Role of subducting component and sub-arc mantle in arc petrogenesis: Andaman volcanic arc

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Geochemical proxies, especially the trace element ratios of arc lavas from Barren and Narcondam Islands of the Andaman–Nicobar Islands group, display dissimilar characteristics. Narcondam lavas (mostly andesitic) are typically characterized by high Ba/La, Ba/Nb and Th/Nd ratios, reflective of the imprint of substantial subduction component in the form of sediment fluid and melt. On the other hand, Barren lavas (mostly basaltic) show relatively high Ba/Th ratios, indicative of fluid-induced subduction component, mainly signature-inducing fluid component, derived from altered ocean crust.

Keywords: Arc lavas, petrogenesis, subduction component, trace element ratio.

SUBDUCTED sediments and aqueous fluids have long been considered as important ingredients in the chemistry of volcanic arcs related to subduction-zone magmatism[1,2]. Difficulties in sampling of subducting slabs on account of the thick overlying sediments pose a major constraint in inferring the nature of the subducting slab and its contribution to arc petrogenesis. Uses of geochemical tracers from arc lavas can however, effectively overcome this handicap, and have proved to be useful tools in studies of arc petrogenesis. Trace element ratios further help in deciphering the subducting slab input, as have been demonstrated in many well-studied intraoceanic arcs like the Mariana and Aleutian arcs[3,4].

The Andaman arc system in the northeastern Indian Ocean defines a zone of underthrusting of the Indian plate below the Southeast Asian ('Burma') plate, and provides a causal link between the Himalayan collision zone and the Indonesian arc geometry (Figure 1). This active subduction has resulted in the formation of a major island arc–trench system (the Burmese–Sunda arc system) extending for over 1000 km from Myanmar in the north to Sumatra in the south. The nature of the subducting slab and sub-arc mantle chemistry beneath the Andaman island arc have been topics of intense academic debate for several years[5]. The present-day active subduction process was initiated during late Miocene, while seafloor spreading in the back arc can be traced back to the last 4 Ma (ref. 6). Barren and Narcondam volcanic islands (indicated by triangles in Figure 1) are the manifestations of subduction zone magmatism. Barren island is an active volcano which has experienced at least five phases of eruption since 1803 (ref. 7). In contrast, the Narcondam island is a dormant volcano. Geological studies of Barren and Narcondam Islands reveal contrasting volcanic rock suites on both[8,9]. Detailed trace elemental data from the volcanics of both the islands, indicate that the difference of magma series must be reflective of a combination of variable subduction processes and difference in sub-arc mantle composition. Based on geochemical proxies (mainly trace element ratios), we further infer that there are distinct geochemical fingerprints imparted to these lavas. Though lack of knowledge on solid–fluid partitioning imposes certain limitations on utilizing the geochemical proxies, they can still provide useful first-order information on the arc lavas, as we demonstrate in this present communication.

Samples considered for this study were collected in the course of field work carried out on Barren and Narcondam Islands during 2009. Tholeiites and andesites were carefully picked from recent eruptions of Barren and Narcondam Islands respectively. The studied volcanics

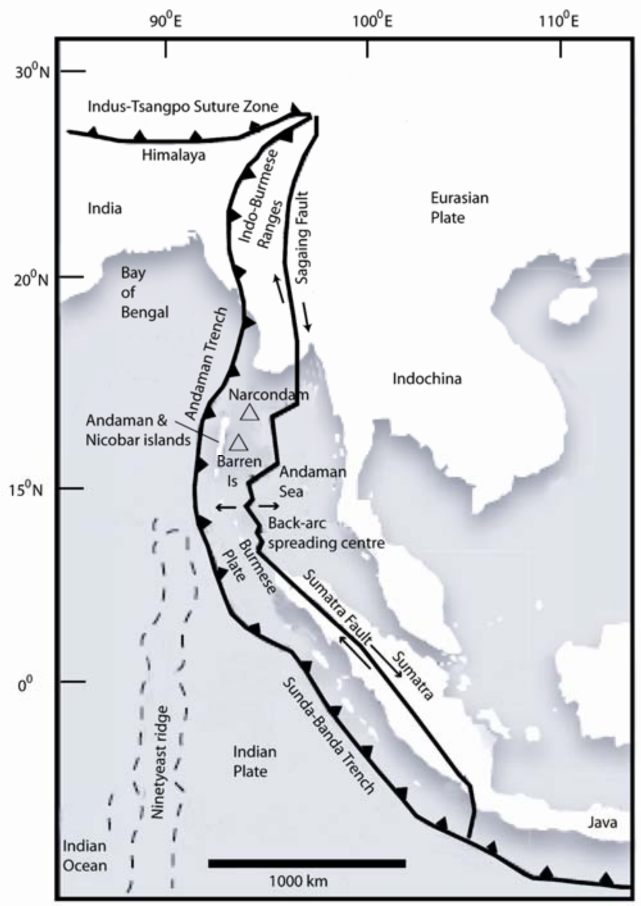

Figure 1. Map showing major geological and tectonic features of the Indian Ocean and southeastern Asia, along with locations of Barren and Narcondam volcanic islands (triangles). Based on Sheth *et al*.[16].

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Table 1. Compositional average and range of major oxides and trace elements for Barren and Narcondam volcanics

	Narcondam (n = 10)[a]		Barren (n = 10)[b]		Narcondam (lit, n = 9)[c]		Barren (lit, n = 18)[d]	
	Average	Range	Average	Range	Average	Range	Average	Range
SiO_2	58.33	52.05–60.67	50.37	48.67–54.08	61.92	61.05–64.87	52.69	50.78–56.05
TiO_2	0.63	0.52–0.89	0.86	0.75–0.97	0.50	0.47–0.52	0.92	0.68–1.21
Al_2O_3	18.42	17.67–19.39	19.15	16.78–22.5	16.13	15.69–17.16	20.23	17.42–21.75
Fe_2O_3	6.44	5.86–8.03	8.56	7.88–9.36	4.34	3.71–5.39	7.54(FeO*)	6.95–8.87(FeO*)
MnO	0.12	0.11–0.13	0.16	0.13–0.18	0.11	0.09–0.13	0.15	0.14–0.19
MgO	2.83	1.04–4.63	6.40	2.87–9.76	2.96	2.14–3.31	4.2	2.9–8.16
CaO	6.85	5.5–9.29	10.13	8.01–11.19	5.91	5.16–6.28	10.28	7.6–11.54
Na_2O	3.29	2.5–3.59	3.06	2.55–3.94	2.98	2.71–3.15	3.25	2.61–4.28
K_2O	1.26	0.61–1.72	0.38	0.27–0.62	1.57	1.47–1.81	0.48	0.32–0.73
P_2O_5	0.10	0.08–0.12	0.09	0.08–0.13	0.13	0.09–0.15	0.12	0.09–0.18
LOI	1.63	0.84–2.23	0.22	0.11–0.3	2.45	1.51–3.51	n.a.	–
Sc	18.62	12.6–30.45	30.68	24.83–35.98	15.22	15–16	31.92	28.9–36.2
V	134.74	72.25–240.42	249.60	207.43–296.29	97.33	77–111	186.72	139–242
Cr	26.78	12.96–57.79	246.51	11.09–480.85	61	6–77	68.72	12–309
Co	16.46	12.24–25.1	27.28	17.42–37.57	30.89	23–38	25.17	22–29
Ni	16.36	8.28–32.44	97.33	12.66–187.28	39	28–51	33.94	13–130
Cu	36.56	21.03–65.21	58.23	33.26–93.12	n.a.	–	81.67	34–125
Zn	42.42	27.69–55.58	69.03	65.37–72.3	n.a.	–	74.56	62–94
Rb	44.29	10.14–62.61	7.83	4.78–11.69	57.11	55–62	12.13	5.3–19.7
Sr	267.80	249.95–304.76	155.62	136.92–185.28	342.11	326–361	197.22	20.9–227
Y	18.29	11.94–31.71	23.88	21.01–29.53	19	15–25	26.15	20–37.5
Zr	49.35	23.8–65.86	67.76	53.69–95.88	98.11	94–104	66.94	48–100
Nb	2.56	2.21–2.86	0.82	0.59–1.03	n.a.	–	0.68	0.42–1.14
Ba	312.64	182.27–435.66	71.41	51.89–105.07	342.67	306–411	90.61	61–136
La	12.69	8.73–19.69	3.86	2.65–5.36	n.a.	–	5.73	3.15–8.88
Ce	21.03	14.99–27.21	9.72	7.1–13.4	n.a.	–	13.57	7.96–20.88
Pr	2.67	2.16–3.94	1.45	1.1–1.97	n.a.	–	1.90	1.16–2.9
Nd	11.01	9–15.73	7.67	6.08–10.14	n.a.	–	9.49	6.1–14.2
Sm	2.57	2.02–3.56	2.42	2.01–3.12	n.a.	–	3.09	2.16–4.56
Eu	0.90	0.68–1.27	0.88	0.76–1.08	n.a.	–	1.11	0.84–1.48
Gd	2.99	2.18–4.43	3.15	2.62–3.95	n.a.	–	3.77	2.8–5.37
Tb	0.45	0.31–0.67	0.55	0.48–0.68	n.a.	–	0.69	0.52–0.98
Dy	2.83	1.92–4.35	3.77	3.31–4.57	n.a.	–	4.56	3.43–6.41
Ho	0.51	0.34–0.82	0.69	0.6–0.84	n.a.	–	0.98	0.75–1.37
Er	2.98	1.97–4.9	4.08	3.55–5.13	n.a.	–	2.76	2.09–3.92
Tm	0.28	0.19–0.46	0.39	0.34–0.48	n.a.	–	0.41	0.32–0.58
Yb	1.75	1.22–2.79	2.47	2.17–3.07	n.a.	–	2.61	2.02–3.67
Lu	0.28	0.19–0.46	0.39	0.34–0.5	n.a.	–	0.42	0.32–0.59
Hf	1.31	0.81–1.63	1.59	1.27–2.23	n.a.	–	1.99	1.49–2.93
Ta	0.16	0.15–0.17	0.07	0.07–0.09	n.a.	–	0.05	0.04–0.09
Pb	6.70	4.25–8.42	1.99	1.36–2.88	n.a.	–	2.44	1.84–3.97
Th	4.04	2.63–5.21	0.58	0.3–0.86	n.a.	–	1.67	0.62–2.73
U	0.96	0.66–1.33	0.15	0.08–0.24	n.a.	–	0.26	0.13–0.42

[a,b]Present study; [c]Pal *et al.*[9]; [d]Luhr and Halder[7]; FeO*, Total Fe as FeO*.

(ten samples from each island) comprise basalts, basaltic andesite and andesite (SiO_2 ~49–61 wt%, Table 1). The porphyritic basalt and basaltic andesite from the Barren Island host phenocrysts of plagioclase and pyroxene in varying proportions (up to 45% and 25% respectively, by volume). Rocks from Narcondam island are principally andesite and rarely amphibole–andesite. The plagioclase content in the Narcondam volcanics varies up to 40% in andesite, while in amphibole andesite, plagioclase and amphibole are found in roughly equal proportions (~25%). Clinopyroxene (~15%) and orthopyroxene (~10%) are the other associated minerals[8].

Major oxides in the lavas were analysed using X-ray fluorescence spectrometer (accuracy better than 5%) and trace elements were analysed by inductively coupled plasma mass spectrometer (accuracy better than 10%). The average and range of the major oxides and trace element data for the present study and published data are provided in Table 1. Basalts and andesite from Barren and Narcondam display two distinct trends: tholeiitic and calc-alkaline respectively (Figure 2). The lavas for tholeiite and calc-alkaline rocks do not fall on a single line of descent and show two distinct differentiation trends (Figure 2). This would indicate that the petrogenesis

Table 2. Average trace element ratios in bulk Andaman sediment, N-MORB, and the range in Andaman arc, Indonesian arc, Mariana arc and Aleutian arc rocks

Ratio	Andaman arc[a] Barren	Andaman arc[a] Narcondam	Andaman sediment[b]	N-MORB[c]	Indonesian arc[d]	Mariana[e]	Aleutian[f]
Ta/Nb	0.08–0.13	0.06–0.08	0.07	0.06	0.07–0.13	0.06–0.1	0.06–0.39
Zr/Nb	67–99	14–26	16.56	31.76	14–23	37–86	21–145
Ce/Pb	4.5–6	2.6–4.7	3.38	25	3–7	3.5–13.4	3.16–34.39
Th/Yb	0.14–0.45	1.5–2.9	4.08	0.04	1–4	0.1–0.5	0.03–0.51
Th/Nb	0.36–1.41	1–1.96	0.75	0.05	0.45–1.12	0.4–0.8	0.08–0.83
Ba/La	16.5–19.6	17–34	17.56	2.52	23–36	22–60	5.2–51.45
Ba/Th	76–180	40–117	64.94	52.5	63–177	187–674	47–708
Sr/Nd	16–24	16–32	13.96	12.33	16–44	18.4–49.4	13–62
$(La/Sm)_N$	0.82–1.22	2.11–3.45	4	0.59	1.92–3.57	0.8–1.7	0.4–1.6

[a]Present study; [b]Plank and Langmuir[20]; [c]Sun and McDonough[13]; [d]Handley *et al*.[23]; [e]Elliot *et al*.[12]; [f]Class *et al*.[3].

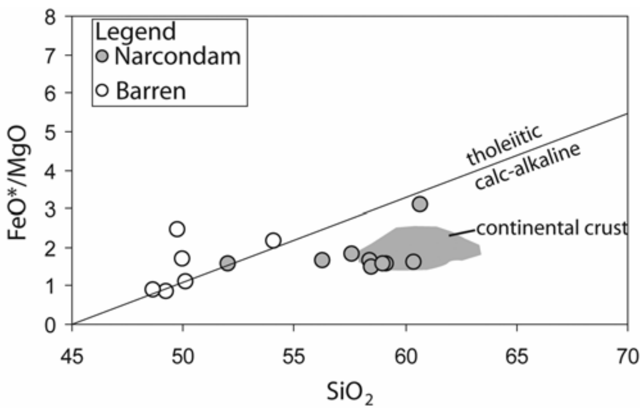

Figure 2. Variation diagrams for Barren and Narcondam volcanics. Tholeiitic/calc-alkaline boundary from Miyashiro[17]; continental crust from Taylor and McLennan[18], and Rudnick and Fountain[19]. Total Fe reported as FeO*.

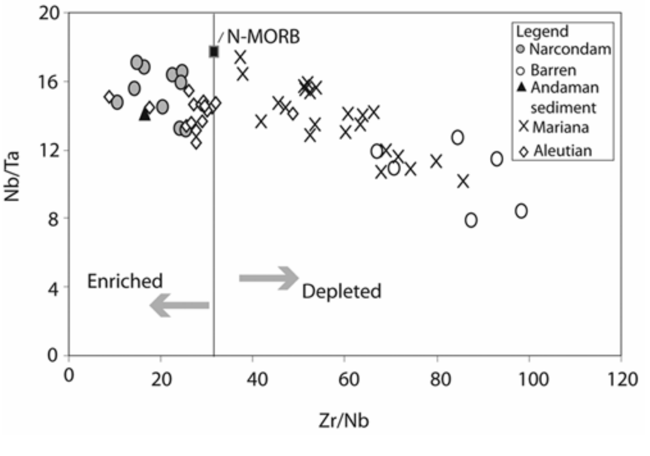

Figure 3. Plot of Zr/Nb versus Nb/Ta for Barren and Narcondam volcanics. N-MORB data from Sun and McDonough[13]. Data Mariana and Aleutian volcanics from Elliot *et al*.[12] and Class *et al*.[3] respectively.

of the tholeiite and calc-alkaline suite cannot be explained by simple fractionation process alone. The discrimination of tholeiite–calc-alkaline is further revealed by the incompatible trace element contents. Thus, for instance, andesite from Narcondam island clearly shows large ion lithophile element (LILE) enrichment (Rb, Ba, K) compared to tholeiite from the Barren island. Such a characteristic is typical of island arc rocks in general[10]. Furthermore, the Narcondam lavas show high light rare element enrichment (La/Sm_N ~ 2.11–3.45). Comparative trace element ratio data from both the islands are presented in Table 1. Selected trace element ratios from Andaman sediment and normal mid-ocean ridge basalt (N-MORB) are also provided for comparison. The volcanics from Barren and Narcondam andesite are compared with Indonesian arc volcanics as these from part of the same arc system and are also relatively better studied. Andaman and Indonesian arc volcanic rocks display comparable Ta/Nb, Ce/Pb, Th/Nb and $(La/Sm)_N$ ratios. Zr/Nb and Ba/La ratios of the Indonesian arc rocks are also comparable with Narcondam andesite of Andaman arc (Table 2).

Mantle wedge is regarded as one of the most important components of arc magma petrogenesis[11]. Considering the proximity of the Barren and Narcondam Islands (~140 km apart), similar mantle-wedge chemistry can normally be expected for the volcanics of the two islands. We use here the concentration of high field strength elements (HFSE) as proxy indicators of mantle-wedge chemistry. HFSE usually constrain the unmodified mantle-wedge composition as they are relatively less affected by the process of sediment addition. Depleted HFSE content and low Nb/Ta ratios in arc volcanic rocks have been regarded as reflecting previous depletion processes due to melt extraction, with the lowest Nb/Ta samples being the most depleted[12]. For example, low Nb/Ta ratios of Mariana arc lavas have been interpreted to support back arc depletion[12]. The Nb/Ta ratios of the Barren volcanic suite (~8–13) are low compared to Narcondam andesite (13–17, Figure 3). Thus, the possibility of previous depletion of unmodified mantle by fractional melting event due to active back-arc spreading cannot be ruled out completely. Zr/Nb ratios of Barren tholeiite also tend to be higher compared to the N-MORB value, suggestive of depletion in mantle wedge (Barren ~67–99 versus N-MORB > 30; Figure 3). In addition, $(La/Sm)_N$ ratio, an index of mantle enrichment, is comparatively high for Narcondam andesite (2.11–3.45), suggestive of the existence of a more enriched sub-arc mantle beneath the Narcondam compared to Barren ($La/Sm_N < 1$). The depletion of sub-arc mantle is further attested by the relatively higher HFSE ratios like Ta/Nb (0.08–0.13) of sediment-poor Barren lavas compared to most normal mid-ocean ridge basalts (0.06)[13]. In contrast, the mantle wedge at Narcondam is characterized by low Zr/Nb ratios (14–26) and low Ta/Nb ratios (0.06–0.08), implying substantial modification due to addition of the subduction component.

Convergent margin volcanism involves the transfer of chemical constituents from the subducting slab into the magma source region in the mantle wedge. One of the current topics of debate revolves around the nature of the transfer agent – an aqueous fluid (either from altered ocean crust or subducted sediment)[2,3], a silicate melt (partial melting of the sediment)[12], or a combination of both. To evaluate the nature of the sediment component in modulating the composition of arc lavas, we take advantage of the fluid mobile nature of Ba and immobile nature of Th and Nb. Arc lavas with lowest Th/Nb can be considered to be derived from sources with least sediment addition. However, the Barren lavas still have high Th/Nb ratios (0.36–1.41), even significantly higher than the N-MORB composition (0.05). So the chemistry of the depleted mantle beneath the Barren island can be expected to have been modified by the input of sediments, as revealed by their high Th/Nb ratios. Addition of aqueous fluid from the subducted slab can readily explain the high Ba/Nb and Ba/La ratios (64–157 and 17–34 respectively) in the Narcondam mantle wedge and, consequently, in the magmas derived from it. Again, Th and the LREE are thought to be less mobile in aqueous fluids than LILE[14], and consequently high Th/Yb ratios in the Narcondam lavas can be taken as an indicator of sedimentary contribution from the slab (Figure 4)[15]. The close resemblance of Narcondam andesite with the Indian Ocean sediments further suggests that the subducted sediments are similar in composition to the Indian Ocean pelagic sediments (Figure 4). The slab fluids added to the Barren mantle wedge were probably derived from an altered ocean crust (AOC, Figure 4).

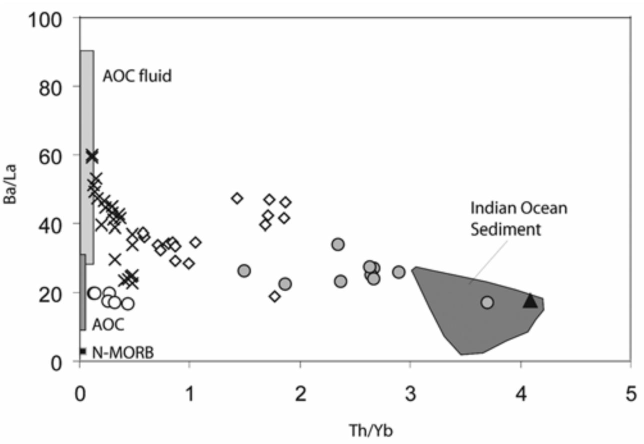

Figure 4. Ba/La–Th/Yb diagram for Barren and Narcondam volcanics. N-MORB data from Sun and McDonough[13]; Andaman sediment from Plank and Langmuir[20]; altered ocean crust (AOC) from Staudigel *et al.*[21], and AOC fluid ratio from Tatsumi *et al.*[22].

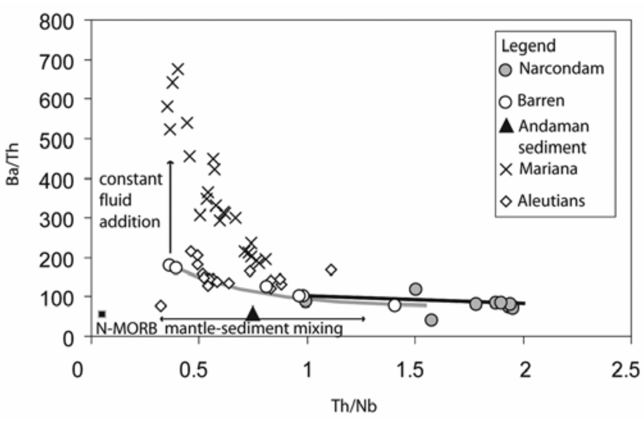

Figure 5. Plot of Ba/Th versus Th/Nb for Barren and Narcondam volcanics. Mariana arc and Aleutian arc data from Elliot *et al.*[12] and Class *et al.*[3] respectively. N-MORB data from Sun and McDonough[13].

Elevated La/Nd and Th/Nb ratios of the sediment component in Mariana lavas, compared to the bulk composition of sediment outboard of the Mariana arc have been taken as evidence for sediment partial melting[12]. The high La/Nd and Th/Nb ratios (0.9–1.25 and 1–1.96 respectively) for Narcondam andesite also support the possible role of sediment melt derived from the subducted sediment. We note that, lavas with the highest Th/Nb ratio are also the most light-rare earth enriched. The tholeiitic and calc-alkaline rocks from Barren and Narcondam show minor increase in Ba/Th with decreasing Th/Nb, producing almost a horizontal trend (Figure 5). This feature contrasts with the Mariana lavas which show a strongly depleted pattern (Figure 5). Elliot *et al.*[12], in their model for Mariana arc suggest that overall inverse correlations of indices of fluid addition, such as Ba/Th, with indices of sediment addition, such as Th/Nb, indicate that an approximately constant fluid flux was added to the mantle that was already variably enriched in sediment component (Figure 5). Strongly depleted mantle with minor sediment addition will produce very high Ba/Th ratios. Samples with high fluid imprint as noted in Barren tholeiite with high Ba/Th ratios further imply that the fluid was formed by dehydration of the altered oceanic Crust[2]. High Th/Nb ratios of andesite (Figure 5) are reflective of sediment melt addition during the subduction process. Thus, variable addition of the sedimentary component could have produced weakly depleted sources that are either relatively sediment-poor (Barren tholeiite) or sediment-rich (Narcondam andesite).

Doubtless, the fundamental result of this study is that there are differences in mantle-wedge chemistry and subduction component between two inner-arc volcanoes, viz. Barren and Narcondam Islands of the Andaman arc system. Narcondam andesite appears to involve substantial sedimentary subducted component as revealed by its high Ba/La, Ba/Nb and Th/Nd ratios. In contrast, the Barren tholeiite displays depleted mantle characteristics and subduction involving substantial aqueous fluid composition derived from an altered ocean crust (high Ba/Th ratio). Sediment melt also played a significant role in modifying the arc geochemistry at the Andamans. Deep drilling in the Andaman trench area and radiogenic isotopic studies of volcanics may possibly refine the understanding of the nature of subducting plate and slab–mantle interaction processes in a more precise way.

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