Newer Dolerite dykes, Jharkhand, India: a case study of magma generation, differentiation and metasomatism in a subduction zone setting

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The NE-SW, NW-SE and E-W trending Proterozoic Newer Dolerite dykes around Chaibasa, Jharkhand, India are found to intrude Singhbhum Granites of late Archean age. Clouded plagioclase, bastitised orthopyroxene and uraltized clinopyroxene, magnetite-ilmenite, quartz-feldspar granophyric intergrowth are the characteristic minerals present in the dolerite dykes which assign a low grade metamorphosed character to the dolerite. Both olivine normative and quartz normative varieties are observed in this suite of dykes. These dolerites have been classified into two groups on the basis of REE distribution patterns: one with LREE (Light Rare Earth Element) enriched pattern (Group I) and the other with flat REE pattern (Group II). A significant positive correlation among trace elements Nb, Zr, La, Ce for Group I dykes suggest variable degree of partial melting of the mantle source. In tectonic discrimination diagrams made with immobile incompatible trace elements Nb, Zr, Ti and Y, Group I dykes show arc-like geochemical signature while Group II dykes are similar to MORBs. Enrichment in some of the LILE and prominent depletion in Nb, P and Ti in Group I dykes suggest that the original melt was derived from a metasomatised mantle source. Group II dykes might derived from a MORB-type mantle source. Melting was triggered by volatiles in case of dykes of Group I while for the Group II dykes, melting was produced by thinning of the lithosphere and subsequent decompression.

Keywords: Newer Dolerite, subduction, clouded plagioclase, decompression, mantle

INTRODUCTION

Mafic dyke swarms provide the most complete record of short-lived, mantle-generated magmatic events through time and space (Bleeker, 2004; Ernst and Buchan, 2001). The Indian shield areas exhibit numerous mafic dykes of Proterozoic age in Bundelkhand, Bastar, Dharwar and Singhbhum Orissa cratons of India (Mondal and Ahmad, 2001; Subba Rao *et al.*, 2004; Srivastava, 2006; Murthy, 1995; Radhakrishna *et al.*, 2007). In Singhbhum region, a spectacular set of reticulating basic dyke swarm, the Newer Dolerite suite, traverses the Precambrian Singhbhum granitic complex (Dunn, 1929; Jones, 1934; Krishnan, 1936; Dunn and Dey, 1942; Saha, 1948, 1952, 1994; Saha *et al.*, 1972, 1973; Mahadevan, 2002) over a wide period from 2100 to 950 Ma (Sarkar and Saha, 1977; Mallick and Sarkar, 1994). There is no detailed geochemical study of these dykes swarms which might provide some indication on time and space evolution of the mantle sources beneath these important Indian cratons of Archean age. According to earlier workers, Newer Dolerites with variable Mg number and iron enrichment

belong to different generations (Saha *et al.*, 1973). The geochemical characters of these dykes are strikingly uniform over a long period of time (Bose, 2008; Mallick and Sarkar, 1994). Bose (2008) suggested that Newer Dolerite dykes generated through partial melting of subcontinental mantle which in turn was metasomatised. Mir *et al.* (2010) documented geochemical characteristics of these dykes similar to those of back arc extension basalts (BABB). In the studied area shear fractures which appears to act as pathways of these mafic intrusives have two dominant trends NE-SW and E-W and a subsidiary NW-SE trends. This might suggest that stress system have not an uniform direction over a long period, but it changed orientation with time. The geochemical classification of these dykes and their linking to possible tectonic settings have not yet been reported by earlier workers. In the present work, attempts have been made to classify these dykes according to their trace and REE composition. The genesis of different chemical types of Newer Dolerite dykes has been discussed in the perspective of possible tectonic setting.

GEOLOGICAL SETTING

There is a prevalent idea to consider the Singhbhum craton as a “greenstone granite terrain” (Mahadevan,

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Fig. 1. Geological map of the studied area, south of the Singhbhum Shear Zone. Solid block indicates the study area which has been blown up to show occurrences of Neuer Dolerite Dykes of Chaibasa within Singhbhum Granite. Important towns and villages around the study area have also been marked.

2002) because of sedimentary and tectonic characteristics similar to those found in greenstone belts. Along the western and eastern margins of the Singhbhum platformal nucleus, extensive volcano-sedimentary sequences containing banded iron formations occur. Sporadic high magnesian lavas having affinity with picrite, komatiite and boninite have been reported (Sengupta *et al.*, 1997; Bose 1982, 2000; Sahu and Mukherjee, 2001; Mandal *et al.*, 2006). All these discrete volcano-sedimentary basins, developed peripheral to the Singhbhum granite pluton, represent sequential development of greenstone belts in changing tectonic environments (Thurston, 1990) from platformal margin to destructive plate tectonic margin (Bose, 2000).

Singhbhum group in East Singhbhum show four phases of folding, F_1 , F_2 , F_3 and F_4 related to compression in an arc setting (Bhattacharyya and Sanyal, 1988; Saha, 1994). Sedimentary facies variations indicate that the Chaibasa formation is a flysch (Saha, 1994; Mahadevan, 2002; Mukhopadhyay, 1988; Sinha-Roy and Gupta, 1995). In the northern fringe of the Singhbhum nucleus there is a Proterozoic Singhbhum basin (PSB) which shows characteristic bimodal volcanic geochemistry (shown in the mid-basinal Dalma volcanic belt) and related tectono-sedimentary features of Archean greenstone belts (Bose and Chakraborty, 1992; Bose *et al.*, 1989; Condie, 1990; Bose, 2000). Reconstruction of

the paleo-tectonic setting (Chakraborty and Bose, 1985) suggests that PSB is a rifted continental margin generated in an extensional tectonic regime (Bose, 1994). The PSB sediments testify dual (granitic basement and basic volcanic) provenances in the mixed lithological package (Bose, 1994) usually observed in many Proterozoic marginal basins formed in a back-arc setting (Smith, 1992). According to (Condie, 2001), komatiites and MORBs possibly represent a Neoproterozoic plume-fed slab captured into an arc, as also suggested by the presence of boninites in the Dalma volcanic rocks (Naqvi, 2005). All these features indicate that the Singhbhum mobile belt was accreted to the Singhbhum nucleus. This type of accretion is common in accretionary sedimentary prisms of volcanic arc.

Newer Dolerite dykes intruding the Singhbhum Granite have ages from Paleoproterozoic to Neoproterozoic (2100–900 Ma). The studied area is located south of Chaibasa (Fig. 1), in the state of Jharkhand, India. The Neuer dolerite dykes outcrop as long serrated ridges, as linearly arranged hills and as stony wastes showing a NE-SW and NW-SE trend within the Singhbhum Granite (Fig. 1). A few E-W trending dykes occur both as long ridges and also as stony wastes. Being a part of the granite greenstone belt of Singhbhum craton, these dykes show petrologic and geochemical signatures suggesting an intrusion in an arc-back arc setting.

Table 1. Representative EPMA data of pyroxene grains in Newer Dolerite dykes of Chaibasa

Analysis No. Description	43/P3 Cpx	6/6* Cpx	113/P9 Cpx	9/6* Cpx	35/P8 Cpx	48/P3 Cpx	6/6* Opx	110/P9 Opx
SiO ₂	51.23	51.54	50.28	52.17	51.84	50.51	51.54	55.81
TiO ₂	0.34	0.61	0.65	0.24	0.38	0.87	0.61	0.15
Al ₂ O ₃	2.56	0.65	1.96	1.54	1.85	1.89	0.65	0.96
FeO	6.64	26.5	13.73	18.42	9.89	13.87	26.5	9.45
Cr ₂ O ₃	0.77	0	0.06	0.1	0.01	0.15	0	0.47
MnO	0.22	0.44	0.16	0.28	0.28	0.29	0.44	0.19
MgO	15.82	19.05	13.94	18.42	16.25	14.67	19.05	30.62
CaO	22.07	2.01	18.39	9.5	18.3	17.75	2.01	1.84
Na ₂ O	0.3	0.08	0.25	0.08	0.22	0.29	0.08	0.05
K ₂ O	0.02	0.01	0.02	0	0.02	0	0.01	0
Total	99.97	100.89	99.44	100.75	99.04	100.29	100.89	99.54
Number of ions on the basis of 6 oxygen								
Si	1.885	1.945	1.902	1.938	1.936	1.892	1.972	1.945
Al	0.111	0.029	0.087	0.067	0.081	0.083	0.03	0.029
Fe ³⁺	0.099	0.054	0.089	0.046	0.042	0.076	0	0.027
Ti	0.009	0.017	0.018	0.007	0.011	0.025	0.004	0.017
Fe ²⁺	0.106	0.782	0.345	0.526	0.267	0.333	0.279	0.782
Cr	0.022	0	0.002	0.003	0	0.004	0.013	0
Mg	0.868	1.072	0.786	1.02	0.905	0.819	1.513	1.072
Mn	0.007	0.014	0.005	0.009	0.009	0.009	0.006	0.014
Ca	0.87	0.081	0.745	0.378	0.732	0.712	0.07	0.081
Na	0.021	0.006	0.018	0.006	0.016	0.021	0.003	0.006
K	0.001	0	0.001	0	0.001	0	0	0
Wo	44.64	4.06	37.82	19.10	37.46	36.07	3.54	4.06
En	44.52	53.50	39.89	51.54	46.28	41.47	81.98	53.50
Fs	10.84	42.44	22.30	29.36	16.26	22.46	14.48	42.44

RESULTS AND DISCUSSION

Petrology

The studied dykes are greenish black to greyish black in color and occur both as fine-grained porphyritic and coarse-grained non-porphyritic varieties. Some huge dykes show fine-grained varieties close to the granite contact gradually becoming coarser away. Thin-section observations reveal that the rocks are essentially composed of clinopyroxene and plagioclase either as phenocryst in porphyritic variety or form an assemblage showing intergranular texture. Clinopyroxene occurs as single prismatic grains and as clusters. Compositionally, clinopyroxene shows a wide range of compositional variation from Wo_{44.6} En_{44.6} Fs_{10.8} to Wo_{4.1} En_{53.5} Fs_{42.4} (Table 1) from augite, subcalcic augite, ferroaugite to pigeonite. Some large clinopyroxene grains show conspicuous zoning. In some dykes, clinopyroxene is variably replaced by chlorite, tremolite and actinolitic amphibole. Minor amounts of actinolite discrete grains have also been observed in few cases. Orthopyroxene, partly altered to bastite (Fig. 2a) occurs as a major mineral (Wo_{3.54} En_{81.98} Fs_{14.48}, Table 1) in some dykes and it is sometimes associated with anorthitic plagioclase

(An_{86.7}) (Table 2). In the studied dolerite dykes, the orthopyroxene appears to be not a magmatic phase but a reaction product from clinopyroxene. Textural study indicates that such transformation as orthopyroxene is always found adjacent to clinopyroxene and is associated with Ca-plagioclase. It is likely that orthopyroxene grains might have formed by contamination of granitic country rock by the parent magma according to the following reaction (Deer *et al.*, 1997):

Fresh plagioclase grains are very rare in the studied dolerites. They are mostly clouded showing dark- to light-colored patchy appearance (Fig. 2b). Wide variations in composition (from An_{86.7} to An_{13.3}) are observed in different parts of a single unzoned clouded plagioclase grain (Table 2). Clouding in feldspar occurs widely in mafic dykes that transect Proterozoic shield areas such as satellite dykes of the Great Dyke in Zimbabwe (Robertson and Van Breemen, 1970), Matachewan dykes of the Canadian shield (Halls *et al.*, 1994), dykes on Wyoming shield, USA (Armbrustmacher and Banks, 1974) and in Dharwar

Fig. 2. (A) Photomicrograph of bastitised orthopyroxene in plane polarized light. (B) Photomicrograph of plagioclase feldspar grains showing clouding in plane polarized light.

Table 2. Representative EPMA data of plagioclase grains in Newer Dolerite Dykes of Chaibasa

No. Description	11/6* clouded plag	19/6* clouded plag	82/P 10 clouded plag	27/8 plag core	47/11 plag	98/12 plag
SiO ₂	43.06	40.93	45.82	65.93	67.56	54.68
TiO ₂	0.04	0.06	0	0.03	0	0.1
Al ₂ O ₃	30.08	28.15	25.98	20.28	19.43	26.66
FeO	1.36	4.97	4.77	0.04	0.14	0.83
MnO	0	0.11	0.07	0	0	0
MgO	0.03	0	0.02	0	0.03	0.05
CaO	21.24	23.36	21.24	1.56	0.5	10.78
Na ₂ O	1.8	0.96	0.59	10.72	11.21	5.22
K ₂ O	0.01	0	0.01	0.09	0.04	0.44
Total	97.62	98.54	98.5	98.65	98.91	98.76
Cations on the basis of 16 oxygens						
Si	4.389	4.42	4.797	5.873	5.976	5.082
Al	3.611	3.58	3.203	2.127	2.024	2.918
Ti	0.003	0	0.004	0	0.001	0.005
Fe ²⁺	0.116	0.036	0.037	0.001	0.082	0.449
Mg	0.005	0	0.004	0	0.012	0
Ca	2.32	0.263	0.493	0.006	0.844	2.703
Na	0.356	1.613	1.418	1.981	1.142	0.201
K	0.001	0.108	0.114	0.007	0.036	0
Ab	13.3	81.3	62.3	99.3	56.5	6.9
An	86.7	13.3	25.3	0.3	41.7	93.1
Or	0	5.4	12.4	0.4	1.8	0

craton, India (Pichamuthu, 1959). The cloudiness is not an original feature of feldspars. It is a product of thermal metamorphism caused either by regional heating connected with depth or by the heat of neighboring igneous magma (MacGregor, 1931). Because there is no evidence for nearby intrusive rocks of later origin, we can consider the low-grade metamorphism as the possible cause for feldspar clouding in our area. Some plagioclases also show alteration like saussuritization (process by which calcium-bearing plagioclase feldspar is altered to a char-

acteristic assemblage of minerals called saussurite) and sericitization. Uncoloured small relict grains of plagioclase are extremely rare showing mostly albitic (Ab_{99.6} to Ab_{56.5}) compositions. The common accessory mineral in the rock is magnetite, associated occasionally with ilmenite. Few biotite and sphene also occur as accessories. Interstitial quartz and micropegmatite are also commonly developed and often constitute significant proportion of the rock. Presence of actinolitic amphibole, bastitised orthopyroxene and clouded plagioclase suggest

Fig. 3. Total alkali silica (TAS) diagram (after Le Maitre, 2002). Newer Dolerite dykes plot in the field of basalt and basaltic andesite.

regional metamorphism under greenschist facies conditions.

Geochemistry

Twelve samples have been selected for whole rock major oxide analyses and thirteen samples for trace element analyses (Table 3). Major oxide analyses were carried out by XRF at the Wadia Institute of Himalayan Geology, Dehradun, India. Trace elements including rare earth elements were analyzed with a Perkin Elmer, Sciex ELAN DRC II ICP-MS at the National Geophysical Research Institute, Hyderabad, India. International rock standards BHVO-1, BR (major elements) and JB2 (trace and REE) were run along with the samples to determine the precision and accuracy. The analyzed and certified values of BHVO-1 and JB2 are given in Table 3. Composition of constituent minerals were determined by Electron Probe Micro Analyses (EPMA) in the laboratory of Geological Survey of India, Kolkata using a CAMECA SX-100 with 15 kV voltage, 12 nA current and a beam size of 1 micron.

The dolerites have basalt to basaltic andesite compositions (Fig. 3). Major oxides show a wide range of compositional variation as shown in Table 3. The wide range of variation in SiO_2 content, Mg-numbers (here calculated as $[\text{Mg}^{2+}/(\text{Mg}^{2+} + \text{Fe}_{\text{tot}})]$) and TiO_2 content possibly indicates the occurrence of more than one chemical type of mafic dykes in the Newer Dolerite suite. The samples show a prominent iron-enrichment trend in the AFM diagram (Fig. 4) indicating their tholeiitic nature. Few dykes also show a calc-alkaline nature. The Mg-numbers vary from 0.39 to 0.65 indicating the presence of primitive to highly differentiated rocks in the Newer Dolerite suite. The dykes with low Mg-numbers are likely to be a crystallization product of an evolved magma or might have generated from a relatively iron-rich mantle source. Such iron enrichment is usually the result of mantle metasomatism processes as reported by Hoal (2003), Hanski and Smolkin (1995) and Kelemen (1990). Among

Fig. 4. Plots of the Newer Dolerite dykes in the AFM diagram (Irvin and Baragar, 1971).

the twelve samples, eight samples are silica-undersaturated and olivine-normative (maximum value of 14.77) while the others are quartz-normative (maximum value of 3.87) as shown in Table 1.

Major element, trace element and REE geochemistry of the Newer Dolerite

When plotted in a chondrite-normalized diagram (Fig. 5), the thirteen dolerite samples of the Newer Dolerite suite fall into two distinct groups: nine dykes in Group I (P1, P2, P3, P4, P5, P6A, P7, P8, P9 and P12) and three others in Group II (P6, P10, P11). The Group-I dykes show a REE abundance ~ 100 times higher than the chondritic composition with a sharply fractionated LREE enrichment pattern and $(\text{La}/\text{Sm})_N$ ratios vary from 2.6 to 3.7. The REE pattern of Group-II dykes is nearly flat with a slight enrichment in LREEs. For Group-II, the $(\text{La}/\text{Sm})_N$ ratio varies from 1.11 to 1.26 which is typical of E-MORB (Sun and McDonough, 1989). MORB normalized LILE-HFSE pattern (Fig. 6A) depicts the distinct characters of Group-I and Group-II dykes. Both groups of dykes show positive anomalies of K and Rb and negative anomalies of Ba, Nb, Ta, Zr and Hf with respect to the MORB and the chondrite compositions. The differences in the selected trace element compositions of Group-I and Group-II dykes are revealed by the nature of anomalies of Th, P and Ti. Group-I dykes show a positive anomaly of Th and a negative anomaly of P and Ti compared to MORB whereas the Group-II dykes do not show these are devoid of these anomalies. Similar features are also observed in the chondrite-normalized trace element diagram (Fig. 6B).

The REE multi-element diagrams (Figs. 5, 6A, 6B) of Group-I dykes show LREE and LILE enrichment and high field strength elements (HFSE) depletion (Nb, P and Ti anomalies) compared to the chondritic and MORB com-

Table 3. Major element (in wt%), CIPW Norm and trace element (in ppm) data (including rare earth elements) of the Newer Dolerite dykes within Singbhum Granitoid complex near Chaibasa of Eastern India

Sample No.	Group I										Group II				
	P1	P2	P3	P4	P5	P6A	P7	P8	P9	P12	P6	P10	P11	BHVO-1 analyzed	BHVO-1 Govindaraju-1994
SiO ₂	52.21	50.33	51.33	55.02	55.06	—	51.35	52.6	51.56	49.92	46.62	48.81	48.62	49.08	49.94
TiO ₂	0.9	0.64	0.53	0.35	0.39	—	0.72	1.15	0.6	0.98	1.05	1.1	1.05	2.72	2.71
Al ₂ O ₃	12.55	11.17	8.63	8.78	11.33	—	9.98	12.98	8.05	12.99	13.58	12.04	12.31	13.89	13.8
FeO	8.45	8.87	9.03	7.61	7.34	—	8.14	9.53	8.57	9.75	10.01	11.95	11.77	9.29	9.36
Fe ₂ O ₃	1.64	1.72	1.75	1.48	1.43	—	1.58	1.85	1.66	1.89	1.94	2.32	2.29	1.8	1.82
MgO	9.46	11.42	15.41	13.32	10.47	—	14.52	6.36	16.2	8	10.95	7.52	7.38	6.98	7.23
CaO	6.75	7.82	7.86	8.71	8.71	—	7.35	7.48	7.67	8.45	9.43	9.25	9.18	11.2	11.4
MnO	0.14	0.16	0.16	0.15	0.14	—	0.13	0.16	0.15	0.16	0.18	0.2	0.21	0.16	0.17
Na ₂ O	2.44	1.74	1.18	1.75	2.02	—	1.75	3.13	1.11	2.21	1.61	1.94	2.42	2.37	2.26
K ₂ O	2.02	1.58	0.82	0.84	1.5	—	1	1.4	0.73	1.48	0.89	0.59	0.46	0.5	0.52
P ₂ O ₅	0.14	0.11	0.07	0.05	0.06	—	0.13	0.17	0.08	0.26	0.11	0.15	0.13	0.25	0.27
LOI	2.65	4.6	3.57	2.35	2.39	—	2.88	1.91	2.72	2.45	2.93	2.34	2.24		
mg no	0.57	0.6	0.67	0.67	0.63		0.68	0.44	0.69	0.49	0.52	0.43	0.43		
CIPW normative compositions (wt%)															
Quartz	0	0	0	3.87	3.52		0	1.54	0.53	0	0	1.06	0		
Orthoclase	12.36	9.78	5.01	5.07	9.01		6.12	8.55	4.48	9.11	5.46	3.64	2.84		
Albite	21.33	15.39	10.31	15.08	17.34		15.3	27.33	9.73	19.44	14.12	17.1	21.35		
Anorthite	17.87	18.8	16.33	13.87	17.66		16.97	17.76	15.37	21.98	28.18	23.34	22.26		
Diopside	12.9	17.09	18.91	24.01	20.89		16.02	16.11	18.93	16.45	16	19.54	20.24		
Hypsthene	29.51	30.76	45.28	35.12	28.59		37.73	23.3	47.1	25.73	16.23	29.29	24.91		
Olivine	1.48	4.05	0.34	0	0		3.78	0	0	1.92	14.77	0	2.56		
Magnetite	2.46	2.61	2.62	2.19	2.11		2.37	2.77	2.5	2.85	2.92	3.51	3.47		
Ilmenite	1.77	1.27	1.04	0.68	0.75		1.42	2.26	1.18	1.94	2.07	2.18	2.07		
Apatite	0.32	0.25	0.16	0.11	0.13		0.29	0.38	0.18	0.58	0.25	0.34	0.3		

Sample No.	Group I										Group II				
	P1	P2	P3	P4	P5	P6A	P7	P8	P9	P12	P6	P10	P11	JB2 analyzed	JB2 Govindaraju-1994
Sc	24.49	28.74	28.49	32.55	30.99	29.31	24.50	27.88	27.15	24.48	27.59	32.30	34.14	54.336	54.4
V	208.18	193.74	175.95	165.76	173.18	173.94	180.67	213.20	175.97	205.79	249.27	253.40	264.44	581.447	578
Cr	181.11	246.83	376.89	237.15	178.53	345.27	320.47	73.49	314.65	81.15	77.28	60.78	62.04	27.456	27.40
Co	62.80	67.18	73.33	70.57	69.94	78.70	67.40	65.13	73.67	67.13	66.92	70.41	68.03	39.868	39.80
Ni	223.41	260.11	343.44	260.12	207.16	339.06	345.55	130.65	363.83	187.94	180.00	124.48	131.39	14.155	14.20
Cu	103.99	98.39	72.65	99.20	94.80	80.46	83.27	124.08	75.04	93.05	112.71	57.00	114.25	226.345	227.00
Zn	101.67	118.44	83.01	74.46	78.82	71.74	85.72	119.96	77.55	95.41	102.67	91.09	84.77	111.498	110.00
Ga	17.67	14.97	11.46	12.18	14.15	12.34	14.52	18.43	12.02	16.93	17.52	17.40	17.33	17.076	17.00
Rb	67.60	61.35	27.02	32.27	49.86	23.94	43.40	50.23	30.89	46.61	32.61	19.79	19.35	6.192	6.20
Sr	174.07	183.08	116.74	116.84	139.88	136.25	169.83	164.56	126.01	206.32	242.79	193.01	160.23	178.115	178.00
Y	31.05	24.33	17.24	17.44	20.64	14.77	22.43	34.38	17.06	28.49	18.40	27.95	25.83	25.004	24.00
Zr	94.06	48.02	31.19	52.70	47.97	33.25	52.27	84.35	29.23	76.59	26.13	29.64	34.18	51.25	51.40
Nd	20.94	14.35	10.06	10.67	13.39	8.36	14.39	21.59	9.90	21.67	9.34	9.44	8.91	6.80	6.70
Nb	10.17	6.09	5.46	6.11	6.40	4.47	7.62	12.32	5.14	10.39	3.79	4.70	4.22	0.809	0.80
Cs	1.88	1.81	0.76	1.25	0.79	1.24	3.27	1.09	2.48	1.09	2.08	0.56	0.47	0.88	0.90
Ba	104.01	56.21	34.99	46.46	50.47	40.31	46.44	55.96	29.66	72.99	34.76	18.88	21.31	208.98	208.00
La	20.52	13.68	9.61	11.65	15.11	7.43	13.61	20.68	9.13	19.78	4.98	4.73	4.77	2.397	2.37
Ce	42.62	28.85	20.09	23.29	30.03	15.76	28.54	43.20	19.32	41.91	12.16	12.22	11.99	6.833	6.77
Pr	4.11	2.79	1.93	2.13	2.74	1.56	2.75	4.18	1.89	4.08	1.48	1.45	1.42	0.945	0.96
Sm	4.30	3.14	2.20	2.21	2.64	1.84	3.05	4.49	2.15	4.36	2.53	2.75	8.91	2.256	2.25
Eu	1.21	0.93	0.67	0.58	0.67	0.61	0.91	1.27	0.69	1.41	1.03	1.02	2.51	0.897	0.86
Gd	5.53	4.12	2.91	2.81	3.48	2.50	4.01	6.02	2.89	5.63	3.37	3.98	0.97	3.476	3.28
Tb	0.86	0.67	0.47	0.47	0.57	0.40	0.64	0.92	0.46	0.85	0.54	0.71	3.68	0.638	0.62
Dy	4.47	3.55	2.54	2.44	2.95	2.14	3.24	4.95	2.48	4.33	2.81	4.00	0.63	3.748	3.66
Ho	0.97	0.77	0.57	0.56	0.64	0.48	0.72	1.09	0.54	0.89	0.61	0.90	3.57	0.831	0.81
Er	3.02	2.37	1.74	1.70	2.05	1.45	2.22	3.33	1.67	2.73	1.77	2.78	0.83	2.561	2.63
Tm	0.52	0.41	0.29	0.30	0.35	0.24	0.37	0.55	0.28	0.45	0.29	0.47	2.58	0.455	0.45
Yb	2.66	2.23	1.60	1.60	1.92	1.40	2.03	3.02	1.61	2.39	1.48	2.54	2.33	2.463	2.51
Lu	0.42	0.33	0.23	0.26	0.29	0.22	0.32	0.47	0.24	0.35	0.23	0.38	0.37	0.392	0.39
Hf	2.32	1.27	0.85	1.29	1.30	0.86	1.38	2.16	0.80	1.84	0.78	0.91	0.94	1.463	1.42
Ta	0.76	0.49	0.57	0.62	0.77	0.69	0.60	1.05	0.43	0.71	0.35	0.51	0.49	0.203	0.20
Pb	5.97	4.67	3.68	4.81	5.72	3.65	4.49	5.64	3.75	4.63	2.89	2.54	3.44	5.523	5.40
Th	3.17	2.04	1.37	2.39	2.92	1.12	2.10	3.27	1.32	1.88	0.33	0.45	0.44	0.304	0.33
U	0.46	0.28	0.18	0.38	0.47	0.15	0.29	0.45	0.17	0.24	0.07	0.07	0.06	0.153	0.16
La/Nb	2.018	2.246	1.759	1.907	2.362	1.660	1.787	1.678	1.777	1.904	1.313	1.007	1.133		
Sm/La	0.209	0.229	0.229	0.190	0.174	0.248	0.224	0.217	0.236	0.220	0.509	0.581	0.525		
Nb/Ce	0.238	0.211	0.272	0.262	0.213	0.284	0.267	0.285	0.266	0.248	0.312	0.384	0.351		
Th/Nb	0.312	0.335	0.251	0.392	0.456	0.250	0.275	0.265	0.257	0.180	0.087	0.096	0.816		
Ti/Zr	57.413	79.968	101.959	39.851	48.780	—	82.648	81.807	123.157	76.771	241.084	222.687	184.329		
Zr/Y	3.029	1.974	1.809	3.022	2.325	2.251	2.330	2.453	1.713	2.689	1.420	1.060	1.323		
Th/Yb	1.191	0.916	0.857	1.497	1.515	0.800	1.033	1.082	0.822	0.784	0.223	0.178	7.872		
Ta/Yb	0.287	0.219	0.358	0.385	0.399	0.493	0.293	0.349	0.270	0.295	0.238	0.201	0.209		
Ti/V	25.939	19.820	18.073	12.669	13.512	—	23.912	32.365	20.458	28.573	25.274	26.046	23.824		
Nd/Yb	7.873	6.430	6.300	6.674	6.959	5.969	7.086	7.152	6.168	9.061	6.303	3.715	3.819		
Nb/Yb	3.821	2.730	3.421	3.822	3.325	3.196	3.750	4.082	3.199	4.343	2.562	1.848	1.807		
Pb/Yb	2.244	2.092	2.304	3.008	2.971	2.609	2.210	1.868	2.334	1.935	1.951	0.998	1.475		

LOI = Loss of ignition, sample No. 6A—major oxide data not determined.

Fig. 5. Chondrite-normalized REE plot (Sun and McDonough, 1989) for the Group I and Group II Newer Dolerite dykes of Chaibasa.

positions. Strong enrichment in LILE (Cs, Rb, K and Sr) over HFSE (Nb, Zr and Ti), LILE (La, Ce, Pr) enrichment over HREE and prominent negative anomalies of Nb, P and Ti suggest arc nature for the Group-I dykes. The multi-element diagram of Group-II dykes (Fig. 6A) is quite similar to E-MORB with enrichment of K and Rb and depletion at Ba, Zr and Hf, compared to MORB. The negative anomaly of Zr found in the MORB normalized plot (Fig. 6A) is indicative of the mantle source since Zr is considered as a relatively immobile element (Floyd and Lee, 1973; Winchester and Floyd, 1977; Macdonald *et al.*, 1988; Mir *et al.*, 2010). The negative Ba anomaly and the relatively lower Ba concentration in both the Group-I and Group-II dykes (29–104 ppm) might indicate lower concentrations of Ba in the mantle source and also presence of a Ba-depleted subducted pelagic sediments for the mantle source of Group-I dykes (Smith *et al.*, 1986; Roy *et al.*, 2002).

Binary variation diagrams between a few major and trace elements (Fig. 7) clearly demonstrate the existence of two different groups of dykes. In all plots, Group-I dykes show a distinctive trend of evolution in contrast to the Group-II dykes. Trace elements like Nb, La, Ce, Zr are sensitive to variable degrees of partial melting of the mantle or to different sources (Weaver and Tarney, 1981; Ahmad and Tarney, 1991; Petterson and Windley, 1992). A good positive linear correlation ($r = 0.9$) between La–Nb, Nb–Ce, La–Zr and Nb–Zr (Fig. 7) of Group-I dykes suggest variable degree of partial melting of a metasomatized mantle source. Group-II dykes form a cluster in these bivariate diagrams indicating a nearly uniform degree of partial melting of a mantle source similar to MORB.

Fig. 6. (A) MORB-normalized (after Pearce 1983) multi-element diagram of Group I and Group II Newer Dolerite dykes. (B) Chondrite-normalized (Thompson *et al.*, 1984) multi-element diagram for Group I and Group II Newer Dolerite dykes.

REE classification of Group I and Group II dykes

The significant differences between the chemical nature and tectonic environment of the Group-I and Group-II dykes have been identified with the help of some trace element ratios like La/Nb, Sm/La, Nb/Ce, Th/Nb and Ti/Zr. It has already been established that the Group-I dykes bear signatures of subduction-related tectonic setting. Then it is important to know whether it was an island arc or an active continental margin. For this purpose, a comparative study has been made between Group-I basalts, island arc basalts (IABs) and active continental margin (ACM) basalts on the basis of some trace element ratios as shown in Table 4. This table also contains data of Group-II dykes, E-MORBs (Sun and McDonough, 1989), IABs and ACM basalts (Wilson, 1989).

La/Nb ratio of Group-I dykes varies within a wide range from 1.68 to 2.36 and matches well with that of basalts of active continental margin setting (Table 4). This

Fig. 7. Binary variation diagrams of (a) La vs. Nb, (b) Ce vs. Nb, (c) La vs. Zr, (d) Nb vs. Zr, (e) MgO vs. Nb, (f) V vs. TiO₂.

suggests that the La/Nb ratio of mantle source of Group-I dykes are similar to that of the mantle source for basaltic rocks of active continental margin. Sm/La is a useful parameter because it is a measure of the extent of LREE depletion or enrichment. The range of the Sm/La and the Nb/Ce ratios (this latter being a useful indicator of mantle metasomatism or contamination) of the Group-II dykes is very close to E-MORB (Sun and McDonough, 1989). The higher Sm/La and Nb/Ce values of some of the dykes are due to higher Sm and Nb concentration relative to E-

MORB. Both the Sm/La and Nb/Ce of Group-I dykes fall either within or very close to the data range of basalt/dolerites of active continental margins. High Th/Nb ratio of Group-I dykes compared to Group II dykes suggests the involvement of partial melt of subducted sediments (Class *et al.*, 2000; George *et al.*, 2003; Plank, 2005) in Group-I dykes. Although the range of Th/Nb ratios of Group-I dykes matches with that of the active continental margin basalts, it also overlaps with that of IABs. This is justified by the fact that melted sediments play an im-

Table 4. Some important trace element ratios of Group I basalts, Group II basalts, E-MORB, island arc basalts (IABs) and active continental margin (ACM) basalts. Data reference: E-MORBs (Sun and McDonough, 1989), IABs and ACM basalts (Wilson, 1989)

Ratio	Group I	Group II	E-MORBs	IABs	ACM Basalts
La/Nb	1.68–2.36	1.01–1.31	1.07	1.85	1.4–2.3
Sm/La	0.17–0.23	0.5–0.8	0.4	0.9	0.19–0.29
Nb/Ce	0.21–0.29	0.31–0.38	0.31	0.189	0.21–0.31
Th/Nb	0.18–0.45	0.08–0.1	0.05	0.26–1	0.2–0.5
Ti/Zr	39–123	184–241	107	147	48.5–70

portant role during the genesis of both the IABs and the ACM basalts. The immobile element Ti/Zr ratios of Group-I dykes (39–123) are very close to the range (given in Table 4) observed in active continental margin basalts (Wilson, 1989). Some dykes of Group I show higher Ti/Zr ratios which are due to a lower Zr concentration in the source, as discussed earlier (Table 3). The Group-II dykes show a much higher Ti/Zr ratio (Table 4) compared to E-MORB (Sun and McDonough, 1989) which might be the result of lower Zr concentration of mantle source of these dykes.

Tectonic setting of the Newer Dolerites

This study reveals that the Newer dolerite rocks have been affected by hydrothermal alteration under lower greenschist facies metamorphism. This is evident from the common occurrence of albitic plagioclase–chlorite–tremolite–actinolite assemblages. Clouding in plagioclase feldspar, bastitisation of orthopyroxene, transformation of pyroxene into tremolite–actinolite minerals has been identified as hydrothermal alteration product. In order to avoid problems of element mobility during metamorphism (Pearce, 1996), we are using abundances of relatively immobile trace elements (which remain unchanged during weathering and low grade metamorphism) to derive our inferences on the tectonic setting of these dolerite dykes. The four diagrams Ti vs. V, Cr vs. Y, Zr/Y vs. Zr and Th/Yb vs. Ta/Yb (Fig. 8) are useful for identifying the tectonic setting of the Newer Dolerite dykes.

The Ti–V diagram of Shervais (1982) is based on variation of partition coefficient of V under varying oxygen fugacities. In this diagram, all the samples of Group-I dykes plot within the fields of volcanic arc basalts (VAB; $Ti/V < 20$) with a few in the MORB field ($Ti/V = 20$ to 50) but the samples of Group-II dykes fall only within the MORB field (Fig. 8). The Cr–Y diagram of Pearce (1982) is useful to discriminate arc basalts, MORBs and within-plate basalts (WPBs) since it relies on Y, which is enriched in MORBs and WPBs relative to VABs. Some of the samples of Group-I dykes fall within the field of VAB while some other samples fall in a field which is a common area of arc basalts, MORBs and WPBs. One sam-

ple of Group-I falls outside the field of VAB and within a field overlapping MORBs and WPBs. The samples of Group-II plot within the VAB field, two of which are very close to the field of MORBs and WPBs (Fig. 8B). In the Zr/Y vs. Zr diagram of Pearce and Norry (1979), the samples of Group-I dykes fall within the fields of arc basalts and MORB (Fig. 8C). The Group-II dykes do not fall within these fields due to their low Zr/Y value. The Th/Yb vs. Ta/Yb diagram of Pearce (1982) can be used to identify the basalts of volcanic arc and their source (Fig. 8D). The preferential enrichment of Th relative to Ta in subduction-related fluids results in samples that plot above the “mantle array” along a vector nearly parallel to the Th/Yb axis. The samples of Group-I dykes plot along such a vertical line indicating their arc nature. Further, the position of Group-I dyke within the field of ACM basalts confirms their continental arc origin. This continental arc origin of Group I dykes has also been identified from trace element ratios like La/Nb, Sm/La, Nb/Ce, Th/Nb, Ti/Zr (Table 4). The samples of Group-II dykes fall within the mantle array in the MORB field suggesting its mantle source similar to MORB mantle.

Nature of the mantle and its melting

Generally during subduction, HFSE are not incorporated in the mantle wedge due to their low mobility in fluids (McCulloch and Gamble, 1991; Brenan *et al.*, 1994) and their low concentration in subducting sediments (Plank and Langmuir, 1998). For this reason, abundance of HFSE has often been used to understand the geochemical nature of the mantle wedge prior to subduction. In order to have an estimate about the contribution of the background mantle and the inputs from subduction and contamination processes, we followed the approach of Pearce *et al.* (1995) for plotting trace element data in diagrams having the form X/Yb versus Nb/Yb , where X represent both mobile and immobile elements. Both Nb and Yb are not mobile in subduction process and their abundances (and their ratio Nb/Yb) remain constant during contamination. The ratio X/Yb changes with input of X from subducted sediment, fluid phase or melt (Pearce, 1983; Pearce and Peate, 1995).

Fig. 8. Tectonic discrimination diagrams. (A) Ti–V diagram of Shervais (1982), Arc-volcanic arc basalt, MORB—Mid-ocean ridge basalt. (B) Cr–Y diagram of Pearce (1982), WPB—within-plate basalt. (C) Zr/Y vs. Zr diagram (after Pearce and Norry, 1979). (D) Th/Yb vs. Ta/Yb plot showing differences between subduction related basalts and oceanic basalts (after Pearce, 1983).

In the plot Nd/Yb vs. Nb/Yb (Fig. 9), the samples of both the Group-I and Group-II dykes fall within the mantle array along a linear trend though two samples of Group-II are more primitive in nature. This figure indicates that the original mantle source of both the Group-I and Group-II dykes were similar in nature with Group-I dykes showing slightly enriched character. This figure also suggests that Nd did not play any role during the modification of the mantle by subduction/crust/SCLM components.

In the Zr/Yb vs. Nb/Yb (Fig. 9), the samples of both the Group-I and Group-II dykes form a linear trend along the lower boundary of the mantle array. This feature suggests a low Zr abundance in the mantle source for both

groups of dykes. This Zr depletion has possibly been attained by extraction of earlier batches of magma from the same source. The depleted geochemistry of N-MORB, which has low Zr value along with other incompatible elements, has been explained with the same logic (Wilson, 1989). During the metasomatic process the mantle feeding the arc gets enriched with LILE but not with HFSE. Being a HFSE, Zr is consequently depleted in the residual mantle source. In the present study, dykes of Group-I and Group-II are thought to have been derived from arc mantle and E-MORB mantle respectively, both of these mantle being depleted in Zr (Misra *et al.*, 1991; Melluso *et al.*, 2003).

In the Th/Yb vs. Nb/Yb plot (Fig. 9), the Group-I dykes

Fig. 9. Plots of Nd/Yb, Zr/Yb, Th/Yb, Pb/Yb vs. Nb/Yb for Newer dolerite dykes. Symbols of Group I and Group II dykes are same as previous plots. The Mantle array indicates the range of incompatible element ratios in average MORB and OIB (Green, 2006).

are displaced from the mantle array towards higher Th/Yb ratios with a flat slope but the Group-II dykes are still plotted within the mantle array. This plot suggests significant Th contribution from the subduction component to the mantle source of Group-I dykes but not for Group-II dykes.

In the Pb/Yb vs. Nb/Yb plot (Fig. 9), the Group-I dykes are displaced off the mantle array towards the higher Pb/Yb ratio. The Group II-dykes (except for one sample) also plot off the mantle array towards higher Pb/Yb ratios. However, the ratio of the Group-I dykes (1.87–3.0) is higher relative to the Group-II dykes (0.95–1.95). As, it has already been established that, Group-II dykes have not been affected by any subduction-related modification, the Pb enrichment in these rocks suggests effects of crustal contamination.

The overall flat trends of plots of both groups of dykes suggest addition of a subduction component to a metasomatized mantle source. Significant variation in abundances for the REE and good positive correlation among incompatible trace elements of Group-I dykes probably indicate varying degree of partial melting of the source and exclude the possibility of fractional crystalli-

zation (Hanson, 1980; Ahmad and Tarney, 1994). Melting was facilitated in the mantle source due to introduction of volatile phases. On the other hand, the unmodified nature of mantle source of Group-II dykes and their compositional similarity with MORB mantle possibly indicate magma generation in the back-arc region where melting was initiated due to decompression. Magmas for both Group-I and Group-II dykes suffered contamination by granitic materials during their migration through crustal conduits (fracture system).

CONCLUSIONS

Newer Dolerite dykes (Singhbhum Craton, India) include two chemical types—Group I and Group II. Group-I dykes shows LREE fractionated character with respect to chondrite (Sun and McDonough, 1989) and high values of some incompatible element ratios such as Th/Nb, Zr/Y, Ta/Yb and Pb/Yb (Table 3) indicating their generation from a metasomatized mantle source. Group-II dykes with nearly flat REE pattern and relatively low values of incompatible element ratios such as Th/Nb, Zr/Y, Ta/Yb and Pb/Yb (Table 3) likely to have been derived from an

unmodified mantle source similar to E-MORB. Occurrences of quartz normative tholeiites, quartz-alkali feldspar intergrowth and positive anomalies of K and Rb might suggest crustal contamination during migration of the basic magma through crustal conduits. Petrogenesis and geochemical character of these dykes suggest their evolution in a subduction zone tectonic setting—one group (Group I) from a modified (metasomatized) over-riding mantle wedge and the other group (Group II) from unmodified mantle in the back arc region.

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