

A Petrogenetic Model of Basalts from the Northern Central Indian Ridge: 3–11° S

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Abstract: Mid-Ocean Ridge Basalts (MORB) from the Northern Central Indian Ridge (NCIR) were recovered between latitudes 3° and 11° S and are olivine tholeiite with higher abundances of K and Rb. They are of typical transitional MORB (T-MORB) variety and appear to have been generated from an enriched-mantle peridotite source. The primitive NCIR MORBs having $Mg^\# > 0.68$ are the product of partial melting at an estimated pressure of ~ 1 GPa. It is inferred that the magma was subsequently modified at a pressure > 1 GPa by crystal fractionation and spinel was the first mineral to crystallize followed by separation of relatively Fe-rich olivine with subsequent decrease in pressure. During progressive fractionation at lower pressure (between 1–0.5 GPa), the bulk composition of the magma became systematically depleted in MgO, and enriched in ΣFeO , TiO_2 , P_2O_5 and Na_2O . There was, however, limited gradual depletion in Al_2O_3 and CaO and concomitant enrichment in K_2O . With the progressive fractionation these basalts became gradually enriched in V, Co, Y, Zr and to some extent in Sr, and depleted in Ni and Cr. In addition, the ΣREE of the magma also increased with fractionation, without any change in $(La/Yb)_n$ value.

Key words: MORB, NCIR, geochemistry, petrogenesis, Indian Ocean, mid-ocean ridge

1 Introduction

The Northern Central Indian Ridge (NCIR) between 3° and 11°S latitudes is joined to the north with the slow spreading Carlsberg Ridge (CR; ~ 24 – 26 mm/a, full spreading rate) and to the south with the intermediate spreading Southern Central Indian Ridge (SCIR; ~ 50 mm/a) (Fig. 1). Earlier petrological investigations of the Central Indian Ridge were concentrated either on or along the CR to the north and at the southern end of the CIR up to the Rodriguez Triple Junction (RTJ, 25°30' S/ 70°00' E) (Hekinian, 1968; Price et al., 1986; Herzig and Plüger, 1988; Humler and Whitechurch, 1988; Banerjee and Iyer, 1991, 2003; Iyer and Banerjee, 1993; Rehkamper and Hofmann, 1997; Mudholkar, 2001; Murton et al., 2005; Nauret et al., 2006). By contrast, the NCIR has been relatively uninvestigated. During the North American (MONSOON, 1960; LUSIAD, 1962–63; DODO, 1964; CIRCE, 1968 and ANTIPODE, 1970–71), Russian (VITIAZ

and AKADEMIC-KURCHATOV cruises during 1964/65) and German (by SO 28, 1987) expeditions, ship-board researchers sampled sporadically along the NCIR, but this proved insufficient to characterize in detail NCIR petrology and geochemistry. Noteworthy work on NCIR petrochemistry include that of Engel and Fisher (1975) on various rock-types (granitic to ultramafic), whilst in more recent times Rehkamper and Hofmann (1997) published high-quality trace and isotopic glass data (samples collected during SO 28). Most recently, Hellebrand et al. (2002) documented partial melting in NCIR peridotites as a method of determining geodynamic variables such as spreading rate and mantle temperature.

In this context, the present work attempts to reduce the long-standing gap in existing knowledge of the NCIR MORBs and provides a set of new high-quality analyses for the Indian Ocean Petrological Database (<http://petdb.ldeo.columbia.edu>). Recent expeditions to the Indian Ocean under the InRidge Programme (Cruise R/V Sagar Kanya #125 and #165 in the year of 1997 and 2001 respectively)

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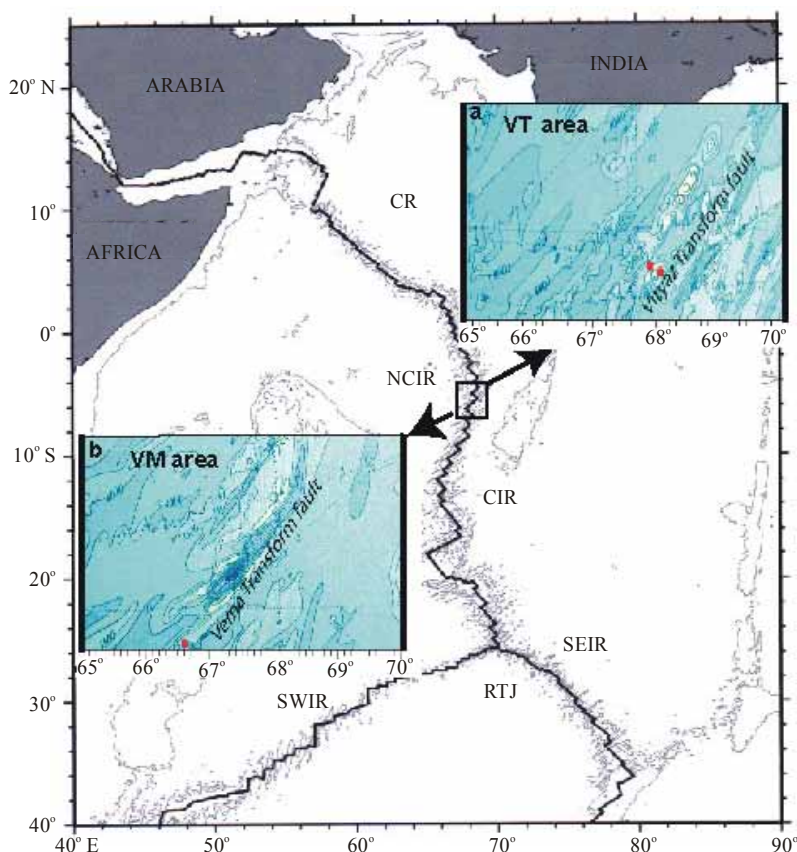


Fig. 1. Generalized map of IORS to show the three sample locations (VT 4, VT 5 and VM 9DG).

CR – Carlsberg Ridge; NCIR – Northern Central Indian ridge; CIR – Central Indian Ridge; RTJ – Rodriguez Triple Junction; SWIR – Southwest Indian Ridge; SEIR – Southeast Indian Ridge. The smaller rectangle on the NCIR indicates the broad boundaries of the present study area. The precise locations of the three samples are shown in two enlarged maps (a. VT area and b. VM area). Depth contour map scale 1: 5000000.

Table 1 Geographic position and depth of sample locations in the NCIR

Station	Lat. (S)	Long. (E)	Depth (m)	Tectonic setting
VT 4	5°39.06'	68°03.8'	3050	Outer ridge flank
VT 5	5°35.2'	67°54.9'	3560	Outer ridge flank
VM 9DG	9°53.64'	66°35.7'	2000	Near axis seamount (summit height 1875 m), west of ridge segment # 3

permitted the sampling of basalts, using a chainbag dredge, from three different geographic as well as tectonic locations (Table 1, Fig. 1). Here, we detail the bulk geochemistry (major, trace and REE) of the NCIR MORBs with the objective of developing a primary petrogenetic model to explain their formation history. In order to achieve this, in addition to the present geochemical dataset, previously published datasets (e.g., data collected from the Petrological Database of Lamont-Doherty Geological Observatory of Columbia University or PETDB MORB database at <http://petdb.ldeo.columbia.edu> and the SO 28

cruise report) are also integrated with our results to help draw a more meaningful conclusion.

2 Sample Description and Petrography

Rocks of sample weight ~64 kg from locations VT 4 and VT 5 (Fig. 1, inset) are homogeneous basalts, comprising fresh to moderately altered vesicular pillow lavas, sometimes displaying a glassy crust (~5–25 mm, Mukhopadhyay et al., 1998). Rocks from the near-ridge seamount in area VM at location 9DG (Fig. 1, inset) consist of uniform column-like basalt blocks, although in a few instances pillows were also recovered. The columns are either cylindrical or conical in shape and often have a thin veneer of glass (thickness ~3–4 mm; Drolia et al., 2003).

Petrographically, the NCIR basalts are usually moderately phryic plagioclase-rich tholeiite (MPPB; Bougalt and Hekinian, 1974), with plagioclase occurring as the dominant mineral in variable morphotypes such as phenocryst, microphenocryst, and even megacryst followed in abundance by olivine and pyroxene with varying proportions of groundmass materials (Pluger et al., 1988). The modal proportion of the plagioclases varies considerably (up to 19 vol%), that of olivine noted is comparatively less (0.04–1.69%) whereas diopside varies the least (up to 0.05 vol%). Microscope study reveals that the newly collected basalts from the NCIR are porphyritic with a few large phenocrysts of mainly prismatic plagioclase ($An_{62}-An_{90}$, microprobe data, personal observation) embedded within a fine-grained groundmass of plagioclase laths ($An_{35}-An_{79}$) and clinopyroxene (diopside, $Wo_{45-51}En_{25-37}Fs_{14-24}$) with some interstitial glass. After plagioclase, the other major phenocryst population includes olivine (Fo_{81-88}) and, in rare instances, clinopyroxene (mainly diopside $\sim Wo_{49-51}En_{31-35}Fs_{16-18}$). The average mineral compositions of NCIR basalts are given in Table 2. Plagioclase from VM basalts displays the maximum variation in anorthite content (An_{52-85}) compared to VT plagioclase (An_{64-83}). Olivine forsterite from both areas varies from Fo_{80} to Fo_{88} . The plagioclase phenocrysts display compositional zoning (Fig. 2a), which is generally absent in groundmass plagioclase. Some tiny spherical materials, perhaps fluid/melt inclusions, are also present within the plagioclase phenocrysts (Fig. 2b). The

Table 2 Average chemical composition of mineral phases in the NCIR basalts

No. of grains No. of analyses	Plagioclase			Olivine			Clinopyroxene			Titanomagnetite		
	VT	VM	VT	VT	VM	VT	VM	VM	VM	VM	VM	VM
	7	6	6	6	3	6	3	6	6	7	21	7
	21	18	18	18	9	18	9	18	18	21	21	21
	average	range	average	range	average	range	average	range	average	range	average	range
SiO ₂	50.92	47.32–56.77	51.95	47.91–56.32	41.31	40.42–41.94	40.67	40.46–41.02	45.51	42.09–48.11	2.74	0.89–6.6
TiO ₂	0.22	0.02–1.23	0.10	0.03–0.18	0.03	0.01–0.08	0.03	0.02–0.04	2.70	1.9–3.29	22.69	18.17–38.53
Al ₂ O ₃	28.69	21.53–32.3	28.30	25.4–32.02	0.18	0.01–0.85	0.05	0.04–0.06	8.09	4.18–13.41	1.67	0.72–2.64
ΣFeO	1.02	0.31–4.11	0.67	0.2–1.09	14.02	12.43–17.26	11.64	11–12.62	10.41	7.85–12.01	63.75	42.9–69.57
CaO	15.02	11.85–17.21	13.75	10.28–17.58	0.34	0.27–0.4	0.2	0.14–0.25	21.66	19.88–23.22	0.46	0.25–0.88
MgO	0.34	0.21–0.78	0.30	0.12–0.54	43.45	41.22–45.01	44.49	43.28–45.62	10.24	6.95–12	0.94	0.8–1.09
MnO	0.08	0.03–0.11	0.07	0.03–0.13	n.d.	-	0.32	0.28–0.35	0.22	0.15–0.3	0.63	0.48–0.74
Na ₂ O	2.76	1.91–3.59	3.33	1.68–5.21	n.d.	-	0.01	-	0.43	0.32–0.75	1.17	-
K ₂ O	0.04	0.01–0.09	0.07	0.03–0.13	0.03	-	0.04	-	0.03	0.01–0.04	n.d.	-
Cr ₂ O ₃	0.03	0.01–0.06	0.11	-	0.06	0.03–0.1	0.11	0.02–0.17	0.12	0.07–0.17	0.52	-
Total	99.06	-	98.51	-	99.39	-	97.50	-	99.30	-	94.72	-
An	74.75	64.35–83.24	69.17	51.91–85.2	Fo 84.65	80.96–86.57	87.19	85.94–88.06	Wo 49.25	45.49–51.07	-	-
Ab	25.04	16.67–35.21	30.44	14.71–47.68	Fa 15.34	13.43–19.04	12.81	11.94–14.06	En 32.16	24.84–36.98	-	-
Or	0.22	0.1–0.5	0.39	0.1–0.93	-	-	-	-	Fs 18.59	13.57–24.10	-	-

n.d. not detected.

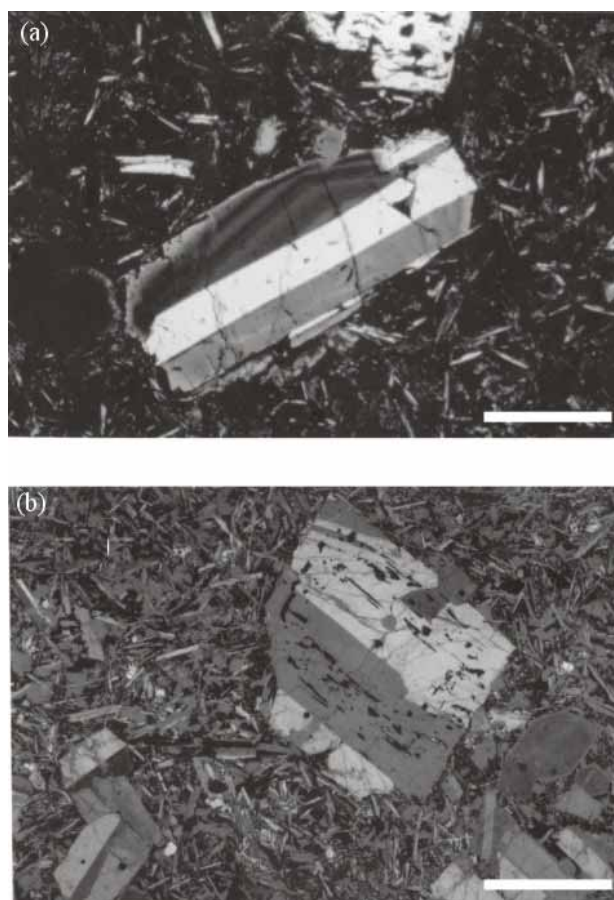


Fig. 2. Photomicrographs of NCIR basalts.

(a) Plagioclase phenocryst: One half showing twinning while the other half is zoned (VT 4/2, crossed nicols, objective 5×). Scale bar 0.4 mm. (b) Stringlet of melt inclusions showing cleavage-parallel orientation (VM 3B, crossed nicols, objective 2×). Scale bar 1 mm.

other common occurrence of plagioclase is as thin slender crystals, which because of their extreme development show acicular form that radiates from a common center, giving rise to spherulitic structures. The olivine phenocrysts occur most commonly as euhedral to rare subhedral equally sized grains, which are almost colorless and rarely show zoning. In a few cases, olivine shows alteration along the inherent fracture to reddish-brown iddingsite. Amphiboles occur in the VT as well as in VM basalts but only as poorly-pleochroic subhedral grains closely associated with clinopyroxene.

The interstitial glasses in the groundmass have locally altered to brown-colored chloropheite and also show devitrification. Opaques of variable shape present in the groundmass are mainly titanomagnetite (ΣFeO ~46–71 wt % and TiO_2 ~13–23 wt%, Table 2). These also occur as inclusions within plagioclase phenocrysts and the glassy groundmass. Semicircular or irregular-shaped vesicles are present in the groundmass, but are generally unfilled with the exception of marginal rim-like infillings in a few samples.

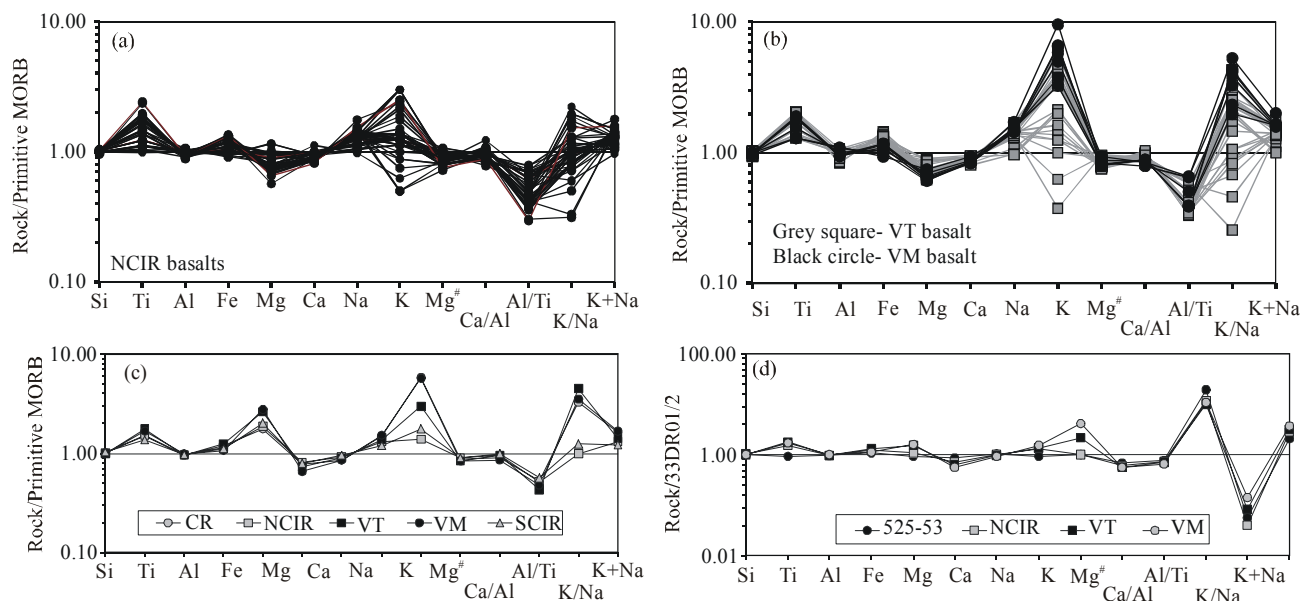


Fig. 3 (a) Primitive MORB normalized spiderdiagram for major oxides and some ratios of NCIR basalts from the literature.

Average primitive MORB composition after Presnall and Hoover, 1987. The abbreviated parameters along the abscissa represent respective oxides and their ratios.

(b) The same diagram for VT- and VM- basalts.

(c) The same for average CR, NCIR, SCIR, VT- and VM- basalts (Table 4).

(d) Primitive NCIR basalt (33 DR 01/2) normalized spiderdiagram showing variation between a primitive MORB sample (525-53, after Presnall and Hoover, 1987), average NCIR, VT-, VM basalts.

3 Geochemistry

3.1 Analytical techniques

Around 50–70 g of fresh, cleanly washed, dry chips of each basalt sample (~17 nos) of NCIR were pulverized to fine rock powder by a tungsten-carbide ring mill installed on board the ORV Sagar Kanya and at the Presidency College, Kolkata, India. The glass samples (4 nos), chipped from the surface of the VT pillow basalts were also powdered and ~10–15 g obtained. The major element analyses of the NCIR samples including basalt (7 nos) and glassy basalts (4 nos) were carried out by x-ray fluorescence spectrometer (XRF) at the Open University, U.K. (ARL 8420+) and IIT, Kharagpur, India (Philips PW 2404), on fused and pressed pellets.

All the trace elements including REE (Sc, V, Cr, Co, Ni, Cu, Zn, Ga, Rb, Sr, Y, Zr, Nb, Cs, Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Hf, Pb, Th and U) were determined on the same sample powders by inductively coupled plasma-mass spectrometry (ICP-MS, model ELAN DRC II, Perkin Elmer Sciex Instruments, USA) at the National Geophysical Research Institute, Hyderabad, India, following the procedure of Balaram et al. (1999). Two runs were carried out at JB-2 standard in the initial and final stages of the analyses of the 21 newly-collected NCIR basalts. All the elements with atomic number between Sc and Ba show a precision better than 4.5

% and those between La and U are have a precision better than 7.5%.

3.2 Major and Trace element geochemistry

The representative whole-rock chemical analyses (major, trace and REE) of the NCIR basalts from the VT and VM areas are presented in Table 3. Samples from VT 4 and VT 5 show low LOI (loss on ignition) between ~0.12 and 0.5 wt%, while the seamount basalts (VM 9DG) have relatively higher LOI values between ~0.63 and 1.27 wt%. The average major oxide compositions of the VT basalts and glasses as well as those of the VM basalts are compared with those of the NCIR basalts, adjacent CR and SCIR basalts (data collected from the literature) and primitive MORB compositions (after Presnall and Hoover, 1987), shown in Table 4.

In the major oxide spider diagram normalized against primitive MORB (average composition after Presnall and Hoover, 1987), the NCIR basalts from the literature show maximum variations of K_2O and K_2O/Na_2O ratios both in the positive and negative sense (Fig. 3a). This is followed by a positive variation of TiO_2 and Na_2O and a negative variation of Al_2O_3/TiO_2 . Subordinate positive variations of ΣFeO and CaO/Al_2O_3 , and positive as well as negative variations of MgO are also noted, though the negative variation for MgO is more pronounced. Minor variations are also observed for Al_2O_3 and CaO .

The basalt samples from the VT and VM areas show

Table 3 Representative major and trace element analyses of NCIR basalt samples (For sample locations see Fig. 1.)

	VT 4/2	VT 4/3	VT 4/4	VT 4/5	VT 4/N1*	VT 4/N2*	VT 5/6A3	VT 5/6A4	VT 5/6B	VM 7A	VM 1B	VM 4A	VM 4B	VM 5B	VM 6A	WS-E and OUG9 **	MO 12 and W2	JB 2
Major (wt%)																		
SiO ₂	49.52	50.10	49.33	48.91	50.11	49.16	49.99	49.96	50.01	52.17	49.25	49.83	49.08	49.50	47.27	±1	±5	
TiO ₂	1.66	1.73	1.14	1.65	1.22	1.17	1.34	1.52	1.55	1.84	1.66	1.15	1.38	1.69	1.15	±1	±5	
Al ₂ O ₃	15.32	16.02	16.43	15.57	16.82	16.18	16.37	15.03	15.17	15.31	15.97	17.93	16.41	15.72	17.64	±1	±5	
ΣFeO	10.01	10.36	8.56	10.62	8.56	8.66	8.88	9.68	9.74	8.34	9.54	7.62	8.51	9.56	8.17	±1	±5	
MnO	0.16	0.16	0.16	0.25	0.14	0.14	0.37	0.17	0.16	0.25	0.19	0.14	0.18	0.18	0.51	±1	±5	
MgO	6.26	6.79	8.61	6.33	9.06	8.39	7.57	6.92	7.08	7.63	6.35	7.48	7.00	6.61	6.07	±1	±5	
CaO	10.94	11.22	11.51	10.94	11.72	11.47	11.50	11.02	10.95	10.49	10.31	11.48	10.74	10.53	10.59	±1	±5	
Na ₂ O	2.72	2.91	2.86	2.81	2.92	2.73	3.01	3.18	3.18	2.92	3.12	3.05	3.06	3.27	3.63	±1	±5	
K ₂ O	0.47	0.17	0.10	0.37	0.03	0.05	0.27	0.33	0.26	0.35	0.52	0.47	0.40	0.26	0.77	±1	±5	
P ₂ O ₅	0.16	0.17	0.09	0.18	0.09	0.08	0.14	0.19	0.18	0.19	0.21	0.18	0.19	0.21	0.25	±1	±5	
LOI	n.d.	n.d.	n.d.	0.38	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.88	0.72	0.63	0.95	1.27	±1	±5	
Total	97.22	99.66	98.79	98.01	100.67	98.03	99.44	98	98.28	99.49	97.35	100.05	97.58	98.48	97.32			
Mg*	0.53	0.54	0.64	0.52	0.65	0.63	0.60	0.56	0.57	0.59	0.54	0.64	0.60	0.55	0.57			
Na ₂ O+K ₂ O	3.19	3.08	2.96	3.18	2.95	2.78	3.28	3.51	3.44	3.27	3.64	3.52	3.46	3.53	4.40			
K ₂ O/Na ₂ O	0.17	0.06	0.03	0.13	0.01	0.02	0.09	0.10	0.08	0.12	0.17	0.15	0.13	0.08	0.21			
CaO/Al ₂ O ₃	0.71	0.70	0.70	0.70	0.70	0.71	0.70	0.73	0.72	0.66	0.67	0.64	0.65	0.67	0.60			
Al ₂ O ₃ /TiO ₂	9.23	9.26	14.41	9.44	13.79	13.83	12.22	9.89	9.79	8.7	9.21	15.58	11.87	9.30	15.35			
Trace (ppm)																		
Sc	37.92	38.30	36.23	37.85	36.06	36.42	37.38	37.10	36.80	37.56	35.91	31.60	32.89	36.12	32.16			+0.05/-2
V	301.12	309.06	247.96	302.51	247.93	253.04	275.03	276.98	280.35	302.31	295.71	235.86	265.93	302.1	251.99			+0.05/-2
Cr	235.46	231.9	329.18	234.39	332.34	329.23	331.06	293.10	302.24	225.52	215.43	238.18	222.93	217.81	191.27			+0.05/-3
Co	69.04	95.07	68.76	60.58	78.47	126.51	58.96	71.32	60.39	140.02	133.65	102.66	134.69	112	217.07			+0.05/-2
Ni	97.83	87.19	139.13	96.87	137.62	134.64	100.54	107.36	110.41	83.20	70.03	104.04	90.35	71.09	133.17			+0.05/-2
Cu	77.49	78.83	89.25	103.53	89.74	90.07	84.06	78.30	81.28	77.5	65.22	80.61	79.94	69.36	122.86			+0.05/-2
Zn	127.9	133.7	112.94	131.60	96.08	99.84	111.67	122.13	125.17	139.03	145.33	89.82	111.29	131.32	97.74			+0.05/-2
Ga	17.61	17.52	15.67	17.05	16.11	16.57	17.08	17.77	17.45	18.57	16.77	13.13	15.65	16.79	16.62			+0.05/-2
Rb	10.49	1.98	1.60	7.53	0.53	1.03	3.57	5.88	5.32	5.24	9.66	6.27	5.85	3.45	21.22			+0.05/-2
Sr	118.45	121.13	112.22	127.60	107.21	108.99	158.55	148.30	140.43	134.46	136.2	160.55	146.01	136.75	227.52			+0.05/-2
Y	44.58	45.04	29.99	44.22	29.38	30.63	34.07	41.94	42.31	42.49	42.07	26.7	34.28	43.19	29.95			+0.05/-2
Zr	132.60	134.94	80.75	134.63	78.38	81.24	109.49	140.9	143.09	146.35	135.95	88.88	116.43	140.97	114.43			+0.05/-2
Nb	2.97	3.06	1.31	3.11	1.29	1.62	3.53	4.08	4.26	6.13	5.76	6.14	5.63	5.59	12.06			-4/-7
Cs	0.67	0.04	0.03	0.42	0.01	0.05	0.17	0.43	0.38	0.08	0.48	0.15	0.13	0.12	1.22			-2
Ba	23.84	27.29	16.89	30.91	9.98	13.64	31.56	35.36	36.26	45.93	43.71	79.5	67.13	45.65	173.57			-1
La	4.43	4.47	2.48	5.59	2.07	2.24	4.64	5.21	6.01	5.46	6.19	4.38	5.27	6.21	11.65			±5

(Continued)

	VT 4/2	VT 4/3	VT 4/4	VT 4/5	VT 4/N1*	VT 4/N2*	VT 5/6A3	VT 5/6A4	VT 5/6B	VM 7A	VM 1B	VM 4A	VM 4B	VM 5B	VM 6A	WS-E and OUG9 **	MO 12 and W2	JB 2
Ce	13.98	14.80	8.28	16.86	7.31	7.68	13.18	15.8	17.01	15.84	17.22	11.23	14.84	16.69	27.39		±5	
Pr	2.04	2.06	1.27	2.23	1.13	1.20	1.79	2.21	2.36	2.17	2.34	1.45	1.93	2.37	2.63		±5	
Nd	13.53	14.07	8.61	14.44	8.26	8.72	11.91	14.99	15.69	14.40	14.9	9.39	12.25	15.11	15.4		±5	
Sm	4.38	4.46	2.94	4.52	2.78	2.94	3.62	4.44	4.56	4.28	4.51	2.73	3.72	4.65	3.83		±5	
Eu	1.5	1.57	1.14	1.58	1.11	1.12	1.38	1.57	1.67	1.52	1.53	1.05	1.34	1.56	1.36		±5	
Gd	6.38	6.56	4.32	6.57	4.15	4.30	5.19	6.33	6.45	6.14	6.39	3.97	5.32	6.56	5.25		±5	
Tb	1.17	1.19	0.79	1.21	0.77	0.80	0.92	1.14	1.16	1.12	1.16	0.70	0.95	1.17	0.88		±5	
Dy	6.75	6.91	4.6	6.86	4.48	4.68	5.36	6.44	6.56	6.42	6.58	4.02	5.47	6.74	4.83		±5	
Ho	1.46	1.5	1.01	1.50	0.96	1.02	1.14	1.38	1.42	1.37	1.44	0.88	1.19	0.46	1.02		±5	
Er	4.68	4.74	3.17	4.76	3.07	3.22	3.58	4.37	4.46	4.37	4.5	2.8	3.69	4.61	3.21		±5	
Tm	0.78	0.8	0.52	0.79	0.52	0.55	0.61	0.76	0.78	0.74	0.76	0.48	0.61	0.75	0.56		±5	
Yb	4.22	4.24	2.84	4.18	2.86	3.02	3.27	4.07	4.08	4.01	3.99	2.55	3.34	4.16	2.95		±5	
La	0.66	0.68	0.45	0.67	0.42	0.45	0.49	0.59	0.61	0.60	0.64	0.38	0.53	0.65	0.44		±5	
Hf	3.19	3.23	2.02	3.22	1.93	1.95	2.56	3.26	3.31	3.34	3.27	2.06	n.d.	3.41	n.d.		±5	
U	0.10	0.09	0.14	0.15	0.05	0.06	0.12	0.13	0.18	0.12	0.14	0.11	0.13	0.15	0.4		±5	
(La/Sm) _h	0.63	0.63	0.53	0.77	0.46	0.48	0.80	0.73	0.82	0.80	0.86	1.0	0.88	0.83	1.9		±5	
(Ce/Yb) _h	0.87	0.92	0.77	1.06	0.67	0.67	1.06	1.02	1.10	1.04	1.13	1.16	1.17	1.05	2.44		±5	
Total Fe calculated as ΣFeO; Mg ²⁺ mole [Mg/(Mg+Fe)]; * Glassy basalts; ** Accuracy in wt%.																		

similar type of major oxide spider diagrams but with some exceptions (Fig. 3b). Most of the samples show positive anomalies for K₂O and K₂O/Na₂O that are ~10 and ~6 times higher respectively than those in the primitive MORB. Negative variation is observed only for MgO. Major element compositions of the glassy basalts are similar to the holocrystalline basalts, except that the glassy basalts have relatively low K₂O values (0.03–0.05, Table 3).

The average NCIR, SCIR and CR basalts can be discriminated efficiently by their K₂O and K₂O/Na₂O ratios in the major oxide spider diagram (Fig. 3c), as these values progressively increase from NCIR (0.11, 0.04), through SCIR (0.14, 0.05) to CR basalts (0.47, 0.13). The VT and VM basalts are relatively enriched in these values compared to published NCIR data and are either intermediate between SCIR and CR basalts or similar to CR basalt in major element composition. The average NCIR, SCIR and CR basalts are very similar in SiO₂, Al₂O₃, ΣFeO, MgO, CaO, Mg[#], CaO/Al₂O₃ and Al₂O₃/TiO₂. Although some variations are noticed for TiO₂ and MnO, there is no systematic pattern. The average NCIR basalt, in general, has higher Na₂O and Na₂O+K₂O compared to those in the SCIR basalt, and the VM basalt in particular shows similar values to those of the CR basalt.

If Mg[#] is taken as a parameter to measure the evolution of the basaltic magmas, sample 33 DR 01/2 (SO 28 cruise report) can be considered as the least evolved member of the NCIR basalts (Table 4). In the major oxide spider diagram normalized vis-à-vis the most primitive NCIR sample (33 DR 01/2), the average NCIR, VT and VM basalts all represent evolved basaltic rock members (Fig. 3d).

The range in trace element enrichment in these samples is well illustrated in Fig. 4, where primitive mantle normalized (data from Sun and McDonough, 1989) patterns for selected samples are shown. The basalt samples collected from VT 4, VT 5 and VM 9DG locations characteristically exhibit differential variation in their trace element concentration, while variation for Rb is recorded at maximum. The variations for Rb are minimum in VT 5 basalts compared to adjacent VT 4 samples. The degree of large ion lithophile elemental (LIL) enrichment is the highest in VM 9DG followed by VT 5 and VT 4 samples. For the elements between Sr and Yb, the basalts from all three locations do not exhibit much variation. The most notable feature observed in the primitive normalized multi-element variation diagram is that many samples show an obvious negative Nb-anomaly (i.e. when normalized to primitive mantle values Nb appears to be more depleted compared to its adjacent elements on either side).

Table 4 Comparison of average major element compositions of NCIR basalts with other Indian Ocean Ridge Basalts (IORB)

	CR ^a		NCIR ^b		SCIR ^c		Primitive MORB ^d	
	Whole-rock and glass (literature)	Whole-rock and glass (literature)	VT glass and whole-rock	VM whole-rock	Least evolved member	Whole-rock and glass (literature)	Average composition	A primitive MORB composition 525-53 ²
Ni=	98	50	26	7	33 DR 01/2 ¹	137	48	48.96
SiO ₂	50.69 (0.82)	50.54 (0.85)	49.35 (1.45)	48.93 (0.84)	49.56	50.97 (0.19)	49.80 (1.19)	48.96
TiO ₂	1.32 (0.27)	1.36 (0.32)	1.56 (0.22)	1.48 (0.24)	0.88	1.22 (0.77)	0.89 (0.63)	0.82
Al ₂ O ₃	15.42 (0.63)	15.74 (0.67)	15.58 (0.95)	16.24 (1.13)	16.14	15.90 (0.50)	16.28 (0.96)	15.75
ΣFeO	9.79 (1.58)	9.36 (0.98)	10.11 (0.93)	8.81 (0.74)	7.72	8.98 (0.02)	8.18 (0.59)	8.44
MnO	0.14 (0.04)	0.15 (0.02)	0.21 (0.09)	0.22 (0.13)	0.14	0.16 (0.58)	0.08 (0.07)	0.13
MgO	7.80 (1.04)	8.17 (1.24)	7.43 (0.84)	6.58 (0.50)	11.59	7.93 (0.64)	10.03 (1.21)	9.79
CaO	10.53 (1.42)	11.36 (0.73)	11.16 (0.42)	10.60 (0.43)	11.53	11.87 (0.27)	12.33 (0.80)	11.92
Na ₂ O	3.16 (0.81)	2.74 (0.32)	2.87 (0.33)	3.20 (0.21)	2.13	2.52 (0.12)	2.11 (0.32)	1.97
K ₂ O	0.47 (0.44)	0.11 (0.05)	0.24 (0.13)	0.46 (0.17)	0.11	0.14 (0.05)	0.08 (0.08)	0.11
P ₂ O ₅	0.14 (0.04)	0.11 (0.05)	0.15 (0.03)	0.20 (0.02)	0.05	0.12 (0.03)		
Mg [#]	0.59 (0.05)	0.61 (0.05)	0.57 (0.04) ³	0.57 (0.03) ³	0.73	0.61 (0.04)	0.68 (0.02)	0.67
CaO/Al ₂ O ₃	0.68 (0.11)	0.72 (0.06)	0.72 (0.03)	0.65 (0.03)	0.71	0.75 (2.69)	0.76 (0.06)	0.76
Al ₂ O ₃ /TiO ₂	12.41 (3.90)	12.35 (3.30)	10.23 (2.05)	11.42 (2.92)	18.34	13.48 (0.35)	23.75 (25.26)	19.21
K ₂ O/Na ₂ O	0.13 (0.10)	0.04 (0.02)	0.08 (0.05)	0.14 (0.05)	0.05	0.05 (0.01)	0.04 (0.04)	0.06
K ₂ O+Na ₂ O	3.62 (1.21)	2.85 (0.33)	3.11 (0.38)	3.67 (0.33)	2.24	2.66 (0.04)	2.19 (0.34)	2.08

^a Data sources: [Hekinian, 1968, Banerjee and Iyer, 1991, Rehkamper and Hofmann, 1997, Cann and Vine, 1967, Sun et al., 1979, Cohen, et al., 1980, Ito et al., 1987]; ^b [Wiseman, 1940, Engel and Fisher, 1975, Ito et al., 1987, Plüger et al., 1988, Schiano et al., 1997, Rehkamper and Hofmann, 1997, David et al., 2000 and Melson et al., 2002] and present study; ^c [Engel and Fisher, 1975, Subbarao and Hedge, 1979, Michard et al., 1986, Herzog and Plüger, 1989, Natland, 1991, Plüger et al., 1988, Mahoney et al., 1989 and Mudholkar, 2001 and Melson et al., 2002]; ^d [Presnall and Hoover, 1987]

Mg[#] [magnesian number, mole Mg/ mole (Mg+Fe)] values, ¹ One of the primitive MORB compositions similar to the least evolved member of NCIR basalt (33 DR 01/2, SO 28 cruise report), ² Primitive MORB composition [from Presnall and Hoover, 1987]

³ Range of Mg[#] values for VT basalts- 0.51–0.65, for VM basalts- 0.54–0.64.

3.3 Major and trace element variation

The NCIR basalts as a whole are compared to the type-I, II and III Indian Ocean Ridge Basalts (IORB) as described by Natland (1991) in a TiO₂ versus a Na₂O plot (Fig. 5a). In general, these basalts are compositionally similar to the type-II IORB, with a gradation towards type-III. The bulk compositional variations of the VT and VM basalts along with those of other NCIR basalts gleaned from the literature are examined against Mg[#] in Fig. 5 (a–h). The Mg[#] is chosen as a reference parameter because it shows a wide variation in range from 0.73 to 0.49 and is widely used to examine bulk compositional variation of basaltic rocks. In the major oxide binary diagram, SiO₂ shows practically no variation with decreasing Mg[#]. A near horizontal or slightly increased trend is also observed for MnO whereas Al₂O₃ and CaO contents show a narrow but systematic decrease (within ~2–3 wt%) for all the samples with decreasing Mg[#] (Fig. 5c, d and e). TiO₂, Na₂O and P₂O₅, on the other hand, show gently increasing trends with decreasing Mg[#] (Fig. 5b, f and g). These oxides have increased by ~1, 1.5 and 0.20 wt% respectively, with decrease in Mg[#] from ~0.73 to 0.49. In contrast, K₂O shows a slightly increasing trend with decreasing Mg[#] (Fig. 5h). The VT and VM basalts roughly follow the same pattern, although they have much higher values of K₂O, up to 0.8 wt% at lower Mg[#] between ~0.55 and 0.50 (Fig. 5h).

An examination of major oxide variation diagrams shows that three geochemical parameters, i.e., Mg[#], TiO₂ and P₂O₅, vary systematically in the NCIR basalts and they can be used as references to examine the variations of trace element compositions of these rocks in bivariate plots. Among the transitional group of elements, Cr and Ni decrease with decreasing Mg[#] (Fig. 6a and b). In the Mg[#] versus Cr plot, the NCIR basalts, however, only show two distinct sub-parallel trends for VM and VT samples. The VM basalts show a much gentler decreasing trend for Cr than that of the VT basalt with decreasing Mg[#]. In the Mg[#] versus Ni plot the variation of Ni is the same both at higher and at lower Mg[#] (Fig. 6a). The HFS elements Y and Zr show similar increasing trends with decreasing Mg[#], though absolute contents of these elements in the NCIR basalts are different (Fig. 6e and f).

The CI carbonaceous chondrite normalized (after McDonough and Sun, 1995) REE spider diagrams of NCIR basalts are plotted in Fig. 7. The spider diagrams for the VT 4, VT 5 and VM 9DG basalts show flat REE patterns except for the VT 4 samples, which show a minor depletion in LREE (La, Ce, Pr) (Fig. 7a). The REE abundances of these basalts are in general ~20 to

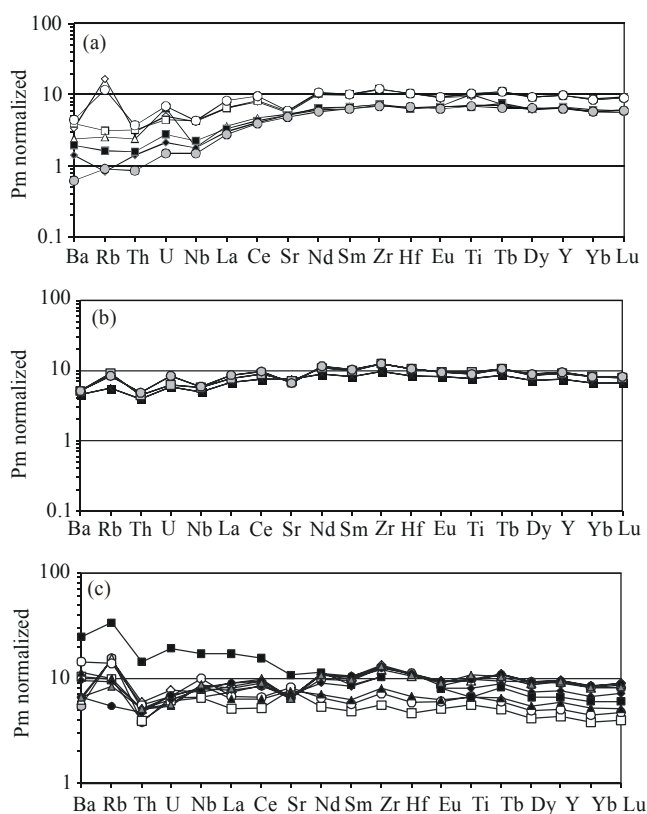


Fig. 4. Primitive mantle normalized trace element abundance patterns in MORB from NCIR.

Panel a, b and c represent the VT 4, VT 5 and VM 9DG samples. Normalizing values from Sun and McDonough, 1989.

30 times higher than the average carbonaceous chondrites (McDonough and Sun, 1995). The $(\text{Ce/Yb})_n$ values for the VT 4 samples vary between 0.67 and 1.06, those for VT 5 samples between 1.0 and 1.08, and for the VM 9DG samples mostly between 1.02 and 1.10. The $(\text{La/Sm})_n$ and $(\text{Gd/Yb})_n$ values for the VT 4, VT 5 and VM 9DG samples vary between 0.46–0.77 and 1.15–1.27, 0.73 – 0.82 and 1.26–1.28, 0.78–1.9 and 1.24–1.44, respectively. Sample 6A of VM 9DG shows highest values for $(\text{Ce/Yb})_n$ (2.44) and $(\text{La/Sm})_n$ (1.9).

The NCIR basalts can further be grouped into three distinct types depending on their REE abundances: (a) basalts having highest REE (~66–72 ppm) (Group-I); (b) an intermediate basalt type having REE between ~45–60 ppm (Group-II); and (c) basalts having lowest REE abundances (~36–42 ppm) (Group-III). Amongst these, the Group-I basalt is most dominant (7 samples) followed by Group-III (5) and Group-II (3) basalts, respectively. The VT 4 basalts contain a Group I–Group III combination, whereas VT 5 samples represent Group I and Group II REE only (Fig. 7a and b). All the spectrum including the three REE groups of basalts are present in the near ridge seamount VM 9DG samples (Fig. 7c). One of the VM samples (# 6A), however,

contains very high La and Ce, otherwise it belongs to Group II REE basalt.

The interrelationship of these three REE groups of basalt is examined in $\text{Mg}^\#$, TiO_2 and P_2O_5 versus total REE (ΣREE) plots (Fig. 7d–f). In all of these plots the ΣREE shows linear increase either with decreasing $\text{Mg}^\#$ or increasing TiO_2 and P_2O_5 . In REE character, the NCIR basalts also show a gradational nature between type-II and type-III IORB of Natland (1991) (Fig. 7e).

3.4 Identification of igneous process(es)

Whether the NCIR magma has undergone significant fractional crystallization after its generation from the mantle source by partial melting is an important aspect of its petrogenesis. In major oxide variation diagrams (Fig. 5), Mg/Fe ratios of the NCIR basalts show a large variation ($\text{Mg}^\# \sim 0.73$ to 0.49) among their bulk constituents due to crystal fractionation. The variations of other major oxides, e.g. SiO_2 (~6 wt%), Al_2O_3 (~4 wt%), CaO (~2 wt%) and Na_2O (~2 wt%) are limited in extent (Fig. 3a). Fractionation causes the maximum variation of minor oxides in TiO_2 (~1 wt%), followed by K_2O (~0.20 wt%) and P_2O_5 (~0.20 wt%). Ni among the transition group of elements shows maximum variation (~150 ppm), followed by Cr (~125 ppm) and Co (~100 ppm) (Fig. 6). Two distinct subparallel trends for Cr with $\text{Mg}^\#$ probably suggest two different fractional crystallization trends in NCIR basalts. Of the incompatible trace elements Zr shows maximum variation (~80 ppm), followed by Sr (~50 ppm) and Y (~25 ppm) (Fig. 6). The nearly flat REE pattern [$(\text{Ce/Yb})_n = 0.67\text{--}1.37$] of the NCIR basalts (Fig. 7) suggests that these trace elements did not suffer any major fractionation during fractional crystallization of the NCIR parent magma, except for a progressive enrichment during fractionation (Fig. 7 d, e and f).

3.5 Composition of parental magma of NCIR basalts

It has been noted that the NCIR basalts show mixed incompatible trace element characters. Incompatible element ratios are highly variable in nature, extending from the values typical of depleted (N-type) MORB, e.g. $\text{Zr/Nb} > 30$, $(\text{La/Sm})_n < 1$, to values characteristic of geochemically enriched (E-type) MORB, e.g. $\text{Zr/Nb} < 16$, $(\text{La/Sm})_n > 1$ (Schilling, 1975, Sun et al., 1979, Roex et al., 1983). Transitional type (T-type) MORBs are classified as those rocks that have intermediate incompatible trace element characters. The VM and VT basalts with $\text{Zr/Nb} = 9.5\text{--}61$, $\text{Zr/Y} = 2.7\text{--}3.8$, $\text{Y/Nb} = 2.5\text{--}23$ and $\text{K/Ti} = 0.03\text{--}0.74$ dominate in three locations of the present study area and could be classified as N-type to T-type MORBs. In the chondrite normalized REE spider diagrams, the mixed magma character of the NCIR basalts is also clearly

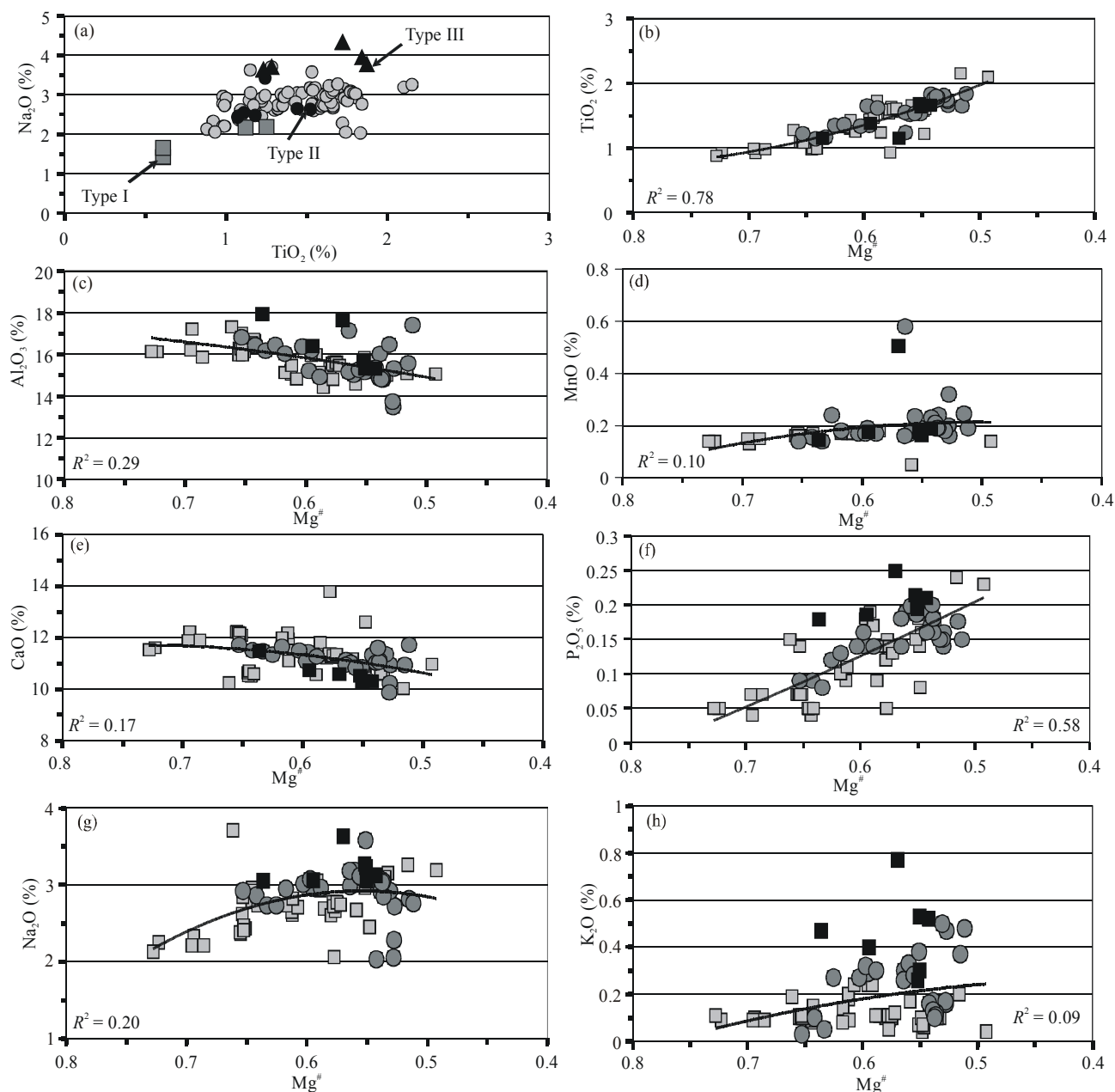


Fig. 5. (a) NCIR basalts in TiO_2 versus Na_2O plot, data as referred to in Table 4 and the present study.

Type I, II, III Indian Ocean Ridge basalts (Natland, 1991).

(b–h) Magnesian number ($\text{Mg}^\#$) versus major oxide plots of NCIR basalts.

Grey square – NCIR data from literature; solid grey circle – VT basalts; Solid black square – VM basalts (data from Table 4).

depicted (Fig. 7). The marginally depleted LREE character of the VT 4 basalt is similar to N-MORB, whereas no depletion or marginally enriched LREE pattern of the VT 5 and VM 9DG basalts reflect E-MORB character (cf. Sun and McDonough, 1989; Thompson et al., 1986).

Incompatible element ratios describe remarkably good mutual correlations in all samples analyzed confirming the compositional variability within the present study area is controlled largely by mixing between geochemically depleted and enriched end-member components. An Nb negative anomaly in many samples is clearly evident,

suggesting the asthenospheric mantle beneath the NCIR is depleted to Nb compared to normal MORB mantle. The present observations, therefore, suggest that the NCIR basalts, in general, evolved by fractional crystallization of a parent magma that showed mixed characters, either enriched with incompatible trace elements (e.g. Ba and Rb) or similar to depleted normal MORB. The differences in the incompatible trace elements including REE suggest comparable differences in their primary compositional characteristics. However, the parent magma for the VM basalts seems to be more fertile than that of the VT basalts.

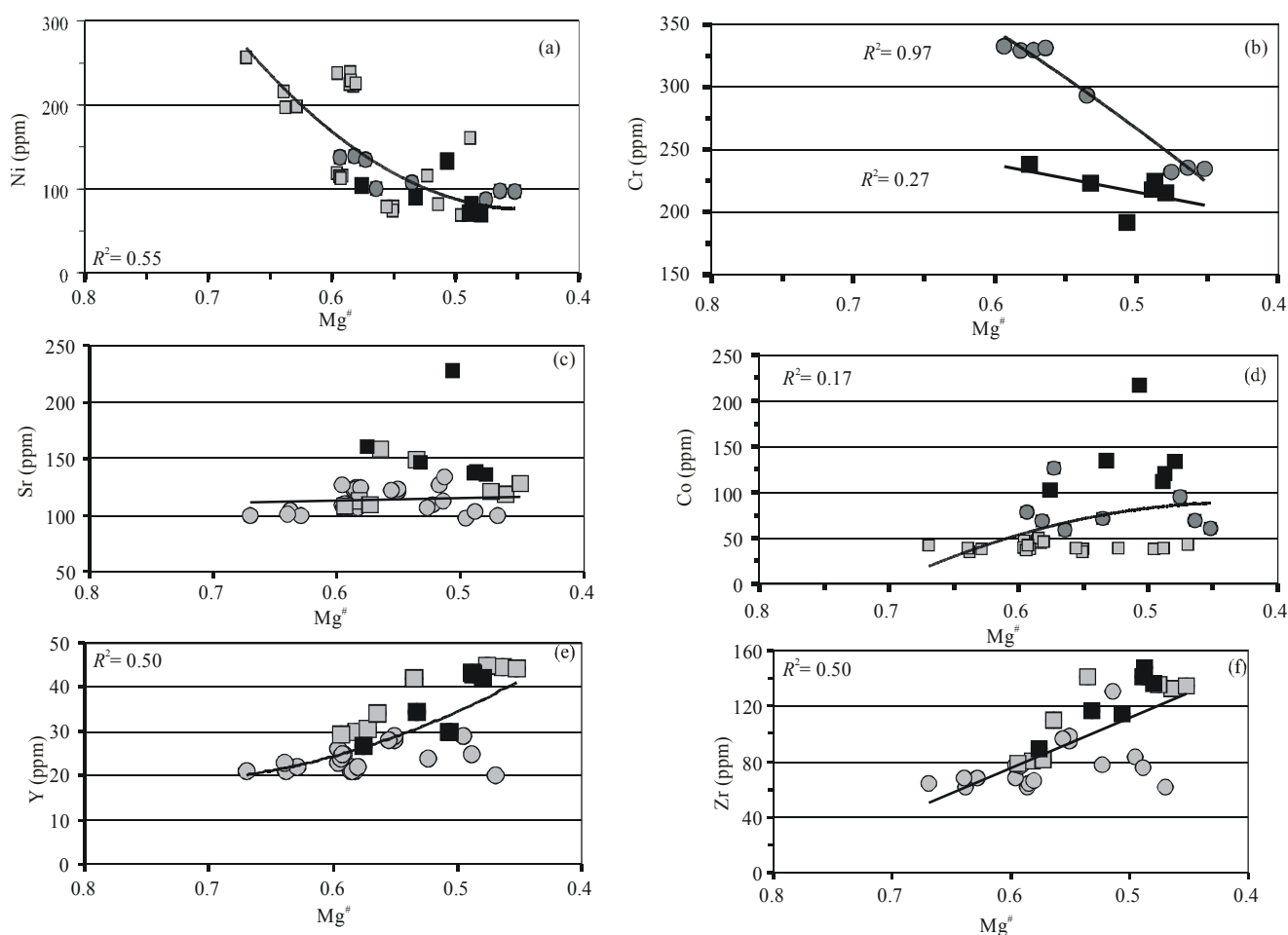


Fig. 6. Plots of some selected trace elements against magnesian number ($Mg^\#$). Symbols as in Fig. 5.

3.6 Physical conditions of magma generation

Among the 83 major oxide analyses of the NCIR basalt (Table 4), 6 % display $Mg^\#$ between 0.69 and 0.73. The presence of megacrystic plagioclase as porphyries within these high $Mg^\#$ basalts (SO 28 cruise report; Pluger et al., 1988) suggests that they are not cumulate phases produced during fractionation of the original parent magma, but represent primary MORB ($Mg^\# > 0.68$), were generated by partial melting of mantle peridotite and did not suffer any significant change in composition after its segregation from the mantle source (Hess, 1992). Among the five primitive magma compositions of the NCIR samples, 33 DR 01/2 is the most primitive member ($Mg^\# = 0.73$) and it is compositionally similar to one of the primitive ocean floor basalts of Presnall and Hoover (1987; Table 4, Fig. 3d).

A plot of the five primitive NCIR basalts in the normative olivine-diopside-silica diagram projected from the plagioclase apex (after Walker et al., 1979, Fig. 8) shows that three of them are plotted very close to the 1 GPa ternary eutectic, while the others plot a little way from this

eutectic and display a close affinity towards the 1.5 GPa ternary eutectic. However, a pressure of primary NCIR magma generation > 1 GPa is unrealistic because most of the primitive members of the NCIR basalts contain plagioclase phenocrysts, a mineral phase that is stable only at pressure ≤ 1 GPa (Yoder and Tilley, 1962). Therefore, these two samples along with other three samples form a cluster around the 1 GPa ternary eutectic.

Most of the evolved NCIR basalts, having $Mg^\# < 0.68$, plot on a linear trend, which is parallel to the 1 GPa cotectic line with decreasing temperature but is skewed towards the diopside end (Fig. 8). This indicates that the evolved NCIR basalts were crystallized at < 1 GPa pressure. The direction of the liquid line of descent towards the olivine-diopside join indicates that their crystallization pressure should be greater than 0.5 GPa (Hess, 1992). Therefore, the pressure of crystallization of the NCIR basalts was between 1 and 0.5 GPa. The NCIR basalts do not contain any primary amphibole in their mineralogy, which indicates low H_2O content of the peridotite source.

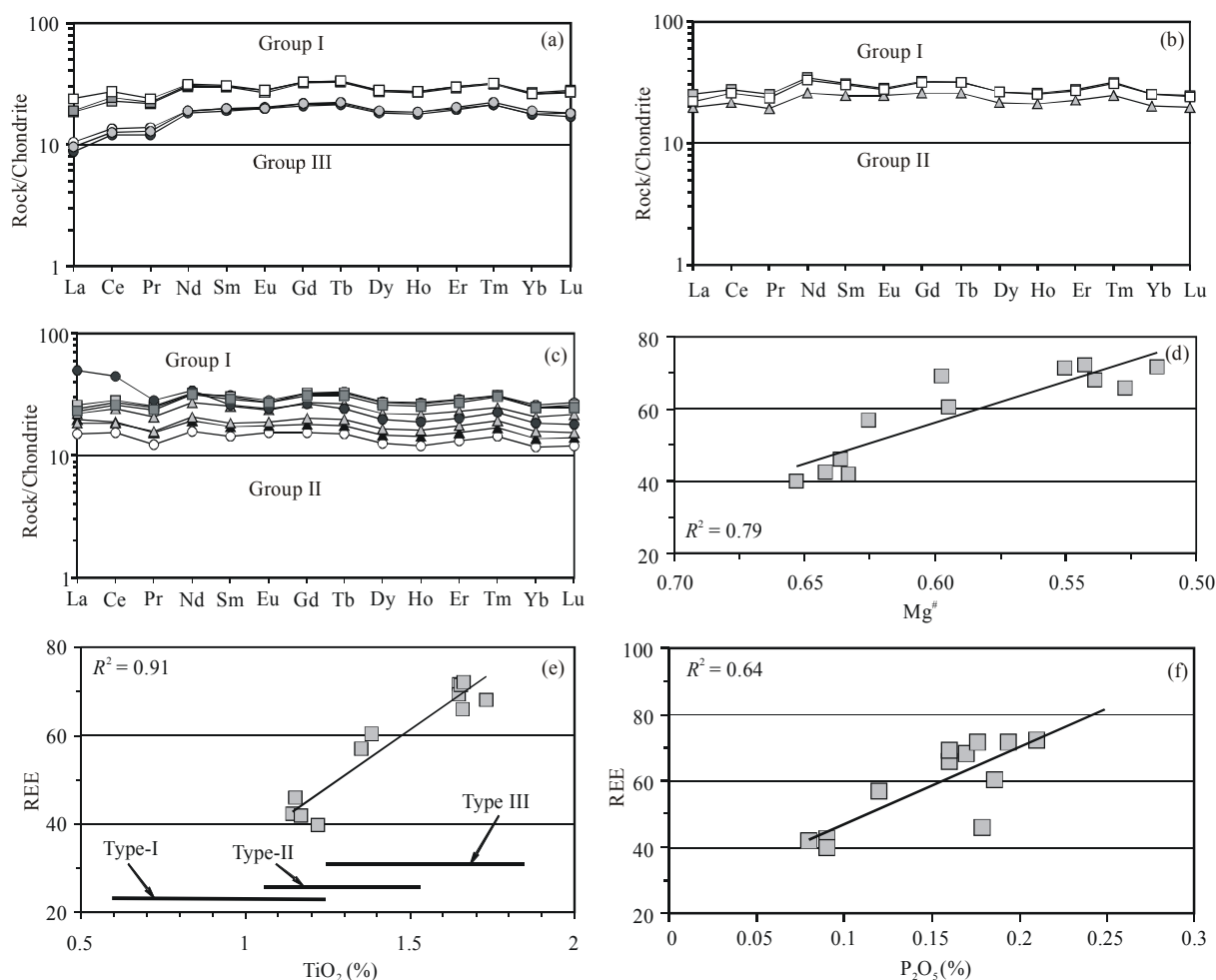


Fig. 7a–c. CI carbonaceous chondrite normalized (after McDonough and Sun, 1995) REE plots of NCIR basalts, a, b and c represent the VT 4, VT 5 and VM 9DG samples respectively.

Fig. 7d–f represent the binary plots of total REE vs $Mg^{\#}$, TiO_2 and P_2O_5 , bars in figure (e) represent variations in TiO_2 contents of Type-I, II, III Indian Ocean basalts, after Natland (1991). Solid grey squares in Fig. 7d–f represent the present dataset of NCIR basalt.

4 Discussion of Petrogenesis of NCIR Basalt

The NCIR basalts between 3° and 11° S are olivine tholeiites (predominance of only normative olivine; mean ~ 10.5 , range ~ 0 – 22%) and the poor presence of normative quartz (0.02 , 0 – 1.5%), which are similar to type-II IORB of Natland (1991) grading to type-III in composition. Thus, the NCIR basalts are T-MORB in nature and appear to have been generated by partial melting of enriched mantle peridotite. In addition, published isotope data from the CIR show an increase in the $^{87}Sr/^{86}Sr$ ratio (0.7031 to 0.7034) along with a decrease in ϵ_{Nd} ($+7.0$ to $+7.9$), accompanied by enrichment in incompatible elements (Murton et al., 2005; Nauret et al., 2006), and these findings also corroborate our geochemical observations.

A few NCIR basalts ($n=5$) show porphyritic texture (presence of megacrysts of plagioclase and clinopyroxene not as cumulate phases generated by fractionation of the

parent magma; Pluger et al., 1988) and have $Mg^{\#} > 0.68$, suggesting their primary MORB nature. In the Di-Ol-Qz ternary plot (after Walker et al., 1979; Hess, 1992) of primitive NCIR basalts it is observed that they were generated at a pressure ~ 1 GPa (Fig. 8) while the bulk of the fractionated basalts were crystallized within a pressure range of ~ 1 to 0.5 GPa.

During fractionation, the NCIR magma was systematically depleted in MgO and enriched in ΣFeO , TiO_2 , P_2O_5 and Na_2O (Fig. 5). There was, however, a very limited gradual depletion in Al_2O_3 and CaO and less systematic enrichment in K_2O . Among the trace elements, the NCIR basalts are progressively enriched in Y and Zr and to some extent in Sr and depleted in Ni and Cr during fractionation (Fig. 6).

The phenocryst population of the NCIR basalt consists of three silicate mineral phases, i.e. mostly calcic plagioclase ($An_{62-90} \leq 19$ vol %), less abundant forsteritic olivine

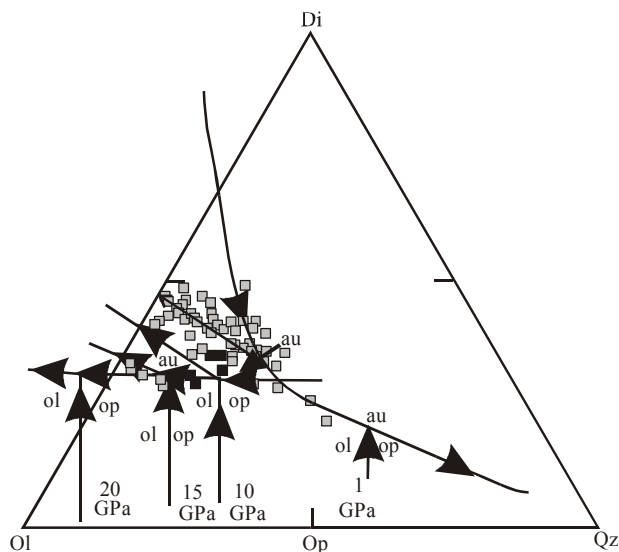


Fig. 8. Plot of the NCIR primary basalts in a normative Ol-Di-Qz diagram projected from the plagioclase apex (after Walker et al., 1979).

Solid square – NCIR primary basalt. Solid grey square – fractionated basalt, for data source see Table 4. ol – olivine, au – augite, opx – orthopyroxene.

(Fo_{81-88} , 0.04–1.69 vol%), and very rare diopside (≤ 0.05 vol%). One or all of these phenocrystic minerals might be the dominant phase(s) in the cumulate assemblage during fractionation of its parent magma. It is understood that major withdrawal of calcic plagioclase phenocryst in the cumulate phase would make the residual liquid relatively depleted in Al_2O_3 , CaO and Na_2O and enriched in TiO_2 , ΣFeO , MnO , MgO and K_2O , while SiO_2 would remain unchanged. If it is only clinopyroxene, the residual liquid would be depleted mostly in TiO_2 and CaO , and enriched in Al_2O_3 , Na_2O and partly in K_2O , while SiO_2 , ΣFeO and MgO would not change in proportions due to fractionation. In the present scenario, among the evolved NCIR basalts, none of the above chemical signatures are reflected. Thus, it is apparently clear that calcic plagioclase or diopside phenocrysts could not be the dominating cumulate phases in these rocks.

In the NCIR basalts, Sr shows an enrichment trend with decreasing $\text{Mg}^\#$ (Fig. 6c). Plagioclase feldspar could be a potential source for Sr (Partition coefficient, K_{Sr} for plagioclase in basaltic liquid is 1.83; cf. Rollinson, 1993). Fractionation of plagioclase from the crystallizing liquid, therefore, would make the residual liquid depleted in Sr. Hence the observed higher enrichment trend of Sr also rules out the possibility of plagioclase being a dominating cumulate phase during fractionation of the NCIR mother magma.

A similar explanation can also be substantiated by the REE pattern of the NCIR basalt (Fig. 7). If plagioclase is the dominating cumulate phase, the evolved NCIR basalt should show a negative Eu anomaly due to major

withdrawal of Eu from the melt by plagioclase. The fractionated REE pattern [i.e. $(\text{La/Yb})_n > 1$] might also have resulted if there was a major withdrawal of HREE by clinopyroxene cumulates during fractionation (Rollinson, 1993). However, none of these REE patterns are shown by the NCIR basalts (Fig. 7) and hence, the probability of early crystallization of calcic plagioclase or diopside as major cumulate phases from the parent NCIR melt is ruled out. Furthermore, a flat HREE $(\text{Gd/Yb})_n$ pattern of the NCIR basalts also eliminates the possibility of major crystallization of HREE bearing other major mafic silicates (e.g. orthopyroxene, garnet, cf. Rollinson, 1993) from the NCIR parent magma.

Therefore, withdrawal of olivine as a major cumulate phase from the NCIR parent magma is the best remaining possibility, which would make the residual liquid relatively enriched in ΣFeO over MgO . Major withdrawal of olivine would additionally make the residual liquid enriched in TiO_2 , Na_2O and K_2O , and marginally in SiO_2 , a pattern that is, in fact, observed for the NCIR magma (Fig. 5). However, a disparity arises when considering olivine alone as the major cumulate phase withdrawn from the NCIR parent magma. Withdrawal of olivine would make the residual liquid relatively enriched in Al_2O_3 and CaO , which are not seen at all in the bulk compositions of the NCIR basalts (Fig. 6). The NCIR magma is marginally depleted in Al_2O_3 (~3 wt%) and CaO (~2 wt%) with decreasing $\text{Mg}^\#$ (Fig. 5).

On the other hand, although Rollinson (1993) reaffirmed that early withdrawal of olivine likely makes the residual liquid depleted mostly in Ni, Co and Mn and very little in Cr, the fractionating NCIR magma does not actually show this chemistry. Instead, the magma shows no change in MnO, strong depletion in Cr and Ni (Fig. 6). Therefore, early crystallization of only olivine from the NCIR parent magma as a cumulate does not satisfy the model. To model the major depletion of Mg, Ni and Cr in the evolved NCIR basalts (Fig. 6) along with its flat REE pattern (Fig. 7), we propose early crystallization of spinel from the NCIR parent magma during its first phase of fractional crystallization. As this mineral is a major source of Al_2O_3 , crystallization of spinel would make the residual NCIR magma depleted in Al_2O_3 . The trace elements, Cr and Ni, are also both withdrawn from the basaltic parent liquid in addition to Mg during early crystallization of spinel (K , Cr and Ni for spinel in basaltic liquid are 10 and 5, respectively, Cox et al., 1979, p. 334). When the ascending magma crossed the ~1 GPa pressure domain, spinel ceased to crystallize and olivine took its place. The crystallization of olivine made the residual liquid again enriched in Al_2O_3 and the marginally depleted slope for this oxide finally resulted for the NCIR magma (Fig. 5c). The crystallization of spinel and olivine does not incorporate any HREE during their crystallization (olivine, of course, incorporates

negligible proportion of HREE, cf. White, 1999, p. 281; Rollinson, 1993), and hence a flat REE pattern of the NCIR magma has resulted.

Although olivine withdraws a major proportion of Co, along with Ni and minor Mn, during its crystallization from basaltic magma, the NCIR magma does not show any depletion of this element during fractionation (Fig. 6d). As Co shows a replacement relationship with Mg in olivine structure (Mason, 1958), we propose that crystallization of the relatively Fe-rich olivine cumulates from the NCIR parent magma. In fact, our microprobe data shows that the olivine phenocrysts of the NCIR magma are relatively Fe-rich and they contain ~0.5 time Fe compared to that of Mg (Table 2). The Fe-rich olivine also incorporates some CaO (cf. Deer et al., 1992, Table 2) and hence, early crystallization of Fe-rich olivine from the NCIR parent magma made the residual liquid marginally depleted in CaO (Fig. 5e).

5 Conclusions

(1) The NCIR basalts from between 3° and 11° S latitude are enriched in highly incompatible elements, and can be classified as olivine basalts, which appear to have been generated from an enriched mantle peridotite.

(2) Comparison with experimental phase diagrams shows that the primitive NCIR MORB, having $Mg^\# > 0.68$, were generated by partial melting of mantle peridotite at a pressure of ~1 GPa.

(3) The parent NCIR magma was modified by fractional crystallization when spinel separated from the melt in the first phase at pressure >1 GPa and was followed by fractionation of Fe-rich olivine at pressure <1 GPa. The bulk of the NCIR daughter magma crystallized within a pressure range of ~1 to 0.5 GPa.

(4) Fractionation is the most likely process, which would have influenced the compositional characteristic of NCIR MORBs during their evolution. During fractionation, the magma was systematically depleted in MgO and enriched in ΣFeO , TiO_2 , P_2O_5 and Na_2O . There was, however, a very limited gradual depletion in Al_2O_3 and CaO, and enrichment in K_2O .

Among the trace elements, the NCIR basalts were depleted in Ni and Cr and progressively enriched in Y and Zr and to some extent in Sr during fractionation. Total REE of the NCIR magma increased with fractionation but there is no change in REE slope $(La/Yb)_n$, particularly that of HREE $(Gd/Yb)_n$, with progressive evolution of the NCIR basalt.

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