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Research Paper

A PETROCHEMICAL APPRAISAL OF DALMA VOLCANISM AND ITS BEARING ON THE GEODYNAMIC EVOLUTION OF THE PROTEROZOIC SINGHBHUM MOBILE BELT: EASTERN INDIAN SHIELD

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The Dalma metavolcanic rocks occupying the median tract of the Singhbhum mobile belt of eastern Indian peninsular shield, despite being extensively studied, still continue to pose serious questions about their precise chemical nature, stratigraphic position and tectonic regime. The present study is an attempt to address the underlined issues through a renewed petrochemical treatment of these metabasites in the type area north of Jamshedpur in Jharkhand state where they occur as metabasalts, agglomerates and tuffs which constitute low-grade greenschist facies rocks typically characterized by tremolite – actinolite as well as albite - epidote – chlorite ± actinolite associations. The chemical attributes suggest tholeiitic protolith for them. The exceedingly low K (0.09-0.24 wt%) and FeO^0/MgO (1.20-1.59) < 1.7 are comparable to the oceanic or abyssal tholeiites similar to the MORB. Presence of ol in the norms indicates their Mg-rich basaltic nature. The Mg number (58-65) characteristically conform to the mafic to somewhat ultramafic character and also the tholeiitic nature which is further substantiated using various chemical parameters as well as on the basis of abundance of trace elements such as V, Cr, Ni, Co, Cu, Rb, Sr. The extremely low Rb (av. 2.7 ppm), Sr (av.137 ppm) and Th/U (~ 4) values also indicate their affinity with MORB low-K tholeiites. The major and trace element data are consistent with fractional crystallization model of differentiation within a limited range. The MORB and Chondrite normalized trace element patterns show similar trends marked by parallelism, negative slope and presence of characteristic Nb-Ta-Ti anomaly typical of subduction related island arc set-up. A relatively smooth pattern showing close proximity to MORB line suggests their back-arc extensional tectonic regime further supported by tectonomagmatic diagrams as well as their close similarity in composition to the East Scotia back-arc tholeiites.

Keywords: Dalma volcanism, Metabasalts, Pyroclastics, MORB low K-tholeiites, Back-arc tectonic regime

INTRODUCTION

The Proterozoic Singhbhum Supergroup rocks occupying the E-W trending arcuate North Singhbhum Mobile Belt (NSMB) that is

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demarcated from Archaean Singhbhum - Orissa craton in the south by famous Singhbhum Shear Zone (SSZ) and from Chotanagpur Granite Gneiss Complex (CGGC) in the north by Tamar - Khatra lineament (TKF) are concordantly overlain in the axial part of the basin by nearly 200 Km long and 3-7 Km wide band of volcanic rocks known as Dalma metavolcanics around which the geology of the area centers round (Dunn and Dey, 1942; Sarkar and Saha, 1962; Gupta and Basu, 1977; Bose and Chakarborti, 1981; Saha 1994; and Mazumder, 2005). Although these rocks from the eastern Indian Peninsular shield find voluminous expression in geological literature, their stratigraphic status is still a matter of conjecture. Dalmas are a thick succession of metamorphosed volcano-sedimentary sequence consisting of carbonaceous and ferruginous phyllitic tuffs as well as agglomerates with numerous ultramafic and mafic intrusive and extrusive phases (Komatiitic and picritic) sometimes exhibiting pillow structure in the lower part whereas the upper part is dominated by metabasalts of monotonous compositional uniformity (Gupta *et al.*, 1977; Gupta and Basu, 1979, Gupta *et al.*, 1980; Chakarborti and Bose, 1985; and Bose, 1994) often vesicular with ophitic to sub-ophitic texture. Such a sequence is typical of several greenstone belts of Precambrian complexes with komatiite and picrite at the lower level followed by younger MORB like basalts and the entire suite of rocks have suffered deformation and low grade metamorphism under greenschist facies conditions. The chemical changes have by and large remained isochemical despite changing grade of metamorphism. The Dalmas are typically characterized by Talc-tremolite-actinolite; tremolite-actinolite (Mg-rich basaltic lava flows) and albite – epidote – chlorite ± actinolite associations (meta-basaltic flows).

The chemical treatment of the Dalma rocks has so far been very scanty and sketchy but has been assigned to a tholeiitic nature (Gupta *et al.*, 1977; Yellur, 1977; Bose *et al.*, 1989; and Nath *et al.*, 2006). In the perspective of their occurrence within the same basin in which the Singhbhum group of rocks along with phases of greenstone associations lie, it becomes imperative to evaluate Dalma volcanism and its tectonic setting to assess its bearing on the overall geodynamic evolution of the Proterozoic Singhbhum Supergroup. The Proterozoic volcano-sedimentary successions in Sighbhum mobile belt record sedimentation and volcanism in rapidly changing tectonic scenario (Eriksson *et al.*, 2006; and Mazumder *et al.*, 2012a and 2012b). A large variability in petrological as well as geochemical attributes have led to divergent views regarding the tectonic set-up of evolution of Dalma rocks ranging from continental margin (Bose, 1994) to island arc (Naha and Ghose, 1960) to even marginal back-arc setting (Bose and Chakarborti, 1981; Bose, 1992, 1994 and 2000). Such a discrepancy arises out of the geochemical bias of the previous works, mafic to ultramafic bimodality of volcanism, limited geochemical approach to the volume and size of the magmatic body, heterogeneity of rock types resulting out of low grade metamorphism and hence the present work.

Geological Set-Up and Location of the Area

The overall geological set-up of the area includes parts of Singhbhum group comprising a thick succession of metamorphosed volcano-sedimentary sequence with older Chaibasa Fm. in the south and younger Dhalbhum Fm. (≡ Iron ore stage of Dunn and Dey, 1942) in the north belonging to ENE-WSW to E-W trending

Singhbhum/Satpura orogeny (c. 850 Ma) with the intervening band of Dalma metavolcanics in the median part of the mobile belt. A small area comprising a segment of Dalma range north of Jamshedpur between Saharbera Forest Gate on NH-33 and Dalma Hill Top besides exposures around Dimna lake (E. of Dalma Top) in the east and Chandil Dam on river Subarnrekha in the west covered under Survey of India toposheet no. 73J/1 bounded by Lat. 22^0 45´ to 23^0 00´ N and Long. 86^0 0´ to 86^0 15´ E has been selected for detailed systematic mapping and sampling on 1:125000 scale (Figure 1).

Field Occurrence

The Dalma hill dominates the landscape of the study area. It forms a precipitous slope and is diversified by a number of streams including Subarnrekha river and its tributaries that superimpose over the Dalma topography. The metabasites here occur as lava flows, agglomerates/pyroclastics and tuffs.

Lava flows dominantly forming the upper parts of the Dalma volcanic piles are fine grained, grey to greyish colored basaltic flows of variable thickness with monotonously homogeneous composition at times showing lenticular flow layering and vesicular nature. These are sometimes intercalated with thin layers of tuffs and pyroclastics. Schistosity, although not very well defined, appears to be parallel to the flow layering with pronounced joints and mineral lineation. Between the layers are found amygdaloidal and vesicular basalt and sometimes faintly retained evidences of pillow structures in the basal part of the flows indicating thereby successive phases and also the sub-marine mode of their eruption. Around Patipani to the NW of Dimna lake, fresh, fine to medium grained and dark grey boulders of basalt showing greenish tinge, porphyritic texture and pitted structure were found scattered on the slope of the hill. A number of exposures of massive vesicular basalt were encountered between the Saharbera Forest Gate of Dalma Range on NH-33 and the Dalma Hill Top at places around Chilgu, Chakuliya Naka post and Pinderabeda Forest Rest House located 5 Km before Dalma Top. Near Dalma Mata Mandir at the Top, carbonaceous phyllites trending ESE-WNW dipping towards NNE at 75^0 were also observed. Components of Dalma volcanic rocks are also found within Dhalbhum Fm north of the main exposure of Dalma hill ranges.

Agglomerates/Pyroclastics forming the most important fragmental volcanic debris constitute a conspicuous horizon at the base of the Dalma hill north of NH-33 near Joriadih, Bhadudih and Chakulia (near canal site inside the Dalma forest). Agglomerates consist of the juvenile fragments of the basic rocks occurring as bombs, lapilli and shards often set within the fine grained glassy matrix or magmatic flows of similar composition (Figure 2a). The size of the vitric fragments is measured on mm to decimeter or even larger scale. Paucity of lithic fragments in them indicates their effusive nature. Apart from this, some of the pyroclastics often poorly sorted contain mostly bomb like fragments of juvenile nature scattered within fine-grained tuffaceous matrix which is often dense and vesicular that shows signs of weathering into hematitic and lateritic masses. They also include subordinate amounts of angular to sub-angular lithic fragments at places but they are very rare.

Tuffs are basic, fine grained, massive, dark grey to grayish green colored, crudely foliated rocks sometimes showing splintery habit and are characterized by the presence of volcanic

Figure 1: Geological Map of the Study Area

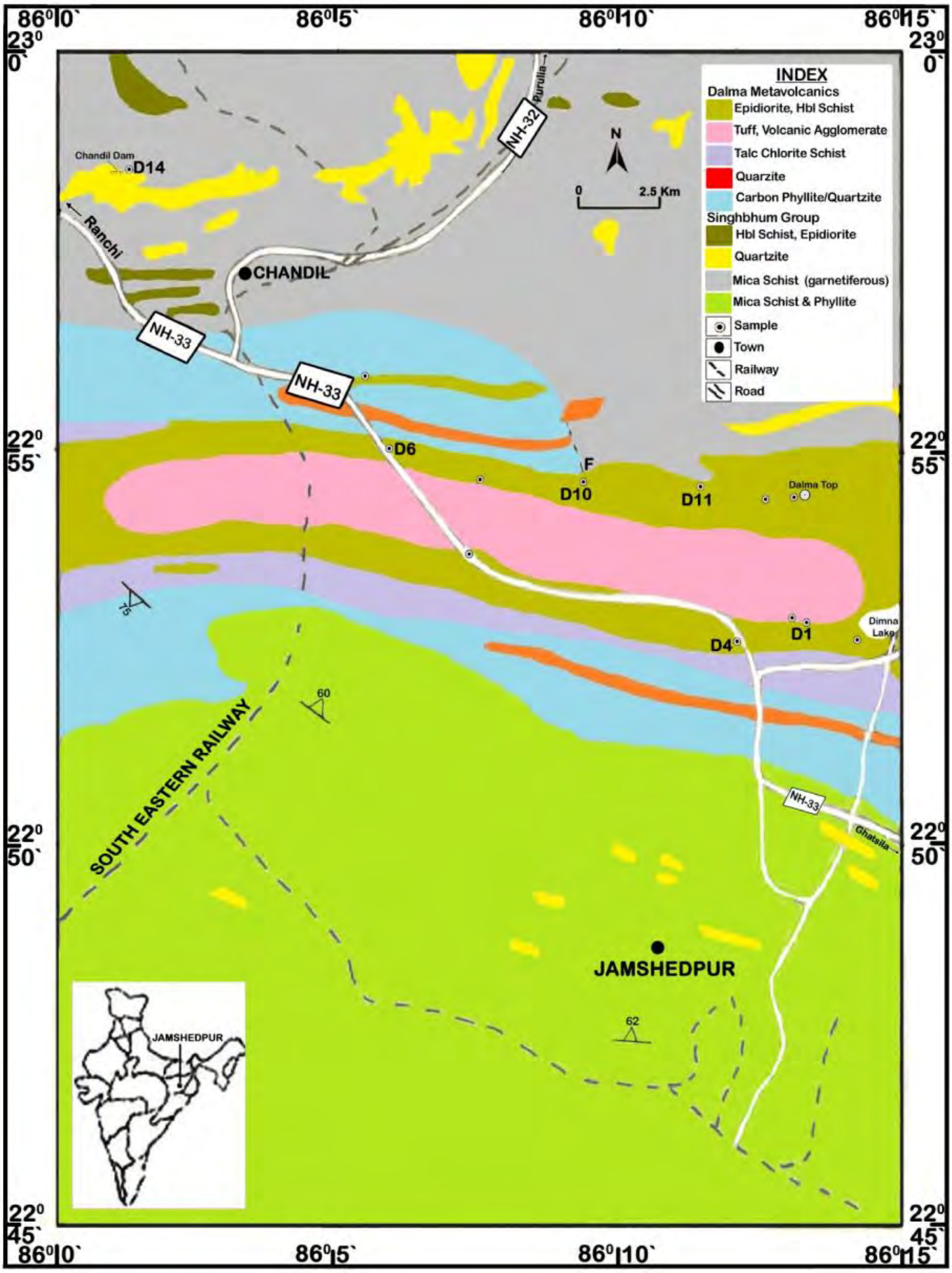
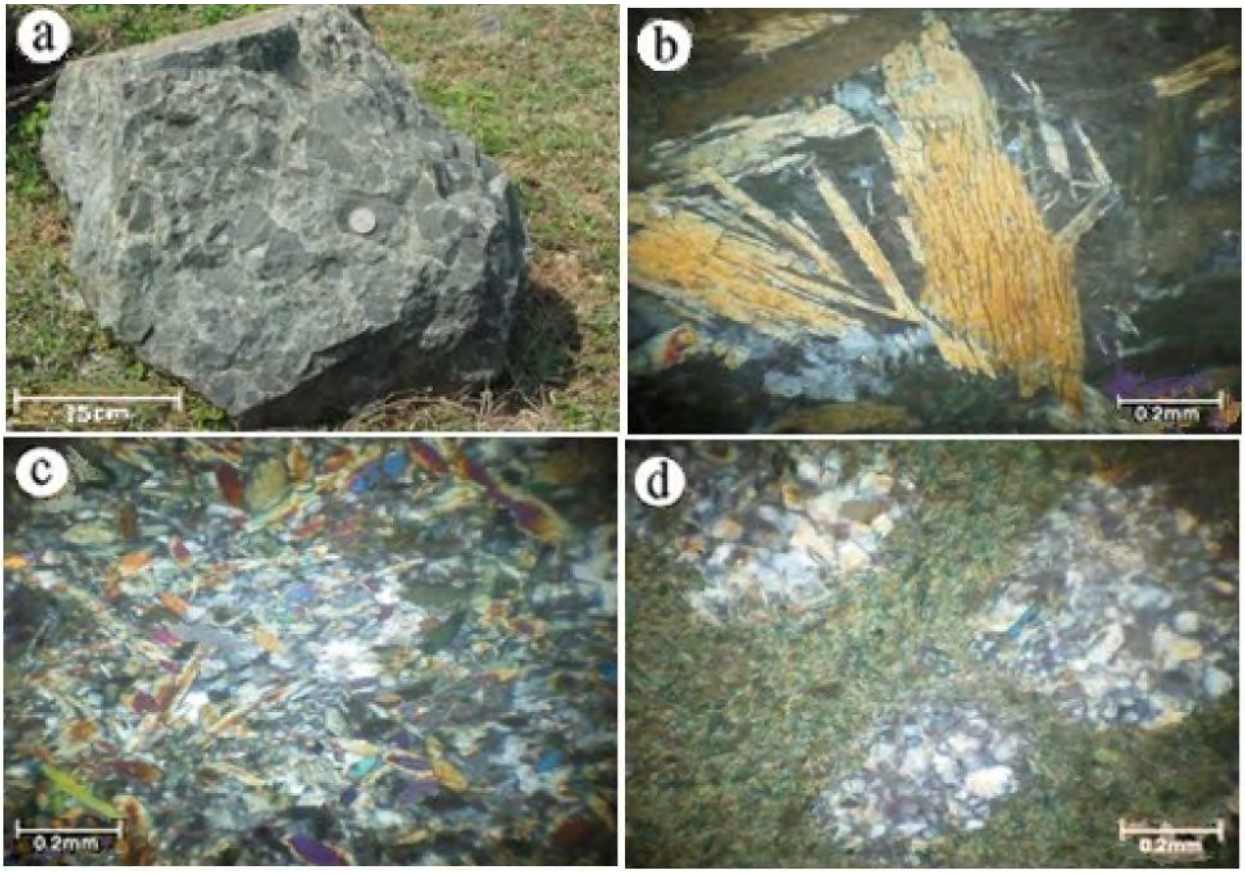


Figure 2: (a) Field Photograph of Typical Agglomeratic Rock with Angular to Sub-Angular Juvenile Bombs from Near Canal Site Inside Dalma Forest, (b) Microphotograph showing Bent Crystal of Tremolite with Fibrolamellar Termination in Dalma Tremolite - Actinolite Schist; x-Nicol (10 x 10), (c) Microphotograph showing Typical Albite - Epidote - Chlorite - Actinolite Assemblage in Dalma Basaltic Rocks Under x-Nicol (10 x 10), (d) Microphotograph of Welded Tuff Associated with Dalma Metavolcanics Containing Numerous Bombs or Airdrops of Varying Shapes and Sizes Entrapped in Somewhat Glassy Matrix that Partly Devitrified into Chlorite Schist; x-Nicol (10 x 10)



debris or in other words constitute the matrix of pyroclastic materials. They occur as thin conformable beds with thickness hardly exceeding 30-40 cm interlayered with metasediments with which they have sharp contacts. These masses are heterogeneous varying widely in texture and composition with variable amounts of vitric or subordinate lithic fragments, glassy shards, lapilli and droplets. Their true nature is often obscured due to alteration and subsequent metamorphic changes under greenschist facies conditions. These igneous looking hard, compact silicified rocks are widely used as road metals. The depositional features like current bedding or graded bedding are conspicuously absent but ripple marks are sometimes present. Induration and welding is also variable. Some of the welded crystal tuffs look like a medium grained gabbroic rock. The variable admixture of sedimentary detritus and volcanic debris is also observed. South of Dimna in the hilly road section leading to the lake the strike of phyllites/tuffs vary from ESE-WNW dipping at 45^0 towards NNE. These tuffs sometimes carry fragments of pyroxene and plagioclase.

Petrography

The petrographic evaluation of Dalma rocks becomes a bit tedious and uncertain because of their fine grained metavolcanic nature and frequent association with volcaniclastic tuffaceous matters of variable texture and mineralogy. For the sake of systematic description these rocks are described as under

Formation	Petrographic Type	Mineral Composition
		Tuffs, welded crystal tuffs & Agglomerates
Dalma metavolcanics	Greenschist facies rocks	Albite-epidote-chlorite±actinolite association (basaltic flows)
		Tremolite-actinolite±anthophyllitic rocks & Talc-chlorite schists (Mg- rich lava flows)

Greenschists

Tremolite-Actinolite Bearing Association: The lower part of the Dalma volcanic belt is predominantly characterized by Mg-rich tremolite-actinolite bearing rocks with talc and chlorite. The fine to medium grained tremolite-actinolite bearing rock types with effusive vesicular character are almost developed in all sections of the study area. In thin section the rocks are characterized by lepidoblastic to nematoblastic and also porphyroblastic texture in which prismatic laths as well as equant grains of colourless tremolite and pale green actinolite together constituting 60-65% by volume are set within subidioblastic flakes of pale green chloritic mass (Figure 2b). Some prismatic needles of tremolite and actinolite often in felted aggregates, with parallel to sub-parallel alignment impart characteristic schistosity. Inclusions of epidote both pistacite and clinozoisite occur as alteration products of calcic plagioclase. Untwined albite and rhombohedral calcite in amphibole and chlorite give rise to poikiloblastic texture. Deep red brown rutile, spindle-shaped pale brown sphene, colourless apatites together with opaques such as magnetite, ilmenite and spinel constitute minor accessories.

Albite – Epidote – Chorite ± Actinolite Assemblage: The greenschist facies rocks representing the Dalma flows of mafic character are mostly dominated by albite-epidote-chlorite±actinolite association (Figure 2c). Under the microscope they are characterized by crude foliation exhibiting nematoblastic to lepidoblastic as well as blastoporphyritic textures. The relict ophitic to sub-ophitic texture is also identifiable in most of the sections. The rocks predominantly consist of subidioblastic flakes of chlorite, xenoblastic to granoblastic grains of colorless, untwinned albite, granules of iron-rich epidote and small microlites of actinolite. Some relict saussuritized laths of calcic plagioclase grains often twinned on albite as well as carlsbad - albite combined laws varying in composition from andesine to labradorite (An_{40-55}) are also identified. Few small grains also exhibit traces of zoning and twinning indicating their magmatic character. Some anhedral grains of quartz and calcite generally occur as secondary filling in veins and voids. Minor accessories include sphene, rutile, magnetite, ilmenite and apatite as well as some hematite.

Agglomerates: Under the microscope show wide variations in the texture of the matrix and vitric fragments evidently indicating inhomogeneities in these rocks that make the thin section study extremely difficult but the study of slides prepared out of the different portions, i.e., matrix and the bombs reveal the precise nature of the agglomeratic rocks. The matrix is normally even grained with crude schistose appearance with almost greenschist facies mineralogy dominated by chlorite, albite, epidote ± actinolite and magnetite. In contrast to that, the vitric fragments which are often pale to brown in colour and widely variable in size are almost chilled and vitrified glasses which are less affected by mineralogical changes during the subsequent processes of metamorphism as compared to the matrix. The devitrification of the glassy matter of the fragments is often associated with silicification. Some deuteric changes within the vitric fragments have altered the pyroxenes into chlorite as well as amphibolitic matter, i.e., actinolite. Saussuritization and kaolinization of plagioclase feldspar associated with the glassy matter impart a turbid appearance to these fragments.

Tuffs: Associated with Dalma metavolcanics have generally been identified as vitric tuffs or crystal tuffs with very little lithic or accidental components. Like other rocks they have also been metamorphosed under greenschist facies rocks described earlier. Under the microscope they exhibit variable proportion of flows with splintery habit and tephra droplets of different shapes and sizes less than 4 mm and are generally glassy in nature imparting heterogeneous character to these rocks (Figure 2d). The fine-grained matrix constitutes the basaltic lava flows that after metamorphism have changed over to greenschist facies rocks. On the other hand, the juvenile fragments often having spherical shape of variable sizes appear to have reacted differently or have remained immune to the process of metamorphism. Chlorite is the most dominant constituent generally pseudomorphous after pyroxene and contains magnetites as common inclusions. Besides chlorite, ferruginous prochlorite and few grains of clinochlore are also present. Colourless untwinned albite occurring as a mosaic of shapeless grains is next in order of abundance. Some tabular crystals of relict calcic- plagioclase often twinned on albite as well as carlsbad-albite combined laws ranging in composition between An_{35-55} also occur. The pale green slender needles of actinolite and granules of pale yellow or brown iron rich epidote and colourless clinozoisite with high relief and anomalous 2nd order interference colour have subordinate status. Wedge shaped sphene, opaque magnetite, ilmenite, deep red rutile and colourless turbid apatite are minor accessories. Besides these, quartz and calcite are found as secondary minerals in veins and vesicles.

Chemistry

For this purpose, a number of truly representative samples based on field and petrographic details were chemically analyzed using XRF (Philips MagiX PRO Model PW 2440 coupled with an automatic sample changer PW 2540) and HR-ICP-MS (Nu Instruments Attom®, UK) at the Geochemistry Division laboratories of NGRI, Hyderabad to obtain analytical data of high precision and accuracy. FeO was determined in the geochemical lab of the department of geology, Patna university.

The whole rock composition of the analyzed rocks in terms of oxides wt % and their CIPW norms along with trace and REE data have been presented in Table 1. The TAS classification diagram (Figure 3) after Le Maitre (2002) clearly shows that the Dalma metavolcanic rocks of the area under study plot in the field of sub-alkalic magma (tholeiitic) series and fall mostly in the field of basalt and basaltic andesite. The tholeiitic nature is also indicated when these rocks are plotted on Alkali

Table 1: Composition (Major, Trace and REE) of Dalma Metavolcanic Rocks of the Area

	Major Oxides (wt %)							Trace & REE (ppm)					
	D-1	D-4	D-6	D-10	D-11	D-14		D-1	D-4	D-6	D-10	D-11	D-14
SiO_2	51.46	54.89	46.41	46.83	47.56	48.54	Sc	40.48	17.27	40.93	38.70	-	48.69
Al_2O_3	12.07	12.72	13.40	12.84	13.07	10.64	V	267.9	144.17	259.19	250	-	313.23
Fe_2O_3	2.49	1.25	2.46	2.90	2.60	2.61	Cr	125.5	47.78	110.18	114.18	-	118.05
FeO	8.50	4.60	9.30	9.76	10.02	9.95	Co	64.59	18.73	61.44	60.85	-	65.32
MnO	0.17	0.06	0.18	0.16	0.17	0.21	Ni	73.64	33.73	72.52	66.31	-	78.81
MgO	7.92	6.25	9.58	9.93	8.68	7.76	Cu	251.4	195.71	161.73	200.54	-	102.23
CaO	11.20	12.03	13.60	12.27	11.62	13.29	Zn	714	418.22	271.56	345.82	-	194.81
Na_2O	2.71	1.09	1.64	2.45	2.76	1.77	Ga	16.31	20.62	20.15	19.98	-	14.69
K_2O	0.09	3.54	0.16	0.19	0.24	0.15	Rb	3.41	146.56	2.54	2.66	-	2.24
TiO_2	0.80	0.92	1.01	0.87	0.94	0.82	Sr	200.6	151.66	115.40	169.61	-	63.54
P_2O_5	0.09	0.13	0.09	0.08	0.09	0.09	Y	22.45	33.43	22.20	21.99	-	21.51
TOTAL	98.63	98.66	100.47	100.82	99.53	98.55	Zr	49.63	478.32	417.37	545.78	-	4339.83
LOI	0.19	0.67	1.62	1.47	0.68	1.63	Nb	1.51	6.02	2.42	1.99	-	9.71
CIPW norms							Cs	0.99	21.79	0.71	1.37	-	0.35
Q	1.53	6.06	0.00	0.00	0.00	0.63	Ba	142.9	247.31	54.37	114.19	-	79.66
Or	0.53	20.92	0.95	1.12	1.42	0.89	Hf	1.22	7.51	10.08	7.39	-	98.04
Ab	22.93	9.22	13.88	18.74	22.87	14.98	Ta	0.29	0.26	0.49	0.35	-	0.25
An	20.50	19.36	28.73	23.48	22.56	20.64	Pb	28.62	1228.4	404.29	30.81	-	12.59
Ne	0.00	0.00	0.00	1.08	0.26	0.00	Th	1.11	8.89	1.01	1.28	-	1.75
Ac	0.00	0.00	0.00	0.00	0.00	0.00	U	0.31	1.68	0.41	0.32	-	0.32
Di	28.11	31.74	31.02	29.98	28.20	36.69	**REE**					-	
Wo	0.00	0.00	0.00	0.00	0.00	0.00	La	7.34	39.83	5.78	7.16	-	3.19
Hy	18.56	6.31	4.49	0.00	0.00	16.46	Ce	15.97	83.48	13.18	15.56	-	7.59
Ol	0.00	0.00	13.09	17.84	16.67	0.00	Pr	2.19	10.02	1.82	2.16	-	1.15
Mt	3.61	1.81	3.57	4.20	3.77	3.78	Nd	10.32	39.15	8.63	10.23	-	6.02
Il	1.52	1.75	1.92	1.65	1.79	1.56	Sm	2.77	6.98	2.48	2.66	-	2.09
Ap	0.21	0.31	0.21	0.19	0.21	0.21	Eu	0.85	1.41	0.93	0.98	-	0.72
							Gd	3.62	6.51	3.40	3.57	-	3.13
Fe_2O_3/FeO	0.29	0.27	0.26	0.3	0.26	0.26	Tb	0.63	0.97	0.62	0.61	-	0.59
$FeO^0/(FeO^0+MgO)$	0.58	0.48	0.55	0.55	0.59	0.61	Dy	3.45	4.93	3.39	3.32	-	3.28
Na_2O/K_2O	30.11	0.31	10.25	12.89	11.5	11.80	Ho	0.71	1.00	0.72	0.69	-	0.69
mg number	63	71	65	65	61	58	Er	2.19	3.11	2.22	2.17	-	2.15
Alkali index	1.94	2.29	3.10	4.60	3.87	2.04	Tm	0.30	0.45	0.31	0.29	-	0.30
θ	33.54	33.83	36.36	31.16	29.93	34.53	Yb	1.85	2.88	1.89	1.78	-	1.86
							Lu	0.27	0.43	0.27	0.25	-	0.27
							Σ REE	52.46	201.15	45.64	51.43	-	33.03
							Σ LREE	39.44	180.87	32.82	38.75	-	20.76
							Σ HREE	13.02	20.28	12.82	12.68	-	12.27
							LREE/HREE	3.03	8.92	2.56	3.06	-	1.69
							Eu/Eu*	0.82	0.64	0.98	0.97	-	0.86
							Ce/Nd	1.55	2.13	1.53	1.52	-	1.26
							Th/Yb	0.60	3.09	0.53	0.72	-	0.94
							$(La/Sm)_N$	1.71	3.68	1.50	1.74	-	0.99
							$(La/Yb)_N$	2.85	9.92	2.19	2.89	-	1.22
							$(La/Ce)_N$	1.19	1.23	1.13	1.19	-	1.08

mg number = $100Mg/Mg+Fe^{2+}$

Alkali index = $Na_2O+K_2O/(SiO_2-43)x0.17$

Sugimura Index (θ) = SiO_2(wt%)-47(Na_2O+K_2O)/Al_2O_3Mol. ratio

FeO^0 = Total Fe as FeO

Figure 3: TAS (Total Alkali vs. Silica) Diagram for the Rocks of the Study Area (After Le Maitre, 2002)

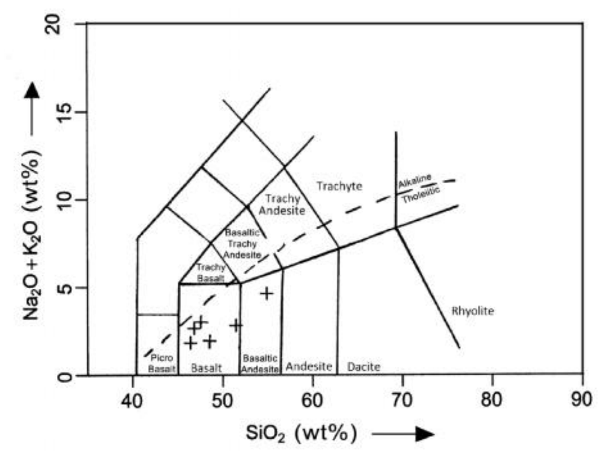


Figure 4: Plot of Alkali Index (AI) vs. Al_2O_3 for Distinction Between Tholeiitic and High - Alumina (Calc-Alkaline) Basalts After Middlemost, 1975

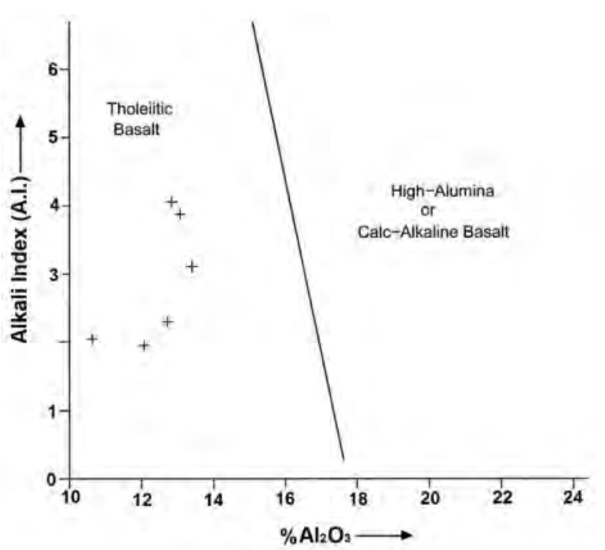
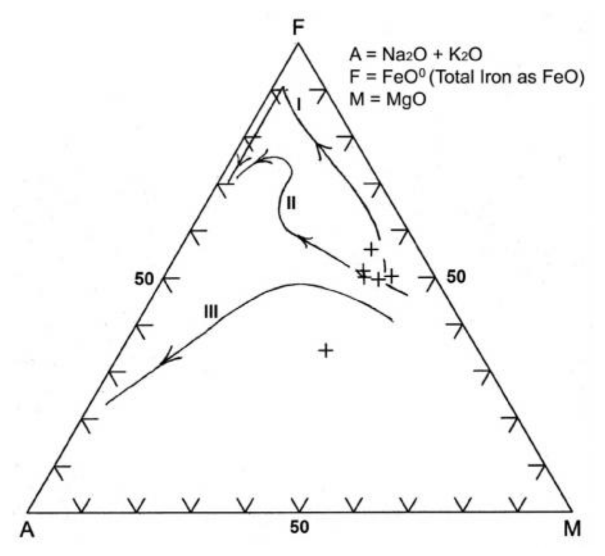


Figure 5: AFM Diagram for the Metabasic Rocks of the Area I: Tholeiitic Trend, Skaergaard Intrusion, After McBirney, 1996 II: Tholeiitic Trend, the Palisades Sills, After Shirley, 1987 III: Calc-Alkaline Trend, the Medicine Lake, After Grove and Baker, 1984



Index vs. Al_2O_3 diagram (Figure 4) after Middlemost (1975). On the AFM diagram (Figure 5), they fall close to the early stage of fractionation trend of the Skaergaard as well as the Palisades tholeiitic suites indicating an initial Fe- enrichment and thereby igneous origin for them is well substantiated giving rise to the rock series basalt $\rightarrow$ basaltic andesite.

The major element chemistry of these rocks exhibit a limited range of basic igneous composition predominantly of tholeiitic nature with few samples showing Mg-rich character which is also supported by a narrow range of FeO^0/MgO (1.20-1.59); FeO^0/FeO^0+MgO (0.55-0.61) and mg-number between 58-65 and, therefore, a limited differentiation consistent with fractional crystallization model is perceived. An exceedingly low K_2O (0.09-0.24 wt%) and higher content of Na_2O (av. 2.27 wt%) coupled with high Na_2O/K_2O (10.25-30.11) and low Fe_2O_3/FeO (0.26-0.3) ratios of these rocks are comparable to the oceanic abyssal tholeiites (Engel et al., 1965) similar to the MORB. The presence of ne and ol in the norms of some of the samples characteristically conform to the mg-rich nature and mafic to somewhat ultramafic character. Based on Al_2O_3/Na_2O+K_2O+CaO ratio (molar basis), these metavolcanic rocks of the area are mostly metaluminous. This is also supported by the normative and the modal composition of these rocks. The excess of Al_2O_3 over Na_2O+K_2O is distributed among hornblende, epidote and biotite in the mode and An, Di and Hy in the norm.

Like major elements, trace elements variations are also consistent with fractional crystallization model to a limited extent. Cr, V, Ni, Co, Zr and Hf exhibit decreasing trends while Rb, Ba, Y, Nb, Ta and U reveal positive trends with respect to SiO_2. Zn, Cu, Sr show no specific trend. The distribution pattern of the individual trace elements, e.g., V, Cr, Ni, Co, Cu, Sr, Rb, Sr, Th/U, etc., also indicates basaltic nature of the Dalma metavolcanics having affinity with that of the low-K oceanic ridge tholeiites (MORB).

The MORB-normalized patterns (Figure 6) of Dalma metavolcanic rocks show striking similarity as they are relatively smooth with few spikes and run almost parallel in close vicinity to one another with somewhat negative slope. They are generally marked by –ve Nb-Ti anomaly. The only exception D-4 showing a relatively more spiky and irregular habit runs wide apart from the rest, indicating thereby some sort of departure from the normal because of its more evolved nature already substantiated on the basis of petrographic as well as major oxide details. These rocks are selectively enriched in LILEs such as Rb, Ba, Th, ± Sr ± K. The Sr - Rb part of the trend in most cases run parallel to the MORB line almost gently touching it which in turn indicates somewhat depleted nature of these rocks. They are also characterized by selective enrichment in HFSEs such as Ta ± Nb ± Ce ± P ± Zr ± Hf ± Sm relative to MORB. A conspicuously parallel depleting trend from Sm to Yb plotting below the horizontal line at 1 is quite noticeable which reflect source rock characteristic. Furthermore, the Chondrite-normalized patterns (Figure 7) for these rocks are also quite similar and their overall shape and extent very nearly resemble the MORB-normalized patterns. An almost parallel and negatively sloping habit between Tb and Yb is observed for these rocks which may indicate source rock composition. These patterns are also characterized by Nb-Ti anomaly.

The REE- patterns of the Dalma rocks of the area normalized to primitive mantle are broadly

Figure 6: MORB-Normalized Trace Element Spiderdiagrams Representing the Rocks of the Area, Normalizing Constants After Pearce (1983)

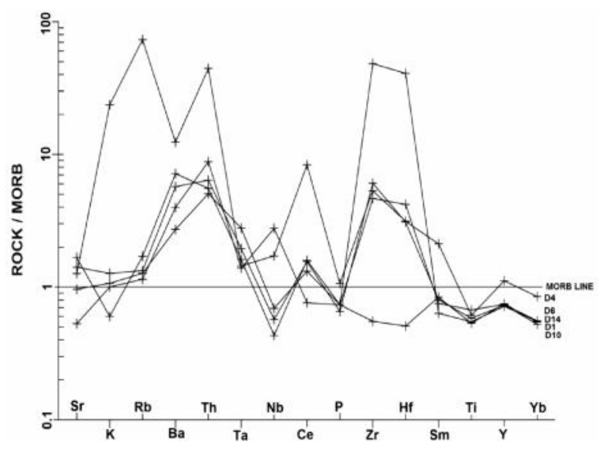
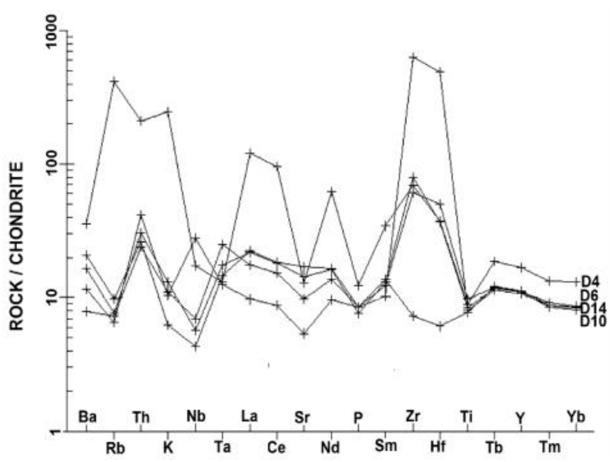
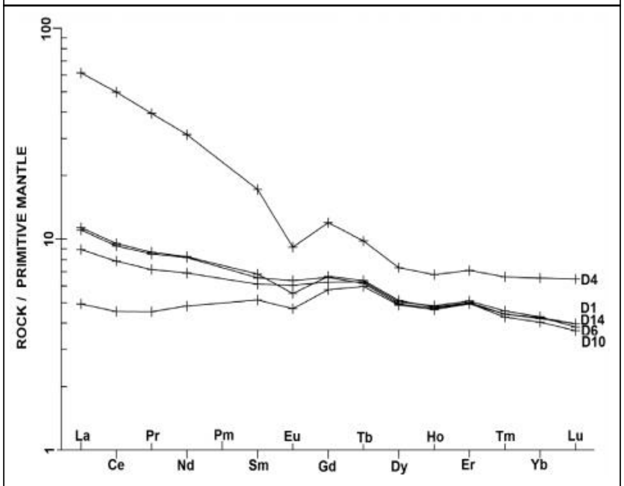


Figure 7: Chondrite-Normalized Multielement Spiderdiagrams for the Rocks of the Area, Normalizing Constants After Thompson et al. (1984)



similar and negatively sloping (Figure 8). They show conspicuous enrichment in LREE (av. 32.94 ppm) about more than 3 times HREE (av. 12.70 ppm) and the latter are markedly depleted. Eu (europium) forms a very small and less prominent trough to almost flat trend in these patterns causing a small negative Eu-anomaly to no remarkable anomaly that is also supported by Eu/Eu*(Eu_N/SQR(Sm_N x Gd_N) values remarkedly < 1 (0.82-0.98). $(La/Sm)_N$ ratio, a good index of degree of incompatible trace element enrichment (Hart and Blusztajn, 2006), is > 1 (1.50-1.74) in most of the cases, however remarkably high in D-4 (3.68) which is probably because of its tuffaceous or more evolved nature. On the other hand, the sample D-14 in which case $(La/Sm)_N$ < 1 (~ 0.99) is slightly LREE-depleted and exhibits a nearly flat REE- pattern for most part of its length. $(La/Yb)_{N,}$ which is simply the ratio of light REE to heavy REE, varies in a short range (1.22-2.89) except D-4 indicating a relatively lesser degree of LREE enrichment. A ratio of the most incompatible very light REE expressed as $(La/Ce)_N$ is greater than 1 for these rocks (1.08-1.19) is important of all as it may help depict the source rock composition.

Figure 8: Primitive Mantle-Normalized REE Patterns of the Rocks of the Area, Normalizing Constants After McDonough and Sun (1995)



DISCUSSION

The study area is part of the Proterozoic Singhbhum Supergroup that comprises of the low grade greenschist facies rocks belonging to Dalma Formation in the central part of the Singhbhum mobile belt. The appraisal of the data accruing out of the field, petrographic and chemical studies of the metabasites associated with these metavolcano-sedimentary succession occurring as hills in a stretch between Chandil dam and Dimna lake to the north of Jamshedpur has been systematically done to demarcate the nature of their protolith, tectonic setting and subsequent metamorphic changes that may throw light on the larger issues like geodynamic evolution of the Proterozoic Singhbhum mobile belt.

The Dalma volcanic piles consist of a thick succession of mafic-ultramafic lava flows and lenses of mafic agglomerates as well as volcaniclastic rocks. The lower part of the sequence comprise of carbonaceous and ferruginous phyllites, tuffs, agglomerates with intrusive and extrusive phases of mafic and ultramafic rocks occasionally showing pillow and pumiceous structures whereas the upper part is dominated by vesicular basaltic flows of amazing compositional homogeneity with intervening tuffaceous and reworked pyroclastics separating the different flows. The Dalma volcanism is of violent eruptive nature that took place both in subaqueous and sub-aerial conditions. The bulk of volcanic sequence in the upper part is massive, compact and is relatively high Mg-basalt which has changed into greenschist facies rocks. The appearance of volcanic rocks as thin layers or lenses at a number of different stratigraphic levels evidently suggests successive phases of volcanic activities that continued over a long period of time that covered sedimentation of both, i.e., Dhalbhum as well as Dalma Fms.

The mineralogical and textural features of the Dalma group of rocks are characterized by their fine- grained nature, crude foliation and variable mineral assemblages. Their igneous character is inferred from the relict textures, presence of minerals like olivine, pyroxene and calcic plagioclase which are often twinned and zoned. The changes in mineral paragenesis in these rocks are largely controlled by varying degree of low grade metamorphism and parent rock composition. They are dominantly characterized by albite – epidote – chlorite – actinolite mineralogy with relict pyroxene and calcic plagioclase as well as secondary calcite and quartz. Some of the mg-rich metabasalts have given rise to the formation of minerals like talc, tremolite, actinolite and anthophyllite in variable amounts. The tuffaceous rocks are characterized by heterogeneity in composition as well as partly altered vitric bombs and airdrops set within glassy matrix. The groundmass often shows granoblastic texture. Some of the rocks contain resorbed feldspar grains altered to kaolinite that are rimmed by dark glassy matter.

The chemical results and variations of the Dalma volcanic rocks support tholeiitic protolith and a differentiation trend consistent with fractional crystallization within a narrow range, perhaps because of their rapid crystallization and eruptive nature, spanning in composition from basalt to basaltic andesite. Their low-K tholeiitic nature has been described as comparable to the oceanic abyssal tholeiitic basalt within the spectrum of MORB. The trace element abundance data and variation diagrams also support the above observations. The concentrations of elements like. V, Cr, Ni, Co, Cu, Sr, Rb (~2-4 ppm), Sr, and ratio; Th/U, etc., have revealed a distinct affinity of the Dalma metavolcanics with that of the low-K oceanic ridge tholeiites (MORB). The multielement MORB- and Chondrite- normalized trace element patterns (Figures 6 and 7) have revealed that the metabasic rocks of the area are selectively enriched in LILEs such as Sr, K, Rb, Ba and Th relative to HFSEs such as Ta, Nb, Ce, P, Zr, Hf, Sm, Ti, Y and Yb coupled with a negative Nb-Ta-Ti anomaly characteristic of subduction related island arc setting. Relatively smooth and distinctive patterns showing close proximity to the MORB line may suggest their association with a back-arc region because the rocks of MORB composition in a trench-arc system are characteristic only of back-arc extensional tectonic environment. The occurrence of a negative Nb-Ta-Ti anomaly is probably because of either their depletion in the source or retention in the refractory phase in the mantle source to which these elements are highly compatible during partial melting (Drummond and Defant, 1990).

REE abundances, their primitive mantle-normalized patterns (Figure 8) and some critical ratios reveal a source related LREE enriched nature of these rocks. The total REE ranging from 33-52 ppm as well as their $(La/Yb)_N$ and $(Ce/Yb)_N$ ratios varying from1.22-2.89 and 1.13-2.43 respectively suggest a moderately fractionated REE pattern within a narrow range. A very small negative to almost no Eu-anomaly in these rocks indicates paucity of plagioclase.

The comparison of some critical constituents in tholeiitic rocks from different tectonic settings with that of the studied Dalma rocks of the area

Table 2: Compositional Ranges of Tholeiitic Series Volcanic Rocks from Various Tectonic Regime

	Abyssal Tholeiite		Island arc tholeiites	Continental tholeiites	Back arc tholeiites	Dalma tholeiites
	N-MORB	Oceanic Island				
SiO_2	47 - 51	45 - 65	46 - 76	45 - 55	50 - 54	46.40 - 51.50
FeO^0	6 - 14	8 - 16	6 - 16	11 - 12	7 - 9	10.75 - 12.37
Na_2O	1.7- 3.30	7 - 4.5	1.1 - 3.6	2.33 - 2.75	1.6 - 3.50	1.64 - 2.77
K_2O	0.07 - 0.4	0.06 - 2.0	0.1 - 2.0	> 0.60	0.24 - 0.57	0.09 - 0.41
TiO_2	0.7 - 2.3	0.2 - 5.0	0.3 - 2.0	1.0 - 3.0	0.6 - 1.5	0.80 - 1.94
FeO^0/MgO	0.8 - 2.1	0.5 - 2.5	1.0 - 7.0	1.0 - 5.0	0.92 - 1.11	1.20 - 1.59

FeO^0 = Total iron as FeO

evidently support that they lie within the ambit of the back-arc tholeiites as their SiO_2 content (46.41-51.46 wt%) and FeO^0/MgO ratios (1.20-1.59) are very similar and comparable to the tholeiites from MORB having affiliation with the back-arc setting (Table 2). Back-arc settings usually have the chemical attributes of both the island arc and the oceanic spreading centers. Basaltic magma erupting in back-arc basins usually vary from low-K tholeiites similar to MORB to calc-alkaline basalt with higher K_2O-contents. Thus their geochemical signature is

Table 3: Trace Element Comparison of Dalma Basalts with MORB and Back-Arc Basalts

Element	N-MORB[a]	E-MORB[b]	Back-arc basalt[c]	Dalma basalt[d]
Rb	0.56	5.04	5.75	4.27
Sr	90	155	181	175
Ni	-	-	59	69
Nb	2.33	8.3	3.75	4.42
Ta	0.13	0.47	0.77	0.39
Y	28	22	24	24.23
Ba	6.3	57	66	105
La	2.5	6.3	6.77	6.44
Ce	7.5	15	13.71	14.94
Nd	7.3	9	9.43	10.35
Sm	2.63	2.6	2.86	2.9
Eu	1.02	0.91	1.06	1.11
Gd	3.68	2.97	3.45	3.87
Dy	4.55	3.55	4.29	3.72
Yb	3.05	2.37	2.48	2.04
Lu	0.46	0.35	-	0.29

a Av. of N-MORB from Sun & McDonough, 1989
b Av. of E-MORB from Sun & McDonough, 1989
c Av. of East Scotia back-arc basalt from Saunder & Tarney, 1979
d Av. of 5 samples of Dalma basalts from study area

Figure 9: Nb/Th vs. Nb Tectonic Discrimination Diagram After Li (1993)

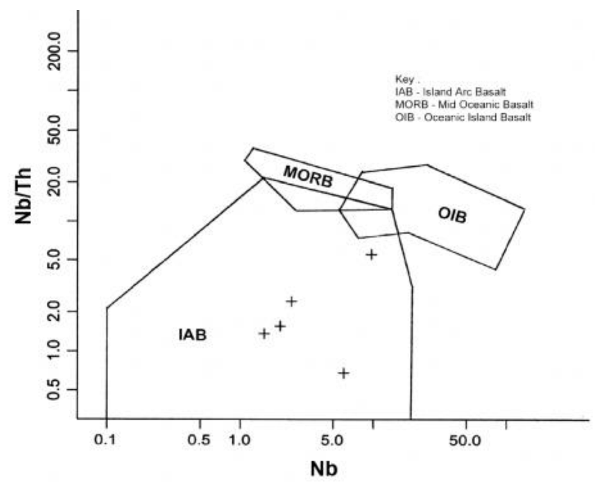


Figure 10: Ti/1000 vs. V Binary Plot After Shervais (1982)

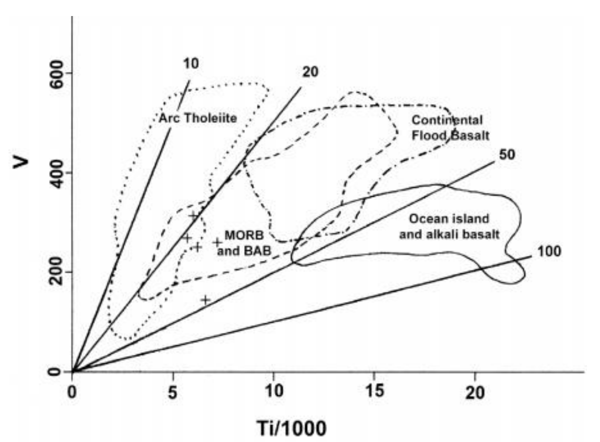
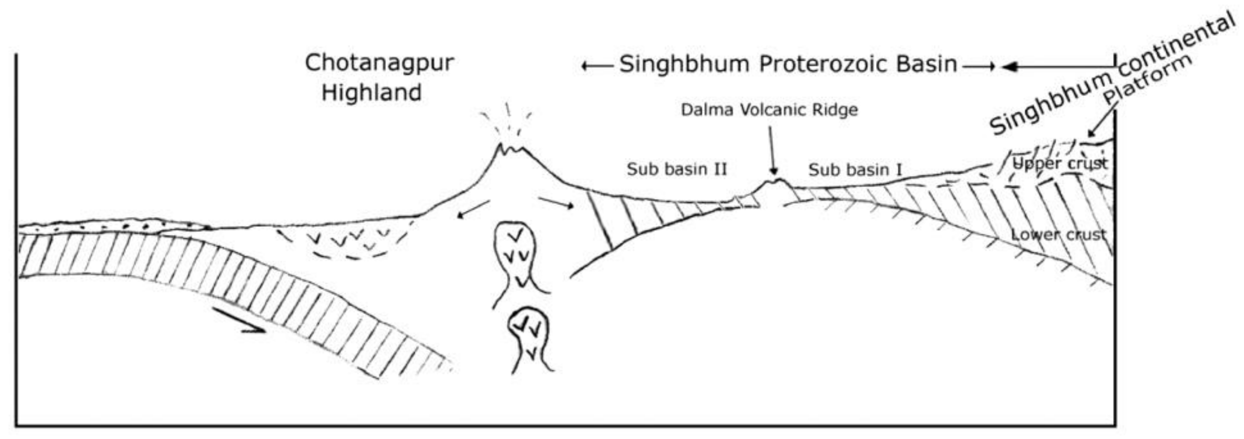


Figure 11: Tectonic Setting of Singhbhum Marginal Basin and Associated Morphostructural Units (Modified After Bose, 1994)



transitional between the MORB and the arc basalt which is relatively enriched in LILEs like K, Rb, Ba and Sr. Dalma metavolcanics are also characterized by exceedingly low-K oceanic abyssal tholeiites falling within the spectrum of MORB and their trace data show resemblance with average E-MORB (Sun and McDonough, 1989) as well as a very close proximity to the East Scotia back-arc tholeiites (Saunders and Tarney, 1979) (Table 3). The above contention is also supported by various tectonomagmatic discrimination diagrams. One such diagram Nb/Th vs Nb after Li (1993) as given in Figure 9 indicates that the studied metabasites fall mainly in the field of island arc basalt. Another binary plot (Figure 10) exhibiting the relationship between V and Ti/1000 after Shervais (1982) depicts that most of the Dalma basaltic rocks fall well within the field of MORB related to the back-arc basin. In addition, the most remarkable feature of these rocks is its bimodal mafic-ultramafic effusion that is highly conspicuous of the back-arc domain (Condie, 1989b).

A comprehensive petrogenic interpretation based on the geologic, petrographic and chemical attributes is suggestive of the fact that Dalmas are quartz-hypersthene, ol-hy as well as undersaturated type ol-ne normative MORB like basalts showing initial olivine and opx fractionation followed by the cpx-plagioclase control having the compositional range from tholeiitic basalt to basaltic andesite that may have been derived from moderate degree of partial melting (10-15%), as evidenced from low to intermediate range of mg-number (58-65), of asthenospheric mantle lherzolite of depleted as well as enriched geochemical signature in the regime of extension or spreading centre that comes into operation in the back-arc basin. The onset of rifting of the oceanic crust and development of the embryonic back-arc basin in an island arc set-up takes place as a consequence of the diapiric upwelling of deep asthenospheric mantle as a result of adiabatic decompression to produce MORB like back-arc basalts. By this time, the arc volcanism ceases before the onset of the back-arc volcanism (Crawford *et al.*, 1981). Absence of boninites in the area of study precludes the possibility of highly depleted or refractory hartzburgite mantle as source for the Dalma volcanic rocks. The low Th/Yb ratio (0.36-0.94), an index of contamination of basaltic magmas ascending through the crustal layer, rules out the possibility of crustal contamination. Extremely limited variations of Ce/Nd ratios (1.26-1.55) of immobile elements reflect the source rock character as well as uncontaminated nature of the mafic suites under study as these two elements are highly incompatible in mafic system (Horan *et al.*, 1987; Rajamani *et al.*, 1989; and Balakrishnan *et al.*, 1990). The Sugimura Index (θ), a parameter suggested by Sugimura (1968) for determining the spatial situation of the volcanic basaltic magmas within the island arc system, having the values ranging between 30 to 36 for the studied Dalma metavolcanics clearly indicates a situation closer to the continent side, i.e., the back-arc basin or continental marginal basin for these rocks.

CONCLUSION

The most significant observation that has emerged out of the present investigation is that the Dalma volcano-sedimentary sequence has been laid down in a back-arc basin condition as far as the tectonostratigraphic status of these rocks are concerned.

The present study is primarily based on the volcanic dominated Proterozoic sedimentary basin which is similar to the many Precambrian greenstone associations related to island arc assemblages. The protoliths of the studied metabasalts have been reviewed in the context of the geological evolution of the Eastern India Archaean – Proterozoic group in general and the Singhbhum – Satpura orogeny in particular. It has been suggested that island arcs and active continental margins have always been the sites of volcanic phenomena as the agents of crustal growth. The Singhbhum crustal province is divided into three distinct tectonic units: Stabilized Singhbhum – Orissa craton (~ 3.55-3.12 Ga), North Singhbhum mobile belt, i.e., Supracrustal Singhbhum Group (2.3-1.7 Ga) and the Chotanagpur granite gneiss complex (1.0 Ga) and has evolved through polyphase orogenic episodes involving sedimentation, tectonism and magmatic activities.

These observations have been integrated into a comprehensive geodynamic model that has a bearing on the stratigraphy of the Proterozoic Singhbhum mobile belt. The outcome of the present work suggests that Dalma volcano-sedimentary sequence was laid down in a back-arc tectonic setting situated over a major subducting northern plate supporting the CGGC. On this basis the Dalma basin is assigned a distinctly younger tectonostratigraphic position and the crust below it an oceanic character. In a convergent margin where an oceanic plate is subducted below the continental plate several forearc, intraarc and backarc basins come into existence because of the diapiric rise of magma beneath the arc creating a zone of rifting and subsidence (Karig, 1971; and Crawford *et al.*, 1981) in which the protoliths of the studied metabasites have erupted. This clearly substantiates the tectonic model (Figure 11) earlier envisaged by Bose and Chakarborti (1981), Bose (1994) and Kumar (2008 and 2014). The subsequent tectonic episodes have led to the evolution of Singhbhum/Satpura orogeny (c. 850 Ma) with ENE-WSW – E-W regional trends.

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