High-Ti type N-MORB parentage of basalts from the south Andaman ophiolite suite, India

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A complete dismembered sequence of ophiolite is well exposed in the south Andaman region that mainly comprises ultramafic cumulates, serpentinite mafic plutonic and dyke rocks, pillow lava, radiolarian chert, and plagiogranite. Pillow lavas of basaltic composition occupy a major part of the Andaman ophiolite suite (AOS). These basalts are well exposed all along the east coast of southern part of the south AOS. Although these basalts are altered due to low-grade metamorphism and late hydrothermal processes, their igneous textures are still preserved. These basalts are mostly either aphyric or phyric in nature. Aphyric type exhibits intersertal or variolitic textures, whereas phyric variety shows porphyritic or sub-ophitic textures. The content of alkalies and silica classify these basalts as sub-alkaline basalts and alkaline basalts. A few samples show basaltic andesite, trachy-basalt, or basanitic chemical composition. High-field strength element (HFSE) geochemistry suggests that studied basalt samples are probably derived from similar parental magmas. Al_2O_3/TiO_2 and CaO/TiO_2 ratios classify these basalts as high-Ti type basalt. On the basis of these ratios and many discriminant functions and diagrams, it is suggested that the studied basalts, associated with Andaman ophiolite suite, were derived from magma similar to N-MORB and emplaced in the mid-oceanic ridge tectonic setting.

1. Introduction

Ophiolites are considered to be masses of ancient oceanic crust and upper mantle thrusted over the edge of a continent and exposed at several places after erosion (Coleman 1977; Winter 2001). It is also well known that ophiolites play an important role in reconstruction of tectonic settings (Sun and Nesbitt 1978). Basalts are an important part of ophiolitic sequence, hence their study helps to understand several geological processes involved during the emplacement of ophiolites. Hamilton (1978) has shown that a number of Late Mesozoic ophiolite occurrences, including Andaman ophiolite suite (AOS), are known to occur at the outer arc ridge and inner volcanic arc, which are tectonically associated with the tectonic elements of Indonesian arc system (figure 1a). AOS falls at the northern end of the outer arc ridge.

The Andaman islands (figure 1b) comprise many ophiolitic exposures; recognized as Andaman ophiolite suite (AOS). A few workers have studied these ophiolites and reported several segmented members of AOS. This includes cumulates of ultramafics (serpentinite/dunite, harzburgite and spinel lherzolite), mafic rocks (gabbro, troctolite, mafic dykes, Fe-Ti enriched mafic rocks and pillow lavas), felsic rocks (plagiogranite, anorthosite and minor dacite/rhyolite), and sedimentaries (ribbon chert/radiolarian chert, limestone and shale) (Haldar 1984; Ray *et al* 1988; Vohra *et al* 1989; Ling *et al* 1996; Shastry *et al* 2001, 2002). For the present study, several basalt samples, exposed along the southern part of south Andaman island, have been collected. Ray *et al* (1988) have studied

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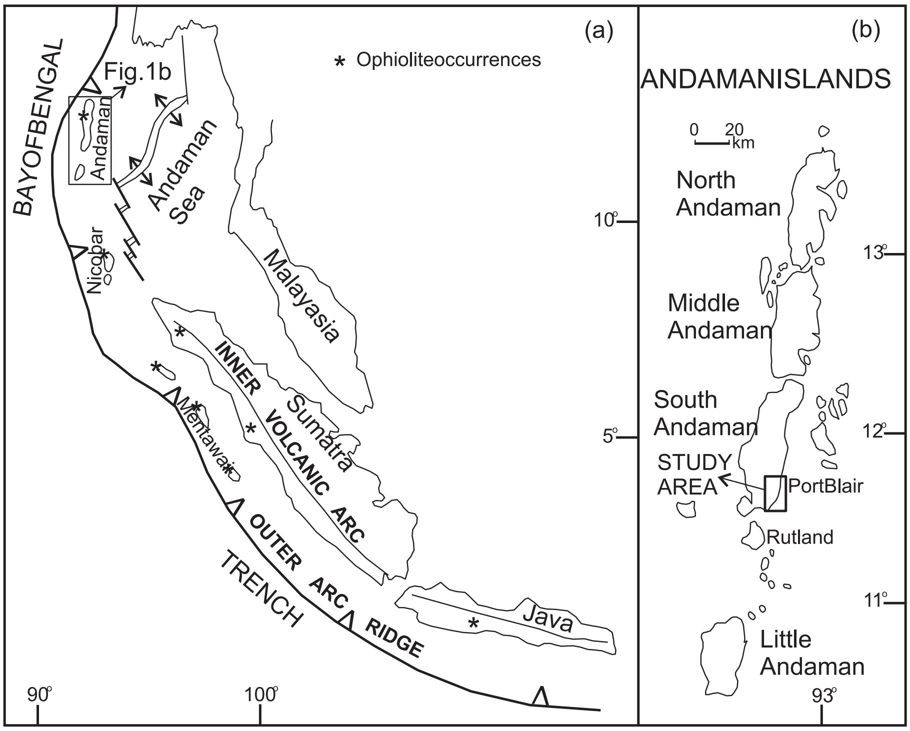

Figure 1. **(a)** Tectonic elements of Indonesian Arc system and their relation with Andaman Island (after Hamilton 1978). **(b)** Andaman Islands and location of study area.

these basalts (and other members of ophiolite) and suggested that they represent the marginal basin floor. These authors also suggested low-pressure fractionation of a basaltic magma in a shallow magma chamber as a possible explanation for the genesis of mafic volcanic rocks. The present paper provides new geochemical data on these basalts and in the light of these data their possible parentage is discussed.

2. Geological setting

Although ophiolite occurrences are reported from almost all the major Andaman islands, but are well-exposed in the south Andaman island (Haldar 1984; Ray *et al* 1988; Vohra *et al* 1989; Shastry *et al* 2001, 2002). As the present study is concentrated on the southern part of south Andaman, only geology of this portion is presented here (figure 2). Basalts are exposed all along the east coast of southern part of south Andaman. Noticeable exposures are encountered at Corbyn's cove, Rangachang, Bednabad, Kodiaghat, and Chiriyatapu (figure 2). For the present study, samples were collected from all these places. Most of the basalt exposures show pillow structure. These basaltic exposures also show effect of shearing and shattering. At many places they are intercalated by chert, shale, and marl and traversed by veins of calcite.

An elongated N-S trending mafic-ultramafic body is exposed within the basaltic exposures. This body consists of peridotite (mainly massive harzburgite), troctolite, and gabbro/olivine gabbro. As it is difficult to show these different mafic-ultramafic members on the map, these are classified as unclassified ophiolites. Basic dykes are also encountered at places, particularly near Rangachang. Sediments that mainly comprise ophiolite-derived material and pelagic material cover a major part of this region. All these rock types are surrounded by flysch material.

There is no radiometric age data available for any unit of the AOS, but on the basis of foraminifers collected from intercalated limestone, it is established that AOS was emplaced during the Middle to Upper Eocene time (Karunakaran *et al* 1968). Ling *et al* (1996) have recorded the Eocene (Middle) and Cretaceous (Campanian) radiolarian fauna from the basement rocks of the south Andaman islands and indicated the sedimentological hiatus that encompassed a part of the Palaeocene to early Eocene ages in these islands, and its extension northward to the Indo-Burma region and south to the outer islands of the Sunda arc.

3. Petrography

Under the polarizing microscope the studied basalt samples show two main varities: phyric and aphyric. Most of the basalt samples show

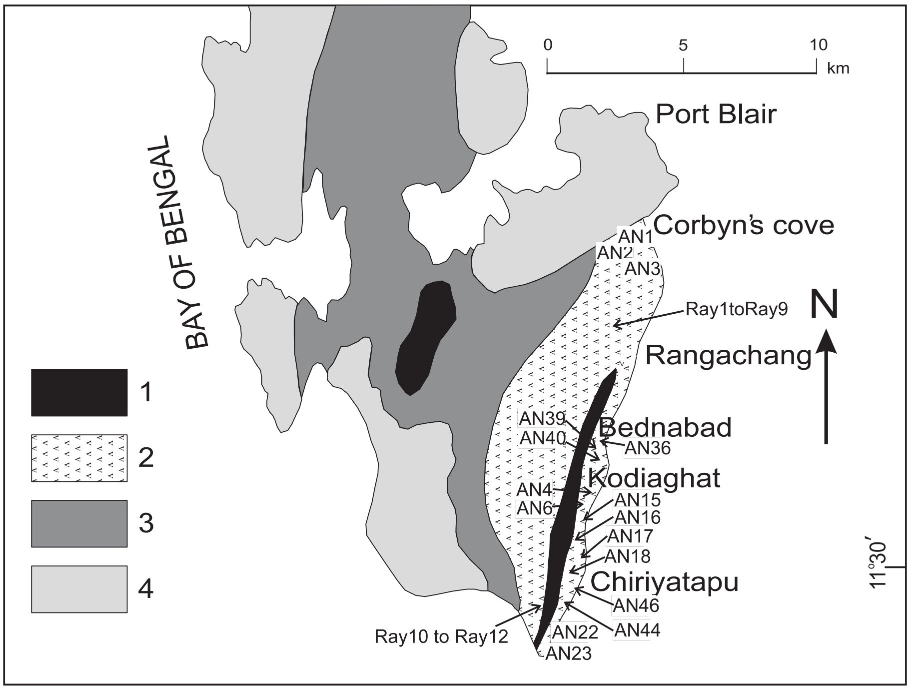

Figure 2. Geological map of southern part of south Andaman (modified after Ray *et al* 1988). **(1)** Unclassified ophiolite, **(2)** Basalts, **(3)** Olistostromal argillites and ophiolite-derived clastic sediments, and **(4)** Andaman flysch. Samples: AN1 to AN46 from present study; Ray1 to Ray12 from Ray *et al* (1988).

alteration due to low-grade metamorphism and late hydrothermal actions, but their igneous textures are still preserved and contain plagioclase (mostly albite; An < 10), chlorite, clinopyroxene, and minor epidote. Phyric variety (AN1, AN2, AN15, and AN23) has phenocrysts of plagioclase feldspar embedded in a fine-grained groundmass showing porphyritic texture. On the other hand, other samples are aphyric and do not have any phenocryst. Most of the aphyric varieties are fine-grained but some medium-grained samples (AN3, AN6, and AN40) are also present. These basalts are mainly composed of plagioclase, chlorite, and glass. Most aphyric basalts show intersertal texture but one or two samples (e.g., AN17) also show variolitic texture. Sub-ophitic texture is noticed in medium-grained basalt samples (AN6 and AN40). Amygdules, filled with calcite, are seen in a few thin sections.

4. Analytical techniques

It is very difficult to get fresh samples from the study area but all efforts were made to collect samples as fresh as possible. Fifty-one samples were collected from the basalt exposures. Sampling was mainly based on the map of Karunakaran *et al* (1968). Sixteen samples were selected to analyse their whole rock major and trace element concentrations (see table 1). Table 1 also contains standardised CIPW norms, Mg Numbers ($Mg\# = 100^{*}Mg^{2+}/Mg^{2+} + Fe^{2+}$), and rock-types for all samples, including samples presented by Ray *et al* (1988). All these calculations were automatically computed using the SINCLAS Computer Programme (Verma *et al* 2002).

All the samples were analysed at the Department of Earth Sciences, Memorial University of Newfoundland, Canada using an ARL 8420+ sequential wavelength-dispersive X-ray spectrometer. Major elements were determined on a fused disk. Two interactions of a LaChance-Trail matrix correction algorithm were applied after background and interference corrections were made to the gross count rate data. Trace elements were determined on pressed pellets using methods described by Longerich (1995). Precision and accuracy for major and trace element contents is better than 5% and 5–10% respectively for all elements above the limit of quantification. Several rock standards (such as SY-2, SY-3, PACS-1, AGV-1 and DTS-1) were run along with the Andaman samples to check the accuracy of the results. Recommended values and Newfoundland values for DTS-1 are presented in table 1 for reference. Loss on ignition (LOI), which represents total volatile content, was analysed at the Department of Geology, Banaras Hindu University, Varanasi by using the method described by Lechler and Desilets (1987).

Table 1. *Major oxides (wt%) and trace element (ppm) composition of mafic volcanic rocks associated to the south Andaman ophiolite suite.*

	AN1	AN2	AN3	AN4	AN6	AN15	AN16	AN17	AN18	AN22
Major oxides										
SiO_2	46.78	48.64	44.82	53.89	49.83	42.01	47.97	49.63	44.46	42.54
TiO_2	1.26	0.96	0.92	1.26	1.05	1.09	1.04	1.33	0.89	1.25
Al_2O_3	15.63	17.13	15.74	13.63	13.50	13.41	12.17	11.65	11.30	13.19
Fe_2O_3	10.09	9.18	8.63	11.16	10.53	10.03	12.82	12.47	9.13	12.73
MnO	0.17	0.16	0.13	0.22	0.20	0.15	0.16	0.19	0.15	0.18
MgO	6.23	7.67	6.38	6.41	7.88	7.16	8.15	8.62	10.47	4.37
CaO	11.60	10.35	10.42	4.23	5.93	12.83	5.90	7.39	17.65	10.40
Na_2O	2.60	3.87	2.95	4.70	3.71	2.65	4.17	3.94	0.36	5.19
K_2O	1.20	0.33	0.28	0.58	0.59	0.60	0.05	0.08	0.08	0.52
P_2O_5	0.12	0.07	0.09	0.26	0.20	0.08	0.11	0.13	0.10	0.52
LOI	3.89	1.33	8.11	3.44	5.89	8.96	6.46	3.88	4.61	8.90
Total	99.57	99.69	98.47	99.78	99.31	98.97	99.40	99.31	99.20	99.79
Mg#	59.07	66.14	63.34	59.10	65.31	62.53	61.53	63.49	72.83	46.34
Trace elements										
Cr	428	486	389	5	14	410	10	10	316	20
Ni	65	72	55	–	–	99	67	18	71	–
Sc	43	36	29	27	33	34	37	40	48	30
V	272	240	219	281	310	247	408	375	251	363
Rb	24	7	7	3	4	12	1	2	1	7
Ba	51	13	23	220	99	34	4	–	8	144
Sr	191	217	212	169	217	230	169	198	37	349
Ga	16	13	13	18	17	14	17	11	12	19
Nb	3.6	1.2	3.1	4.3	2.5	2.7	0.8	0.7	1.0	3.5
Zr	75	50	59	159	103	73	55	59	63	112
Y	28	23	21	34	23	25	20	24	18	29
CIPW norm										
Quartz				2.66						
Orthoclase	7.48	2.00	1.84	3.59	3.76	3.98	0.33	0.50	0.50	3.42
Albite	19.85	27.36	27.72	41.67	33.91	9.18	38.55	35.30	3.25	18.31
Anorthite	28.93	29.10	32.23	15.06	19.92	25.71	15.67	14.68	30.89	12.41
Nepheline	1.82	3.36	0.07			8.65				16.55
Diopside	25.32	18.71	20.20	4.20	8.48	36.76	12.67	18.88	49.70	34.26
Hypersthene				26.07	26.11		14.85	15.90	2.26	
Olivine	11.44	15.36	13.64		1.67	10.71	11.19	7.68	9.19	6.70
Magnetite	2.35	2.08	2.13	3.60	3.50	2.49	4.32	4.07	2.15	4.36
Ilmenite	2.52	1.87	1.95	2.51	2.15	2.32	2.16	2.67	1.80	2.64
Apatite	0.29	0.17	0.23	0.63	0.50	0.21	0.28	0.32	0.25	1.34
Al_2O_3/TiO_2	12.40	17.84	17.11	10.82	12.86	12.30	11.70	8.76	12.70	10.55
CaO/TiO_2	9.21	10.78	11.33	3.36	5.65	11.77	5.67	5.56	19.83	8.32
Rock name	AB	AB	AB	BA	BA	AB	BA	BA	SAB	BSN

(*to be continued*)

5. Geochemistry

The basalt samples from the south Andaman ophiolite suite (data from this study as well as from Ray *et al* 1988) were plotted in the IUGS recommended TAS diagram (figure 3a; Le Bas *et al* 1986; Le Maitre 2002). These data were adjusted on 100% anhydrous basis with Fe_2O_3/FeO calculated according to Middlemost (1989), using a computer programme SINCLAS (Verma *et al* 2002). The rocks are distinguished as alkaline and sub-alkaline varieties on the basis of normative minerals (see table 1) as suggested by Le Bas *et al* (1986) or Le Maitre (2002). Other divisions such as those by Irvine and Baragar (1971) or MacDonald and Katsura (1964) were not included here because of the considerable uncertainty that exists in such a classification scheme (see Sheth *et al* 2002 for more explanation).

The Andaman ophiolite samples are mainly basalts (20 samples), with some basaltic andesites (6 samples) and minor trachybasalt (1 sample) and basanite (1 sample), and are roughly equally divided into alkaline and sub-alkaline types. The variation of the Andaman basalt samples from alkaline to andesite is also observed on SiO_2 and Zr/TiO_2 classificatory diagram (figure 3b; Winchester and Floyd 1977).

Table 1. (*Continued*)

	AN23	AN36	AN39	AN40	AN44	AN46	Ray1	Ray2	Ray3	Ray4
Major oxides										
SiO_2	47.82	50.02	50.92	49.20	44.35	43.59	48.78	46.61	48.84	49.36
TiO_2	1.10	1.50	1.50	1.52	0.73	1.17	1.40	0.96	1.28	1.38
Al_2O_3	14.71	13.85	14.13	13.67	16.04	12.64	14.46	17.79	17.29	14.75
Fe_2O_3	11.95	14.18	14.16	14.53	9.62	13.11	10.35	9.42	10.78	10.61
MnO	0.17	0.18	0.29	0.27	0.16	0.20	–	–	–	–
MgO	5.00	7.48	8.88	8.82	11.29	8.81	8.14	4.94	5.35	8.72
CaO	9.25	4.97	6.97	6.50	10.91	9.01	9.18	9.20	8.28	10.20
Na_2O	5.36	3.23	2.18	2.26	2.15	2.55	3.41	3.32	3.39	2.81
K_2O	0.36	0.29	0.43	0.38	0.47	0.39	0.32	0.94	0.94	0.51
P_2O_5	0.20	0.19	0.22	0.22	0.09	0.22	–	–	–	–
LOI	3.11	3.38	1.03	1.99	3.39	7.88	3.78	5.52	5.08	2.02
Total	99.03	99.27	100.71	99.36	99.10	99.57	99.82	98.70	101.23	100.36
Mg#	51.28	57.03	59.45	58.66	73.29	61.10	64.77	55.07	53.71	65.77
Trace elements										
Cr	22	27	10	9	506	91	339	452	422	313
Ni	5	–	3	1	140	42	106	101	90	122
Sc	34	34	39	41	42	43	43	38	45	42
V	395	410	478	442	227	296	–	–	–	–
Rb	7	3	6	5	7	4	1.2	2.9	3.0	0.6
Ba	222	44	29	30	18	23	–	–	–	–
Sr	577	224	247	254	144	146	123	150	133	51
Ga	18	20	16	16	17	17	–	–	–	–
Nb	2.9	4.5	3.9	3.9	1.3	2.6	–	–	–	–
Zr	76	107	83	87	47	61	–	–	–	–
Y	23	26	24	23	22	35	–	–	–	–
CIPW norm										
Quartz		2.93	2.97	1.73						
Orthoclase	2.24	1.81	2.58	2.33	2.93	2.54	1.99	6.02	5.83	3.09
Albite	31.10	28.84	18.73	19.89	14.94	23.82	30.32	29.29	30.12	24.40
Anorthite	15.81	23.67	27.92	27.08	34.45	24.17	24.39	33.41	30.64	26.82
Nepheline	9.02				2.28			0.61		
Diopside	25.72	0.85	4.70	4.07	17.63	19.28	19.04	13.17	10.29	20.36
Hypersthene		33.82	36.51	38.02		3.58	7.35		9.59	10.42
Olivine	9.54				23.85	20.39	11.71	13.29	8.47	9.82
Magnetite	3.88	4.61	3.18	3.34	2.24	3.20	2.41	2.26	2.50	2.41
Ilmenite	2.20	3.01	2.89	3.00	1.46	2.45	2.79	1.97	2.55	2.69
Apatite	0.49	0.46	0.52	0.53	0.22	0.56				
Al_2O_3/TiO_2	13.37	9.23	9.42	8.99	21.97	10.80	10.33	18.53	13.51	10.69
CaO/TiO_2	8.41	3.31	4.65	4.20	14.95	7.70	6.56	9.58	6.47	7.39
Rock name	TB	BA	SAB	SAB	AB	SAB	SAB	AB	SAB	SAB

(*to be continued*)

It is observed from the field evidence as well as petrography that the studied basalts are altered either by low-grade metamorphism or late hydrothermal alterations. Under such conditions a few elements such as large ion lithophile (LIL) elements (Cs, Sr, K, Rb, Ba, etc.) may be mobile (Pearce and Cann 1971, 1973; Pearce 1983; Seewald and Seyfried 1990; Rollinson 1993) and these elements cannot represent melt concentrations. On the other hand, there are a few elements that are thought to be relatively immobile under medium grade metamorphic conditions, alteration, and sea-floor alteration (Pearce and Cann 1971, 1973; Winchester and Floyd 1976, 1977; Floyd and Winchester 1978; Verma 1992; Rollinson 1993; Jochum and Verma 1996). This group includes the high-field strength (HFS) elements viz., REE, Y, Sc, Zr (Hf), Ti, Nb (Ta), P, Th, etc. Considering these features, a variation diagram is presented to observe the geochemical characteristics of the studied basalts of AOS (figure 4). This diagram presents variation of a few major oxides and trace elements plotted against Mg number (Mg#). SiO_2, alkalies ($Na_2O + K_2O$), TiO_2, Y, Zr, and Ga increase with differentiation (i.e., with increasing Mg#), whereas Sr shows no change in concentration.

Following Verma (2004), statistical parameters for linear correlations between Mg# and different major or trace elements were also computed

Table 1. (*Continued*)

	Ray5	Ray6	Ray7	Ray8	Ray9	Ray10	Ray11	Ray12	A	B
Major oxides										
SiO_2	46.51	49.40	47.90	46.40	48.60	42.75	46.88	51.88	40.41 ± 0.47	39.48
TiO_2	1.68	1.42	1.22	1.20	1.30	1.18	1.58	0.87	0.005	0.01
Al_2O_3	13.85	16.80	16.00	15.90	16.50	13.72	15.49	14.13	0.19	0.22
Fe_2O_3	10.56	10.50	9.70	9.40	10.10	8.96	12.34	9.18	8.68 ± 0.24	9.27
MnO	–	–	–	–	–	–	–	–	0.12 ± 0.01	0.13
MgO	7.91	4.80	6.30	6.10	6.10	5.18	5.82	6.41	49.59 ± 0.33	49.58
CaO	10.22	9.00	10.90	12.10	10.00	13.61	8.79	9.69	0.17 ± 0.03	0.15
Na_2O	3.11	3.70	3.30	3.00	3.20	3.77	4.57	4.67	0.01	0.32
K_2O	0.87	0.75	0.36	0.45	0.69	–	0.01	0.21	0.001	0.04
P_2O_5	–	–	–	–	–	–	–	–	0.002	0.08
LOI	3.62	1.80	3.40	4.80	2.40	10.40	4.59	2.66		
Total	98.33	97.17	99.08	99.35	98.89	99.57	100.07	99.40		
Mg#	63.65	51.66	60.29	60.27	58.53	57.47	52.44	63.72		
Trace elements										
Cr	329	–	–	–	–	205	65	350	3990 ± 300	3990
Ni	109	–	–	–	–	78	36	91	2360 ± 170	2360
Sc	44	–	–	–	–	33	36	39	3.5 ± 0.3	2.7
V	–	–	–	–	–	–	–	–	11	11
Rb	2.0	–	–	–	–	1.1	1.1	1.6		
Ba	–	–	–	–	–	–	–	–		
Sr	131	–	–	–	–	148	139	210		
Ga	–	–	–	–	–	–	–	–		
Nb	–	–	–	–	–	–	–	–		
Zr	–	–	–	–	–	–	–	–		
Y	–	–	–	–	–	–	–	–		
CIPW norm										
Quartz										
Orthoclase	5.48	4.65	2.25	2.84	4.27		0.06	1.29		
Albite	23.49	32.79	28.88	22.12	28.31	13.17	32.78	40.35		
Anorthite	22.66	28.30	29.29	30.50	29.93	23.20	23.01	17.62		
Nepheline	2.47		0.31	2.68		12.41	4.42	0.37		
Diopside	25.47	15.24	22.63	27.37	17.96	43.54	19.11	26.23		
Hypersthene		6.07			4.63					
Olivine	14.54	7.70	11.96	9.84	9.99	2.89	14.55	9.49		
Magnetite	2.49	2.43	2.26	2.22	2.34	2.24	2.89	2.94		
Ilmenite	3.40	2.83	2.44	2.43	2.58	2.54	3.18	1.72		
Apatite										
Al_2O_3/TiO_2	8.24	11.83	13.11	13.25	12.69	11.63	9.80	16.24		
CaO/TiO_2	6.08	6.34	8.93	10.08	7.69	11.53	5.56	11.14		
Rock name	AB	SAB	AB	AB	SAB	AB	AB	BA		

AN1 to AN46: present study; **Ray1 to Ray12:** from Ray *et al* (1988); (–) not determined Rock Name: **AB** – Alkali basalt; **SAB** – Sub-alkaline basalt; **BA** – Basaltic andesite; **BSN** – Basanite; **TB** – Trachy basalt. **A** – Recommended values for USGS Geostandarad DTS-1 (Govindaraju 1994); **B** – Average of 12 analyses done at Memorial University of Newfoundland for DTS-1.

(table 2). Meaningful correlations (significant at 95% confidence level; $P_{c(r,n)} < 0.05$; table 2) with Mg# exist for only a few major oxides (TiO_2, FeO and total alkalis; note that for oxides not the original data but adjusted values were used). A significant correlation with FeO may also be due to the fact that this oxide enters in the definition of Mg#. However, there were significant correlations of Mg# with several trace elements (Ba, Cr, Ga, Nb, Ni, Sc, Sr, V, and Zr; table 2). The correlations were negative for most elements (except Cr and Ni for which positive correlations were observed), implying that the concentrations of most elements increased with decreasing Mg# (i.e., during differentiation). As expected, both the Cr and Ni, being highly compatible elements, show rapidly decreasing concentrations in evolved magmas, i.e., strongly positive correlations with Mg#. These observations suggest that studied basalt samples are genetically related to each other and probably derived from similar parental magmas.

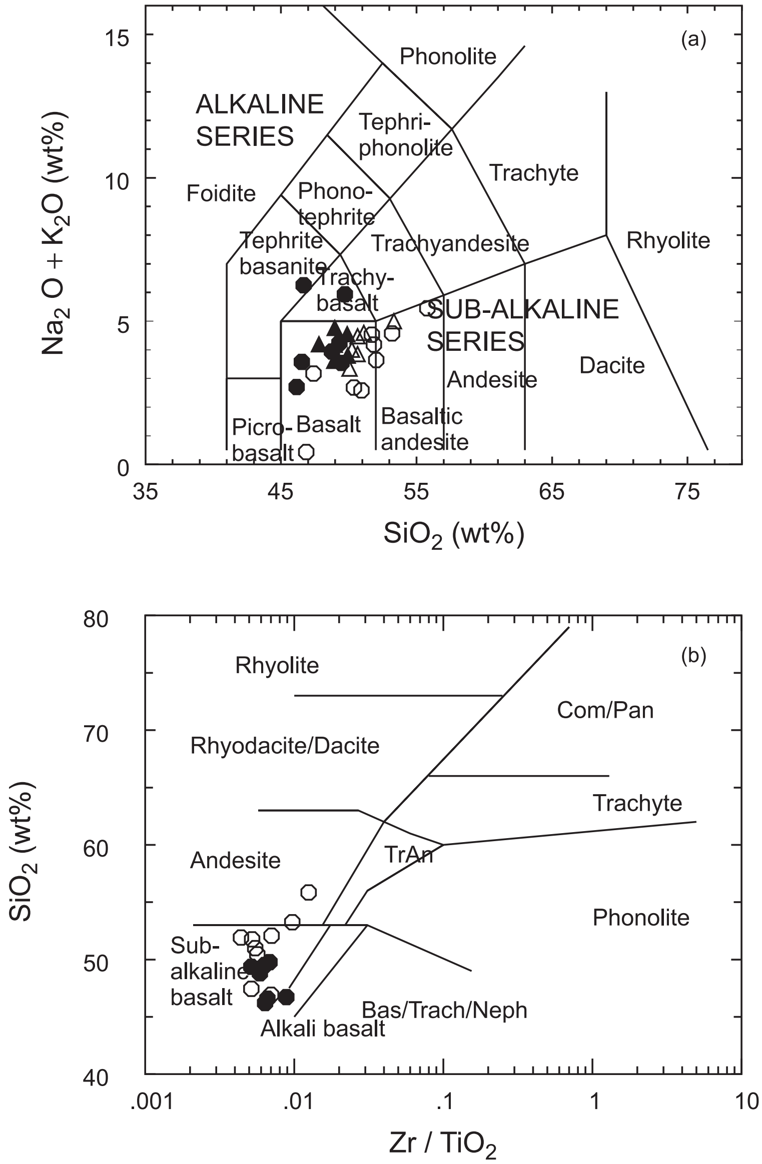

Figure 3. **(a)** Total-alkali and silica (TAS) diagram (after Le Maitre 2002). **(b)** Chemical classification scheme after Winchester and Floyd (1977). Symbols: Present work – Sub-alkaline basalts (open circles) and Alkaline basalts (filled circles); Ray *et al* (1988) – Sub-alkaline basalts (open triangles) and Alkaline basalts (filled triangles). Data are adjusted on 100% anhydrous basis.

Nb concentration of a few samples have lower concentration (< 2 ppm) than other samples (> 2 ppm), but samples with $Nb > 2$ show good differentiation trend. Probably other samples ($Nb < 2$) are locally contaminated. However, isotope data is required to prove this inference.

These observations are further perceived on MORB normalized multi-element plots (figure 5a). All LIL elements plotted on this diagram (Sr, K, Rb, and Ba) show a very wide range due to their mobility during alterations, whereas most of the HFS elements (Zr, Ti, Y, and Sc) have very limited variations. Most of the samples show lower concentration of HFSE than the MORB values but mostly LILE content is higher than the MORB values, probably suggesting that their parental melt has originated from a very depleted mantle source. The samples with high Mg# (AN18 and AN44: Mg# ~ 73), which probably show primitive composition amongst the studied samples, have lower concentration of HFSE. The wider concentration range of LILE as compared to HFSE may also be partly due to their different incompatibility (i.e., different mineral/melt partition coefficient values; Torres-Alvarado *et al* 2003). Similar to the variation diagram of Mg# versus Nb, here again Nb divides the samples into two groups, but no other element shows such discrimination.

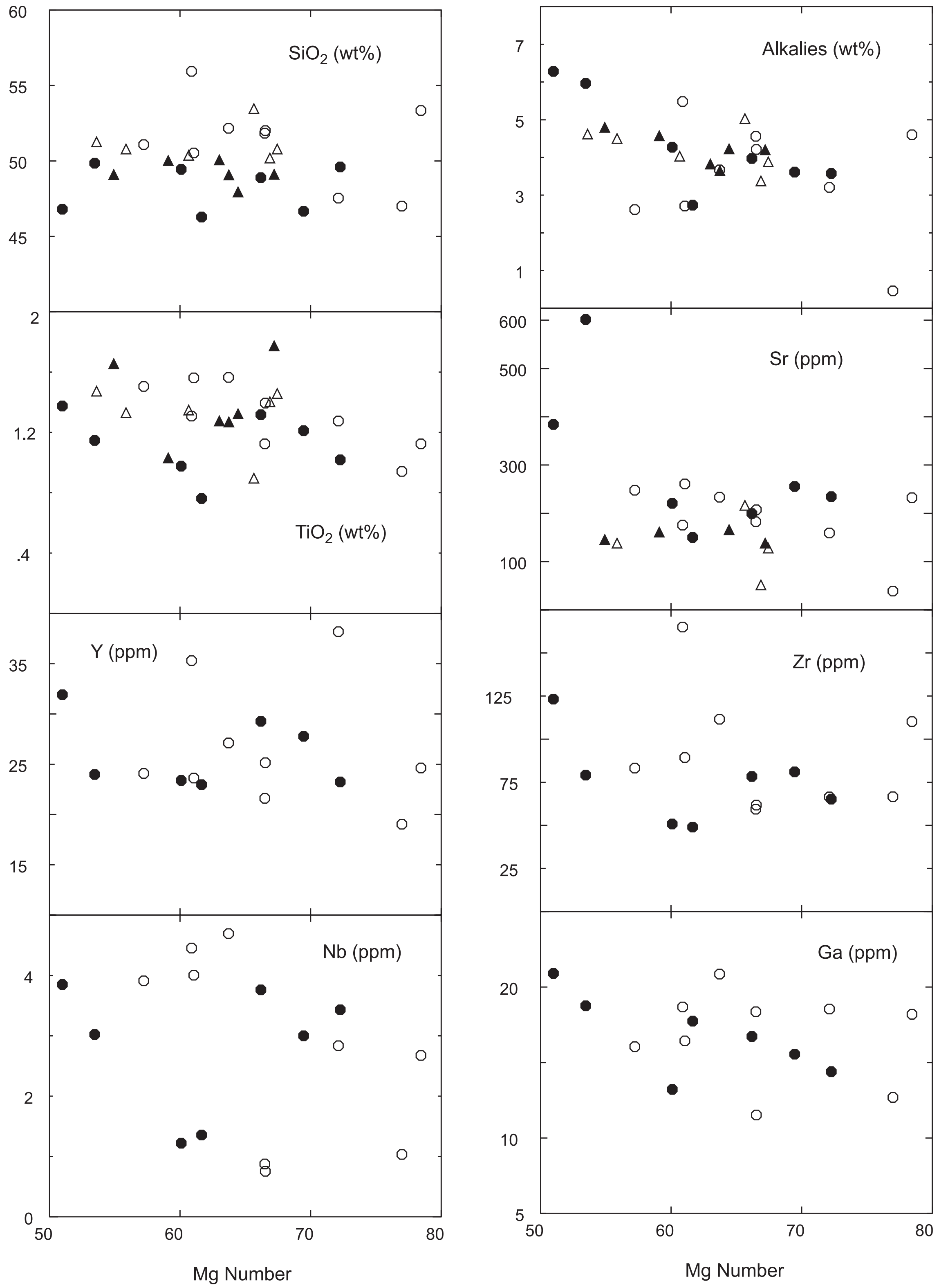

Figure 4. Variation diagram plotted between Mg# and a few major oxides and trace elements. Symbols as in figure 3. Ray *et al* (1988) samples do not have Y, Zr, Nb, and Ga.

On the basis of the present data, it is difficult to explain this observation but this may be because of some contamination with Nb depleted material.

6. Discussion

On the basis of petrological and geochemical data presented above, it is thought that basalts of the

Table 2. *Statistical data for linear correlations between Mg# and a major oxide or a trace element for Andaman ophiolite suite.*

Element	N	r	Slope ± 1s	$P_{c(r,n)}$
$(SiO_2)_{adj}$	28	0.1033	-0.04 ± 0.07	0.6010
$(TiO_2)_{adj}$	28	0.4657	-0.019 ± 0.007	**0.0125**
$(Al_2O_3)_{adj}$	28	0.2899	-0.08 ± 0.05	0.1345
$(Fe_2O_3)_{adj}$	28	0.3627	-0.032 ± 0.016	0.0578
$(FeO)_{adj}$	28	0.3886	-0.081 ± 0.038	**0.0410**
$(CaO)_{adj}$	28	0.2648	-0.13 ± 0.10	0.1732
$(Na_2O + K_2O)_{adj}$	28	0.6685	-0.125 ± 0.027	**0.0001**
$(P_2O_5)_{adj}$	28	0.2896	-0.0063 ± 0.0041	0.1350
Ba	15	0.5956	-6.3 ± 2.3	**0.0191**
Cr	24	0.4214	13 ± 6	**0.0403**
Ga	16	0.5743	-0.22 ± 0.08	**0.0200**
Nb	16	0.6164	-0.118 ± 0.040	**0.0110**
Ni	20	0.4733	3.3 ± 1.4	**0.0350**
Rb	24	0.0918	-0.073 ± 0.17	0.6695
Sc	24	0.4156	-0.36 ± 0.17	**0.0433**
Sr	24	0.5390	-8.9 ± 3.0	**0.0066**
V	16	0.5498	-6.8 ± 2.8	**0.0274**
Y	16	0.4473	-0.31 ± 0.16	0.0824
Zr	16	0.4500	2.15 ± 1.0	**0.0488**

Abbreviations are: **n** = number of data pairs available for the linear regression; **r** = correlation coefficient of the linear model; **Slope** = slope of the linear regression; **s** = standard deviation of the slope value; $\boldsymbol{P}_{c(r,n)}$ = the probability that the two variables are not correlated (statistically significant correlations at 95% confidence level are indicated by boldface numbers).

AOS are probably derived from similar parental magmas. As we have not presented rare earth element (REE) and isotopic data, it is difficult to establish genetic relationship between the samples; but Ray *et al* (1988) have presented REE data and suggested that these basalts from East Coast and tholeiitic pillow basalts are genetically connected. They have further stated that most of the Andaman basalts have La^N/Ce^N ratios higher than those of ocean ridge basalts. On this basis Ray *et al* (1988) concluded that the REE concentration observed in Andaman basalts show transitional nature between normal MORB and ocean-island tholeiites and they do not represent rocks erupted at transitional ridge segment. On the basis of new data presented in this communication, we now discuss the possible parentage of these basalt samples.

Ophiolitic complexes may be generated in different tectonic environments (Miyashiro 1973; Sun and Nesbitt 1978). Most of the ophiolite complexes are either oceanic or island arc origin (Church and Coish 1976). Geochemical data on the AOS basalts are compared with N-type MORB (Saunders and Tarney 1984), average MORB (Pearce 1983), and OIB (Sun 1980) (figure 5b). The AOS basalts show close similarities with MORB data rather than OIB, suggesting that these basalts are derived from MORB-type magma. MORB nature of these rocks is further corroborated on a few discrimination diagrams presented in figure 6. The Ti-Zr variations (figure 6a) can discriminate island-arc, MOR, and calc-alkaline basalts (Pearce and Cann 1973). On this diagram the AOS basalts fall in the MORB fields (fields B and D in the diagram). The other discrimination diagram that can successfully separate the MORB samples from the other basalt samples is based on Ti and V contents. The Ti and V variations in basalts are effectively used to discriminate volcanic-arc basalts, MORB, and alkali basalts (Shervais 1982; figure 6b). Most of the AOS basalt samples have Ti/V ratios between 20 and 50, which is characteristic of the MORB samples. The ocean-island and alkali basalt samples have Ti/V ratios > 50 and the island-arc tholeiite samples have a ratio < 20. Thus, on the basis of these discrimination diagrams, it is suggested that the AOS basalts are derived from N-type MORB magma and not from the island-arc type magma. These diagrams do not give any conclusive evi-

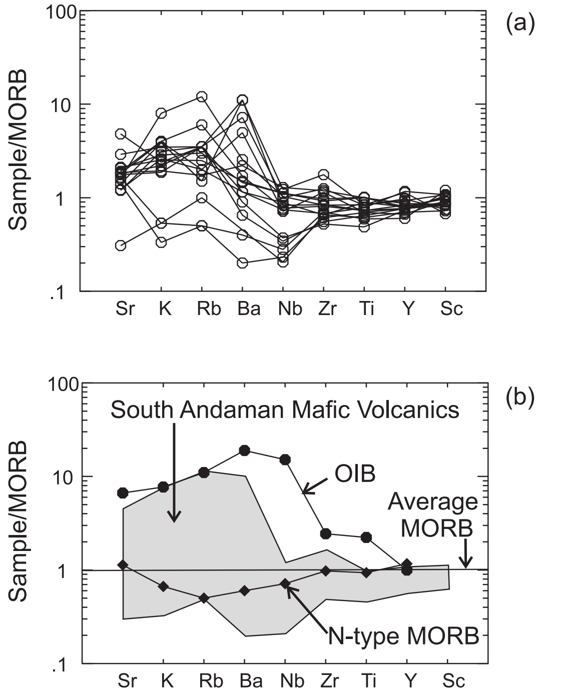

Figure 5. **(a)** MORB normalized multi-elements spidergrams. Normalized values are taken from Pearce (1983). **(b)** Comparison of AOS basalts with N-type MORB (Saunders and Tarney 1984), average MORB (Pearce 1983), and Oceanic Island basalts (OIB; Sun 1980). Only present samples plotted.

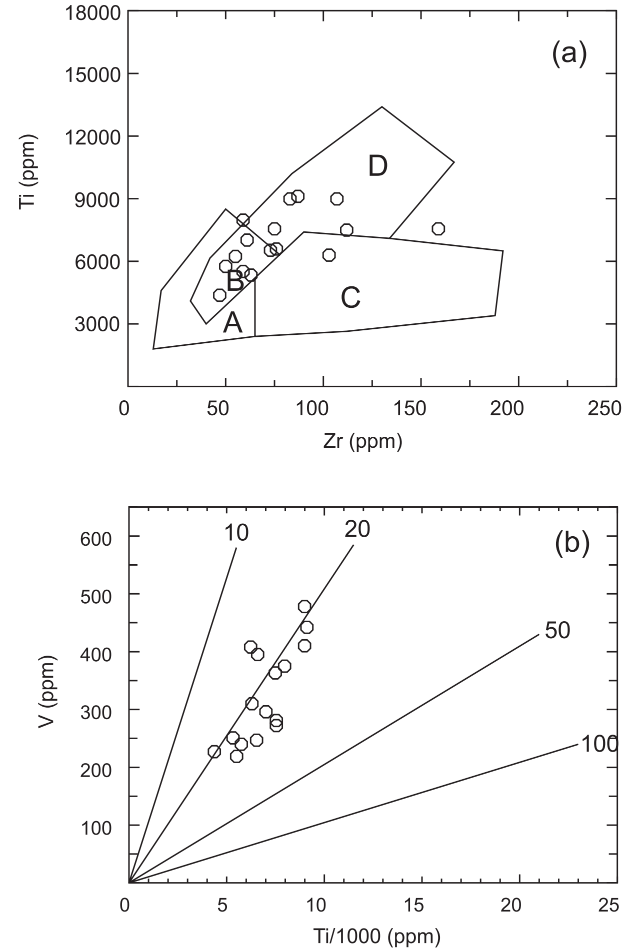

Figure 6. Discrimination diagrams to know emplacement environment of AOS basalts. **(a)** The Ti-Zr diagram (after Pearce and Cann 1973). Fields: A – island-arc tholeiites, B – MORB, C – Calc-alkaline basalts, and D – Overlapped by all the three types. **(b)** The Ti-V diagram (after Shervais 1982). MORB has Ti/V ratios between 20 and 50, Ocean-island and alkali basalt samples have Ti/V ratios > 50 and island-arc tholeiite samples have a ratio < 20. Only present samples plotted.

dence for tectonic setting but can provide some idea on this issue (for more detail see recent paper by Vasconcelos-F *et al* (2001). Thus, we decided to present some more discrimination diagrams.

Five discriminant function diagrams (figures 7 and 8) have been proposed very recently by Agrawal *et al* (2004), to discriminate four tectonic varieties of basic rocks. These diagrams are based on major elements only, but the concentrations must be adjusted to 100% on an anhydrous basis with the Fe_2O_3/FeO adjustments according to the Middlemost (1989) option of the SINCLAS programme (Verma *et al* 2002; see Verma *et al* 2003 for more details on these adjustments). The discriminant function equations based on the linear combinations of these major element concentrations are described in the original paper. The diagrams also give the percentage success rates that were obtained by the authors during the testing stage of their work. One diagram (figure 7) discriminates all the four tectonic settings, whereas the other four diagrams (figure 8a–d) work for three tectonic settings at a time. Although Agrawal *et al* (2004) pointed out that the three-field at a time discrimination (use of four separate diagrams) is somewhat better than the four-field classification diagram, they also suggested that all five diagrams should be applied to the data set from a given locality. If a high percentage of success for a particular tectonic setting is obtained, i.e., if 85% or more unknown samples fall in the field of the same tectonic setting in most of the diagrams, our confidence in the correct classification of the unknown will certainly increase manifold. Intermediate rocks are not recommended to be plotted on these diagrams.

In figure 7 for the Andaman basic rocks, 8 of the 13 alkaline samples are classified as MORB, 3 as IAB, and 1 each as CRB and OIB. For sub-alkaline rocks, this diagram gives 5 as MORB, 2 each as IAB and CRB, respectively. Thus, 13 samples (out of 22; $\sim 59\%$) are classified as MORB; 5 samples ($\sim 23\%$) as IAB; only 2 and 1 sample as CRB and OIB, respectively. Thus, although the percentage success rate is rather low ($\sim 59\%$), this diagram suggests a MORB setting as a possibility for the Andaman samples.

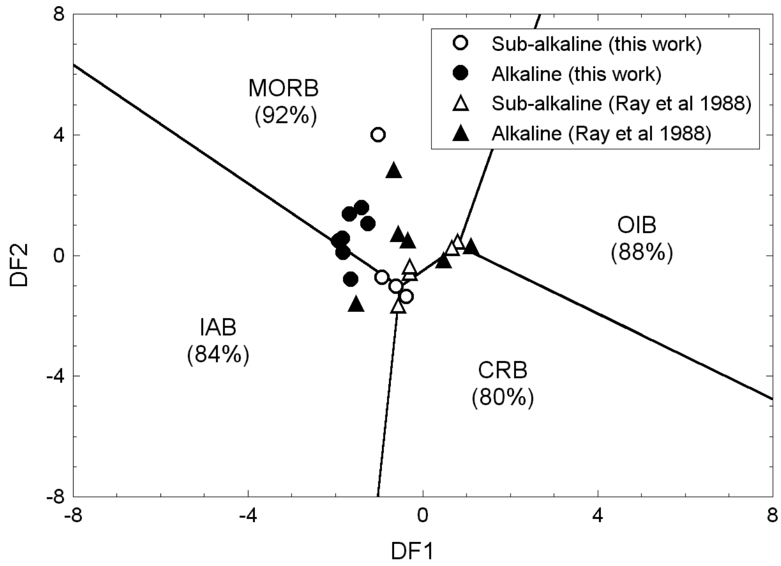

Figure 7. Discrimination diagram IAB-CRB-OIB-MORB displaying basic rocks from the Andaman ophiolite suite. The fields are: **IAB** = island arc basic rocks; **CRB** = continental rift basic rocks; **OIB** = Ocean island basic rocks; **MORB** = Mid-Ocean Ridge basic rocks. The percentages next to the field names refer to the percentage of the correct classification as inferred in the original paper by Agrawal *et al* (2004).

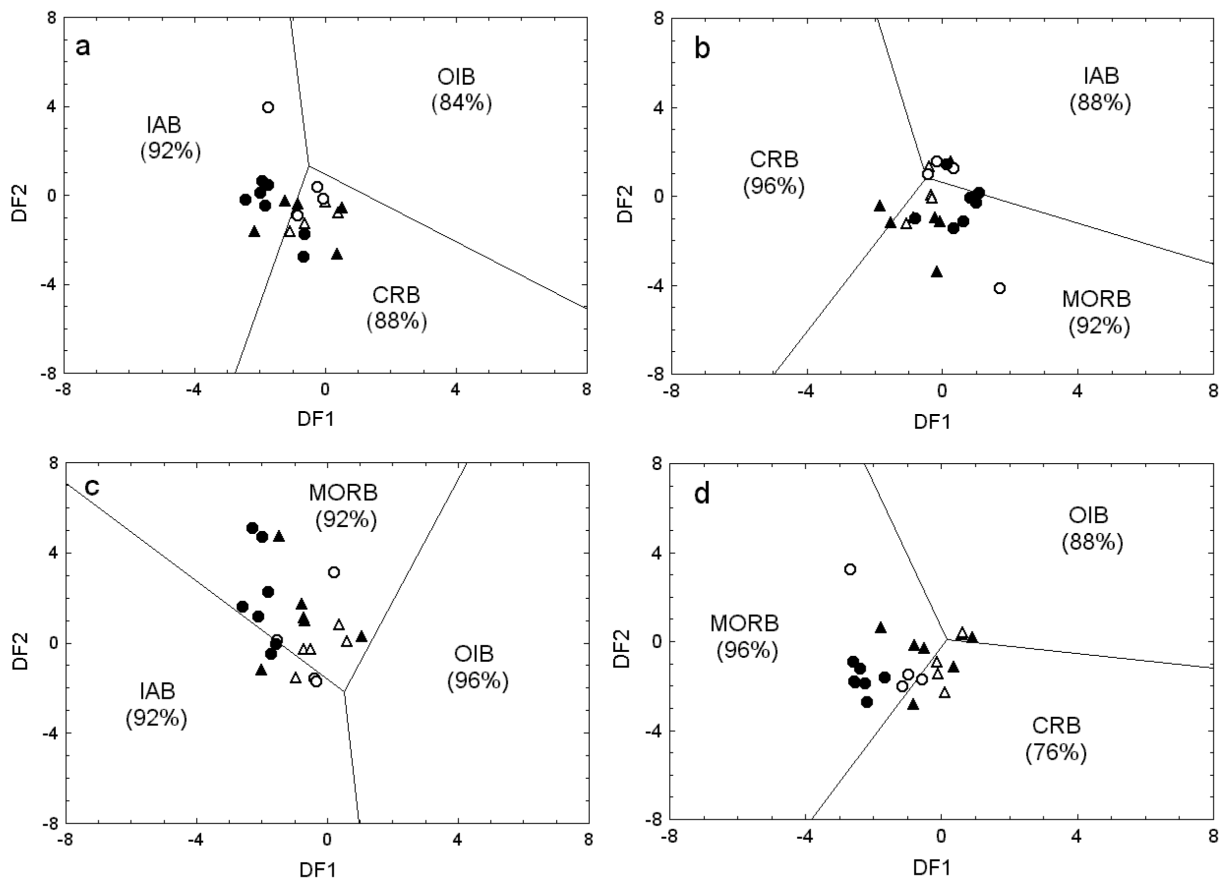

Figure 8. Discrimination diagram for three of the four groups (IAB-CRB-OIB-MORB) of tectonic settings at a time (Agrawal *et al* 2004) displaying basic rocks from the Andaman ophiolite suite. For more explanation, see caption of figure 7. **(a)** Group IAB-CRB-OIB; **(b)** Group IAB-CRB-MORB; **(c)** Group IAB-OIB-MORB; **(d)** Group CRB-OIB-MORB.

Using the three groups at a time diagrams, the first such diagram IAB-CRB-OIB (figure 8a) does not have the MORB field. The Andaman samples fall mostly in the CRB field (16 samples; $\sim 73\%$); the others occupy IAB ($\sim 18\%$) and OIB ($\sim 9\%$). In the second diagram IAB-CRB-MORB (figure 8b) most of the samples are discriminated as MORB (15 samples; $\sim 68\%$), whereas the others plot as IAB (6 samples; $\sim 27\%$) and CRB (1 sample; $\sim 5\%$). In the third diagram IAB-OIB-MORB (figure 8c), the sample distribution is as follows: MORB (16 samples; $\sim 73\%$) and IAB (the remaining 6 samples; $\sim 27\%$). Finally, in the last such diagram CRB-OIB-MORB (figure 8d), the samples are discriminated as follows: MORB (13 samples; $\sim 59\%$) and CRB (6 samples; $\sim 27\%$), and OIB (the remaining 3 samples; $\sim 14\%$).

In conclusion, from the use of these five new discriminant diagrams proposed by Agrawal *et al* (2004), we observe that the MORB is the suggested tectonic setting for the Andaman ophiolite suite, although the percentage success rate ($\sim$ 59–73%) observed for these samples is not as high as that ($\sim 85\%$) suggested by the authors of these diagrams.

Sun and Nesbitt (1978) discussed the geochemical regularities and genetic significance of basalts associated with the ophiolitic complexes by using Al_2O_3/TiO_2 and CaO/TiO_2 ratios to establish the genesis of low-Ti and high-Ti basalts of the ophiolitic suite. On the basis of these ratios, these authors discriminated low-Ti and high-Ti basalts. The high-Ti basalts have Al_2O_3/TiO_2, and CaO/TiO_2 ratios either equal or less than chondritic values (20 and 17 respectively). On the other hand, the low-Ti basalts have these ratios higher than chondritic values and may reach up to ~ 60. These ratios are plotted against TiO_2 and presented in figure 9. In this diagram the AOS ophiolitic basalt samples show close similarities with high-Ti MORB and basalt samples; Al_2O_3/TiO_2, and CaO/TiO_2 ratios are either equal or less than chondritic values. Sun and Nesbitt (1977) suggested that increasing the degrees of melting of the mantle could produce a progressive enhancement of Al_2O_3/TiO_2, and CaO/TiO_2 in the melts, but at a critical point these ratios would not change. This is simply because Ti is essentially incompatible and Al and Ca are compatible and if the amount of melting increases, the Al-Ca retaining phases in the source become exhausted, and the Al_2O_3/TiO_2, and CaO/TiO_2 ratios will no longer increase in the resultant melt (Sun and Nesbitt 1977, 1978). On the basis of these ratios, Sun and Nesbitt (1978) recommended that basalts derived from MORB-type magma have high titanium ($> 0.7\%$ TiO_2) contents, whereas basalts from island-arc and inter-arc basins have low titanium ($< 0.4\%$ TiO_2). Report of high-Ti (8.78 wt%) basic rock (Shastry *et al* 2001), associated with AOS, also supports the view that Andaman ophiolite rocks are derived from magmas rich in Ti. Thus, on the basis of TiO_2 contents, and Al_2O_3/TiO_2 and CaO/TiO_2 ratios observed for basalts of AOS (figure 9), it is clear that these basalts are high-Ti type and show very close geochemical similarities with the N-type MORB; suggest that these basalts were probably formed at the mid-oceanic ridge and not at the island arc setting.

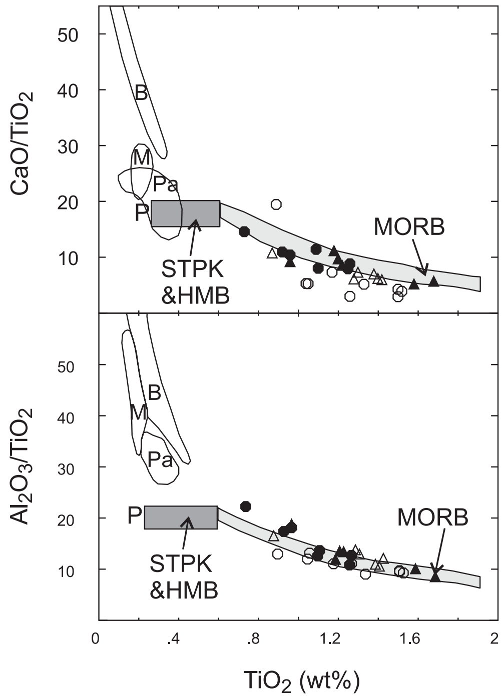

Figure 9. TiO_2, Al_2O_3/TiO_2, and CaO/TiO_2 variations in different basalts (after Sun and Nesbitt 1978). Fields of different basalts are shown, which includes Archaean spinifex–textured peridotitic komatiites (STPK), high-Mg basalts (HMB), MORB, island-arc basalts (Pa – Papua; M – Mariana Trench), and ophiolitic basalts (B – Betts Cove). "P" is model pyrolite. Symbols as in figure 3.

7. Conclusion

The basalts, associated with the Andaman ophiolite suite, are well exposed at different localities in the southern part of the south Andaman Island. On the basis of present work it is concluded that –

- Petrographically these basalts are classified as aphyric and phyric types. Aphyric type shows intersertal or variolitic textures, whereas phyric types exhibits porphyritic and sub-ophitic textures.
- IUGS classification scheme, based on total alkalies and silica compositions, classify these basalts into sub-alkaline and alkaline types. One

sample each shows trachybasalt and basanite composition.

- These basalts exhibit alteration due to low-grade metamorphism and late hydrothermal actions but on the basis of incompatible immobile trace element geochemistry it is suggested that they are probably derived from similar parental magma batches.
- Al_2O_3/TiO_2 and CaO/TiO_2 ratios and TiO_2 contents are similar to the high-Ti type ophiolite associated basalts. These ratios and discriminant functions and discrimination diagrams suggest that these basalts were formed at the mid-oceanic ridge tectonic setting.

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