by Abhishek Saha*, Abhay V. Mudholkar, and K.A. Kamesh Raju

Magma genesis at Andaman volcanic arc regime, North-eastern Indian Ocean: Role of slab-mantle interaction

CSIR-National Institute of Oceanography, Dona Paula, Goa- 403004, India;

*Corresponding author, E-mail: asaha.nio2015@gmail.com; asaha@nio.org

(Received : 29/11/2018; Revised accepted : 23/05/2019)

<https://doi.org/10.18814/epiiugs/2020/020019>

This study reports new petrological and geochemical data of submarine volcanic rocks dredged from the Andaman arc, northeastern Indian Ocean and evaluates their petrogenetic and tectonic implications. The studied samples exhibit wide range of compositions including basalts, andesites, dacites and rhyolites depicting BADR trend of magmatic differentiation. The basalts are porphyritic and composed of calcic plagioclase phenocrysts embedded in the groundmass consisting of plagioclase, clinopyroxene and volcanic glass. Andesite and dacites comprise clusters of plagioclase phenocrysts embedded in glassy ground mass depicting glomeroporphyritic and vitrophyric textures. Plagioclase microlites in andesites show primary flow texture. Rhyolites from the study area porphyritic in nature predominantly consisting K-feldspar, quartz and plagioclase phenocrysts embedded in a silica rich merocrystalline groundmass of quartz, K-feldspar, biotite, opaque and glass. Plagioclase compositions in basalts and rhyolites correspond to An₇₆₋₇₈ and An₅₋₈ respectively. Geochemical and tectonic attributes marked by uniform LILE-LREE enriched, HFSE depleted trends corroborate (i) Mariana-type subduction of old, cold, thick and dense Indian Ocean lithosphere (ii) slab-dehydration, variable slab-mantle interaction, metasomatism and flux melting of mantle wedge and (iii) magma underplating and melting of lower oceanic crust resulting into calc-alkaline magmatism of B-A-D-R compositional spectra.

Introduction

Arc-back- arc magmatism associated with active oceanic subduction systems provide a comprehensive window to understand the processes consequent to the sinking of oceanic lithosphere into the mantle such as slab dehydration, mantle wedge metasomatism and hybridization, delamination and recycling of subducted oceanic

slab that collectively account for variable extents of ocean-crust-mantle interactions, generation of juvenile crust, hydrothermal activity, ore mineralization and magmatism (McCulloch and Gamble, 1991; Stern, 2002; Tatsumi, 2005). The elemental fractionation between the subducted oceanic slab and mantle wedge, the different stages of subduction from initiation to maturation and associated melt generation processes account for the diverse compositional spectra of arc magmatism. The diagnostic geochemical features of arc magmas including island arc tholeiites (IAT), calc-alkaline basalt-andesite-dacite-rhyolite (BADR) associations, boninites, arc picrites, siliceous high-Mg basalts (SHMB), adakites, high-Mg andesites (HMA) and Nb-enriched basalts (NEB) are influenced by the tectonic framework along the arc, geometry of the subducting plate, modification and enrichment of depleted mantle wedge by influx of materials released from subducting oceanic slab, role of slab-derived subduction components (silicate slab melts or slab-dehydrated aqueous fluids) and melting conditions in the mantle wedge. Petrological and geochemical signatures of intraoceanic subduction zone magmas are therefore one of the most viable tools to understand subduction processes, elemental cycling and chemical heterogeneity of sub-oceanic lithospheric mantle (SOLM) controlled by tectonic pulses (Foley et al., 2002).

Arc basalt-boninite and adakite-HMA-NEB associations, reflecting initial and matured stages of subduction respectively, are documented from ~43 Ma old Izu-Bonin-Mariana plate convergence systems. The adakite-HMA-NEB assemblage occurring in association with “normal” tholeiitic to calc-alkaline subduction-derived magmas have been reported from many Cenozoic arcs (Viruete et al., 2007 and references there in). It has been postulated that this assemblage represents shallow subduction of hot, young (<25 Ma) oceanic crust where melting of subducted slab generates adakites, hybridization of peridotitic mantle wedge by adakitic melts gives rise to HMA and NEB are produced by the melting of this hybridized residue (Hastie et al., 2011 and references there in). Besides these, geochemical signatures of magmas generated in East Scotia, Lau and Manus back arc basins of Pacific subduction zones are equated with variable mixing of melts derived by decompressional melting of MOR-type mantle and flux-melting of arc mantle concomitant to geodynamic transition from slab-proximal incipient back arc rifting to slab-distal mature back arc spreading. Geochemical mapping in Mariana Trough have been carried out to track mantle input, subduction input, mantle-subduction interaction, melting and crystallization processes involved

in back arc basin basalt genesis (Pearce and Stern, 2006; Pearce et al., 2005).

The Andaman arc- back arc system of northeast Indian Ocean represents the sole active subduction regime in the Indian EEZ and a potential site to study the modern subduction zone magmatism and geodynamic conditions associated with geochemical heterogeneity and dynamic evolution of sub-oceanic mantle. Significant geophysical surveys have been extensively carried out so far (Kamesh Raju et al., 2004; Curray, 2005; Diehl et al., 2013; Jourdain et al. 2016.), however, petrological and geochemical studies of Andaman subduction zone are less attended and yet of immense importance to understand the tectonomagmatic processes influencing the petrogenetic evolution of oceanic crust in an active arc-back arc regime. This paper reports new petrological and geochemical data of submarine volcanic rocks dredged from six different locations in the Andaman arc, northeastern Indian Ocean during the cruise SSK 033 and evaluates their characteristics to yield important information on (i) principal proponents for arc magmatism (ii) mantle depletion and enrichment processes (iii) variable interactions between mantle and subducted oceanic slab (iv) different stages of subduction from initiation to maturation and its reflection on compositional diversity of magmatism

Geological Overview

In the northeast Indian Ocean, the subduction of Indian Plate beneath the Southeast Asian Plate initiated during the early Cretaceous

following the Gondwanaland breakup. This major tectonic event marked the formation of the Indo-Burma range and the Andaman arc-trench system comprising the Andaman-Nicobar islands. The Andaman subduction zone is one of the few accretionary convergent margins where all the important components of a convergent margin are exposed including a trench, an outer arc accretionary prism, a forearc, a volcanic arc, a back arc basin etc. This accretionary prism or wedge consists of Cretaceous ophiolites, Eocene Mithakari Group of sediments, Oligocene Andaman Flysch Group and Archipelago Group of Mio-Pliocene (Haldar, 1984; Bandyopadhyay, 2005; Chakraborty and Pal, 2001). The Cretaceous Andaman Ophiolites (representing obducted Tethyan oceanic lithosphere) and Eocene sediments were thrust as allochthonous nappe sheets during terminal collision in Oligocene on the present subduction margin that initiated during Miocene. Different petrogenetic and tectonic aspects of Andaman ophiolites have been studied to provide insights into their emplacement, magma generation and melt-rock interaction processes (Pal et al., 2003; 2010; Ghosh et al., 2009; 2017; Saha et al., 2010; 2018a and references therein). The Andaman Basin extends from Myanmar in the north to Sumatra in the south and from Malay Peninsula in the east to Andaman and Nicobar islands in the west with prominent morphological features including the Nicobar deep, Barren-Narcondam volcanic islands, Invisible bank, and Alcock and Sewell seamount complexes (Fig. 1A). Geophysical studies including bathymetric, magnetic, gravimetric, heat flow and seismic surveys have collectively suggested active ocean floor spreading and opening

Figure 1. (A) Map showing the location of study area along with some important tectonic features of Andaman basin. (B) Multibeam bathymetric map showing Andaman volcanic arc with sample locations. Inset map shows the Indian Ocean, Andaman Sea and the study area.

of the Andaman Sea commenced at 4 Ma at a full rate of 16mm/yr, increasing to 38 mm/yr from 2.5-2 Ma to present classifying it as a slow-spreading ridge – rift system with a westward propagation (Kamesh Raju et al., 2004). Eruptive styles of volcanoes from Barren Islands have been studied by Alam et al. (2004) and Sheth et al. (2009). Block and ash flow deposits and dacite-andesites from Narcondam Island volcanoes have been documented by Pal et al. (2007) and Pal and Bhattacharya (2011). Petrological and geochemical studies of lava flows and associated intrusive from Barren Island have characterized them as low-K basalts to basaltic andesites derived from an arc-related mantle source (Chandrasekharam et al., 2009). ^{14}C dates of inorganic carbon in sediment beds and Sr- Nd isotopic ratios of seven discrete ash layers from a marine sediment core revealed seven major ash eruptions at Barren Island spanning from ~70 ka to 10 ka (Awasthi et al., 2010). $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology yielded oldest age of 1.58 ± 0.04 (2σ) Ma for the subaerial lava flows of Barren Island indicating a genetic relationship between the arc crust and the ophiolitic basement of the Andaman accretionary prism. Submarine volcanism, its relationship with the chemical evolution of magmas and its connection with the geodynamic processes from Andaman arc-back arc system have limited studies so far and few data are available till date. Saha et al. (2018b) discussed the geochemistry of Andaman back arc basin basalts and their implications on tectonic evolution from incipient to matured stages of back-arc rifting. Recent study on geochemical characteristics of rhyolitic pumice from submarine volcanoes of Andaman subduction zone have suggested their genesis by heating, melting, mobilization and assimilation of lower arc crust by melts generated through partial melting of a metasomatized mantle wedge in an intraoceanic arc regime (Saha et al., 2019). This study aims to address the geochemical attributes of underwater volcanic rocks dredged from the Andaman volcanic arc in the northeastern Indian Ocean and to understand the geodynamic conditions for magma genesis.

Analytical Procedures

The studied samples from Andaman arc were collected during the SSK 033 expedition. Dredging was carried out at six different locations, selected on the basis of morphology and tectonic setting (Fig.1B and Table 1). The studied volcanic rocks were dredged and

Table 1. Details of studied samples from Andaman volcanic arc.

Cruise no.	Dredge No.	Lat (N)	Long (E)	Depth (m)
SSK 033	DR 05	07°32.018'	94°09.922'	2116
	DR 06	06°55.565'	94°34.139'	2251
	DR 07	07°22.693'	94°24.107'	2217
	DR 09	07°31.500'	94°18.000'	1750
	DR 10	07°53.000'	94°02.000'	604
	DR 11	07°56.116'	94°02.387'	485

large quantities of unaltered rocks were recovered from the Andaman arc (Fig.1B). After petrographic screening, 15 samples were selected for major, trace and rare earth element (REE) analyses. The rock samples were powdered in an agate mortar. Major elements were determined by X-Ray Fluorescence Spectrometer (XRF; Phillips MAGIX PRO Model 2440) with relative standard deviations within 5%, and totals were all 100 ± 1 wt. %. Trace elements including REE

were determined by Inductively Coupled Plasma Mass Spectrometer (ICP-MS; Perkin Elmer ELAN DRC II) at the CSIR-National Geophysical Research Institute (NGRI), Hyderabad. The following method has been employed for sample dissolution. A mixture of doubly distilled acids ($\text{HF} + \text{HNO}_3 + \text{HCl}$, 5:3:2 ml) was added to ca.50 mg rock powder in Savillex Vessels and kept on a hot plate at 150 °C for three days. Following this, the entire mixture was evaporated to dryness. The decomposition procedure was repeated by adding 5 ml of the above acid mixture for two days. When the sample was dry, 10 ml of 1:1 HNO_3 was added and heated at 150 °C for 10–15 min. Then 5 ml Rh (1 ppm concentration) was added as an internal standard. After cooling, the volume of the solution was made up to 250 ml. Certified reference materials JB-2, BCR-1, JA-1 and JR-1 were used as analytical standards. The relative standard deviations (RSD) for major elements is <3% and better than 5% for the majority of trace elements. Chondrite and primitive mantle values used for plotting and calculating trace element ratios (e.g., Ce/Ce^* and Eu/Eu^* , Nb/Th , $(\text{La}/\text{Yb})_{\text{N}}$, $(\text{La}/\text{Sm})_{\text{N}}$, and $(\text{Gd}/\text{Yb})_{\text{N}}$) are from Sun and McDonough (1989).

Results

Petrography

The submarine volcanic rocks from Andaman arc show wide range of compositions from basalts to rhyolites with presence of intermediate andesite and dacite varieties depicting BADR trend of magmatic differentiation. The basalts are dominantly composed of plagioclase feldspar with varying proportion of clinopyroxene and volcanic glass. Calcic plagioclase (An_{76-78}) phenocrysts are the dominant minerals embedded in the groundmass consisting of plagioclase, clinopyroxene and glass (Fig.2A). Andesite and dacites, the intermediate members of the suite, contains clusters of plagioclase phenocryst (An_{44-36} and An_{32-24} respectively) embedded in glassy ground mass of volcanic glass (Fig. 2B) depicting glomeroporphyritic and vitrophyric textures. In andesites, microlites of plagioclase exhibit a primary flow texture (Fig.2C). The rhyolites are porphyritic in nature with K-feldspar, quartz and plagioclase phenocrysts embedded in a silica rich merocrystalline groundmass of quartz, K-feldspar, tiny flakes of biotite, opaque and glass. In some cases, K-feldspar are perthitic showing fine exsolution lamellae of plagioclase within the host K-feldspar. Compositionally, plagioclase grains in rhyolites are albitic (An_5 to An_8 ; determined by X^{*010} symmetric extinction angle) and often highly saussuritized.

Geochemistry

Whole-rock geochemical data, including major, minor, trace, and rare earth elements (REEs), on 15 samples are given in Table 2. The volcanic rocks from the Andaman volcanic arc can be classified on the basis of their total alkali ($\text{Na}_2\text{O} + \text{K}_2\text{O}$) versus silica (SiO_2) variations (Fig.3). The samples plot in the fields of basalt, basaltic andesite, andesite, dacite and rhyolite in the total alkali versus silica (TAS) diagram (Fig. 3; Le Bas et al., 1986) reflecting a subalkaline compositional trend. AFM plot shows calc-alkaline affinity of the precursor magmas. Geochemical parameters like Mg#, silica contents used for constraining the extent of magmatic differentiation show a wide range of variation which corroborate magma differentiation and the highly evolved nature of the studied volcanic rocks.

Figure 2. Photomicrograph showing (A) occurrences of plagioclase and clinopyroxene phenocrysts in studied basalts from Andaman arc (B) cluster of plagioclase phenocrysts floating on a glassy groundmass depicting vitrophyric texture in andesites (C) parallel orientation of plagioclase microlites depicting the primary flow texture in dacite (D) occurrence of K-feldspar phenocryst in rhyolites from Andaman arc.

Figure 3. Total alkali vs. silica diagram for the studied volcanic rocks from Andaman arc (after LeBas et al., 1986).

Major element chemistry of the basalt is marked by moderate SiO_2 (44.78 wt. %), MgO (5.83 wt. %), MnO (5.1 wt. %), with moderately high Al_2O_3 (16.24 wt. %), Fe_2O_3 (11.00 wt. %), CaO (9.9 wt. %), TiO_2 (0.9 wt. %) and low total alkali ($\text{Na}_2\text{O} + \text{K}_2\text{O} = 2.46$ wt. %) and P_2O_5 (0.19 wt. %) contents with respect to their intermediate and felsic counterparts. The intermediate volcanic rocks having basaltic andesitic to andesitic composition, exhibit a non-uniform compositional spectrum characterized by moderately high to high

SiO_2 ranging from 52.6 to 59.9 wt. %, medium TiO_2 varying between 0.6 and 1.16 wt. %, moderate to high Al_2O_3 in the range of 16.7–18.8 wt. %, moderate Fe_2O_3 ranging from 6.9–10.7 wt. %, and low to moderately high CaO (3.3–9.6 wt. %) with low MgO (2.7–3.1 wt. %), MnO (0.11–0.23 wt. %) and P_2O_5 (0.27–0.36 wt. %) contents. The total alkali content of the samples ranges from 3.1 to 4.7 wt. %. The volcanic rocks with dacitic composition show high SiO_2 varying from 64.6 to 70.3 wt. %, medium TiO_2 in the range of 0.5 and 0.6 wt. %, moderate to high Al_2O_3 in the range of 14.7–16.7 wt. %, and low to moderate Fe_2O_3 varying between 4.00 and 7.5 wt. %, with characteristically low CaO (0.4–3.6 wt. %), MgO (0.6–2.7 wt. %), MnO (0.1–0.4 wt. %), and P_2O_5 (0.12–0.17 wt. %) and moderately high total alkali contents ($\text{Na}_2\text{O} + \text{K}_2\text{O} = 4.85$ – 5.82 wt. %). Major oxide compositions of the rhyolites are characterized by extremely high SiO_2 showing a restricted range from 73.2–74.32 wt. % and moderately high Al_2O_3 varying between 13.7–13.9 wt. % with low concentrations of TiO_2 (0.25–0.27 wt. %), Fe_2O_3 (2.6–2.73 wt. %), MnO (0.13 wt. %), MgO (0.7–0.8 wt. %), CaO (2.56–2.63 wt. %), and P_2O_5 (0.06 wt. %). The total alkali content of the samples ranges from 4.9 to 5.3 wt. %. Among transitional elements, the Andaman arc volcanic rocks display overall depletion in Ni, Cr, and Co concentrations. Incompatible trace element abundances of these rocks suggest an overall enrichment in large ion lithophile elements (LILEs) and relative depletion in high field strength elements (HFSEs; Table 2). REE contents of studied samples exhibit light (L) REE enrichment

Table 2 Major and trace element composition of studied volcanic rocks from Andaman arc.

Sl. No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Sample no.	DR10-01	DR06	DR09-01	DR09-02	DR5-2-1	DR11-01	DR11-02	DR11-03a	DR11-03b	DR5-2-2	DR07-01	DR07-03	DR07-04	DR07-05	DR07-06
wt. %															
SiO ₂	44.78	52.82	52.63	52.87	59.89	70.29	68.29	69.67	68.52	64.64	73.20	73.81	74.21	74.32	73.45
TiO ₂	0.90	1.15	1.16	1.15	0.60	0.49	0.52	0.52	0.50	0.61	0.27	0.26	0.26	0.26	0.25
Al ₂ O ₃	16.24	18.92	18.81	18.76	16.66	14.82	15.72	15.74	14.69	16.68	13.72	13.78	13.89	13.91	13.68
Fe ₂ O ₃	11.00	10.71	10.64	10.66	6.91	4.88	5.30	3.99	6.00	7.49	2.60	2.61	2.57	2.73	2.60
MnO	5.09	0.23	0.21	0.23	0.11	0.20	0.36	0.30	0.41	0.06	0.13	0.13	0.13	0.13	0.13
MgO	5.83	3.09	2.71	3.11	3.10	0.78	0.85	0.60	0.74	2.68	0.79	0.68	0.72	0.72	0.74
CaO	9.89	9.56	9.55	9.59	3.32	3.42	3.61	3.58	3.56	0.39	2.62	2.62	2.63	2.59	2.56
Na ₂ O	1.98	2.63	2.66	2.57	2.66	4.30	4.90	4.62	4.21	2.11	4.10	4.06	4.03	3.87	3.96
K ₂ O	0.48	0.48	0.67	0.50	2.01	0.83	0.92	0.92	0.79	2.74	1.09	1.14	1.05	1.03	1.34
P ₂ O ₅	0.19	0.14	0.14	0.14	0.12	0.12	0.13	0.15	0.17	0.13	0.06	0.06	0.06	0.06	0.06
Total	96.37	99.72	99.17	99.58	95.38	100.12	100.60	100.08	99.59	97.54	98.57	99.14	99.54	99.61	98.78
ppm															
Sc	38.45	39.64	41.04	28.96	14.28	17.54	19.44	13.88	14.97	19.78	8.00	8.19	7.11	7.04	7.10
V	253	255	282	255	111	25	28	29	29	149	30	29	34	-	31
Cr	65.53	2.45	4.77	2.37	29.75	2.05	2.21	1.47	2.05	26.03	2.82	1.61	5.41	2.17	2.80
Co	190	25	24	19	22	3	7	5	3	15	3	2	3	2	3
Ni	256	5	51	14	23	3	17	15	7	33	10	46	6	2	2
Cu	95	59	62	41	19	5	3	3	5	8	4	5	4	2	4
Zn	144	117	118	81	61	101	99	85	97	97	50	57	60	52	55
Rb	10	11	15	8	80	19	16	16	16	181	22	21	23	20	24
Sr	277	351	361	251	176	191	156	146	203	96	126	127	140	92	141
Y	28	31	33	24	11	38	39	28	35	12	28	21	26	26	24
Zr	47	66	64	47	83	125	133	106	101	99	135	127	138	120	136
Nb	1.36	2.06	2.20	1.58	2.88	2.27	2.73	2.24	2.15	5.78	2.64	2.51	2.56	2.33	2.66
Cs	0.51	0.42	0.60	0.32	1.96	1.07	0.25	0.30	1.03	4.09	1.27	1.13	1.16	1.03	1.16
Ba	68	94	100	-	255	232	166	153	193	404	175	189	210	-	217
Hf	1.20	1.84	1.84	1.38	2.39	3.59	3.81	3.14	3.01	2.79	3.62	3.38	3.62	3.23	3.50
Ta	0.11	0.20	0.19	0.12	0.29	0.15	0.18	0.09	0.11	0.61	0.14	0.17	0.12	0.12	0.14
Pb	29.44	2.81	3.30	2.30	10.81	6.21	23.97	26.61	11.95	7.01	4.27	4.36	5.49	3.52	4.75
Th	2.33	1.24	1.32	0.99	5.85	3.27	3.41	2.99	3.43	8.25	3.66	3.00	3.52	3.46	3.44
U	1.01	0.34	0.39	0.20	1.61	0.72	0.55	0.52	0.95	2.34	0.37	0.59	0.72	0.41	0.75
La	9.29	5.84	6.18	4.56	10.39	11.92	14.14	11.50	11.87	17.00	13.81	11.39	13.19	12.93	12.27
Ce	21.95	14.36	14.87	11.30	21.99	26.69	25.00	13.46	25.03	37.78	15.84	19.77	23.58	14.91	24.10
Pr	2.45	2.26	2.38	1.72	2.67	3.65	4.11	3.41	3.59	3.62	3.85	3.19	3.57	3.53	3.30
Nd	10.47	9.33	9.72	7.19	10.24	14.69	15.41	11.31	14.08	14.84	12.25	11.43	12.84	11.16	12.35
Sm	2.95	3.42	3.55	2.58	2.18	4.33	4.72	3.84	4.17	2.44	3.53	2.88	3.23	3.18	2.94
Eu	0.96	1.22	1.24	0.91	0.47	1.32	1.39	1.31	1.41	0.52	0.90	0.74	0.83	0.80	0.74
Gd	3.39	3.86	3.96	2.86	2.02	4.65	5.00	3.78	4.41	2.45	3.46	2.93	3.26	3.04	2.92
Tb	0.60	0.72	0.74	0.54	0.31	0.87	0.92	0.71	0.82	0.32	0.61	0.50	0.57	0.55	0.50
Dy	4.99	6.15	6.40	4.74	2.43	7.38	7.76	5.95	6.95	2.42	5.21	4.21	4.64	4.66	4.24
Ho	0.82	1.00	1.02	0.76	0.38	1.19	1.25	0.95	1.12	0.38	0.85	0.68	0.76	0.77	0.70
Er	2.26	2.63	2.77	2.02	1.08	3.32	3.46	2.56	3.06	1.10	2.41	1.96	2.19	2.18	2.03
Yb	2.57	2.98	3.09	2.23	1.28	3.90	4.18	3.01	3.59	1.42	3.21	2.59	2.90	2.89	2.67
Lu	0.41	0.45	0.46	0.34	0.21	0.62	0.66	0.47	0.57	0.23	0.52	0.43	0.48	0.48	0.44
Na ₂ O+K ₂ O	2.46	3.11	3.32	3.07	4.67	5.12	5.82	5.54	5.00	4.85	5.19	5.20	5.08	4.90	5.31
(La/Sm) _N	2.03	1.10	1.12	1.14	3.08	1.78	1.94	1.94	1.84	4.49	2.53	2.56	2.64	2.62	2.70
(Ce/Yb) _N	2.38	1.34	1.34	1.41	4.77	1.90	1.66	1.24	1.94	7.37	1.37	2.12	2.26	1.43	2.51
(Dy/Yb) _N	1.30	1.38	1.38	1.42	1.27	1.27	1.24	1.32	1.30	1.14	1.09	1.09	1.07	1.08	1.06
(Gd/Yb) _N	1.09	1.07	1.06	1.06	1.30	0.99	0.99	1.04	1.01	1.42	0.89	0.93	0.93	0.87	0.90
Zr/Y	1.64	2.13	1.93	1.93	7.48	3.33	3.42	3.75	2.86	8.09	4.84	5.93	5.29	4.57	5.75
Nb/Y	0.05	0.07	0.07	0.06	0.26	0.06	0.07	0.08	0.06	0.47	0.10	0.12	0.10	0.09	0.11
Zr/Sm	15.82	19.43	17.94	18.29	38.22	28.94	28.29	27.61	24.20	40.50	38.12	44.00	42.67	37.53	46.41
Nb/Zr	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.06	0.02	0.02	0.02	0.02	0.02

Table 2. Contd...

Sl. No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Sample no.	DR10-01	DR06	DR09-01	DR09-02	DR5-2-1	DR11-01	DR11-02	DR11-03a	DR11-03b	DR5-2-2	DR07-01	DR07-03	DR07-04	DR07-05	DR07-06
wt. %															
Nb/La	0.15	0.35	0.36	0.35	0.28	0.19	0.19	0.19	0.18	0.34	0.19	0.22	0.19	0.18	0.22
Zr/Nb	34.40	32.20	28.99	29.93	28.91	55.15	48.88	47.36	46.93	17.10	50.95	50.50	53.87	51.40	51.32
Zr/Hf	39.00	36.08	34.70	34.26	34.89	34.87	35.06	33.76	33.56	35.52	37.15	37.46	38.06	37.04	39.02
Th/Ce	0.11	0.09	0.09	0.09	0.27	0.12	0.14	0.22	0.14	0.22	0.23	0.15	0.15	0.23	0.14
Nb/Th	0.58	1.66	1.67	1.59	0.49	0.69	0.80	0.75	0.63	0.70	0.72	0.84	0.73	0.67	0.77
Ba/Th	29.34	75.60	75.60	-	43.56	70.96	48.73	51.09	56.30	48.97	47.65	62.91	59.66	-	63.12
Nb/Ta	12.10	10.27	11.75	13.47	9.86	15.35	15.25	26.00	19.91	9.53	19.27	14.41	20.78	20.22	19.40
Th/Ta	20.79	6.18	7.05	8.50	20.03	22.10	19.07	34.76	31.72	13.58	26.74	17.23	28.62	30.09	25.09
Ba/Nb	50.41	45.49	45.36	-	88.47	102.16	60.94	68.29	89.72	69.83	66.14	75.23	82.16	-	81.64
Th/Nb	1.72	0.60	0.60	0.63	2.03	1.44	1.25	1.34	1.59	1.43	1.39	1.20	1.38	1.49	1.29

Sl no. 1: basalt; 2-4: basaltic andesite; 5: andesite; 6-10: dacite; 11-15: rhyolite; Normalization values are from Sun and McDonough, 1989

over heavy (H) REE. Primitive mantle-normalized incompatible trace element patterns for basalt (Fig.4) exhibit pronounced positive Rb and Th anomalies and negative Nb-Ta, Zr-Hf, and Ti anomalies. The low $(\text{Nb/Th})_{\text{PM}}$ and $(\text{Nb/La})_{\text{PM}}$ ratios for basalt [$(\text{Nb/Th})_{\text{PM}} = 0.12$; $(\text{Nb/La})_{\text{PM}} = 0.34$] are in agreement with relative LILE-LREE enrichment and Nb depletion of the parental melts. These observations are conformable with distinct Th enrichment over Nb and La. Chondrite-normalized REE patterns for basalt (Fig.4) reflect LREE enrichment over MREE and HREE with negative Eu anomaly. $(\text{Ce/Yb})_{\text{N}} = 2.4$, $(\text{La/Sm})_{\text{N}} = 2.03$, $(\text{Gd/Yb})_{\text{N}} = 1.1$ and $(\text{Dy/Yb})_{\text{N}} = 1.3$ account for prominent LREE/HREE and LREE/MREE fractionation with feeble to moderate MREE/HREE fractionation respectively. The basaltic andesite and andesite samples display positive Rb and Th anomalies and negative Nb-Ta, Zr-Hf, and Ti anomalies on primitive mantle-normalized multi-element diagrams (Fig.4). The low $(\text{Nb/Th})_{\text{PM}}$ and $(\text{Nb/La})_{\text{PM}}$ and relatively high $(\text{La/Nb})_{\text{PM}}$ ratios for these rocks [$(\text{Nb/Th})_{\text{PM}} = 0.15-0.32$; $(\text{Nb/La})_{\text{PM}} = 0.2-0.3$; $(\text{La/Nb})_{\text{PM}} = 3.9-5.5$] are consistent with primitive mantle-normalized incompatible trace element abundances reflecting enrichment in LILEs and LREEs with relative depletion in Nb. Elevated $(\text{Th/La})_{\text{PM}}$ (0.6–1.8) and $(\text{Th/Nb})_{\text{PM}}$ (3.12–6.86) ratios for these rocks are suggestive of Th enrichment over La and Nb. Chondrite-normalized REE patterns (Fig. 4) show LREE enrichment over MREE and HREE with $(\text{Ce/Yb})_{\text{N}}$ ranging from 1.34 to 4.8 and $(\text{La/Sm})_{\text{N}}$ varying from 1.1 to 3.1 suggesting moderate to steep LREE/HREE fractionation trends, whereas $(\text{Gd/Yb})_{\text{N}} = 1.1-1.3$ and $(\text{Dy/Yb})_{\text{N}} = 1.3-1.42$ corroborate moderate MREE/HREE fractionation. Primitive mantle-normalized incompatible trace element abundances for dacite (Fig. 4) demonstrate distinct positive Rb, Th, La anomalies with negative Nb-Ta, Zr-Hf, and Ti anomalies, which collectively suggest enriched LILE-LREE compositions with relative Nb depletion and higher Th abundances over Nb and La. These observations are further supported by low $(\text{Nb/Th})_{\text{PM}}$ and $(\text{Nb/La})_{\text{PM}}$ values and comparatively higher $(\text{La/Nb})_{\text{PM}}$, $(\text{Th/La})_{\text{PM}}$, and $(\text{Th/Nb})_{\text{PM}}$ ratios for dacite [$(\text{Nb/Th})_{\text{PM}} = 0.11-0.14$; $(\text{Nb/La})_{\text{PM}} = 0.23-0.33$; $(\text{La/Nb})_{\text{PM}} = 3-4.3$; $(\text{Th/La})_{\text{PM}} = 2-3$; and $(\text{Th/Nb})_{\text{PM}} = 7.2-9.25$] samples. The chondrite normalized REE patterns for the studied rocks (Fig. 4) reflect prominent LREE enrichment over MREEs and HREEs, complemented by moderate to strongly fractionated LREE/MREE and LREE/HREE patterns [$(\text{La/Sm})_{\text{N}} = 1.8-4.5$, $(\text{Ce/Yb})_{\text{N}} = 1.24-7.4$]. These dacites show moderate MREE/HREE fractionation [$(\text{Gd/Yb})_{\text{N}} = 0.99-1.42$; $(\text{Dy/Yb})_{\text{N}} = 1.14-$

1.32]. The rhyolites are characterized by low $(\text{Nb/Th})_{\text{PM}}$ (0.1–0.12) and $(\text{Nb/La})_{\text{PM}}$ (0.24–0.3) ratios, and relatively higher $(\text{La/Nb})_{\text{PM}}$ (3.4–4.23), $(\text{Th/La})_{\text{PM}}$ (2.3–2.5), and $(\text{Th/Nb})_{\text{PM}}$ (8.4–9.7) ratios, which collectively show LILE and LREE enrichment with relative Nb depletion and higher Th abundances over Nb and La. These geochemical features are comparable with positive Th, Rb and La anomalies and negative Nb-Ta, Zr-Hf, and Ti anomalies on the primitive mantle-normalized multi-element diagram (Fig. 4). Chondrite-normalized REE patterns for the rhyolites (Fig. 4) reflect prominent LREE enrichment over MREEs and HREEs, complemented by moderately strong LREE/MREE and LREE/HREE and feeble to moderate MREE/HREE fractionations [$(\text{La/Sm})_{\text{N}} = 2.53-2.7$, $(\text{La/Yb})_{\text{N}} = 1.4-2.5$, $(\text{Gd/Yb})_{\text{N}} = 0.87-0.93$, $(\text{Dy/Yb})_{\text{N}} = 1.06-1.09$].

Discussion

Tectonic Implications

The studied volcanic rocks of BADR compositions from Andaman arc exhibit negative anomalies at Nb, Ta, Zr, Hf and Ti on primitive mantle normalized trace element diagram (Fig. 4), LILE>HFSE, LREE>HFSE, HFSE/HFSE* < 1, depletion of Nb-Ta with relative enrichment of Th, U, La, low Nb/Th and Nb/La ratios. These geochemical attributes collectively provide evidence for subduction zone magmatism. Plots of studied volcanic rocks on Ba/Yb vs. Nb/Yb and Th/Yb vs. Ta/Yb (Fig.5) indicate their geochemical and tectonic coherence with Mariana arc and Okinawa trough magmatism in the Pacific Ocean. They are collinear with the low Ce–Yb trend of intraoceanic arc basalts from Aleutians, north Lesser Antilles, Marianas and south Sandwich Islands (Fig.6, Hawkesworth et al., 1993). It has been envisaged that the geodynamic conditions prevailing in an active subduction system are controlled by the (a) velocity of the subducted slab roll-back and (b) the oceanward velocity of the overriding plate. Dewey (1980) advocated three families of arc systems based on these two parameters. If $a > b$, then extensional arcs are formed with back-arc extensional basins e.g. Mariana and Tonga arcs in eastern Indonesia; if $a \sim b$, well-developed subduction complexes are formed without back-arc extensions and are called neutral arcs e.g. Alaskan, Aleutian and Sumatran arcs; and if $a < b$, then compressional arcs are formed causing thrusting in both overridden oceanic and overriding continental plate as documented in Peruvian Andes Cordillera. The

Figure 4. Chondrite normalized REE patterns and primitive mantle normalized multi-element spiderdiagram for the studied samples (normalization values are from Sun and McDonough, 1989)

Andaman subduction system with well-developed back-arc basin can be categorized as an extensional arc characterized by greater roll-back velocity of subducted Indian ocean slab compared to the oceanward velocity of the overriding Burmese Plate. However, extensive geophysical studies in the Andaman subduction zone have deduced (i) variable velocities for the subducting slab and (ii) variable rates of extension for Andaman back arc basin ranging from 16mm/yr to 38 mm/yr over a 4 Ma timespan thereby classifying it as a slow-spreading ridge – rift system with a westward propagation (Kamesh Raju et al., 2004). Petrological and geochemical signatures complement the geophysical observations and further reveal (i) Mariana-type subduction of old, cold, thick and dense Indian ocean lithosphere (ii) slab-dehydration, variable slab-mantle interaction,

metasomatism and flux melting of mantle wedge- (iii) generation of calc-alkaline magmas of B-A-D-R compositional spectra.

Petrogenesis of BADR suite

The overall trace and REE compositions of the studied volcanic rocks from Andaman arc region are consistent with the geochemical characteristics of subduction zone magmas generated in arc settings. Negative Nb-Ta anomalies, Ti depletion, $Th/Ta > 2$, $La/Nb > 1.4$, $Nb/Y = 0.1-1$, $Nb/Th < 10$, $Zr/Nb > 10$, $La/Sm > 1.5$, and $Nb/La \ll 1$ (Table 2) for the studied volcanics, exclude their association with mid-oceanic ridge, oceanic-island, or oceanic plateau settings and imply a subduction-related ocean–ocean convergent plate margin setting

Figure 5. Plots of studied samples from the Andaman basin in (A) Ba/Yb and (B) Th/Yb vs Ta/Yb diagram. The figure is modified from Pearce et al. (2005) and Chen et al. (1995). Data of Okinawa Trough basalt cited from Shinjo et al. (1999), is average; data of N-MORB, E-MORB and primitive mantle are cited from Sun and McDonough (1989); data of Okinawa Trough pumice from Shinjo and Kato (2000); data of Mariana Trough basalt from Pearce et al. (2005)

(Condie, 2015). The LILE-LREE enrichment, HFSE depletion, negative Nb-Ta, Zr-Hf and Ti anomalies inferred to be inherited through fluid-controlled metasomatism of sub-arc mantle wedge driven by dehydration of subducted Indian oceanic lithosphere and influx of fluid mobile non-conservative large ion lithophile elements into the adjacent mantle with selective retention of fluid immobile conservative HFSE in the subducted slab. Geochemical signatures of modern arc-related magmatism suggest that the Ba/Nb ratio is an effective geochemical proxy to evaluate the fluid/water content in the mantle source, while Ba/La can be used as a tracer for the total slab-derived input into the sub-arc mantle wedge (He et al., 2017). The Ba/Nb ratios for the Andaman arc volcanics ranging from 45.5-

Figure 6. Ce vs. Yb plot showing a comparison of Andaman arc volcanics with other Phanerozoic island arcs (Hawkesworth et al., 1993).

102.2, corroborate the presence of hydrous minerals (e.g., phlogopite or amphibole) in the source region, and their Ba/La (7.35-24.5) ratios endorse subduction input in the source of the parent magmas (He et al., 2017). Ba/Th (29.34-75.6) ratios in comparison with relatively lower values for Th/Nb (0.6-2.03) ratios corroborate higher magnitude of shallow subduction input. Ba/Yb vs. Nb/Yb and Th/Yb vs. Ta/Yb plots (Fig. 5) for the studied volcanic rocks implicate increased influx of subduction-derived fluids and sediments inducing metasomatism and partial melting of the mantle wedge. Consistently lower Dy/Yb ratios with moderately fractionated LREE/MREE and LREE/HREE ratios attest to parent melt generation at a shallower depth corresponding to stability field of spinel peridotite.

The migration of slab-dehydrated fluids promotes mobilization of elements and contributes to 3-25% of melting of mantle wedge at a depth of 30-50 km and at 1250-1350°C mantle temperatures. Island arc tholeiites contain 1-8 wt.% of subduction derived hydrous fluids compared to the mid oceanic ridge basalts (MORB, 0.2 wt.%) and ocean island basalts (OIB, 0.8 wt.%) (Plank et al., 2013; Kimura and Nakajima, 2014). Th and U enrichment in island arc magmas has been attributed to the influx of metasomatic fluids into mantle wedge and higher solubility of Th and U in slab-dehydrated fluids. Metasomatic fluids are generated during dehydration of subducted slab and decarbonation of amphibolite facies minerals in the slab. Due to higher solubility, uranium will be released from the subducted slab and dissolved into the fluid phase with increasing pressure and temperature (Bailey and Ragnarsdottir, 1994). These metasomatic fluids serve as the most viable transporters of Th and U into the overlying sub-arc mantle wedge. Mobility of Th over HFSE and HREE in fluids released by dehydration of subducted oceanic slab accounts for the elevated abundances of Th in the resultant arc magmas. Th/Ce ratios (>0.1) and LREE enrichment over HFSE and HREE particularly point towards contribution from the subducted sediments which are characteristic to island arc magmas. Nd-Hf compositions of arc

magmas reveal that in comparison with Hf, Nd behaves as a mobile element in slab-derived fluids/melts. It has been suggested that subduction-metasomatized mantle wedge have increased concentrations of Nd compared to Hf (Aldanmaz et al., 2008; Saha et al., 2018a). The LILE-LREE-HFSE systematics of the Andaman volcanic pumice marked by elevated abundances of Nd with Hf depletion manifested in terms of high Nd/Hf ratios (3.4-8.8) in combination with Ba/Nb, Ba/La, Ba/Yb, La/Sm, La/Yb, Th/Ce ratios conform to metasomatism of mantle wedge melts by addition of dehydrated fluids and sediments released from the subducted Indian ocean lithospheric slab. The plots of the studied B-A-D-R rocks on Nb/Zr vs. Th/Zr diagram (Fig.7A) suggest variable enrichment of mantle by subduction-derived fluids correlatable with progressive intraoceanic subduction process. HFSE ratios involving Nb, Th, and Yb provide significant insights into the genesis of volcanic rocks in different tectonic settings. Plots of studied rocks on Th/Yb vs. Nb/Yb (Fig.7B) diagram reflect pronounced subduction input for the genesis of calc-alkaline magmas in an oceanic arc environment. Accessory residual phases such as rutile, titanite and allanite in the source and their transport through fluids and hydrous melts control Nb-Ta fractionation in arc system. Amphibole plays a more important role in the Nb-Ta budget of subduction zone magmas generated under hydrous conditions. The fractionated Nb/Ta values (9.9-26) for the studied samples are due to crystallization of amphibole from slab-

derived, silica-rich aqueous fluids that fractionate Nb from Ta in the residual fluids. The Zr/Nb ratios (17.1-55.15) for the Andaman arc volcanics compared to N-MORB (Zr/Nb=11-39) and Recent oceanic primitive arc tholeiites (Zr/Nb= 9-87) suggest depleted or enriched nature of the mantle wedge lithosphere marked by interaction between depleted lithospheric mantle and subduction-derived fluids and sediments. Zr/Hf >, Zr/Sm > and Nb/Ta < primitive mantle values of 36, 25 and 17 respectively indicate enrichment of depleted, MORB-type mantle by subduction components and hydrous metasomatism of mantle wedge (Manikyamba et al., 2015; Saha et al., 2017; 2018a). Negative Zr-Hf anomalies observed in these arc volcanics have been suggested as primary magmatic features resulting from amphibole fractionation and metasomatism of depleted MORB-type mantle wedge by subduction-derived fluid flux. Sheth et al. (2009) synthesized the past and recent eruptive styles of lava flows from the active Barren Island volcano in the Andaman Sea and propounded a temporal record of the variations in their morphological features. They further suggested that the prehistoric eruptions during 1787-1832, 1991, 1994-1995, 2005-2006 have produced subaerial aa and blocky aa lava flows of predominantly basaltic and basaltic andesite composition, volcanoclastic and surge deposits with pyroclastic fall, whereas the 2008 eruptions comprised only tephra. The morphology and processes of formation of viscous, crystal-rich, isotopically homogeneous, subalkaline basaltic toothpaste lava in aa flows of 1994-1995 eruption of Barren Island volcano have been extensively described by Sheth et al. (2011) and interpreted to be rheologically similar to those previously reported from Kilauea (Hawaii), Paracutin and Etna volcanoes. Geochemical resemblance and genetic coherence for prehistoric Barren Island lava flows and dyke with the Quaternary low-K volcanic rocks of Sunda arc has been envisaged by Alam et al. (2004). Petrological, geochemical and Sr-Nd isotopic characteristics indicate a temporally uniform low-K to basaltic andesite compositions for Barren Island lava flows from past and recent eruptive phases and invoke the role of a heterogeneous mantle source for their evolution (Chandrasekharam et al., 2009; Santo, 2016). Pal et al. (2007) studied dacite-andesite from Narcondam Island in the Andaman Sea, deciphered their LILE enriched-HFSE depleted composition with respect to N-MORB and attributed their genesis to magma mixing in the inner arc of Andaman-Jave subduction system. This study elucidates a complete BADR compositional spectrum for the submarine volcanic rocks of Andaman arc region. The calc-alkaline B-A-D-R compositional spectra displayed by the Andaman arc volcanics implicate crust-mantle interactions, assimilation and fractional crystallization of island arc basalts derived by slab-dehydration, fluid infiltration and flux melting processes in an intraoceanic subduction system. Subduction zone magmas of intermediate to acidic compositions are generated and evolved through variable extents of mixing between crustal and mantle components. Partial melting of lower oceanic crust triggered by subduction-derived magmas underplated at the base of the overriding plate or solidified mafic magma stalled in the lower crust and fractional crystallization with or without crustal assimilation are the principal mechanisms that control the generation of intermediate-felsic magmas in various tectonic settings (Ayalew and Ishiwatari, 2011). The submarine B-A-D-R volcanism at Andaman arc complies with felsic magma generation under cold, wet, oxidizing environments in convergent plate margin settings (Bachmann and Bergantz, 2008). The evolution of magmas parental to the studied oceanic arc volcanics from Andaman was controlled by reheating, remobilization, partial melting and

Figure 7. A. Nb/Zr vs. Th/Zr diagram (after Zhao and Zhou, 2007) showing the studied samples in an array consistent with fluid-related enrichment of mantle through subduction process; B. Th/Yb vs. Nb/Yb plots for the studied samples showing calc-alkaline lineage in intra oceanic arc domain (Pearce, 2008).

assimilation of andesitic component of lower oceanic crust by ascending basaltic melts derived by slab-dehydration and mantle wedge melting and magma differentiation under cold, hydrous, oxidizing conditions in an oceanic arc regime. The principal proponents of arc magmatism in Andaman subduction regime include (i) subduction of old, cold, thick and dense Indian ocean lithosphere beneath the Burmese Plate (ii) dehydration of subducted slab and influx of slab-derived fluids and sediments into the adjacent mantle wedge (iii) fluid-driven metasomatism and flux melting of mantle wedge generating island arc basalts (iv) crust-mantle interaction through underplating of basaltic magma beneath lower oceanic arc crust. This was ensued by remobilization and intracrustal melting and assimilation fractional crystallization of melts resulting into basalt-andesite-dacite-rhyolite spectrum. Geochemical signatures suggest metasomatic enrichment of a depleted mantle wedge associated with a Mariana-type subduction system. The studied volcanic rocks from Andaman arc display a calc-alkaline B-A-D-R trend thereby conforming to variable interactions between subducted oceanic slab and sub-arc mantle wedge with influx of subduction-derived fluids and sediments during intermediate stage of subduction.

Conclusions

- Submarine volcanic rocks dredged from Andaman arc, northeastern Indian Ocean display petrographic and geochemical characteristics conforming to a basalt-andesite-dacite-rhyolite (B-A-D-R) spectrum derived from calc-alkaline melts.
- Trace and REE chemistry reflects distinct LILE-LREE enrichment with relative HFSE depletion that can be equated in terms of variable interactions between subducted oceanic slab and sub-arc mantle wedge with influx of subduction-derived fluids and sediments during intermediate stage of subduction.
- Geochemical signatures collectively suggest metasomatic enrichment of a depleted mantle wedge associated with a Mariana-type subduction system.
- Petrogenesis and tectonic implications are in compliance with (i) subduction of old, cold, thick and dense Indian ocean lithosphere beneath the Burmese Plate (ii) Mariana-type subduction and dehydration of old, cold, thick and dense Indian ocean lithosphere beneath the Burmese Plate (ii) variable slab-mantle interactions, metasomatism and flux melting of mantle wedge generating island arc basalts (iii) crust-mantle interaction through basaltic magma underplating beneath lower oceanic arc crust ensued by intracrustal melting and fractional crystallization generating basalt-andesite-dacite-rhyolite spectrum.

Acknowledgement

Authors are grateful to the Director, CSIR-National Institute of Oceanography for his encouragement, support and permission to publish this work. The authors are thankful to Dr. Fareeduddin for the invitation to contribute in the 36th IGC Legacy Volume. The authors thank two anonymous reviewers for their insightful suggestions which have greatly improved the quality of the manuscript. The authors are thankful to Dr. V. Balaram, CSIR-National

Geophysical Research Institute for providing trace element data. The authors acknowledge the supports received from CSIR-NIO ship-cell staffs during SSK 033 and the funding supports from Council of Scientific and Industrial Research (CSIR) and Science and Engineering Research Board (SERB), New Delhi under MLP-1703 and ECR/2018/000309 (GAP 3291) project respectively. This is NIO's contribution No. 9596.

Reference

- Alam, M. A., Chandrasekharam, D., Vaselli, O., Capaccioni, B., Manetti, P., and Santo, P. B., 2004. Petrology of the prehistoric lavas and dyke of the Barren Island, Andaman Sea, Indian Ocean. *Journal of Earth System Science*, v. 113, pp. 715-721.
- Awasthi, N., Ray, J. S., Laskar, A. H., Kumar, A., Sudhakar, M., Bhutani, R., ... and Yadava, M. G., 2010. Major ash eruptions of Barren Island volcano (Andaman Sea) during the past 72 kyr: clues from a sediment core record. *Bulletin of Volcanology*, v.72, pp.1131-1136.
- Ayalew, D., and Ishiwatari, A., 2011. Comparison of rhyolites from continental rift, continental arc and oceanic island arc: implication for the mechanism of silicic magma generation. *Island arc*, v. 20, pp.78-93.
- Bachmann, O., and Bergantz, G. W., 2008. Rhyolites and their source mushes across tectonic settings. *Journal of Petrology*, v. 49, pp.2277-2285.
- Bailey, E. H., Ragnarsdottir, K. V., 1994. Uranium and thorium solubilities in subduction zone fluids. *Earth and Planetary Science Letters*, v. 124, pp. 119-129. 14
- Bandopadhyay, P. C., 2005. Discovery of abundant pyroclasts in the Namunagarh Grit, South Andaman: evidence for arc volcanism and active subduction during the Palaeogene in the Andaman area. *Journal of Asian Earth Sciences*, v. 25, pp. 95-107.
- Chakraborty, P. P., and Pal, T., 2001. Anatomy of a forearc submarine fan: Upper Eocene—Oligocene Andaman Flysch Group, Andaman Islands, India. *Gondwana Research*, v. 4, pp. 477-486.
- Chandrasekharam, D., Santo, A. P., Capaccioni, B., Vaselli, O., Alam, M. A., Manetti, P., and Tassi, F., 2009. Volcanological and petrological evolution of barren island (Andaman Sea, Indian Ocean). *Journal of Asian Earth Sciences*, v. 35, pp. 469-487.
- Chen, C. H., Lee, T., Shieh, Y. N., Chen, C. H., and Hsu, W. Y., 1995. Magmatism at the onset of back-arc basin spreading in the Okinawa Trough. *Journal of Volcanology & Geothermal Research*, v. 69, pp.313-322.
- Condie, K. 2015. Changing tectonic settings through time: indiscriminate use of geochemical discriminant diagrams. *Precambrian Research*, v. 266, pp. 587-591.
- Curry, J. R., 2005. Tectonics and history of the Andaman Sea region. *Journal of Asian Earth Sciences*, v. 25, pp.187-232.
- Dewey, J.F., 1980. Episodicity, sequence, and style at convergent plate boundaries. *Geological Association of Canada Special Paper*, v. 20, 553-573.
- Diehl, T., Waldhauser, F., Cochran, J. R., KameshRaju, K. A., Seeber, L., Schaff, D. and Engdahl, E. R., 2013. Back arc extension in the Andaman Sea: Tectonic and magmatic processes imaged by high precision teleseismic double difference earthquake relocation. *Journal of Geophysical Research: Solid Earth*, v.118, pp.2206-2224.
- Foley, S., Tiepolo, M., and Vannucci, R., 2002. Growth of early continental crust controlled by melting of amphibolite in subduction zones. *Nature*, v. 417, pp.837.
- Ghosh, B., Pal, T., Bhattacharya, A., and Das, D., 2009. Petrogenetic implications of ophiolitic chromite from Rutland Island,

- Andaman—a boninitic parentage in supra-subduction setting. *Mineralogy and Petrology*, v. 96, pp. 59-70.
- Ghosh, B., Bandyopadhyay, D., and Morishita, T., 2017. Andaman–Nicobar Ophiolites, India: origin, evolution and emplacement. *Geological Society of London, Memoirs*, v.47, pp. 95-110.
- Haldar, D. 1984. Some aspects of the Andaman Ophiolite Complex. *Records of Geological Survey of India*, v. 119, pp.1–11.
- Hastie, A. R., Mitchell, S. F., Kerr, A. C., Minifie, M. J., and Millar, I. L., 2011. Geochemistry of rare high-Nb basalt lavas: Are they derived from a mantle wedge metasomatised by slab melts?. *Geochimica et Cosmochimica Acta*, v. 75, pp.5049-5072.
- Hawkesworth, C. J., Gallagher, K., Hergt, J. M., and McDermott, F. 1993. Mantle and slab contributions in arc magmas. *Annual Review of Earth and Planetary Sciences*, v. 21, 175-204.
- He, X. F., Santosh, M., Ganguly, S. 2017. Mesozoic felsic volcanic rocks from the North China craton: Intraplate magmatism associated with craton destruction. *GSA Bulletin*, v. 129, 947-969.
- Jourdain, A., Singh, S. C., Escartin, J., Klinger, Y., KameshRaju, K. A., and McArdle, J., 2016. Crustal accretion at a sedimented spreading center in the Andaman Sea. *Geology*, v. 44, pp. 351-354. 15
- KameshRaju, K. A., Ramprasad, T., Rao, P. S., Rao, B. R. and Varghese, J., 2004. New insights into the tectonic evolution of the Andaman basin, northeast Indian Ocean. *Earth and Planetary Science Letters*, v.221, pp.145-162.
- Kimura, J. I., Nakajima, J., 2014. Behaviour of subducted water and its role in magma genesis in the NE Japan arc: A combined geophysical and geochemical approach. *Geochimica et Cosmochimica Acta*, v. 143, pp. 165-188.
- Le Bas, M. J. R., R. W. Le Maitre, A. L. Streckeisen, and B. Zanettin, 1986. A chemical classification of volcanic rocks based on the total alkali-silica diagram. *Journal of Petrology*, v. 27, pp.745-750
- McCulloch, M.T., and Gamble, J.A., 1991. Geochemical and geodynamical constraints on subduction zone magmatism. *Earth and Planetary Science Letters*, v. 102, pp. 358-374.
- Pal, T., and Bhattacharya, A., 2011. Greenschist-facies sub-ophiolitic metamorphic rocks of Andaman Islands, Burma–Java subduction complex. *Journal of Asian Earth Sciences*. V. 39, 804-814.
- Pal, T., Chakraborty, P. P., Gupta, T. D., and Singh, C. D., 2003. Geodynamic evolution of the outer-arc–forearc belt in the Andaman Islands, the central part of the Burma–Java subduction complex. *Geological Magazine*, v. 140, pp. 289-307.
- Pal, T., Ghosh, B., Bhattacharya, A., and Bhanduri, S. K., 2010. Felsic tuff from Rutland Island- A pyroclastic flow deposit in Miocene-sediments of Andaman Java subduction complex. *Journal of Earth System Science*, v. 119, pp.19-25.
- Pal, T., Mitra, S.K., Sengupta, S., Katari, A., Bandyopadhyay, P.C., and Bhattacharya, A.K., 2007. Dacite-andesites of Narcondam volcano in the Andaman Sea — an imprint of magma mixing in the inner arc of the Andaman–Java subduction system. *Journal of Volcanology and Geothermal Research*, v.168, pp. 93–113.
- Pearce, J.A., 2008. Geochemical fingerprinting of oceanic basalts with applications to ophiolite classification and the search for Archean oceanic crust. *Lithos*, v.100, pp.14-48.
- Pearce, J.A., and Stern, R.J. 2006. Origin of Back-Arc Basin Magmas: Trace Element and Isotope Perspectives. *Back-Arc Spreading Systems: Geological, Biological, Chemical and Physical Interactions. Geophysical Monograph Series*, v.166, pp.63-86.
- Pearce, J. A., Stern, R. J., Bloomer, S. H., Fryer, P., 2005. Geochemical mapping of the Mariana arc-basin system: Implications for the nature and distribution of subduction components. *Geochemistry Geophysics Geosystems*, v. 6, pp.542-557.
- Plank, T., Kelley, K. A., Zimmer, M. M., Hauri, E. H., Wallace, P. J. 2013. Why do mafic arc magmas contain < 4 wt% water on average?. *Earth and Planetary Science Letters*, v. 364, pp.168-179.
- Saha, A., Dhang, A., Ray, J., Chakraborty, S., Moecher, D., 2010. Complete preservation of ophiolite suite from south Andaman, India: A mineral-chemical perspective. *Journal of Earth System Science*, v.119, pp. 365-381
- Saha, A., Ganguly, S., Ray, J., Koeberl, C., Thöni, M., Sarbajna, C., and Sawant, S. S., 2017. Petrogenetic evolution of Cretaceous Samchampi-Samteran Alkaline Complex, Mikir Hills, Northeastern India: Implications on multiple melting events of heterogeneous plume and metasomatized sub-continental lithospheric mantle. *Gondwana Research*, v. 48, pp. 237-256. 16
- Saha, A., Santosh, M., Ganguly, S., Manikyamba, C., Ray, J., and Dutta, J., 2018a. Geochemical cycling during subduction initiation: Evidence from serpentinized mantle wedge peridotite in the south Andaman ophiolite suite. *Geoscience Frontiers*, v.9, pp.1755-1775.
- Saha A., Mudholkar, A.V., Kamesh Raju, K. A., Doley, B., and Sensarma, S., 2018b. Geochemical characteristics of basalts from Andaman subduction zone: Implications on magma genesis at intraoceanic back arc spreading centres. *Geological Journal*. DOI: 10.1002/gj.3345
- Saha, A., D’Mello, N. G., Sensarma, S., Mudholkar, A. V., Doley, B. 2019. Geochemical characteristics of submarine rhyolitic pumice from Andaman subduction zone: Inferences on magmatism and tectonics of north eastern Indian Ocean. *Geological Journal*. <https://doi.org/10.1002/gj.3506>
- Santo, A. P., 2016. Geochemical data on the 2005 lava flow of Barren Island volcano, Andaman Sea. *Current Science*, v. 110, 1896-1899.
- Sheth, H.C., Ray, J.S., Bhutani, R., Kumar, A., and Smitha, R.S., 2009. Volcanology and eruptive styles of Barren Island: an active mafic stratovolcano in the Andaman Sea, NE Indian Ocean. *Bulletin of Volcanology*, v.71, pp.1021–1039.
- Sheth, H. C., Ray, J. S., Kumar, A., Bhutani, R., and Awasthi, N., 2011. Toothpaste lava from the Barren Island volcano (Andaman Sea). *Journal of Volcanology and Geothermal Research*, v. 202, pp.73-82.
- Shinjo, R., and Kato, Y., 2000. Geochemical constraints on the origin of bimodal magmatism at the Okinawa Trough, an incipient back-arc basin. *Lithos*, v.54, pp.117-137.
- Shinjo, R., Chung, S. L., Kato, Y., and Kimura, M., 1999. Geochemical and Sr-Nd isotopic characteristics of volcanic rocks from the Okinawa Trough and Ryukyu arc: Implications for the evolution of a young, intra-continental back arc basin. *Journal of Geophysical Research: Solid Earth*, v. 104, pp.10591-10608.
- Song, X-Y., Qi, H-W., Robinson, P.T., Zhou, M-F., Cao, Z-M., and Chen L-M., 2008. Melting of the subcontinental lithospheric mantle by the Emeishan mantle plume; evidence from the basal alkaline basalts in Dongchuan, Yunnan, Southwestern China. *Lithos* v.100, pp. 93-111.
- Stern, R. J., 2002. Crustal evolution in the East African Orogen: a neodymium isotopic perspective. *Journal of African Earth Sciences*, v. 34, pp.109-117.
- Sun, S.-S., and McDonough, W.F., 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. In: A. D. Saunders and M. J. Norry, (Eds.), *Magmatism in Ocean Basins*, Geological Society of London, Special Publication. v. 42, pp. 313–345,
- Tatsumi, Y., 2005. The subduction factory: how it operates in the evolving earth. *GSA today*, v.15, pp.4-10.
- Viruete, J. E., Contreras, F., Stein, G., Urien, P., Joubert, M., Pérez-

Estaún, A., ... and Ullrich, T., 2007. Magmatic relationships and ages between adakites, magnesian andesites and Nb-enriched basalt-andesites from Hispaniola: record of a major change in the Caribbean island arc magma sources. *Lithos*, v.99, pp.151-177.

Zhao, J.J., Z and hou, M.F. 2007. Geochemistry of Neoproterozoic mafic intrusions in the Panzhihua district (Sichuan Province, SW China): implications for subduction related metasomatism in the upper mantle. *Precambrian Research*, v.152, pp. 27–47.

Dr. Abhishek Saha is working as a Scientist at CSIR-National Institute of Oceanography, Goa. Awarded Ph.D. from University of Calcutta in 2012 and joined as Research Associate and INSA-DST Inspire Faculty at University of Calcutta and CSIR-NGRI respectively. Research fields include formation and emplacement of ancient and modern day oceanic crust, chemical geodynamics, crustal evolution and metallogeny. Published more than 35 research papers in different international journals. Worked as onboard inorganic geochemist in IODP Expedition 345. Recipient of National Geoscience Award 2017 (Young Scientist category), Young Scientist Award 2019 by MoES, Govt. of India, Early Career Research Award by DST, Govt. of India, Gold medals from Geological Society of India, Indian Society of Applied Geochemists and Asiatic Society. Also received Best reviewer Award 2018 from *Geoscience Frontiers*, Elsevier. Presently leading the project “Survey and Exploration of polymetallic nodules” of India.

Dr. K.A. Kamesh Raju served CSIR-NIO, Goa, since 1983 and retired as Chief Scientist. At present he is a visiting scientist at NCPOR, Goa. His area of specialization is Marine geophysics with focus on Tectonics and Geodynamics. He has worked extensively in the Andaman Sea and the Mid-Ocean Ridges of the Indian Ocean. Conducted first ever Ocean Bottom Seismometer experiment in the Andaman Sea in 2013. He is the recipient of National Mineral Award - 2007, for excellence in Applied Geophysics. InterRidge steering committee member 2002-2012. Worked at ORI, Tokyo, invited as visiting scientist by LDEO, US and IPGP, Paris.

Dr. Abhay V. Mudholkar, graduated from Fergusson College (1979) and Post-Graduate (1981) and Doctorate (1988) from University of Pune (now SPPU), Pune. Joined CSIR-NIO, Goa in 1983 as a Jr. Scientist in national project “Surveys for Polymetallic Nodules (SPN)” funded by Dept of Ocean Development (now Min Earth Science, MoES, New Delhi). Worked on the nodules and associated sediments. In 1992, worked at Earthquake Research Institute, Univ Tokyo, Japan, on MORBs from Carlsberg Ridge under JSPS fellowship. Involved in exploration of Carlsberg Ridge and later Andaman Back-arc Basin till retirement as Chief Scientist.