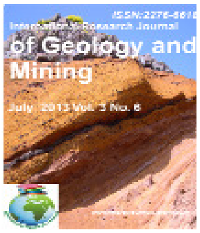
International Research Journal of Geology and Mining (IRJGM) (2276-6618) Vol. 3(6) pp. 213-223, July, 2013
Available online http://www.interesjournals.org/IRJGM



Full Length Research Paper

A subduction zone geochemical characteristic of the newer dolerite dykes in the singhbhum craton, Eastern India

***[1]Akhtar R Mir, [2]Shabber H Alvi, [3]V. Balaram, [1]Fayaz A. Bhat, [1]Sumira Z. and [2]Shamim A. Dar**

[1]Department of Earth Sciences,University of Kashmir, Srinagar, 19006, India
[2]Department of Geology, Aligarh Muslim University, Aligarh, 202002, India
[3]National Geophysical Research Institute, Hyderabad, 500007, India

Abstract

Newer Dolerite Dykes (NDD) traverses the Singhbhum Granitoid Complex (SGC) in distinct orientations viz., NNE-SSW, NNW-SSE and E-W, among which the NNE-SSW trend is the most dominant. These dykes are subalkaline in nature and show compositional variation from basalt through basaltic andesite to andesite. The relationship shown by various oxides against MgO is consistent with fractional crystallization of a mafic magma. Variations in major elements, particularly SiO_2, Al_2O_3, CaO, TiO_2 contents, and CaO/TiO_2 and Al_2O_3/TiO_2 ratios in the studied dykes indicates that their Ca and Al are held in the residual mantle phases such as clinopyroxene, plagioclase, spinel and garnet. Low Ni and highly variable Cr values suggest that olivine and clinopyroxene fractionation controlled the abundances of Ni and Cr in these rocks. The high $(La/Yb)_N$ and $(Gd/Yb)_N$ in combination with relatively low HREE abundance of the Newer Dolerites dykes suggest that they may have formed by low degrees of partial melting of a garnet bearing source. The higher Th/Zr, Rb/Y, Ba/Nb and Ba/Th ratios of these dykes suggest that their mantle source was enriched/ metasomatised by slab derived fluids. Their geochemical characteristics particularly Ti/Y, Zr/Y, Th/Nb, Ba/Nb, La/Nb, $(La/Sm)_{PM}$ are similar to subduction zone basalts that occur along the plate margin. The enriched LREE-LILE and depletion of high-field strength elements (HFSE) especially Nb, P and Ti and detectable slab-derived components of the studied dykes are all features typical for subduction zone-related petrogenesis.

Keywords: Newer dolerite dykes, singhbhum craton, basalt geochemistry, back-arc basalts.

INTRODUCTION

Precambrian mafic dykes occur in a wide variety of geological and tectonic settings (Hall and Hughes, (1987), Le Cheminant and Heaman, (1989), Parker et al., (1990), Baer and Heimann, (1995), Ernst and Buchan, (2001), Hanski et al., (2006), Bleeker and Ernst, (2006), Subba Rao et al., (2008), Srivastava, (2011)) and their detailed study through space and time is imperative for an understanding of global geodynamic processes and they provide a constructive window to monitor mantle evolution and changing magmatic style (Tarney, (1992; Hall and Hughes, 1993; Srivastava, 2011). Dykes and dyke swarms, having different orientations, are conspicuous and important features in all of the Proterozoic protocontinents of the Indian Shield, viz. Aravalli-Bundelkhand, Dharwar, Bastar-Bhandara, and the Singhbhum Protocontinents (Naqvi, 2005; Srivastava et al., 2008; Hou et al., 2008; Mir et al., 2011).

The Singhbhum Craton (SC) contains several types of granitoids, metasedimentary rocks including banded iron formations (BIF), and mafic volcanic and intrusive rocks. It is a classic region for the study of different stages of Precambrian crust-mantle evolution. Proterozoic magmatism in the SC is manifested mainly as mafic metavolcanic suites and dyke swarms. Various dykes of mafic to felsic composition intrude the Singhbhum Granitoid Complex, and are collectively referred to as the Newer Dolerite Dykes in the geological literature (Dunn, 1940; Saha, 1994; Mahadevan, 2002). The most common trend of these dykes is NNE-SSW and NW-SE. They traverse a number of rock types, including the

---

*Corresponding Author Email: mirakhtar.r@gmail.com

Table 1. Magmatic event stratigraphy of the eastern Indian shield (after, Alvin and Raza,1992)

Age	Formation
Middle Proterozoic	Dolerite dyke across Chakradpur Granite; Phase II
	Dalma metavolcanic rocks (unconformably overlying the meta- Sedimentary rocks of Singhbhum orogenic belt)
	Dhanjori/Ongarbira/Jagannathpur volcanic rocks and dolerite dykes across Singhbhum Granite; Phase I
Early Proterozoic	Bonai range metavolcanic rocks (occurring at the base of the Koira-Noamundi BIF sequence)
Late Archaean	Gorumahisani-Ukampahar metabasic rocks (intrusive into and extrusive onto the Gorumahisani-Badampahar BIF sequence).

Gorumahisani-Badampahar BIF, Gorumahisani greenstones, and the Bonai Granite, but do not cut across Paleoproterozoic rock suites on the periphery of the Singhbhum Granitoid Complex (SGC) — specifically the Noamundi-Koira BIF, Dhanjori, Ongarbira and Jagannathpur metavolcanic suites (Banerjee, 1982). Geochemical data on these dykes are a prerequisite for a better understanding of the tectono-magmatic evolution of the Singhbhum Craton. The magmatic event stratigraphy of the eastern Indian Shield (Banerjee, 1982; Alvi and Raza, 1992) is presented in Table 1.

Geology of the area

The eastern Indian shield comprises the Chotanagpur Granite-Gneiss Complex (CGGC) in the north, the Singhbhum Craton (SC) in the south and the E-W trending Singhbhum Mobile Belt (SMB) between the two. The SC is roughly a triangular shaped region, bounded by the arcuate shaped Singhbhum Shear Zone (SSZ) on the north, the Sukinda thrust on the south, and Tertiary sediments of the Bengal Basin to the east. A major part of the craton is occupied by the 3.2 Ga to 2.8 Ga Singhbhum Granitoid Complex (Moorbath et al., 1986; Figure 1). The complex is made up of at least twelve separate magmatic bodies that are considered to have been emplaced during two major phases of magmatism (Saha, 1994). The early granitoid phase has an age of 3.25 ± 0.05 Ga based on an eight point Pb/Pb whole rock isochron (Moorbath et al., 1986). Available ages for the later phase of the Singhbhum granitoids are 3.06 Ga (Pb/Pb whole rock) and 2.9 Ga (Rb/Sr whole rock) compiled by Saha (1994). The SGC is bordered by BIF belts such as the Gorumahisani-Badamphar in the east, the Tomka-Daiteri in the south and southwest and the Noamundi-Koira in the west. Metavolcanic and metasedimentry rocks of the 3.3 Ga Older Metamorphic Group (OMG), the oldest recognized unit in this craton (Sharma et al., 1994) occur as enclaves ranging in size from a few square meters to several hundred square km.

The Dhanjori metavolcanic suite (the Dhanjori Group of Dunn and Dey, 1942) is present along the eastern margin of the Singhbhum shear zone. The metavolcanic rocks were originally considered to be 2072 ± 106 Ma old (Sm/Nd isochron; Roy et al., 2002), but a later study has shown them to be older —ca. 2858 ± 17 Ma old by whole rock Pb/Pb dating and 2787 ± 270 Ma by Sm-Nd $_{(CHUR)}$ model (Misra and Johnson, 2005). A younger suite of volcanic rocks, the calc-alkaline Jagannathpur suite, is a remarkably fresh or little metamorphosed volcanic assemblage that is well exposed in the vicinity of Noamundi and Jagannathpur (Figure 1). These rocks are younger than the BIF Noamundi-Koira sequence occurring farther east (Banerjee, 1982). Geochemical studies of Jagannathpur lava flows have suggested that they are calc-alkaline basalts and represent an early arc volcanism (Alvi and Raza, 1991). The Jagannathpur lavas have been dated around 1629 ± 30 Ma by (K/Ar; Saha, 1994) and 2250 ± 81 Ma by Pb/Pb whole rock isochron method (Misra and Johnson, 2005). Newer Dolerite dykes have not been observed to intrude the Jagannathpur suite. It, therefore, appears that it is either equivalent in age or younger than the Newer Dolerite dykes (NDD). NDD traverses within the Singhbhum Granitoid Complex having a NNE-SSW to NE-SW as dominant trend and NW-SE and E-W as subsidiary trends (Mallick and Sarkar, 1994; Saha, 1994; Mir et al., 2011). The most common rock types are quartz dolerites and norites, however Granophyre, microgranite, syenodiorite are rarely found with the Newer dolerites and minor ultramafic intrusions are much subordinate to the Newer dolerites. Most significant of the ultramafic intrusions are those of Keshargaria. The NDD marks the termination of cratonization in the Singhbhum crustal province. However, consistent geochronological data of these dykes are lacking (K–Ar ages range from 923 to 2144 Ma; Saha 1994). According to Mallick and Sarkar (1994), the available data (mostly K–Ar ages) apparently indicate three pulses of mafic intrusive activity, viz. 2100+100, 1500+100 and 1100+200 Ma. However, Roy et al. (2004) suggested that the associated ultramafic members are 2613+177 Ma (Rb–Sr isochron age) and claimed that these ultramafic members of the NDD swarm attest to the oldest stabilization event of all of the cratonic blocks of India. Nevertheless, the genetic relation of mafic and ultramafic dykes is not clear. Whether these two compositionally different (mafic and

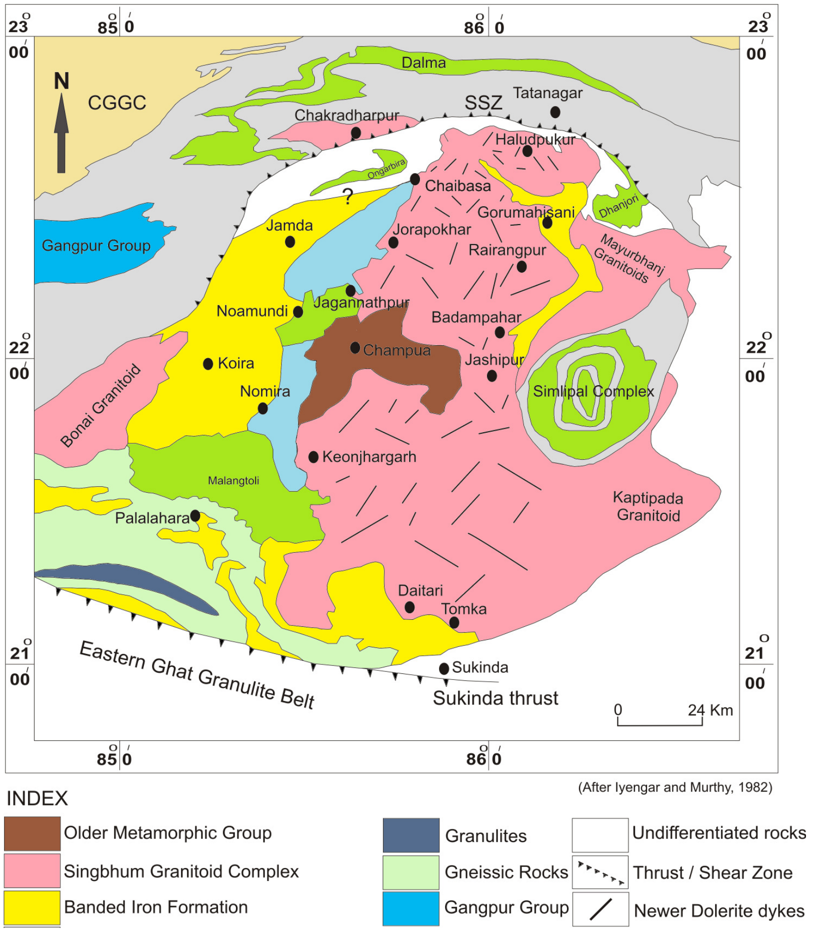


Figure 1. Simplified geological map of the Singhbhum Craton after (Iyengar and Murthy, 1982)

ultramafic) sets of dykes represent two independent, temporally distinct magma sources and had different emplacement histories.

Petrography

The NDD are characterized by ophitic to sub-ophitic textures. The essential mafic minerals are pyroxenes (20% to 77%) and plagioclase of labradorite composition (30% to 76%). Euhedral to subhedral tabular plagioclase phenocrysts display lamellar twinning, and saussuritization in some samples. The clinopyroxene is mainly augite in the form of euhedral to subhedral prismatic phenocrysts. It is colourless to pale brown and occasionally shows Carlsbad twining. Quartz (0.5% to 3%) is present as subhedral to anhedral crystals. Accessory minerals are opaques, apatite, and rutile. Micropegmatitic material is observed along some grain boundaries of feldspars.

Analytical techniques

Newer Dolerite Dyke samples collected from Rairangpur (Latitude 22º15′N: Longitude 86º10′E), Haludphukur (Latitude 22º36′ N: Longitude 86º08′E), Jashipur (Latitude 21º58′N: Longitude 86º4′E) and Chaibasa (Latitude 22º34′N: Longitude 85º49′E), Rairangpur, Chaibasa and Haludpukhor areas lie near the border region of the Singhbhum Granitoid Complex, while Jashipur area lies towards the interior of the Singhbhum Granitoid Complex (Figure1 done at), the least altered samples were selected for whole-rock major and trace element analyses. Whole rock geochemical analysis was National Geophysical Research Institute, Hyderabad. Major elements were analyzed by X-ray fluorescence (XRF) using fused pellets. The pellets were backed with boric acid. Trace elements including REE were determined by inductively coupled plasma–mass spectrometry (ICP-MS; Perkin Elmer, Sciex ELAN DRC II). All of the available data were standardized against the international reference rock standard JB-2. The procedure, precision and detection limits are the same as given by Balaram and Gnaneshwara Rao (2003).

RESULTS AND DISCUSSION

Geochemical characteristics

The major element and trace element (including REE) data of the studied dykes is given in Table 2. Major element data is given in wt. % and trace element data in parts per million.These samples have SiO_2, TiO_2, MgO, Al_2O_3, Fe_2O_3, CaO, K_2O and Na_2O in the range of (45.88-58.79), (0.27-2.24) , (6.61-21.91), (9.55-12.32), (8.25-17.23), (5.86-8.78), (0.29-0.84) and (0.83-2.75) respectively. They show compositional variation from basalt through basaltic andesite to andesite (Figure 2; Le Bas, 2000) and their tholeiitic nature is shown by AFM ($A=Na_2O+K_2O$, $F=FeO^*$, M=MgO) diagram (Figure 3). In addition, Nb/Y ratios (< 0.7) indicate that the magma of these rocks had subalkaline affinity (Pearce and Gale, 1977). However, some samples such as J4B, J4C, C2, C16 and C17 have geochemical characters such as, high-SiO_2 (>52%), high MgO (>8%) and low-TiO_2 (<0.5%), similar to those found in boninitic rocks (Crawford et al., 1989; Hall and Hughes, 1990; Le Bas, 2000; Smithies, 2002; Srivastava, 2006, 2008).

Crustal contamination and fractional crystallization

Generally in dykes the degree of crustal contamination is negligible or absent in comparison to volcanic rocks (Tarney and Weaver, 1987), though, prior to the interpretation of geochemical data of the studied dykes it is necessary to identify the effects of post-igneous alteration processes on the rock chemistry. The low values of Na_2O and K_2O (Table 2) and least scattering of these oxides against MgO (Figure 4) preclude major element mobility in the studied rocks. Large ion lithophile elements (LILE) are generally considered as mobile during secondary processes like metamorphism, metasomatism and hydrothermal alterations (Pearce and Cann, 1973; Seewald and Seyfried, 1990; Verma, 1992; Condie and Sinha, 1996), however, Th is believed to be either immobile or less mobile even during high degrees of alteration (Lafleche et al., 1992). High field strength elements (HFSE; such as Ti, Zr, Y, Nb, P, REE etc.) are thought to be relatively immobile during hydrothermal alteration and mid-amphibolite facies metamorphic conditions (Pearce and Cann, 1973; Winchester and Floyd, 1976; Floyd and Winchester, 1978; Rollinson, 1993; Jochum and Verma, 1996). Here, the effect of alteration on LILE concentrations is verified by using Rb/Sr ratio. Since Rb/Sr ratio is very low (0.007) in least altered mafic rocks and very high (8) in highly altered mafic rocks (Lafleche et al., 1992), hence, low Rb/Sr ratio (0.05 to 0.48) in investigated ND dykes do not specify any major effects of post-igneous processes on primary concentrations of LILE. SiO_2 abundances cover a wide compositional range in the studied dykes from 45.88 to 58.79 wt. %. MgO contents range from 6.61 to 21.91 wt. % in these dykes. Variations in geochemical analyses are generally examined with respect to MgO content or Mg number (Mg # = molar 100 Mg / Mg + Fe^{total}). Decreasing values of MgO or Mg# (Table 2) in the Newer Dolerites reflect fractionation of liquidus or near liquidus ferromagnesian phases (Wilson, 1989). Various binary diagrams (Figure 4) have been plotted to assess the evolution of the NDD mafic magmas. MgO has been taken as the reference oxide because of its wide range of values and important behavior during fractional crystallization of mafic melts. The studied dykes show systematic increases in SiO_2, Na_2O, Fe_2O_3, Al_2O_3 and TiO_2, with decreasing MgO. Whereas, CaO and K_2O shows decreasing trends with the decrease of MgO (Figure 4). These variations are consistent with fractional crystallization of a mafic magma wherein major mineral constituents had fractionated and minor minerals like apatite, titanite, ilmenite had crystallized at later stages. Ni (9–125 ppm) and Cr (31–733 ppm) concentrations do not meet requirements for primary mantle melts (Ni > 200 ppm, Cr > 400 ppm), which together with the range of Mg no. (80–43) in the studied dykes implies processes of fractional crystallization of olivine and pyroxenes. Trends shown by Al_2O_3 and CaO against MgO may be suggestive of plagioclase crystallization. Variation of high field strength elements such as Zr, Hf, Nb, Nd, Ce and Y against MgO is shown in Figure 5. All these elements show negative correlation with MgO which is consistent with crystallization of minor minerals at advanced stages of crystallization (Srivastava, 2012).

Source characteristics

Studied NDD samples except J4G and R6 show enriched chondrite-normalized light rare earth element patterns (LREE; $(La/Sm)_n$ = 0.88 to 3.00) and fractionated heavy rare earth element (HREE; $(La/Yb)_n$ = 1.06 to 4.80) profiles (Figure 6a). The higher than Chondrite $(La/Yb)_n$, $(Gd/Yb)_n$ values and lower than Chondrite Al_2O_3/TiO_2 values, in combination with relatively low HREE abundance of the studied dykes, suggest that they may have been formed by low degrees of partial melting of a garnet-bearing source (Mir et al., 2010). Magmas that erupted at destructive plate boundaries are commonly considered to be derived from mantle sources previously more depleted than the sources of mid-ocean ridge basalts (MORB), and are subsequently enriched by a subduction component in island arcs (Knittel and Oles 1995). Magmas erupted in supra-subduction related environments are predominantly enriched in LILEs (Rb,

Table 2. Major and trace element data of the Newer Dolerite Dykes from the Singhbhum-Orissa Craton, Eastern India

Sample	**J4B**	**J4C**	**C2**	**C16**	**C17**	**J4A**	**J4E**	**J4F**	**J4G**	**R4**	**R6**	**R7**	**R10**	**R12**	**H1**
SiO_2	53.29	58.79	55.86	53.87	57.61	53.08	52.84	53.59	52.37	53.09	51.89	45.88	54.61	52.13	51.54
TiO_2	0.5	0.44	0.29	0.27	0.47	1.4	1.55	1.6	1.3	2.24	1.33	0.31	0.92	1.46	0.5
Al_2O_3	9.65	11.66	12.32	10.35	10.42	10	11.43	11.4	11.79	10.64	10.84	9.55	10.70	10.41	10.71
Fe_2O_3	12.59	10.04	8.56	8.25	10.94	17.23	15.71	15.52	14.23	17.05	16.17	13.22	14.12	14.25	12.34
MgO	15.25	9.39	12.16	16.51	10.35	8.54	7.82	6.99	8.59	6.61	9.65	21.91	9.03	12.82	15.41
CaO	6.48	6.81	7.75	8.78	7.21	7.42	7.60	7.69	8.08	6.72	7.21	7.52	7.69	5.86	6.98
Na_2O	1.31	2.11	2.2	1.34	2.04	1.75	2.33	2.48	2.75	2.33	2.27	0.83	2.29	2.43	1.48
K_2O	0.72	0.58	0.7	0.48	0.79	0.29	0.43	0.42	0.48	0.74	0.39	0.58	0.44	0.43	0.84
MnO	0.17	0.14	0.13	0.14	0.15	0.21	0.18	0.18	0.15	0.19	0.2	0.18	0.17	0.17	0.17
P_2O_5	0.03	0.03	0.02	0.02	0.03	0.07	0.12	0.13	0.26	0.39	0.05	0.02	0.04	0.05	0.03
Total	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Mg #.	71	65	74	80	65	50	50	47	54	43	54	77	56	64	71
Ni	44	30	39	43	31	18	24	22	9	18	25	125	32	69	67
Cr	389	147	115	225	186	83	92	81	31	42	105	733	74	255	462
Co	58	46	43	49	50	54	59	62	44	59	59	74	63	57	60
V	176	146	125	128	157	271	304	309	326	399	288	141	250	298	171
Sc	28	24	24	27	27	37	32	32	16	32	33	33	32	23	27
Pb	4	4	7.63	6.64	8.02	4	4	4	4	4	4	3	4	5	4
Zn	68	67	59	57	80	118	118	106	97	123	120	59	78	80	65
Cu	75	61	76	22	66	85	147	149	71	101	106	50	130	123	78
Ga	13	15	13	9	13	15	17	18	18	19	16	9	15	21	13
Rb	42	26	28	20	39	21	20	20	45	49	21	27	24	29	36
Sr	103	244	193	126	112	116	133	136	483	158	147	219	181	547	149
Ba	186	273	174	117	143	59	159	72	37	228	79	179	108	130	151
Zr	59	49	42	43	52	90	101	103	109	133	96	47	83	99	57
Nb	3.55	3.60	2.66	1.86	7.33	5.26	6.84	7.25	1.84	10.91	3.36	0.92	2.47	6.17	2.74
Ta	0.22	0.23	0.17	0.12	0.46	0.33	0.43	0.45	0.12	0.68	0.21	0.06	0.15	0.39	0.17
Y	18	19	14	13	26	36	43	44	18	62	33	13	18	27	19
U	0.43	0.25	0.15	0.09	0.33	0.09	0.16	0.16	0.02	0.25	0.05	0.05	0.08	0.31	0.10
Th	3.67	2.68	1.63	1.06	3.85	1.73	1.74	1.86	0.16	2.87	0.52	0.49	0.95	3.68	1.36
Hf	1.51	1.26	1.08	1.10	1.33	2.31	2.59	2.64	2.79	3.41	2.46	1.21	2.13	2.54	1.46
Cs	4.15	1.59	0.75	0.52	0.84	1.99	1.55	1.71	2.81	2.95	0.75	0.78	1.60	0.71	0.81
La	10.99	12.52	7.98	5.38	17.56	7.05	12.53	13.06	7.86	22.43	4.81	3.13	5.96	15.27	8.56
Ce	24.34	28.12	17.46	12.27	38.69	18.49	31.84	33.34	23.00	56.38	13.64	7.02	14.55	36.70	19.55
Pr	2.48	2.88	1.71	1.26	3.70	2.25	3.71	3.89	3.00	6.48	1.77	0.73	1.63	4.21	2.03
Nd	12.14	14.84	8.58	6.53	17.52	13.77	21.35	22.33	18.95	37.12	11.46	3.88	9.54	23.60	10.80
Ce	24.34	28.12	17.46	12.27	38.69	18.49	31.84	33.34	23.00	56.38	13.64	7.02	14.55	36.70	19.55
Sm	2.60	2.97	1.82	1.53	3.68	3.88	5.50	5.81	4.44	8.97	3.46	0.87	2.33	5.60	2.54
Gd	3.09	3.43	2.27	1.93	4.45	5.35	6.89	7.11	4.98	10.83	4.66	1.27	3.08	6.18	3.10
Tb	0.49	0.55	0.39	0.34	0.72	0.98	1.21	1.25	0.68	1.80	0.87	0.25	0.52	0.95	0.54
Dy	2.71	2.86	2.11	1.95	3.91	5.52	6.66	6.87	3.29	9.53	5.05	1.65	2.85	4.71	2.94
Ho	0.57	0.62	0.47	0.42	0.85	1.20	1.42	1.48	0.64	2.02	1.10	0.41	0.59	0.92	0.64
Er	1.85	1.98	1.47	1.33	2.72	3.81	4.44	4.56	1.82	6.27	3.46	1.48	1.89	2.66	1.90
Tm	0.31	0.34	0.24	0.24	0.48	0.65	0.74	0.79	0.26	1.04	0.59	0.27	0.31	0.42	0.34
Lu	0.26	0.26	0.20	0.19	0.38	0.52	0.61	0.64	0.18	0.82	0.46	0.25	0.24	0.31	0.25
Ti	2998	2638	1739	1619	2818	8393	9292	9592	7794	13429	7973	1858	5515	8753	2998
P	131	131	87	87	131	306	524	567	1135	1702	218	87	175	218	131
CaO/Al_2O_3	0.67	0.58	0.63	0.85	0.69	0.74	0.66	0.67	0.69	0.63	0.67	0.79	0.72	0.56	0.65
Zr/Y	3.28	2.58	3.00	3.31	2.00	2.50	2.35	2.34	6.06	2.15	2.91	3.62	4.61	3.67	3.00
La/Nb	3.10	3.48	3.00	2.89	2.40	1.34	1.83	1.80	4.27	2.06	1.43	3.40	2.41	2.47	3.12
Th/Ta	16.68	11.65	9.59	8.83	8.37	5.24	4.05	4.13	1.33	4.22	2.48	8.17	6.33	9.44	8.00
Th/Yb	2.16	1.46	1.23	0.85	1.52	0.49	0.43	0.44	0.13	0.52	0.17	0.31	0.56	1.71	0.77
Ta/Yb	0.13	0.13	0.13	0.10	0.18	0.09	0.11	0.11	0.10	0.12	0.07	0.04	0.09	0.18	0.10
Ti/Y	167	139	124	125	108	233	216	218	433	217	242	143	306	324	158
$(Ce/Yb)_N$	3.71	3.96	3.40	2.56	3.95	1.36	2.02	2.02	4.73	2.63	1.15	1.14	2.22	4.42	2.88

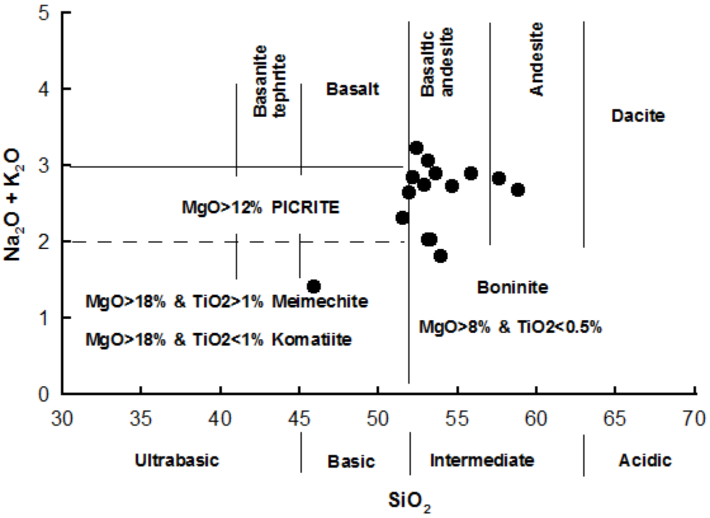


Figure 2. Total Alkali Silica (TAS) diagram after (Le Bas, 2000) for the classification of the Newer Dolerite Dykes

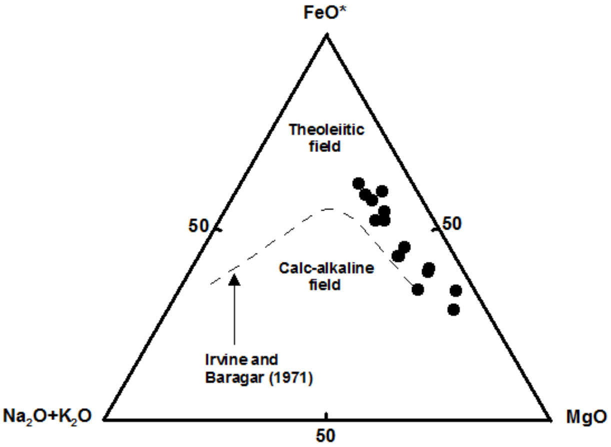


Figure 3. Na_2O+K_2O-FeO*-MgO (AFM) triangular diagram showing Fe-enrichment (tholeiitic) trend in the Newer Dolerite Dykes. Boundary line between calc-alkaline and tholeiitic fields is after Irvine and Baragar, 1971

Ba, Th, K,) relative to HFSEs (Nb, Zr, Ti) because of mobile and immobile nature of LILEs and HFSEs respectively. The studied ND dykes show sharp negative Nb and Ti anomalies relative to Th, La and Ce (Figure 6b). Most conspicuous features of this diagram are the positive anomaly of Th and negative anomaly of Nb; these features are considered to represent a subduction zone component (Wood 1980; Pearce 1983). The troughs at Sr, P, and Ti could be related to residual plagioclase, apatite, and Fe–Ti oxides or the earlier removal of Fe–Ti phases. In addition to these features, studied dykes are characterized by relatively higher Zr/Y (2.00–6.06), Th/Ta (1.33–16.68), Th/Yb (0.13–2.16) and Ta/Yb (0.04–0.18) ratios than normal mid-ocean ridge basalts (2.64, 0.75, 0.04 and 0.052, respectively; Sun and McDonough, 1989). These features are similar to some subduction-related basalt, back-arc basalts and the more enriched type of mid-ocean ridge basalts (Saunders and Tarney, 1984; Sun and McDonough, 1989). The enriched LREE and LILE and depleted HFSE geochemical signatures of majority of studied dykes is due to subduction-induced mantle metasomatism (Mir et al., 2010). The fluid released from the dehydrating slab + sediment is normally hydrous with CO_2 and chloride. Such acidic medium will readily carry LILE like Rb, Sr and Ba at the expense of HFSE like Zr, Hf and Nb (Downes, 2001). But Rb is much less acidic and will thereby, under normal conditions, have higher concentration compared

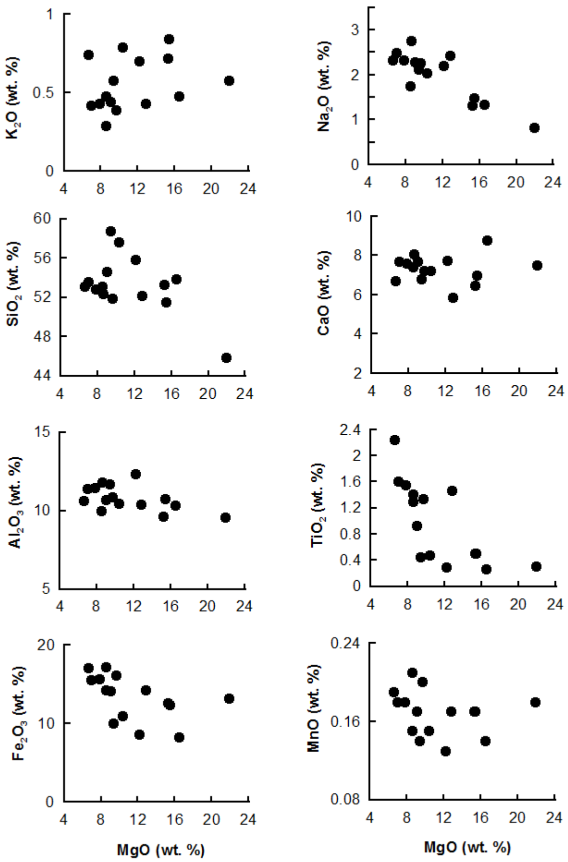


Figure 4. MgO vs. various major element oxide plots for the Newer Dolerite Dykes

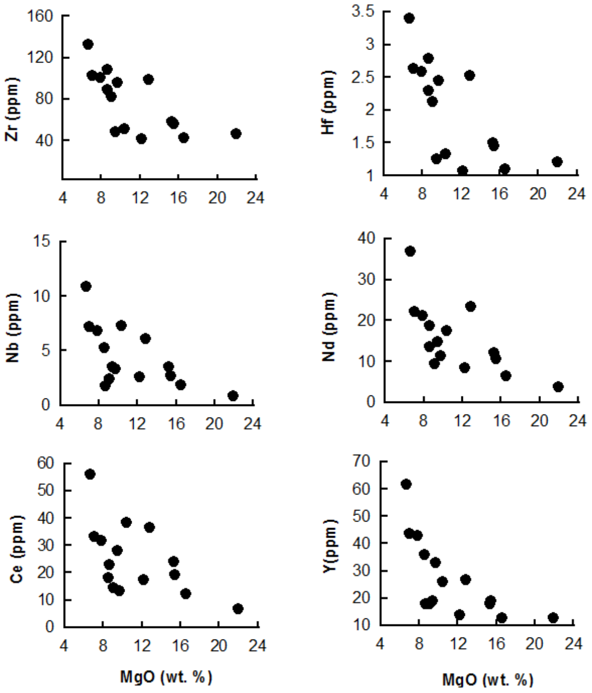


Figure 5. MgO vs. various high field strength element plots for the Newer Dolerite Dykes

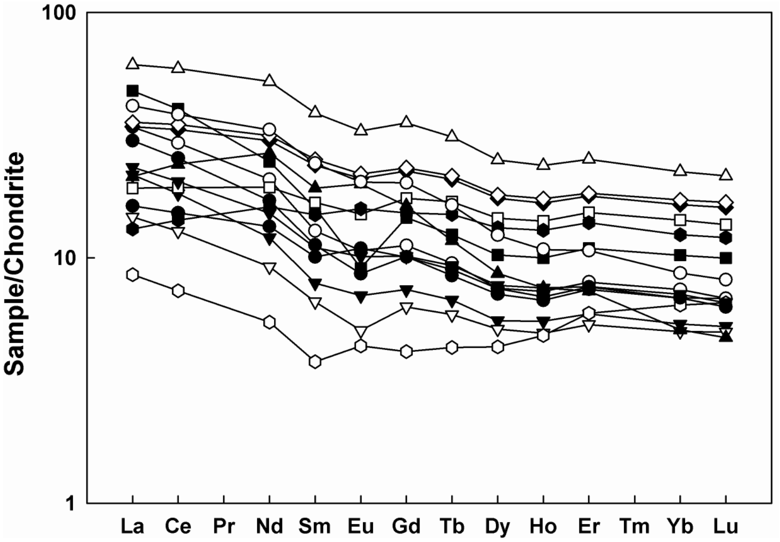


Figure 6a. Chondrite Normalized pattern of the Newer Dolerite Dykes. Normalizing values are after Taylor and McLennan (1985)

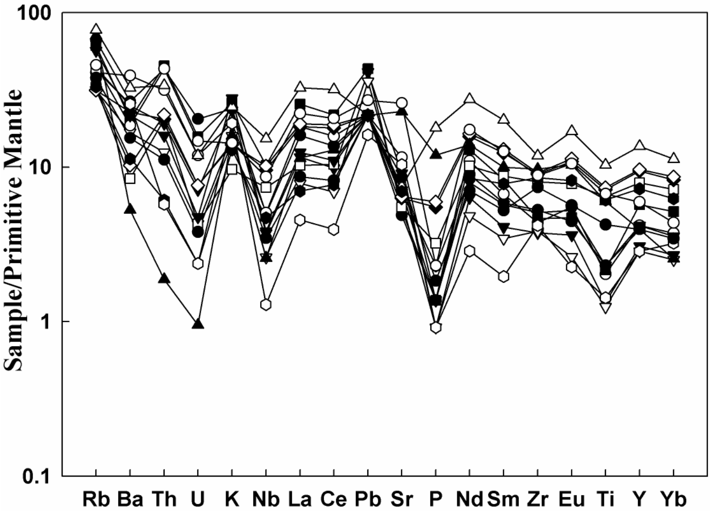


Figure 6b. Primitive mantle normalized patterns for the Newer Dolerite Dykes. Normalizing values are after Sun and McDonough (1989)

to Ba. Therefore, a preferential Ba enrichment over Rb has to be explained by Ba-enriched components in the subducted sediments. Therefore, effect of subducting dehydrating sediments over the mantle wedge appears to be the most plausible explanation for the observed incompatible trace element patterns (Figure 6b). From the foregoing discussion, melting of a hybridized sub-continental lithospheric mantle wedge (with inputs from dehydrating / partially melting sediments from subducting plate) appears to be the most convenient source for the studied dykes. On Zr/Y–Ti/Y diagram of Pearce and Gale (1977), the studied dykes plot in the plate-margin basalt tectonic setting field (Figure 7a). Zr/Y vs Zr tectonic discrimination diagram given by Pearce and Norry (1979) provides an effective discrimination between the basalts from ocean-island arcs, mid-ocean basalts, within-plate basalts and back-arc basalts. As such, the studied NDD plot in the field of back-arc basalts on Zr/Y vs Zr diagram (Figure 7b). Such characteristics may suggest their supra-subduction zone emplacement settings.

CONCLUSIONS

Present Newer Dolerite Dykes intruding the Singhbhum Granitoid complex are subalkaline in nature and show

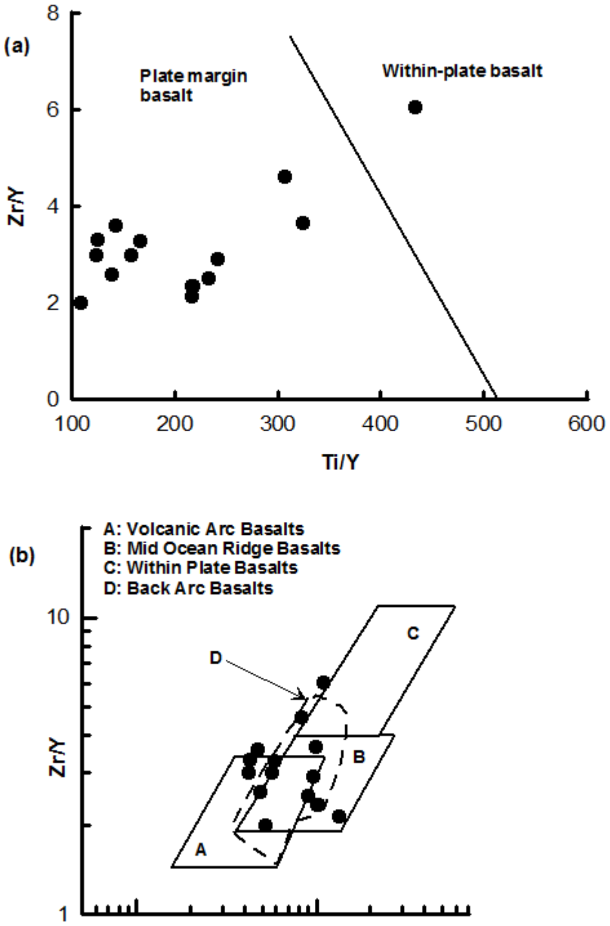


Figure 7. (a) Ti/Y vs. Zr/Y discrimination diagram after Pearce and Gale (1977) and (b) Zr vs. Zr/Y tectonic discrimination diagram after Pearce and Norry (1979) for the Newer Dolerite Dykes. Back-arc basalts discrimination field is taken from Floyd et al. (1991)

compositional variation from basalt to andesite. Their chemistry shows no involvement of crustal contamination. Their geochemical characteristics such as enrichment of LILEs (Rb, Ba, Th, K,) relative to HFSEs (Nb, Zr, Ti), significant negative Nb anomaly and higher Zr/Y, Th/Ta, Th/Yb and Ta/Yb ratios than normal mid-ocean ridge basalts suggests melting of a hybridized sub-continental lithospheric mantle wedge (with inputs from dehydrating / partially melting sediments from subducting plate) to be the proper source for them. Discrimination diagrams for distinguishing tectonic environments indicated studied dykes have supra-subduction zone geochemical characteristics.

ACKNOWLEDGEMENTS

Authors are sincerely thankful to the Director, NGRI, for providing permission to analyze these samples. First author pays sincere thanks to Prof. Shakeel Romshoo, Head, Department of Earth Sciences, University of Kashmir, Srinagar for providing various facilities and genuine time to time guidance to complete this article. Constructive comments and valuable suggestions from anonymous reviewer are duly acknowledged.

REFERENCES

Alvi SH, Raza M (1991). Nature and magma type of Jagannathpur volcanics, Singhbhum, Eastern India. J. Geol. Soc. India, 38:524–531.
Alvi SH, Raza M (1992). Geochemical evidence for the volcanic arc tectonic setting of the Dhanjori volcanics, Singhbhum craton, Eastern India. Geol. Magazine, 92:337-348.
and other trace elements in geological samples by microwave acid
Baer G, Heimann A (1995). Physics and Chemistry of Dykes. Balkema, Rotterdam, pp. 339.
Balaram V, Gnaneshwara Rao T (2003). Rapid determination of REEs
Banerjee PK (1982). Stratigraphy, petrology and geochemistry of some Precambrian basic volcanic and associated rocks of Singhbhum

district, Bihar and Mayurbhanj and Koenjhar districts, Orissa. Geol. Sur. India, Mem., 111:58.

Banerjee PK (1988). On some features of metallogeny in the Precambrian stratigraphy of Eastern India. In*:* Mukhopadhyay D (Ed.), Precambrian of the Eastern Indian Shield. Geol. Sur. India Mem., 8:199–216.

Blackburn WH, Srivastava DC (1994). Geochemistry and tectonic significance of the Ongarbira metavolcanic rocks, Singhbhum district, India. Precamb. Res. 6:235–248.

Bleeker W, Ernst RE (2006). Short-lived mantle generated magmatic events and their dyke swarms: the key unlocking Earth's paleogeographic record back to 2.6 Ga. In: Hanski E, Mertanen S, Rämö T, Vuollo J (Eds.), Dyke Swarms –Time Markers of Crustal Evolution. Taylor and Francis, London, 3-26.

Condie KC, Sinha AK (1996). Rare earth and other trace element mobility during mylonitization: a comparison of the Brevard and Hope Valley shear zones in the Appalachian Mountains, USA. J. Met. Geol. 14:213-226.

Crawford AJ (1989). Boninites and related rocks: London, UK, Unwin Hyman, 465.

digestion and ICP-MS. Atomic Spectr., 24:206–212.

Downes H (2001). Formation and modification of the shallow sub-continental lithospheric mantle; a review of geochemical evidence from ultramafic xenolith suites and tectonically emplaced ultramafic massifs of western and central Europe. J. Petrol. 42: 233-250.

Dunn JA (1940). The stratigraphy of South Singhbhum. Geol. Sur. India Mem., 63(3):303–369.

Dunn JA, Dey AK (1942). The geology and petrology of Eastern Singhbhum and surrounding areas. Geol. Sur. India Mem., 69:281–456.

Ernst RE, Buchan KL (2001). Large mafic magmatic events through time and links to mantle-plume heads. In: Ernst RE, Buchan KL (Eds.), Mantle Plumes: Their identification through time. Geol. Soc. America Spec. Paper, 352:483-575.

Floyd PA, Winchester JA (1978). Identification and discrimination of altered and metamorphosed volcanic rocks using immobile elements. Chem. Geol. 21:291-306.

Hall RP, Hughes DJ (1987). Norite dykes of southern Greenland, early Proterozoic boninitic magmatism. Contrib. Mineral. Petrol., 97:169-182.

Hall RP, Hughes DJ (1990). Norite magmatism. In: Hall RP, Hughes DJ (eds.) Early Precambrian Basic Magmatism, Glasgow, UK, Blackie, 83–110.

Hall RP, Hughes DJ (1993). Early Precambrian crustal development: changing styles of mafic magmatism. J. Geol. Soc. 150:625–635.

Hanski E, Mertanen S, Rämö T, Vuollo J (2006). Dyke Swarms: Time Markers of Crustal Evolution. Taylor and Francis, London, pp. 273.

Hou G, Santosh M, Qian X, Lister GS, Li J (2008). Configuration of the Late Paleoproterozoic supercontinent Columbia: insights from radiating mafic dyke swarms. Gond. Res. 14:395-409.

Jochum KP, Verma SP (1996). Extreme enrichment of Sb, Tl, and other

Knittel U, Oles D (1995). Basaltic volcanism associated with extensional tectonics in the Taiwan-Luzon island arc: evidence for non-depleted sources and subduction zone environment. In: SMELLIE, J.L. (ed) Volcanism Associated with Extension at Consuming Plate Margins. Geological Society, London, Special Publications 81, 77-93.

Kumar A, Ahmad T (2007). Geochemistry of mafic dykes in part of Chotanagpur gneissic complex: petrogenetic and tectonic implications. Geochem. J. 41:173–186.

Lafleche MR, Dupuy C, Bougault H (1992). Geochemistry and petrogenesis of Archean volcanic rocks of the southern Abitibi Belt, Quebec. Precamb. Res. 57:207–241.

Le Bas MJ (2000). IUGS reclassification of the high-Mg and picritic volcanic rocks. J. Petrol. 41:1467–1470.

Le Cheminant AN, Heaman LM (1989). Mackenzie igneous events, Canada: Middle Proterozoic hotspot magmatism associated with ocean opening. Earth Planet. Sci. Lett. 96:38–48.

Mahadevan TM (2002). Geology of Bihar and Jharkhand. Text Book Series, Geol. Soc. India, Bangalore, pp. 563.

Mallick AK, Sarkar A (1994). Geochronology and geochemistry of mafic dykes from Precambrians of Keonjhar, Orissa. Indian Minerals, 48:3–24.

Mantovani E, Vivi M, Babbucci D, Tamburelli C, Albarell D (2008). Back arc extension: which driving mechanism? J. Virt. Expl., 3:17-44.

Mir AR, Alvi SH, Balaram V (2010). Geochemistry of mafic dikes in the Singhbhum Orissa craton: implications for subduction-related metasomatism of the mantle beneath the eastern Indian craton. Int. Geol. Rev., 52(1):79–94.

Mir AR, Alvi SH, Balaram V (2011). Geochemistry of the mafic dykes in parts of the Singhbhum Granitoid complex: petrogenesis and tectonic setting. Arab. J. Geosci*.,* 4:933-943

Misra S, Johnson PT (2005). Geochronological constraints on evolution of the Singhbhum Mobile belt and associated basic volcanics of Eastern Indian Shield. Gond. Res. 8:129–142.

mobility in sub-seafloor hydrothermal systems: constraints from basalt alteration experiments. Earth Planet. Sci. Lett., 101:388-403.

Moorbath S, Taylor PN, Jones NW (1986). Dating the oldest terrestrial rocks – facts and fiction. Chem. Geol. 57:63-86.

Mukhopadhyay D (1984). The Singhbhum Shear Zone and its place in the evolution of the Precambrian mobile belt of north Singhbhum. Ind. J. Earth Sci. CEISM Seminar 205–212.

Naqvi SM (2005). Geology and evolution of the Indian plate. Capital Publishing Company, New Delhi, India 450.

Parker AJ, Rickwood PC, Tucker DH (1990). Mafic Dykes and Emplacement Mechanisms. Balkema, Rotterdam, 541.

Pearce JA (1983). Role of sub continental lithosphere in magma genesis at active continental margins. In: Hawkesworth CJ, Norry MJ (eds.) Continental Basalts and Mantle Xenoliths. Shiva, Nantwich, p. 230–249.

Pearce JA, Cann JR (1973). Tectonic setting of basic volcanic rocks determined using trace element analyses. Earth Planet. Sci. Lett.; 19:290-300.

Pearce JA, Gale GH (1977). Identification of ore deposition environment from the trace element geochemistry of associated igneous host rocks. Geological Society of London Special Publication 7:14–24.

Pearce JA, Norry MJ (1979). Petrogenetic implications of Ti, Zr, Y and Nb variations in volcanic rocks. Contribution to Mineralogy and Petrology 69, 33–47.

Rollinson HR (1993). Using geochemical data: evaluation, presentation, interpretation. Longman Scientific Technical, Essex, U.K. pp. 344.

Roy A, Sarkar A, Jeyakumar S, Aggrawal SK, Ebihara M, Satoh H (2004). Late Archaean mantle metasomatism below eastern Indian craton: evidence from trace elements, REE geochemistry and Sr-Nd-O isotope systematics of ultramafic dykes. Proceedings Indian Academy of Sciences (Earth Planetary Science), 113: 649–665.

Roy A, Sarkar AR, Jeyakumar S, Aggrawal SK, Ebihara M (2002). Sm-Nd age and mantle source characteristics of the Dhanjori volcanic rocks, Eastern India. Geochem. J. 36:503–518.

Saha AK (1994). Crustal evolution of Singhbhum- North Orissa, Eastern India. Geological Society of India, Memoir 27: 341.

Saunders AD, Tarney J (1984). Geochemical characteristics of basaltic volcanism within back-arc basin. In: Kokelaar BP, Howells MF, (Eds.), Marginal Basin Geology. Geological Society of London Special Publication 16:59–76.

Seewald JS, Seyfried WE (1990). The effect of temperature on metal

Sharma M, Basu AR, Ray SL (1994). Sm-Nd isotopic and geochemical study of the Archaean tonalite-amphibolite association from the eastern Indian craton. Contrib. Mineral Petrol. 117:45–55.

Smithies RH (2002). Archaean boninite-like rocks in an intracratonic setting. Earth Planet Sci Lett, 197: 19–34.

Srivastava RK (2006). Geochemistry and petrogenesis of Neoarchaean high-Mg low-Ti mafic igneous rocks in an intracratonic setting, Central India craton: Evidence for boninite magmatism. Geochem J, 40: 15–31.

Srivastava RK (2011). Dyke Swarms: Keys for Geodynamic Interpretation. Springer-Verlag, Heidelburg, pp. 605.

Srivastava RK (2012). Petrological and Geochemical Studies of Paleoproterozoic Mafic Dykes from the Chitrangi Region, Mahakoshal Supracrustal Belt, Central Indian Tectonic Zone: Petrogenetic and Tectonic Significance, J. Geol. Soc. India, 80:369-381.

Srivastava RK, Sivaji Ch, Chalapathi Rao NV (2008). Indian Dykes: geochemistry, geophysics and geochronology. Narosa Publishing House Pvt. Ltd., New Delhi, pp.626.

Subba Rao DV, Balaram V, Naga Raju K, Sridhar DN (2008). Paleoproterozoic boninite-like rocks in an intercratonic setting from Northern Bastar Craton, Central India. J. Geol. Soc. Ind.; 72:373–380.

Sun SS, McDonough WF (1989). Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. In: Saunders AD, Norry MJ (Eds.), Magmatism in the Ocean Basins. Geol. Soc. London Special Pub., 42:313–345.

Tarney J (1992). Geochemistry and significance of mafic dyke swarms in the Proterozoic. In: Condie KC (Ed.), Proterozoic Crustal Evolution. Elsevier, Amsterdam, pp. 151–179.

Tarney J, Weaver BL (1987). Geochemistry and petrogenesis of early Proterozoic dyke swarms. In Halls HC, Fahrig WF (Eds.), Mafic Dyke Swarms. Geol. Assoc. Canada Spec. Pap., 34:81-94.

Taylor SR, McLennan SM (1985). The continental crust: its composition and evolution. Blackwell, Oxford trace elements in altered MORB. Chem. Geol., 130:289-299.

Verma SP (1992). Seawater alteration effects on REE, K, Rb, Cs, Sr, U, Th, Pb, and Sr-Nd-Pb isotope systematic of midocean ridge basalts. Geochem. J. 26:159-177.

Wilson M (1989). Igneous Petrogenesis, Chapman and Hall, London.

Winchester JA, Floyd PA (1976). Geochemical magma type discrimination; application to altered and metamorphosed basic igneous rock. Earth Planet. Sci. Lett., 28:459-469.

Wood DA (1980). the application of a Th-Hf-Ta diagram to problems of tectonomagmatic classification and to establishing the nature of crustal contamination of basaltic lavas of the British Tertiary volcanic province. Earth and Planetary Science Letter, 50, 11-30.