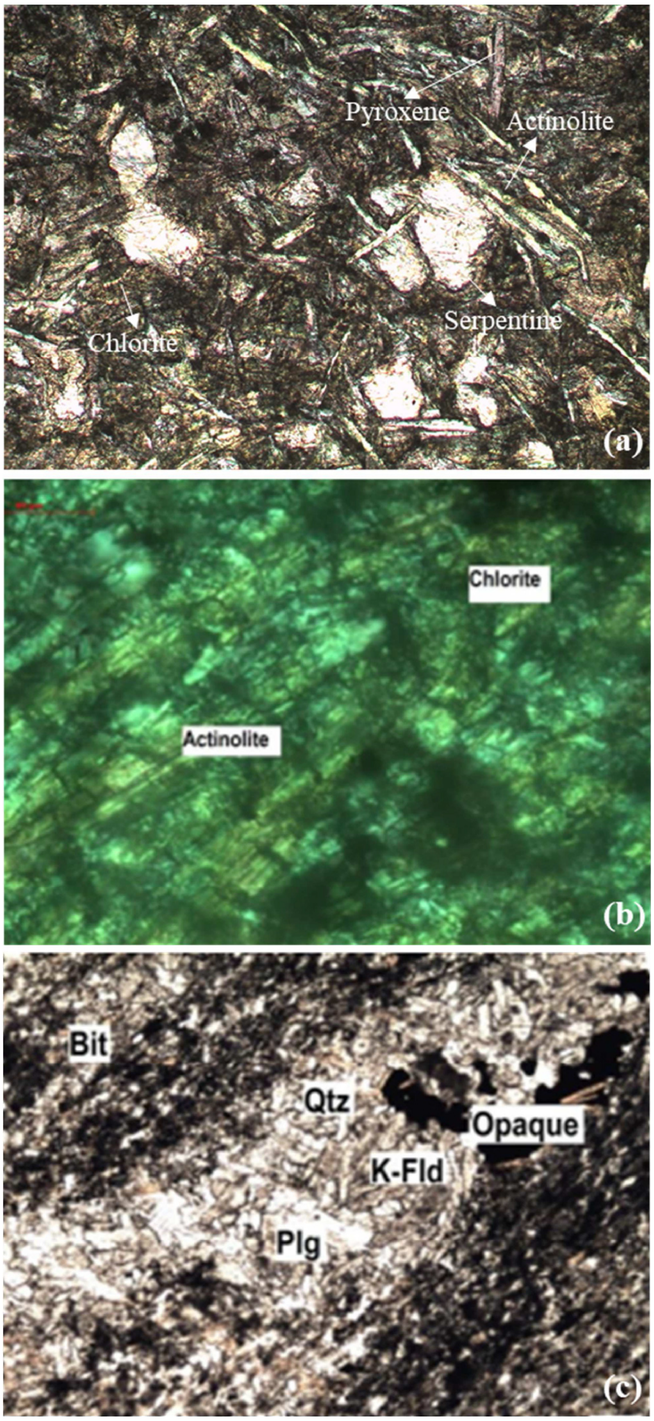

Fig.2. Photomicrograph of **(a)** ultramafic rock sample showing presence of relic pyroxene, serpentine, actinolite and chlorite; **(b)** basalt sample showing presence of actinolite, hornblende, chlorite etc. and **(c)** tuff sample showing presence of K-feldspar (K-fld), plagioclase (Plg), quartz (Qtz), Biotite (Bit) etc.

Table 1. Major and trace element data of representative samples of Dalma metavolcanic suite, Eastern Indian shield (where "nd" represents not defined).

Sample ID	S1	S8	DL4	DL6	DL7	C7	D11	T1	T3
Rock type	Ultramafic		Basalts					Tuffs	
SiO_2	39.81	41.5	46.69	48.29	48.27	45.74	48.12	49.83	48.98
TiO_2	0.47	0.65	0.64	0.97	0.69	0.66	0.95	0.8	0.71
Al_2O_3	9.01	6.55	10.44	12.67	13.9	11.84	9.34	13.6	13.85
Fe_2O_3	16.08	18.56	15.94	14.3	11.69	15.07	16.18	13.23	11.73
MgO	22.39	23.94	10.79	8.48	10.02	13.62	11.64	8.43	9.07
CaO	7.77	3.91	12.53	10.7	12.23	9.09	7.65	11.03	11.69
Na_2O	0.9	0.5	1.33	4.42	3.07	2.25	0.91	2.56	2.26
K_2O	0.05	0.01	0.15	0.22	0.14	0.15	0.04	0.29	0.13
MnO	0.17	0.15	0.16	0.17	0.15	0.17	0.21	0.16	0.15
P_2O_5	0.06	0.03	0.12	0.15	0.14	0.13	0.1	0.13	0.12
LOI	3.69	4.51	1.93	1.84	1.79	2.12	3.96	1.83	2.11
Total	100	100	101	100	100	101	99	101	101
Trace elements (in ppm)									
Th	0.07	0.17	2	2	2	3.5	2	2	2
U	0.03	0.09	2	2	2	2.5	2	2	2
Y	20	15	16	13	12.8	17.9	23.2	17.1	15
Zr	47	32	42	40	29	65	60	44	42
Hf	1.21	0.82	1.08	1.03	0.74	1.67	1.54	1.13	1.08
Nb	2	2	3.6	2	2	5.5	8.1	3.3	2
Ta	0.13	0.13	0.23	0.13	0.13	0.34	0.51	0.21	0.13
Cr	1512	1874	310	236	477	129	103	296	102
Ni	1037	1185	163	137	182	57	51	107	41
Co	84	90	80	58	90	62	52	53	46
V	330	260	310	431	329	233	157	353	160
Sc	26	22	29	32	33	30	26	32	26
Cu	104	9	11	115	53	23	49	49	194
Zn	55	54	67	68	59	67	58	55	54
Rb	1	1	1	1	1	1	2	7	2
Sr	9	35	62	198	156	80	62	129	76
La	0.49	0.8	1.6	1.11	1.39	0.85	6.24	4.53	1.67
Ce	2.04	2.52	5.69	4.11	3.5	2.72	14.57	9.96	3.78
Pr	nd	nd	nd	nd	nd	nd	nd	nd	nd
Nd	2.5	3.4	4.61	5.71	3.78	3.16	8.81	7.14	4.44
Pm	nd	nd	nd	nd	nd	nd	nd	nd	nd
Sm	0.94	1.41	1.73	2.33	1.49	1.46	1.97	2.17	1.51
Eu	0.31	0.55	0.36	0.81	0.76	0.6	0.72	0.92	0.59
Gd	1.78	1.97	2.28	3.14	2.3	2.67	2.48	2.7	2.45
Tb	1.33	0.28	0.33	0.53	0.41	0.39	0.27	0.48	0.32
Dy	1.84	1.89	2.22	3.45	2.49	2.94	1.9	3.2	2.47
Ho	0.4	0.31	0.47	0.72	0.6	0.5	0.33	0.68	0.41
Er	1.06	1.08	1.4	1.98	1.26	1.86	1.24	1.86	1.4
Tm	nd	0.21	nd	nd	nd	0.31	0.21	nd	0.27
Yb	1.11	0.97	1.4	2.03	1.39	1.63	1.05	1.81	1.41
Lu	0.19	0.14	0.25	0.24	0.28	0.22	0.17	0.33	0.19
Ti	2818	3897	3837	5815	4137	3957	5695	4796	4256
K	415	83	1245	1826	1162	1245	332	2407	1079
P	262	131	524	655	611	567	436	567	524
Elemental Ratios									
Ti/Y	140.88	259.78	239.80	447.32	323.17	221.04	245.48	280.47	283.76
Ti/Zr	59.95	121.77	91.35	145.38	142.64	60.87	94.92	109.00	101.34
Zr/Nb	23.50	16.00	11.67	20.00	14.50	11.82	7.41	13.33	21.00
Th/Ta	0.56	1.36	8.89	16.00	16.00	10.18	3.95	9.70	16.00
Ce/Nb	1.02	1.26	1.58	2.06	1.75	0.49	1.80	3.02	1.89
Ti/V	9	15	12	13	13	17	36	14	27
Nb/Y	0.10	0.13	0.23	0.15	0.16	0.31	0.35	0.19	0.13
Zr/Ti	0.02	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01
Hf/3	0.40	0.27	0.36	0.34	0.25	0.56	0.51	0.38	0.36
Th/Yb	0.06	0.18	1.43	0.99	1.44	2.15	1.90	1.10	1.42
Ta/Yb	0.11	0.13	0.16	0.06	0.09	0.21	0.48	0.11	0.09

the greenschist facies (in east) to the amphibolite facies (in west) (Bhattacharyya and Sanyal, 1988). As a result, primary magmatic structures and textures have been obliterated. Most of the samples do not show a striking conformity with the trends defined by the unaltered volcanic rocks, indicating that the major element oxides particularly K_2O and Na_2O of the Dalma metavolcanic suite have changed due to post igneous alteration processes. The high-field strength elements (HFSEs; e.g. Ti, Zr, Y, Nb, Ta, Hf), rare earth elements (REE) and transition elements (e.g. Ni, Cr) have relatively immobile geochemical characteristics during low-grade hydrothermal alteration and metamorphism (Winchester and Flyod, 1977). Therefore, inferences regarding the petrogenesis and tectonic setting of the Dalma metavolcanic suite are based on these immobile trace elements. The geochemical characteristics of ultramafics, basalts and tuffs are discussed below.

Ultramafics

Ultramafic samples have high MgO (> 21 wt.%) and low SiO_2 (<42 wt.%), Al_2O_3 (< 10 wt.%) and Na_2O+K_2O (< 1 wt.%). CaO shows large variation in these samples from 3.91 to 7.77 wt.% which indicates

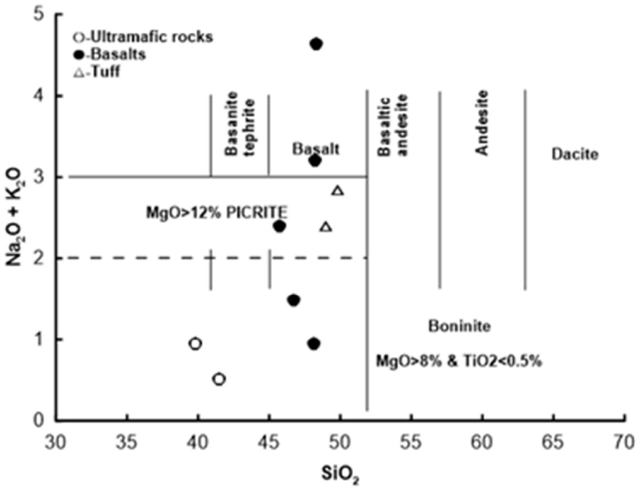

Fig.3. Total alkali vs silica diagram (TAS) after Le Bas (2000) for the Dalma metavolcanic suite.

fractionation of plagioclase. The studied ultramafics do not show spinifex texture so they do not qualify the komatiite identification criteria as proposed by Arndt (1994), however, they may be classified as picrites in total-alkali silica (TAS) diagram (Le Bas, 2000) (Fig. 3). These samples contain the highest values of Cr (1512-1874 ppm) and Ni (1037-1185 ppm) as compared to basalts and tuffs. While observing chondrite normalized REE patterns, studied ultramafics show depleted light rare earth element (LREE) patterns (Fig. 5a). Slight depression shown by Eu and flat pattern is followed by heavy rare earth elements (HREE). Primitive mantle normalized multi-element patterns show overall parallel patterns with depleted LILE and slightly enriched REE and HFSE patterns (Fig. 5b). K, Th, La and Sr show prominent negative anomalies.

Basalts

In studied basalt samples SiO_2, TiO_2, Al_2O_3, MgO and alkalis

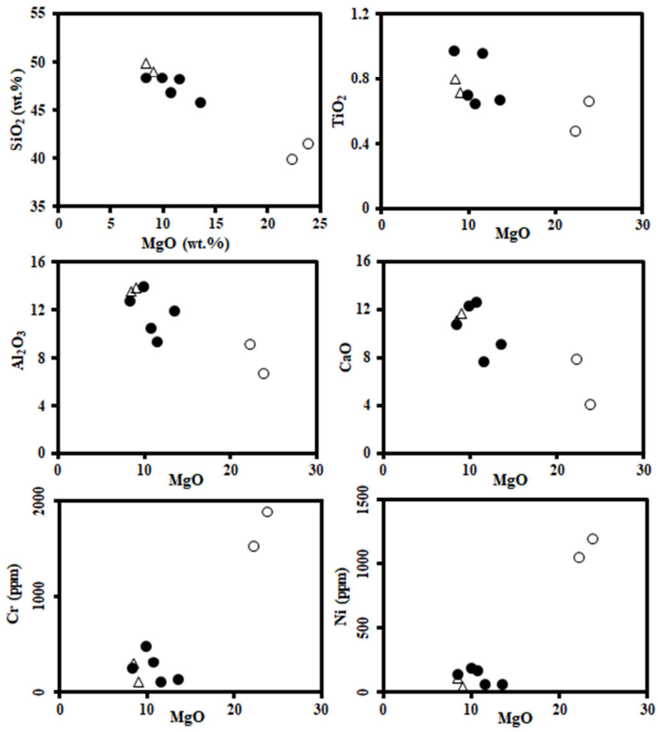

Fig.4. Harker variation diagrams for studied Dalma metavolcanic suite showing major and trace element variation against MgO.

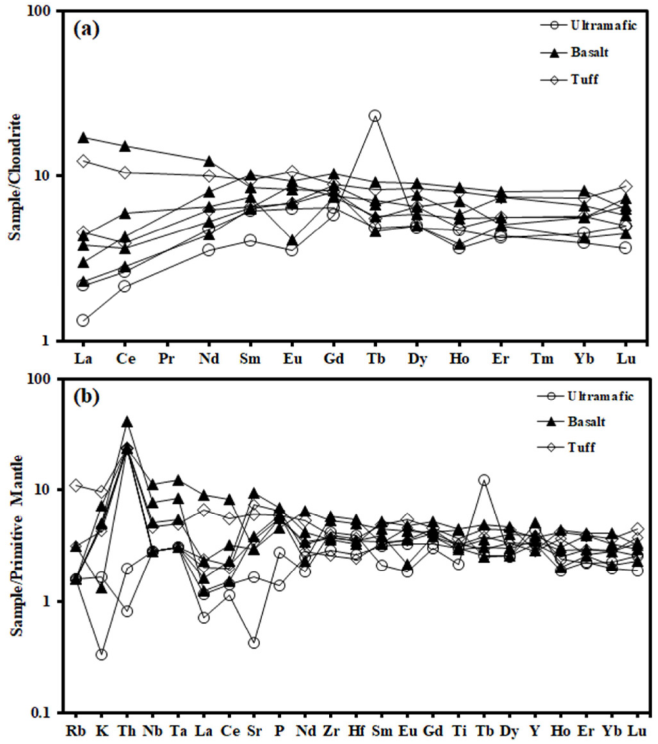

Fig.5. (a) Chondrite normalized REE patterns (normalizing values are after Taylor and Mclennan, 1985) and **(b)** primitive mantle normalized multi-element patterns (normalizing values are after Sun and McDonough, 1989) of the studied Dalma metavolcanic rocks.

(Na_2O+K_2O) show variation like (45.74-48.29), (0.64-0.97), (9.34-13.90), (8.48-13.62) and (0.95-4.64) respectively. In studied basalts, the negative correlation of SiO_2, TiO_2, Al_2O_3, CaO, Cr and Ni against MgO (Fig. 4) reflects fractionation of the mafic minerals i.e., olivine and pyroxene. However, the absence of a negative Eu-anomaly in the chondrite normalized REE-patterns (Fig. 5a) indicate that plagioclase was not an important fractionating phase. The overall, chondrite normalized REE-patterns are parallel with depleted LREE and flat HREE. Primitive mantle normalized multi-element patterns (Fig. 5b) are sub-parallel with enrichment in LILE (e.g., Rb, K and Th) and depletion in Sr. Such patterns are similar to those shown by island arc basalts (Pearce, 2008).

Tuffs

In studied tuffs, SiO_2, TiO_2, Al_2O_3, MgO and alkalis show variation from (48.98-49.83), (0.7-0.8), (13.6-13.9), (8.43-9.07) and (2.39-2.85) respectively. The high concentration of SiO_2, Al_2O_3, CaO, K_2O and P_2O_5 in tuffs relative to studied basalts indicates the evolved nature of tuffs with the presence of quartz and plagioclase as dominant phases. They possess flat and parallel chondrite normalized REE-patterns with slightly enriched LREE and flat HREE patterns (Fig. 5a). These samples do not show any prominent Eu anomaly which may indicate accumulation of plagioclase. Also, their primitive mantle normalized multi-element patterns (Fig. 5b) are sub-parallel with enrichment in LILE e.g., Rb, K and Th with flat REE and HFSE.

Trace element ratio $Nb/Y < 0.7$ shows that the studied samples are sub-alkaline in nature (Winchester and Floyd, 1977). The ratios of immobile and highly incompatible elements like Ti/Y, Ti/Zr, Zr/Nb and Ti/V (Table 1) in ultramafics, basalts and tuffs are widely variable. However, majority of these ratios are similar to those found in arc related volcanic suites. In variation diagram (Fig. 4) MgO shows negative correlation with SiO_2, TiO_2, Al_2O_3, CaO and positive correlation with Cr and Ni. The ultramafic rocks plot as distinct group

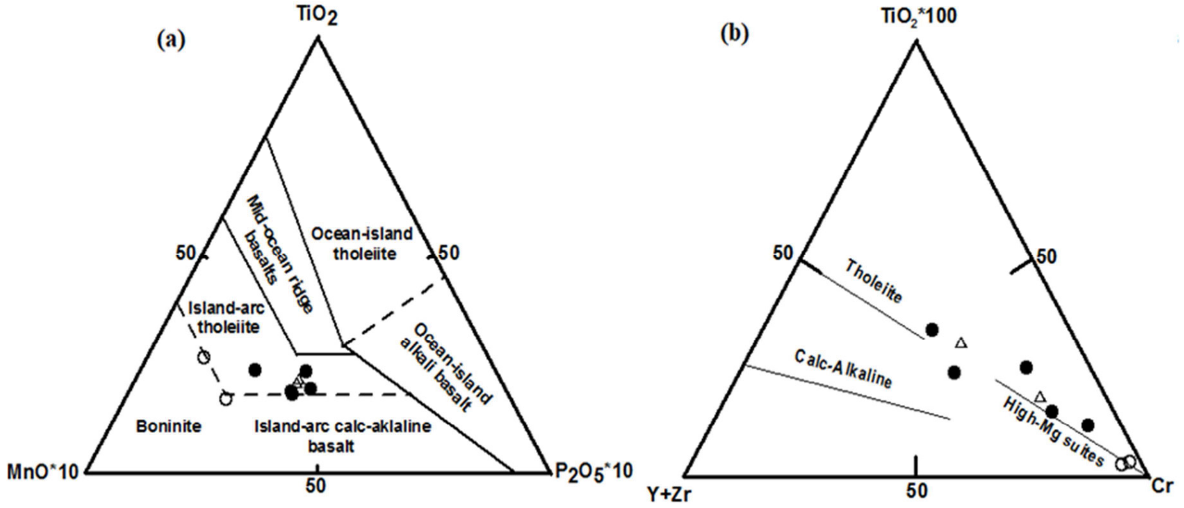

Fig.6. (a) MnO-TiO_2-P_2O_5 ternary diagram (after Mullen, 1983) where studied Dalma metavolcanics fall in island arc tholeiite series and **(b)** YTC (Y = Y + Zr, Ti = TiO_2% x 100, C =Cr) ternary diagram (after Davies et al., 1979) indicating Dalma metavolcanics plot along the tholeiite to high Magnesian suite trend line.

towards higher MgO end, whereas, basalts and tuffs plot towards lower MgO in all the binary diagrams. Ultramafic rocks contain high values of Cr (1512-1874 ppm) and Ni (1037-1185 ppm) whereas, basalts and tuffs contain low values of Cr (103-310 and 102-296 ppm) and Ni (51-182 and 41-107 ppm) respectively. Such values of Ni and Cr of basalts and tuffs are lower than primary basaltic magma Cr (300-500 ppm) and Ni (300-400 ppm) (Frey, 1979), reflecting somewhat differentiated nature of these samples. On the variation diagrams (Fig. 4), their positive correlations for MgO vs Cr and Ni and negative correlations for MgO vs SiO_2, TiO_2, Al_2O_3 and CaO are indicative of the fractionation of olivine, Fe-Ti oxides and clinopyroxene. A ternary diagram of MnO-TiO_2-P_2O_5 (after Mullen, 1983) demonstrates that Dalma metavolcanic suite dominantly belongs to island arc tholeiite series (Fig. 6a). On YTC (Y = Y + Zr, Ti = TiO_2% x 100, C =Cr; Fig. 6b) ternary diagram (after Davies et al., 1979) the studied samples plot along the tholeiite to high-magnesian suite trend line. In this diagram, the ultramafic samples plot towards Cr corner; basalts and tuffs show enrichment in TiO_2 and plot towards low Cr side. This plot confirms the cogenetic nature of the studied Dalma metavolcanic samples.

Petrogenesis

On the Nb/Yb vs Th/Yb diagram (Fig. 7a; after Pearce and Peate, 1995) the studied samples plot above the mantle array defined by mid ocean ridge basalts and oceanic island basalts (MORB-OIB array), in an oceanic arc region on account of their high Th/Yb ratio. Th and Nb are generally believed to be immobile elements (Leat et al., 2004), however, in subduction zones Th shows mobile nature and is enriched in the magma chamber due to hydrous fluid input released from the subducted slab, whereas Nb generally remains immobile. This subduction signature suggests that the Dalma metavolcanic suite were originated from the mantle wedge overlying the subduction zone modified by the slab dehydration fluids. Incompatible and immobile trace element ratios (e.g., Ti/Yb and Nb/Yb) are important to inspect source heterogeneity or depth of melting. Diagram TiO_2/Yb vs Nb/Yb (Fig. 7b) after Pearce (2008) differentiates between shallow and deep melting sources. In this diagram, studied samples show affinity with shallow melting array because of low Ti/Yb ratio and plot in-between depleted to enriched MORB compositions.

The subduction zone magma derived from the mantle wedge above a subducted lithosphere is characterized by high LILE/HFSE and

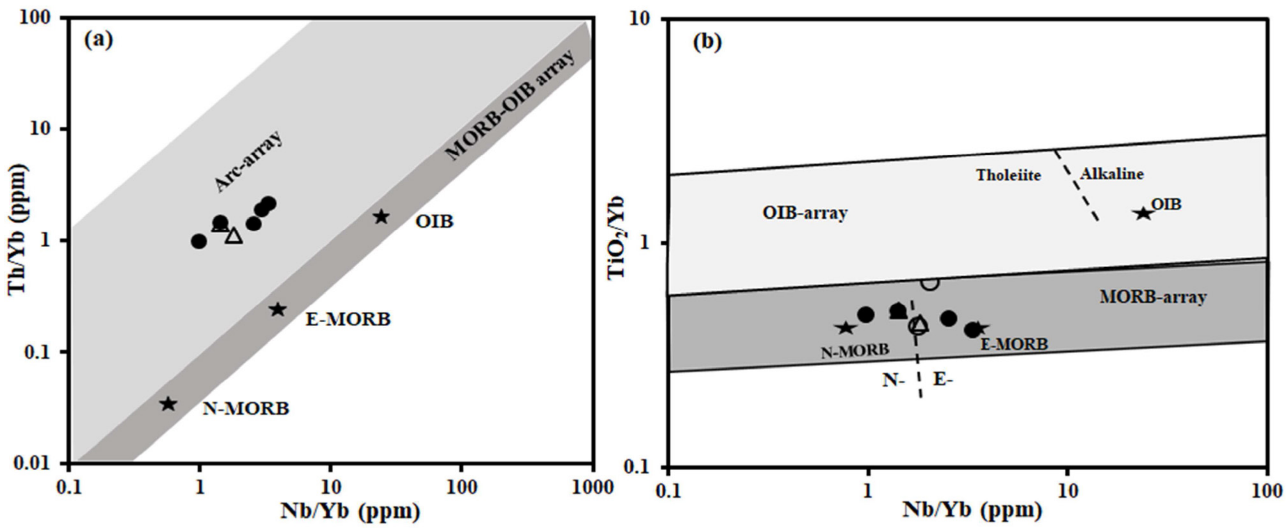

Fig.7. (a) Nb/Yb vs. Th/Yb plot (after Pearce and Peate, 1995) showing studied Dalma metavolcanics plot in Arc array field and **(b)** Nb/Yb vs. TiO_2/Yb plot (after Pearce, 2008) highlighting the shallow melting for studied Dalma metavolcanics.

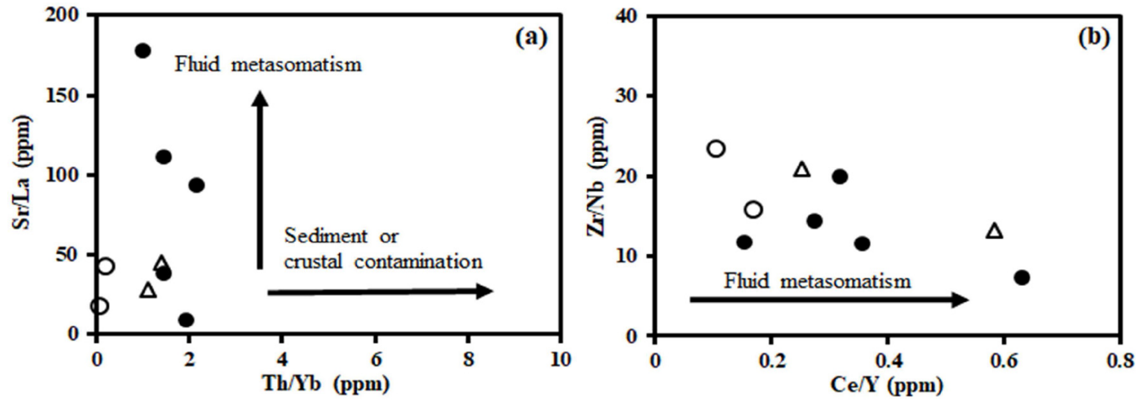

Fig.8. (a) Sr/La vs Th/Yb and (b) Zr/Nb vs Ce/Y diagrams showing involvement of fluid metasomatism in the petrogenesis of the studied Dalma metavolcanics.

LREE/HFSE ratios than typically observed in MORB and OIB. An ideal tracer for determining the type of mantle wedge involved in the magma genesis is Zr/Nb ratio. OIB and MORB have distinctly different values of Zr/Nb. OIB and enriched mid ocean ridge basalt (E-MORB) have low Zr/Nb i.e., 5.83 and 8.80 (after Sun and McDonough, 1989) respectively, however, N-MORB have Zr/Nb ratio of 31.76 (after Sun and McDonough, 1989). The Zr/Nb ratio in studied samples ranges from 7-23 which is consistent to the N-MORB type signature. Majority of studied samples have lower Ti/Y < 300 and Ti/Zr < 110 ratios as compared to MORB which may be expected because of the influence of the subduction components (slab-released fluids with high LILE–LREE/HFSE ratios) in the development of the chemical nature of the subcontinental lithospheric source(s) and greater stability of the Ti-bearing phases in such sources (Brenan et al. 1994; Mir et al., 2010; Mir et al., 2011). In Th/Yb vs Sr/La diagram (Fig. 8a) the studied samples follow fluid metasomatism trend line. Similar results are observed in Ce/Y vs Zr/Nb diagram (Fig. 8b). The constant Th/Yb and Zr/Nb with respectively increasing Sr/La and Ce/Y ratios are consistent with the addition of slab-derived fluids to the mantle wedge. Elevated Th/Yb ratio above the MORB-OIB mantle array (Fig. 7a), further supports fluid addition to the source composition (Woodhead et al., 1998). In Sm/Yb vs La/Sm diagram (Fig. 8), the studied samples plot along the spinel lherzolite mantle source indicating generation of their melts by higher degrees of partial melting (20-30%) at shallow depth comparable to asthenospheric mantle.

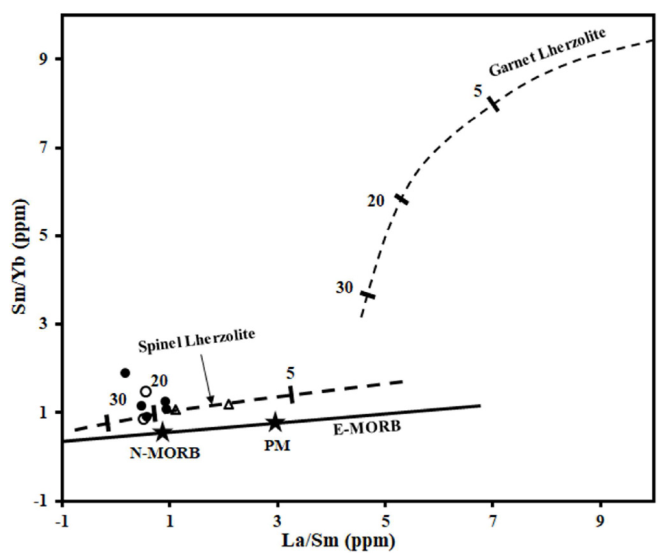

Fig.9. Sm/Yb vs La/Sm diagram (after Bezard et al., 2011) showing spinel lherzolite source for the studied Dalma metavolcanics.

Tectonic Setting

The origin of Dalma volcanic rocks is still debated; so far different conclusions have been drawn related to their tectonic setting by early workers. Naha and Ghosh (1960) has suggested an island arc setting for the Dalma volcanism. Gupta et al., 1980 considered these metavolcanics as within plate basalts while as Sarkar (1982a) regards them as tectonically emplaced ophiolite in response to the collision of Singhbhum cratonic plate and Chotanagpur plate. Chakraborti and Bose (1984) have considered Dalma metavolcanics as marginal basin basalts. Bose et al. (1989) and Bose (1994) proposed a back-arc setting. A plume-related origin is given by (Roy, 1998) and (Roy et al. 2002). Mazumder (2005) supported the plume origin and had proposed an intracontinental rift setting for the Dalma volcanism. However, present work shows subduction zone setting of Dalma metavolcanics on the bases of geochemical characteristics as discussed in forthcoming paragraph.

From primitive mantle normalized multi-element patterns, Nb-Ta depression is usually observed in the rocks of continental and island arc settings whereas it is uncommon in basalts of oceanic affinity (Holm, 1985). Studied samples show Nb-Ta negative anomaly (Fig. 5b) which implies their formation in island arc setting. Further, relatively immobile trace elements such as Ti, Zr, Y, Nb and Yb are more useful for determining the tectonic settings. Basalts originating within plate (oceanic island or continental basalts) can be separated from those originating at plate margins (ocean ridge to ocean floor basalts and calc-alkali basalts of arc volcanos) using the ratios of these elements. On Ti/Y vs Zr/Y diagram (Pearce and Gale, 1977) studied samples plot in plate margin basalt field (Fig. 10a). On Zr vs Zr/Y discrimination diagrams (Pearce and Norry, 1979) majority of studied samples plot in volcanic arc basalt field and few samples fall in MORB (Fig. 10b). Further, on Zr vs Ti plot (Pearce and Cann,

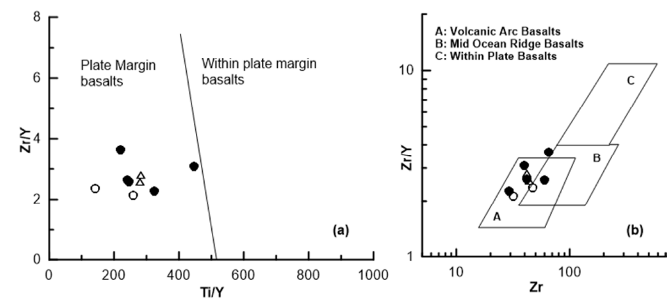

Fig.10. (a) Ti/Y vs Zr/Y diagram (Pearce and Gale, 1977) showing plate margin basalt nature of studied samples; and **(b)** Zr vs Zr/Y diagram (Pearce and Norry, 1979) showing majority of studied samples plot in volcanic arc basalt field and few samples fall in MORB.

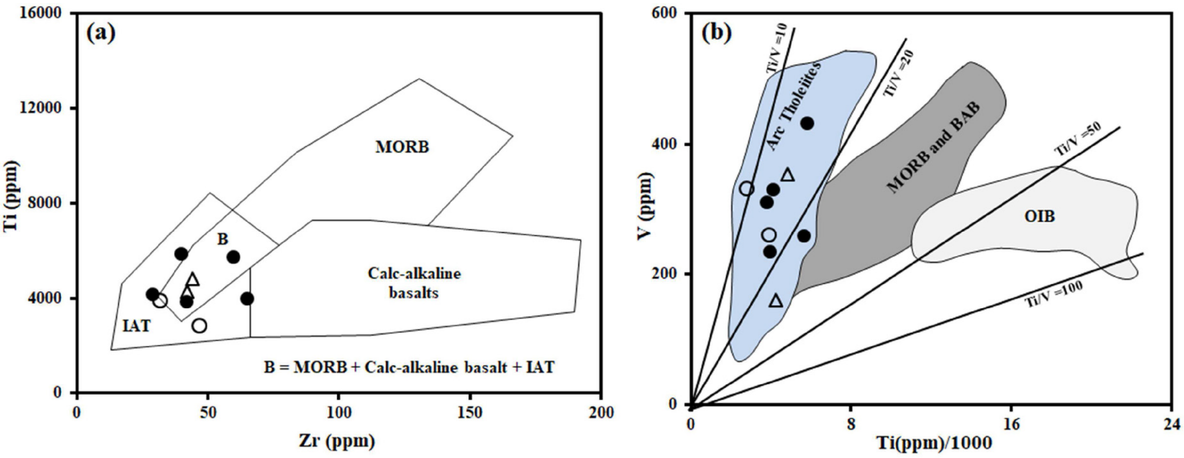

Fig.11. Tectonic discrimination diagrams for Dalma metavolcanic suite **(a)** Zr - Ti plot (after Pearce and Cann, 1973) and **(b)** Ti –V plot (after Shervais, 1982). Both the plots indicate island arc tholeiite tectonic setting of the studied Dalma metavolcanics. MORB = mid ocean ridge basalt; IAT = island arc tholeiite; BAB = back arc basalt and OIB = ocean island basalt.

1973; Fig. 11a) and Ti vs V plot (Shervais 1982; Fig. 11b) studied samples clearly show island arc tectonic affinity. Hence, various geochemical parameters and discrimination diagrams suggest an island arc (subduction zone) tectonic setting for Dalma metavolcanic belt. Therefore, it is recommended to have detailed structural, sedimentological and isotope data to furnish the tectonic setting of the Dalma metavolcanic belt and to revisit the geodynamic evolution of the Proterozoic SMB.

CONCLUSIONS

Geochemically, the Dalma metavolcanic suite shows sub-alkaline tholeiitic nature. The overall depleted LREE and flat HREE patterns in studied samples resembles to that of N-MORB patterns. However, in primitive mantle normalized multi-element patterns, the basalt and tuff samples are characterized by enrichment of LILE and depletion of HFSE. Such patterns are similar to those found in subduction zone related basalts. In addition, ratios like Ti/Y, Ti/Zr, Zr/Nb and Ti/V are similar to those found in arc related magmatic suites. Discrimination diagrams like MnO-TiO_2-P_2O_5, Ti/Y vs Zr/Y, Zr vs Zr/Y, Zr vs Ti plot and Ti vs V supports subduction zone or island arc tectonic setting of the studied metavolcanic suite. Addition of fluids from the subducting slab to the mantle source of studied samples is suggested on the bases of high Sr/La, Rb/Zr, Th/Yb, Ce/Y and La/Yb coupled with low Th/Nb, Nb/Y, Ta/Yb and Zr/Ti ratios. Based on the present study it is suggested that the melts of Dalma volcanics were generated by 20% - 30% partial melting of the spinel lherzolite mantle source. Keeping in view of different suggested tectonic settings of Dalma metavolcanic belt it is recommended to refurnish the tectonic setting of the Dalma metavolcanic belt based on detailed structural, geochemical and isotope data.

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