INDONESIAN JOURNAL ON GEOSCIENCE
Geological Agency
Ministry of Energy and Mineral Resources

Journal homepage: http://ijog.geologi.esdm.go.id
ISSN 2355-9314, e-ISSN 2355-9306

Geochemical Characteristics of Sunda Volcanic Arc in Sumatra and Andaman

Hananto Kurnio

Marine Geological Institute, Research and Development Agencies for Energy and Mineral Resources
Jln. Dr. Djundjunan No. 236, Bandung

Corresponding author: hanantokurniosalamun@gmail.com
Manuscript received: July, 3, 2017; revised: February, 26, 2018;
approved: October, 22, 2018; available online: January, 22, 2019

Abstract - Geochemical characteristics of Sunda volcanic belt are recognized from each characteristic of Weh Island, Tabuan Island in Semangko Bay, South Sumatra, and Andaman Islands. Trace and rare earth elements (REE) are produced by fumaroles in a marine environment of submarine volcano of Weh Island characterized by barium (Ba) as an indicator of sea water influence in the mineralization process, while sulphide minerals do not occur in this area. REE pattern compared to Mid Oceanic Ridge Basalt (MORB) shows a characteristic of subduction tectonics and is distributed in shallow coastal water of high energy. Based on comparison of REE contents in all samples, it reveals that volcanism process causes REE enrichments either in the past or ~~in~~ recent. Geochemical characteristics of Tabuan Island in Semangko Bay reveal the occurrence of hydrothermal mineralization followed by pervasive occurrences of sulphide minerals in vein-type disseminations enriched in Au, Ag, Zn, Pb, Cu, As, Sb, Ba, and Mn. Geochemical characteristics of Andaman Islands reveal imprint of substantial subduction component in the form of sediment fluid and melt and fluid-induced subduction component derived from altered oceanic crust.

Keywords: geochemical characteristics, Sunda volcanic belt, Weh Island, Semangko Bay, Andaman Islands

How to cite this article:

Kurnio, H., 2019. Geochemical Characteristics of Sunda Volcanic Arc in Sumatra and Andaman. *Indonesian Journal on Geoscience*, 6 (1), p.1-16. DOI: 10.17014/ijog.6.1.1-16

Introduction

Background

Sunda volcanic arc is located in the western coastal zone of Sumatra, to the north between Weh and Andaman Islands (Figure 1). The intense earthquake area is a transition tectonic zone between Sumatran active transform fault in the south and Andaman back - arc spreading in the north (Curray *et al*., 1979; Curray, 2005).

The Sunda volcanic arc of Sumatra is characterized by a chain of volcanoes formed above the subducting plate of Indo - Australian oceanic Plate below the Eurasia continental Plate (Bowin *et al*., 1980). This volcanic arc is parallel to an oceanic trench located in the west of Sumatra and marked an active convergent boundary. The volcanic arc was formed due to the oceanic plate saturated with water and volatiles are drastically lowering the melting point of mantle as it is further subducted. Greater pressures with increasing depth cause water to squeeze out of the plate and introduce it to the mantle and melts to form magma. The magma ascends to the surface to form an arc of volcanoes parallel to the subduction zone.

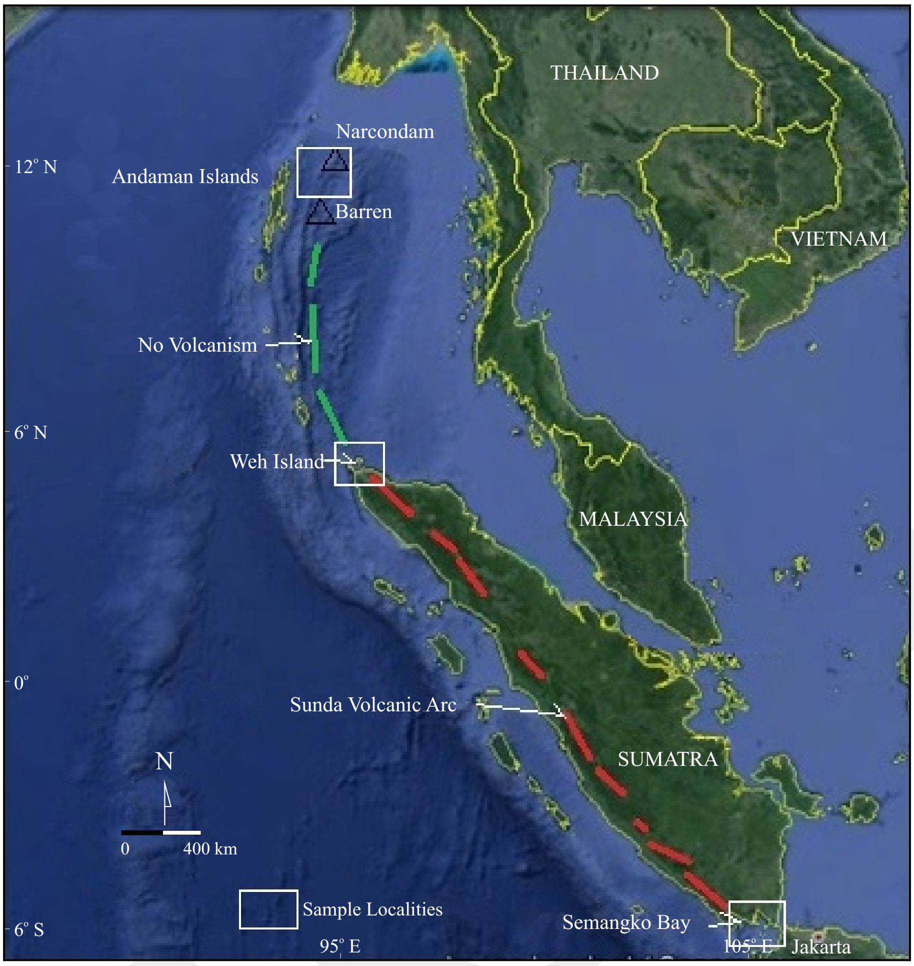

Figure 1. Sunda volcanic arc Sumatra to Andaman (source: google earth) and locations of geochemical data used. No volcanic activities between Weh and Andaman Islands.

The Sunda Arc is a classic example of a volcanic island arc, in which all elements of geodynamic features can be identified. In Sumatra, the volcanic arc forms the topographic summit, especially in the western coastal zone. The Sunda Arc is also the home for some of the world most dangerous and explosive volcanoes. One example was the Toba super - eruption in North Sumatra which the resulting caldera that has become Lake Toba today.

Volcanic activity periods of Sunda belt of Sumatra dated back to Jurassic to Early Cretaceous period (203 - 130 Ma) based on dating of K/Ar mineral ages from the Barisan Mountains of southern Sumatra (McCourt *et al*., 1996). Much older period of volcanic activity was also recognized in the Permian (287 - 256 Ma) from exposed plutons in western Sumatra. The periods continued to Mid - Late Cretaceous (117 - 80 Ma), Early Eocene (60 - 50 Ma), and Miocene - Pliocene (20 - 5 Ma). On the other hand, a periodic volcanic activity in northern Sumatra had been started in the Late Eocene (Cameron *et al*., 1980). Three volcanic activities are recognized from three Tertiary volcanic rock supergroups which are marked by an unconformity in the Late Oligocene and a tectonic event in the Middle Miocene. The later volcanic event occurred in Pleistocene and in conjunction with sea - floor spreading commencement in the Andaman Sea, the rise of Barisan Mountains, and the growth of Sumatran Fault System.

Chemical characteristics of volcanoes around the arc systems could be correlated directly to their tectonic environment (Hutchinson, 1981). One factor that influences geochemical characteristics of the arc is the depth to the underlying Benioff Zone and whether continental or oceanic crust that constructs the volcanoes. The depth to the underlying Benioff Zone beneath the volcanoes is located between 165 km and 190 km. The volcanic rocks vary in composition from calc - alkaline to highly potassic. Based on the very low Ni concentrations and low Mg/Mg+Fe composition of andesite, Foden and Varne (1981) suggested that this volcanic rock was derived from mantle and have probably been modified by fractional crystallization processes. They further proposed that the calc-alkaline suite probably originated by partial melting of the peridotite mantle - wedge overlying the active Benioff Zone.

Samples and Methodology

Data used are geochemical data consisting of major, trace, and rare earth elements of volcanic rocks obtained from the Semangko Bay, Weh Island, and Andaman Islands. The first two locations are the places where the author was involved in the surface rock samplings in the field as well as in its laboratory analyses, while Andaman data are secondary derived from Ray *et al*. (2012). Semangko Bay data were geochemically analyzed in BGR, Germany, during the programme of visiting researcher in 2004 sponsored by DAAD, and Weh Island samples were analyzed in PT Intertek Jakarta. The method used for analyses were ICPMS (Inductively Couple Plasma Mass Spectrometry) which could simultaneously determine major, trace, and rare elements of volcanic rocks. Eighteen samples were used for this study.

Methods of the study on geochemical characteristics of Sunda volcanic belt in Sumatra and Andaman are the application of diagrams such as AFM plot and multi - element spider diagrams to identify its magma origin and tectonic setting. Geochemical data used are from Kurnio *et al*. (2005, 2008), Ray *et al*. (2012), and Kurnio *et al*. (2016), while rocks analyzed are lava and pyroclastic of basaltic - andesitic composition.

Results

Weh Island, Aceh

Weh Island is the administrative area of Sabang City, Aceh Province, located at the westernmost of the Indonesian Territory. A zero kilometre monument was built in this island to remind its westernmost position. From Banda Aceh, the capital city of Aceh Province, it takes about one hour to reach this island using a speed ferry.

Selected seafloor samples closed to active fumaroles in Weh Island submarine volcano (Figure 2) collected either by grab sampling from the boat or directly by divers exposed plenty of trace and rare earth elements (Kurnio *et al*., 2016). On the other hand, examinations of main sulphide elements using statistical method, Pearson correlation coefficient (r) (Rollinson, 1995), between Fe, Zn, Ni, and S showed negative values. Pearson correlation method is a measure of strength of the association between two variables. Variables used here are element contents of trace and rare earth elements as previously mentioned. Negative statistical results interpret that sulphide minerals do not occur in Weh Island. Mineralization in Weh Island is also influenced by sea water, as shown by r high values (0.543213 - 0.8638) between Pb, Zn, Ni, and Ba (Kurnio *et al*., 2016). Ba is an indicator of mineralization process in a marine environment (Durbar *et al*., 2014). Contents of trace element are shown in Table 1.

Trace element contents from seafloor rock samples (Table 2) show positive and negative correlations with the sea depth as seen in Figure 3. The negative correlations of Fe, Cr, Ti, and La are possibly due to less marine energy influence on its deposition, and they could only be deposited at high energy environment of shallow marine that is close to the coastal zone. On the other hand, positive correlations are shown in contents of Cu, Ba, Li, and La. According to Dehairs (1980), Danielsson (1980), and Till *et al*. (2017) the increase contents of Ba, Cu, and La to a deeper sea are related to biogeochemical cycle in open seas. Elevated contents of lithium (Li), from about 1 to 17 ppm in Weh coastal water, could be related to

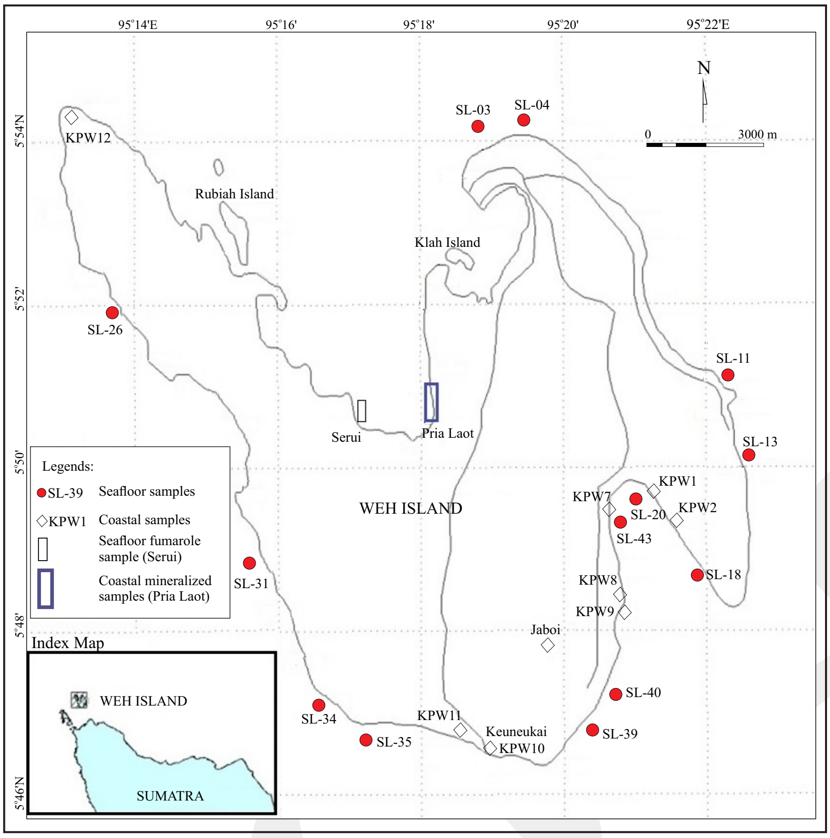

Figure 2. Sample location map of Weh Island used in this study.

Table 1. Trace Elements from Seafloor Samples (SL-), Mineralization Zone (PRIA LAOT-), Coastal Zone (KPW-), and Diving Sites (SERUI-)

NO	IDENT	Cu	Zn	Pb	Ni	As	Mo	Ba
	UNITS	ppm	ppm	ppm	ppm	ppm	ppm	ppm
	DET.LIM	1	1	1	1	1	0.1	1
	SCHEME	4A/OE	4A/OE	4A/MS	4A/OE	4A/MS	4A/MS	4A/MS
1	SL-18 / 30 M	21	63	17	13	6	1.6	212
2	SL-20 / 34 M (SAND)	11	94	13	16	6	0.5	175
3	PRIA LAOT SUNGAI KECIL	3	6	1	3	5	0.4	16
4	PRIA LAOT SILIFIKASI	5	4	2	4	9	0.4	6
5	PRIA LAOT HONEY COMB	9	7	1	5	25	0.5	97
6	CLAY PRIA LAOT	16	6	12	3	6	2.8	218
7	KPW 01 (tuf)	107	65	18	12	34	0.9	280
8	KPW 02 (tuf)	49	68	18	10	19	0.8	334
9	KPW 07 (lava)	54	75	19	11	15	0.7	463
10	KPW 08 (lava)	67	74	19	14	20	0.7	358
11	KPW 09 (lava)	111	63	20	10	34	0.9	385
12	KPW 10 (lava)	39	96	10	16	10	0.4	212
13	KPW 11 (lava)	16	69	19	9	11	0.7	292
14	KPW 12 (lava)	45	86	18	12	11	0.5	499
15	JABOI 244/60	18	4	2	4	6	2.5	17
16	BALOHAN LOKASI TAMBANG (tuf)	221	64	16	11	61	0.8	249
17	SERUI - B - 15 M (DIVING) (S)	14	60	19	10	63	3.2	261
18	SERUI - C - 23 M (DIVING) (S)	13	66	15	12	16	4.6	171

Table 2. Selected Samples of Seafloor Trace Element Contents

NO	Sampe ID / Trace Element	Fe (%)	Cr (ppm)	Cu (ppm)	Ba (ppm)	Ti (ppm)	Li (ppm)	La (ppm)	Lu (ppm)	Sea Depth (m)
1	SL-03	0.15	7	3	9	102	1.6	0.8	0.025	20
2	SL-04	0.24	2.5	2	13	176	1.5	0.9	0.025	28
3	SL-11	2.19	12	4	21	1810	3.1	2.5	0.05	17
4	SL-13	8.18	28	8	99	6110	15.5	11.5	0.36	7
5	SL-18	3.84	47	21	212	3140	23.4	17.4	0.22	30
6	SL-20	6.28	21	11	175	4430	20.1	14.7	0.3	34
7	SL-26	0.17	2.5	1	11	158	0.9	0.3	0.025	27
8	SL-31	4.94	22	5	27	3130	5.2	3.9	0.1	21
9	SL-34	1.97	15	4	16	1460	3.4	2	0.07	15
10	SL-35	0.57	7	2	13	480	2.2	1.3	0.025	21
11	SL-39	0.8	8	2	17	627	3.5	1.8	0.025	28
12	SL-40	0.38	7	1	14	327	1.9	1	0.025	17
13	SL-43	2.39	36	7	153	1600	20.3	10.8	0.2	17

areas of geothermal activities as well as seafloor thermal vents (Garrett, 2004).

The contents of light rare earth elements (LREE) of Weh Island are higher than the standard of Mid Oceanic Ridge Basalt (MORB) (Figure 4), while heavy rare earth elements (HREE) are lower than the MORB. These Weh Island geochemical characteristics resemble the subduction pattern as revealed from the figure. All analyses for REE provenance mentioned were done on andesitic lava and andesitic fragments which are close to seafloor fumaroles.

Seafloor sediment of the studied area was determined by its provenance using triangle diagram Sc - Th - La (Cingolani *et al.*, 2003). Plotting of the three elements from seafloor sediments belong to continental and oceanic - island - arcs (Figure 5). The evidence is shown by a progressive decrease in total Fe as Fe_2O_3 + MgO, TiO_2, Al_2O_3/SiO_2, and a decrease in K_2O/Na_2O and $Al_2O_3/(CaO + Na_2O)$ (in sediments as the tectonic setting changes from oceanic - island - arc to continental - island - arc (Tables 3 and 4) (Bhatia, 1981). Megascopically, plotted sediment on continental - island - arc is characterized by gravel - size andesite rock, while sediment plotted on oceanic - island - arc is sand rich in mafic minerals of magnetite.

Sediments on seafloor of Weh coastal water are determined by its provenance using diagram of Sc - Th - La (Cingolani *et al.*, 2003). The plotting diagram of Weh Island seafloor sediments falls into continental - and oceanic - island - arcs (Figure 5). This distribution is possibly correct as the studied area was regionally formed by the interaction between oceanic and continental plates of Indo - Australia and Eurasia. But the interpretation should thoughtfully be reached, because certain tectonic settings do not automatically generate rocks with unique geochemical signs (McLennan *et al.*, 1990; Bahlburg, 1998).

Rare earth elements consisting of Lanthanum (La), Cerium (Ce), Praseodymium (Pr), Neodymium (Nd), Promethium (Pm), Samarium (Sm), Europium (Eu), Gadolinium (Gd), Terbium (Tb), Dysprosium (Dy), Holmium (Ho), Erbium (Er), Thulium (Tm), Ytterbium (Yb), and Lutetium (Lu) occur in seafloor sediments (SS), altered andesitic lava (AAL), tuff (T), unaltered lava (UL), and sediments close to seafloor fumaroles (SSF) in Weh Island. From all fifteen REE mentioned, only Promethium that was not appeared from the analyses; this is due to Pm do not occur in the nature. It is artificially made in the laboratory (Pallmer and Chikalla, 1971). Comparison of rare earth element contents in samples mentioned demonstrates that unaltered or fresh lava (UL) and seafloor fumarole sediments (SSF) have higher REE contents than the others (Figures 6 - 8). This

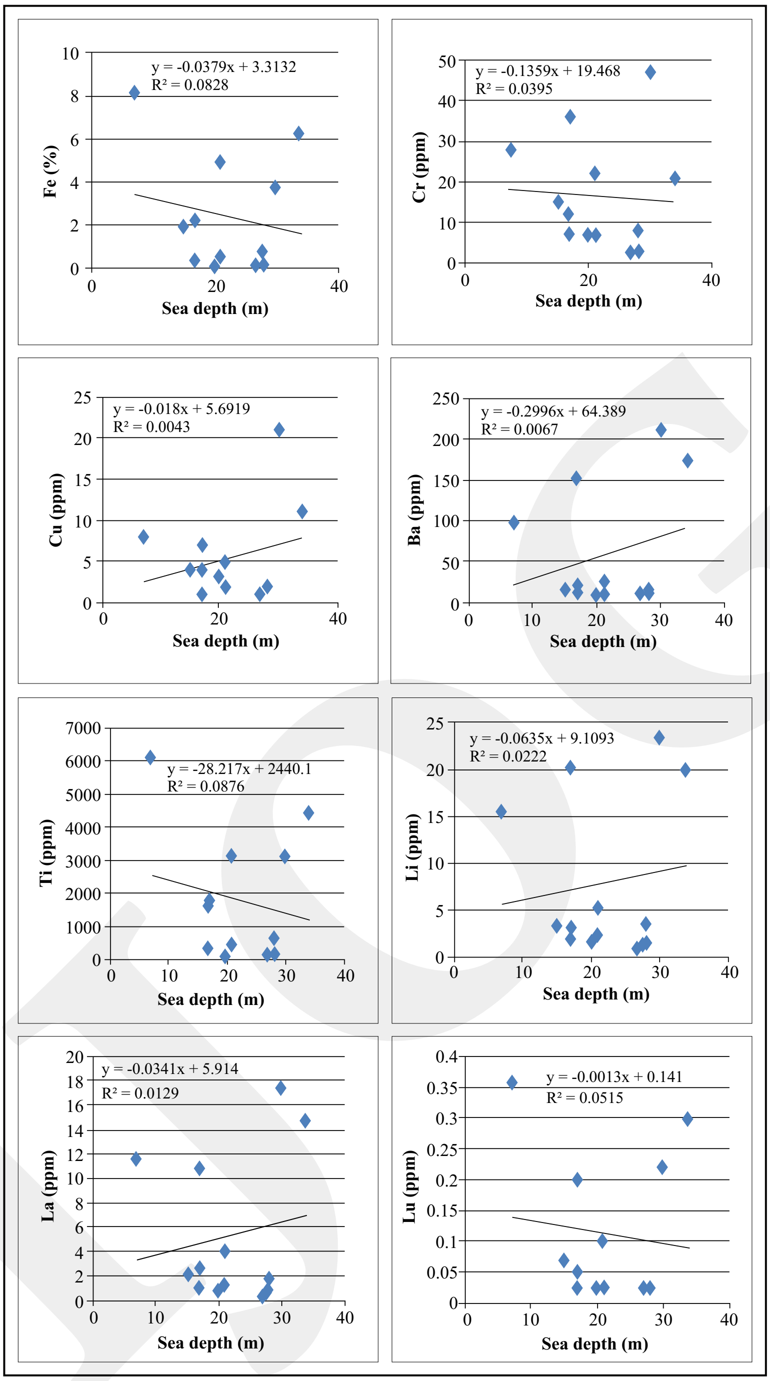

Figure 3. Correlation between trace elements and sea depths which shows some increased (Cu, Ba, Li, and La) and decreased (Fe, Cr, Ti, and Li) contents in deeper seas. Blue symbols in Table 2 represent sea floor samples.

explains that volcanism process causes REE enrichment either in the past (unaltered lava) and in recently (sediments closed to seafloor fumaroles).

In a volcanism process, REE mobility is significantly influenced by hydrothermal processes; but during hydrothermal alteration they are immobile. REE in the geothermal region are strongly influenced by the hydrothermal mobility formed by sulfuric acid fluids that may be found at the top of a volcano or around caldera rings. This is a place of groundwater mixing with magmatic gas rising to the surface (Lintjewas and Setiawan, 2018). On the other hand, REE primary deposits are associated with igneous rocks relatively rich

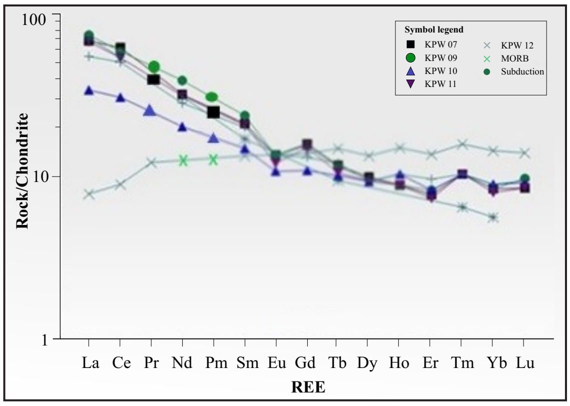

Figure 4. REE spider diagram for andesitic lava in Weh Island. MORB diagram from Regelous *et al.* (2002), subduction diagram from Nakamura (1974).

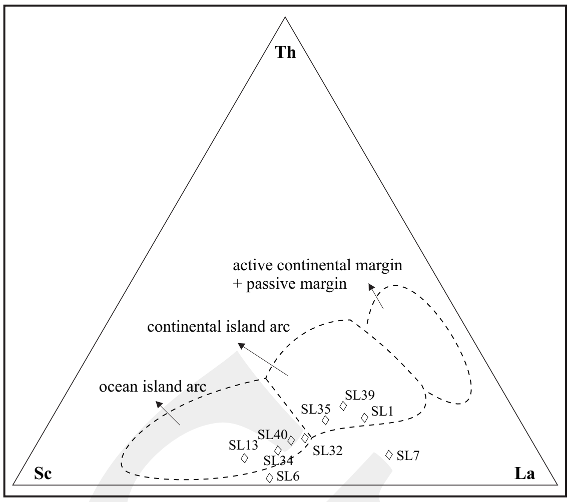

Figure 5. Seafloor sediment provenance of Weh Island is distributed among the continental and oceanic-island-arc (Bhatia and Crook, 1986).

in Light - REE (LREE). The LREE consist of Sc, La, Ce, Pr, Nd, Pm, Sm, and Eu; also known as the cerium group. While heavy rare earth elements (HREE) comprise Y, Gd, Tb, Dy, Ho, Er, Tm, Yb, and La, which belong to the yttrium group. Examination and comparison of LREE and HREE of samples of Unaltered Lava (UL) and sediments are close to seafloor fumaroles (SSF) reveal more abundances of LREE in the latter sediments than the previous rocks, while HREE show almost the same contents from both (Table 5). Imprints of REE deposition were observed surrounding the active seafloor crater rim (Kurnio *et al*., 2016).

Seafloor sediment samples of Sc - Th - La diagram above which falls into continental - island - arc, megascopically are characterized by the existence of andesitic - cobble - size rock fragments. On the other hand, oceanic - island - arc samples are described enriched in

Table 3. Major Elements of Some Seafloor Sediments Used in Bhatia and Crook Diagram (Figure 5)

IDENT	Al_2O_3	CaO	Fe_2O_3	K_2O	MgO	Na_2O	SiO_2	TiO_2
UNITS	%	%	%	%	%	%	%	%
SL-13 / 7 M (S)	14.26	12.54	12.56	0.62	5.8	2.7	44.15	1.13
SL-34 / 15 M	1.06	43.9	3.28	0.07	4.73	0.85	3.69	0.26
SL-40 / 17 M	0.62	50.72	0.63	0.04	1.03	0.79	2.4	0.04
SL-35 / 21 M	0.56	47.87	0.99	0.03	2.6	0.96	2.18	0.06
SL-39 / 28 M	1.03	46.52	1.47	0.09	2.54	0.96	3.63	0.1

Table 4. Progressive Decrease of Fe_2O_3 + MgO, TiO_2, Al_2O_3/SiO_2, and Increase of K_2O/Na_2O and $Al_2O_3/(CaO + Na_2O)$ from Oceanic-Island-Arc to Continental-Island-Arc

IDENT	Fe_2O_3 +MgO	Al_2O_3/ SiO_2	TiO_2	K_2O/ Na_2O	Al_2O_3/CaO +Na_2O	Notes
SL-13 / 7 M (S)	18.36	0.32299	1.13	0.2296296	0.935695538	Oceanic Island Arc
SL-34 / 15 M	8.01	0.287263	0.26	0.0823529	0.023687151	Oceanic Island Arc
SL-40 / 17 M	1.66	0.258333	0.04	0.0506329	0.012036498	Oceanic Island Arc
SL-35 / 21 M	3.59	0.256881	0.06	0.03125	0.01146836	Oceanic Island Arc
SL-39 / 28 M	4.01	0.283747	0.1	0.09375	0.021693345	Oceanic Island Arc

Table 5. Comparison of LREE And HREE in Unaltered Lava (UL) and Sediments Closed to Seafloor Fumaroles (SSF)

UL	LREE						HREE								
Ident	**La**	**Ce**	**Pr**	**Nd**	**Sm**	**Eu**	**Y**	**Gd**	**Tb**	**Dy**	**Ho**	**Er**	**Tm**	**Yb**	**Lu**
Units	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**
KPW01	19.1	42.4	4.92	19	4	0.8	15.9	3.8	0.46	3.1	0.6	1.8	0.3	1.7	0.31
KPW02	18	39.2	4.51	16.7	3.9	0.8	16	3.5	0.48	3	0.6	1.7	0.3	1.7	0.31
KPW07	21	50.3	5.2	19.2	4.1	1	15.8	4.2	0.53	3.3	0.6	1.7	0.3	1.8	0.28
KPW08	19.7	46.4	5.43	20.7	4.7	1.1	17.6	4.2	0.56	3.6	0.7	2.1	0.3	2	0.32
KPW09	22.9	48.1	6.13	23.2	4.6	1	15.9	4.1	0.52	3.2	0.6	1.8	0.3	1.8	0.32
KPW10	10.7	25.3	3.02	12.2	2.9	0.8	16.1	2.9	0.46	3.1	0.7	1.8	0.3	1.9	0.3
KPW11	20.8	43.9	5.04	18.8	4	0.9	15.9	4	0.48	3.1	0.6	1.6	0.3	1.7	0.28
KPW12	17.1	41	4.37	16.9	3.9	1	18.5	3.5	0.55	3.1	0.7	2.1	0.3	1.9	0.31
Average	**18.6625**	**42.075**	**4.8275**	**18.3375**	**4.0125**	**0.925**	**16.4625**	**3.775**	**0.505**	**3.1875**	**0.6375**	**1.825**	**0.3**	**1.8125**	**0.30375**
SSF	**LREE**						**HREE**								
Ident	**La**	**Ce**	**Pr**	**Nd**	**Sm**	**Eu**	**Y**	**Gd**	**Tb**	**Dy**	**Ho**	**Er**	**Tm**	**Yb**	**Lu**
Units	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**
Serui - A - 5 m (diving)	17.4	37.6	5.14	20.4	5	1	20.8	4.2	0.63	4.4	0.9	2.3	0.4	2.2	0.83
Serui - A - 10 m (diving) (S)	13.7	30	3.56	14.5	2.9	0.6	12.3	2.7	0.38	2.4	0.5	1.4	0.2	1.4	0.21
Serui - B - 10 m (diving)	14.3	30.8	4.4	18.3	4.9	1	24.3	4.7	0.75	4.1	0.9	2.6	0.4	2.5	0.41
Serui - B - 15 m (diving) (S)	202	42	4.58	18.6	3.7	0.8	15.3	4	0.49	3.1	0.6	1.8	0.2	1.7	0.28
Serui - C - 10 m (diving)	13.9	35.2	4.78	21.8	5.5	0.9	23.5	5.2	0.73	5	1	2.7	0.4	2.6	0.42
Serui - C - 23 m (diving) (S)	15.5	35.2	4.05	17.2	4.2	0.8	16.8	4.2	0.55	3.4	0.7	1.9	0.3	1.8	0.29
Serui - D - (diving)	17.7	39	4.78	21.8	5.3	0.9	26.5	5.3	0.69	4.8	1	2.6	0.4	2.5	0.37
Serui - E (diving)	0.6	1.5	0.17	0.7	0.1	0.05	0.8	0.2	0.025	0.1	0.05	0.05	0.05	0.1	0.025
Pria Laot A (diving)	16.5	37.3	5.51	23.2	6	1	26.7	5.2	0.82	5.6	1	3	0.4	2.4	0.46
Pria Laot B (diving)	35.4	99.3	12.1	35	2.8	0.4	2.9	3.8	0.25	0.9	0.1	0.4	0.05	0.3	0.06
Average	**16.52**	**38.82**	**4.907**	**19.15**	**4.04**	**0.745**	**16.99**	**3.95**	**0.5315**	**3.38**	**0.675**	**1.875**	**0.28**	**1.75**	**0.3355**

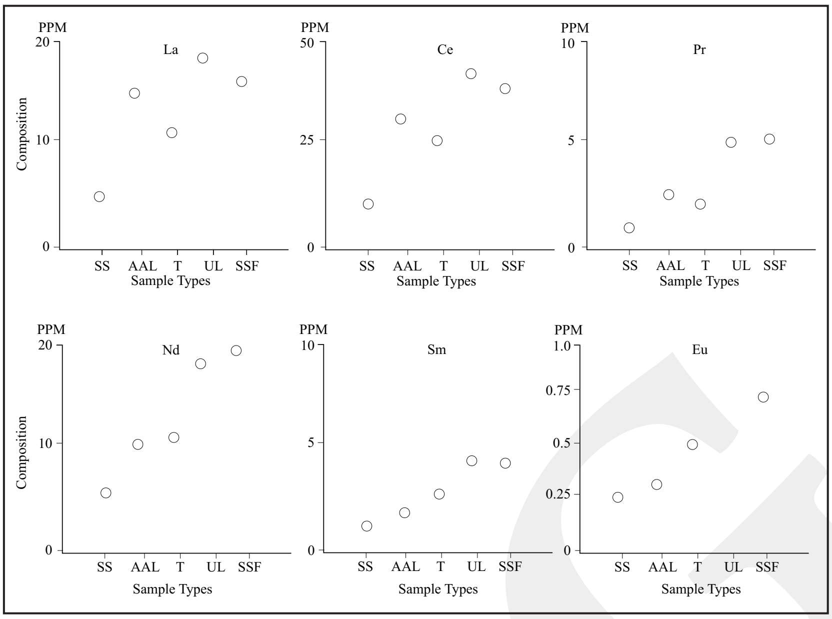

Figure 6. REE scatter diagrams of La, Ce, Pr, Nd, Sm, and Eu in sample types of seafloor sediments (SS), altered andesitic lava (AAL), tuff (T), unaltered lava (UL), and sediments that are close to seafloor fumaroles (SSF).

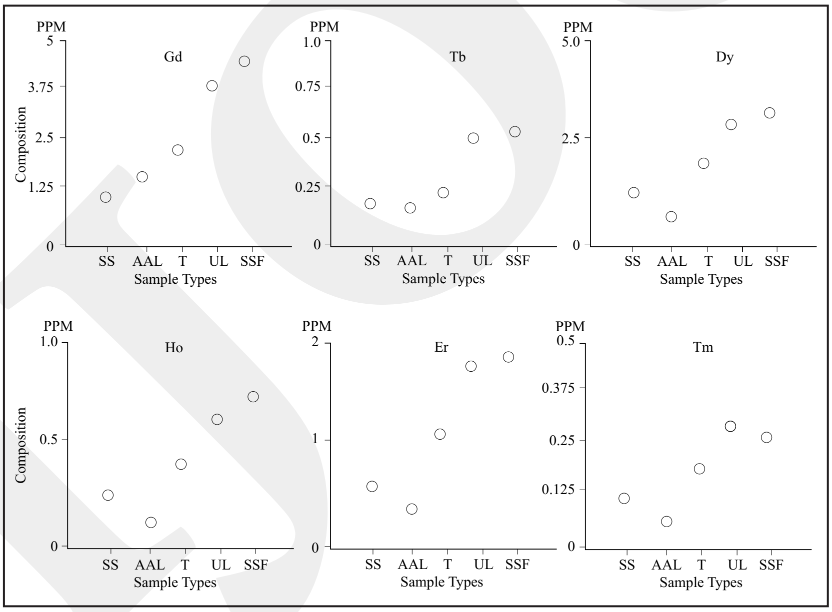

Figure 7. REE scatter diagrams of Gd, Tb, Dy, Ho, Er, and Tm in sample types of seafloor sediments (SS), altered andesitic lava (AAL), tuff (T), unaltered lava (UL), and sediments closed to seafloor fumaroles (SSF).

mafic minerals of magnetite, magnesium, and titanium.

Ternary diagram of Al_2O_3 - MgO - FeO shows geochemical characteristics of Weh Island, North Sumatra, Narcondam and Barren - Andaman and Semangko Bay - South Sumatra (Figure 9). They mostly fall into a spreading centre island, except Barren volcano which is included into an orogenic tectonic regime. The tectonic regime of spreading in the centre of the island is in accordance with Sunda volcanic belt that changes from subducting related tectonism in Sumatra to back - arc spreading in Andaman Sea in the north (Ray *et al.*, 2012; Figure 10). Orogenic tectonic of Barren Island could possibly be related to Himalaya orogenic belt in Indian Micro - continent in the north.

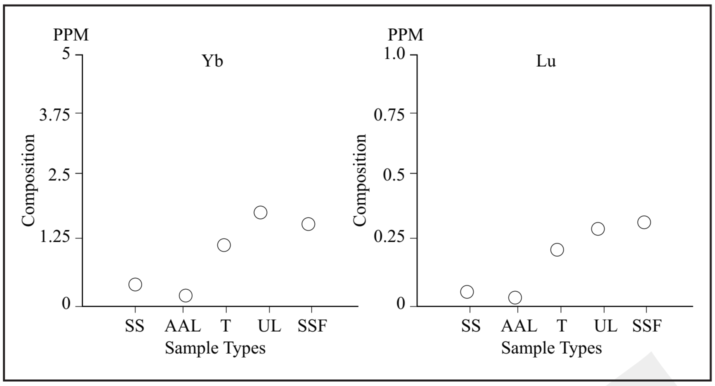

Figure 8. REE scatter diagrams of Yb and La in sample types of seafloor sediments (SS), altered andesitic lava (AAL), tuff (T), unaltered lava (UL), and sediments that are close to seafloor fumaroles (SSF).

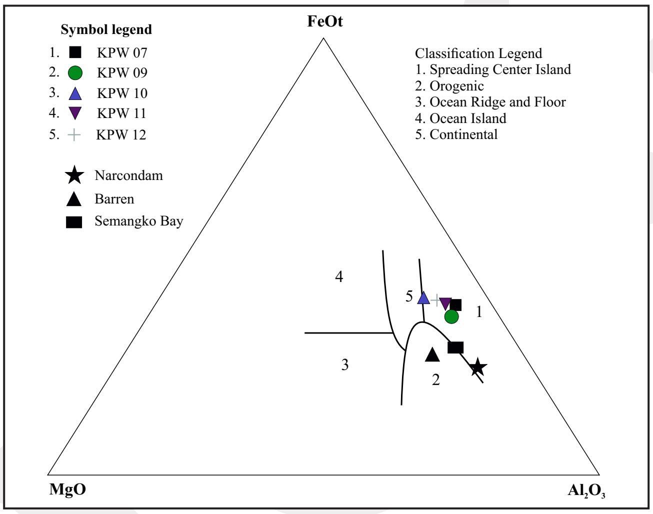

Figure 9. Basalt, basaltic andesite, and andesite lavas of Weh Island, Narcondam and Barren - Andaman and Semangko Bay.

Semangko, Southern Sumatra

Geochemical characteristics of Tabuan Island in Semangko Bay, Southern Sumatra, were first studied by Kurnio *et al.* (2008) in Federal Institute for Geoscience and Natural Resources (BGR), Germany. The geochemical characteristics reveal the occurrence of hydrothermal mineralization which was suggested from seismic identification of small intrusive bodies which form elongated northwest - southeast ridges passing through the island. The mineralization was followed by pervasive occurrences of sulphide minerals in vein - type disseminations. Enrichments in Au, Ag, Zn, Pb, Cu, As, Sb, Ba, and Mn follow the mineralization. Great potential for epithermal type Au - Ag and metal deposits occurs in Semangko Bay area, as revealed by the association of subaerial island - arc volcanism and subvolcanic intrusive bodies, the regional extensional and strike - slip structural regime, and the occurrence of epithermal - style alteration and mineralization in the same volcanic sequence along the coastal zone (Kurnio *et al.*, 2008).

Andaman

Geochemical characteristics of Andaman Islands reveal imprint of substantial subduction component in the form of sediment fluid (Figure 11) and melt and fluid - induced subduction component derived from altered oceanic crust (Ray *et al.*, 2012). The characteristics were derived from the trace element ratios of arc lavas which show high Ba/La, Ba/Nb, Th/Nd, and relatively high Ba/Th ratios.

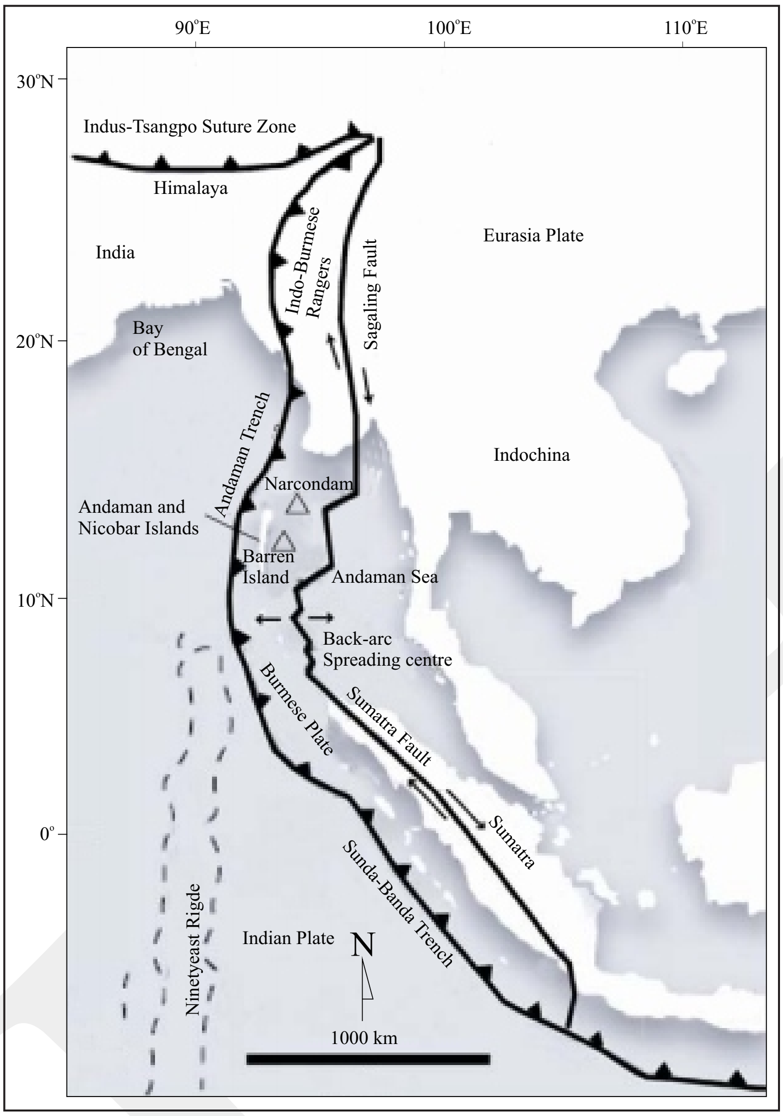

Figure 10. Major geological and tectonic features of the Indian Ocean and southeastern Asia (Ray *et al.*, 2012).

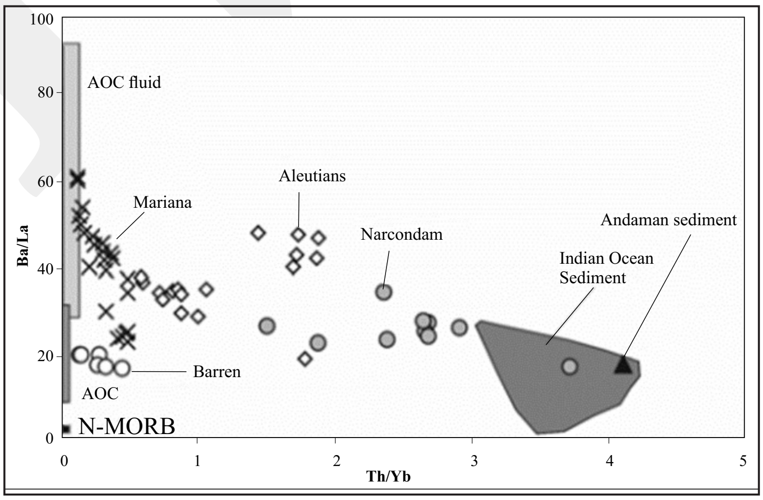

Figure 11. Indication of induced sediment fluid from Indian Ocean is shown in the dark grey area (Ray *et al*., 2012). AOC: Altered Ocean Crust, N-MORB: Normal Mid Oceanic Ridge Basalt.

REE contents of Andaman and Weh volcanic rocks are listed in Table 6. Spider diagram (Figure 12) is used to examine the changing of tectonic regime from subduction in Sumatra to back - arc spreading in Andaman. The figure clearly shows that andesitic volcanic rocks of Andaman (diamond symbol) and Weh (square symbol) belong to subduction tectonic regime as demonstrated by its diagram pattern. On the other hand, Andaman basalt (triangle symbol in Figure 12) displays REE spider diagram resemble Mid Oceanic Ridge Basalt (MORB); an evidence that tectonic regime of Andaman is back - arc spreading as mentioned earlier.

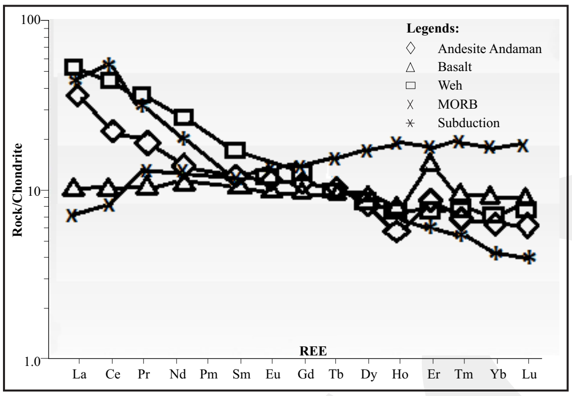

Figure 12. REE spider diagrams for Andaman and Weh Islands which consist of andesite and basalt; and andesitic volcanic rocks. MORB diagram from Regelous *et al.* (2002), subduction diagram from Nakamura (1974).

Discussion

The role of H_2O in the dehydration and hydration reactions of down going lithosphere and the overlying mantle wedge is very important in the production of magmas at convergent plate boundaries such as Sunda subduction system where geochemical characteristics of its volcanic belt is being studied. The subduction causes liberation of H_2O from the slab (Tatsumi, 1989).

The slab - derived H_2O reacts with the fore - arc mantle wedge in the crystallization process of hydrous minerals further dragged downward to higher PT regions and is released to shallower magma source in the mantle wedge. Those hydrous minerals decompose beneath the fore - arc region (Tatsumi, 1989). Geochemical characteristics of arc magmas which include subduction components large ion lithophile elements (LILE) are governed by the migration of H_2O through the above processes.

The LILE (Figure 13) as its abbreviation stands - Large Ion Lithophile Elements - are

Table 6. REE Contents of Andaman Andesite and Basalt (Ray *et al.*, 2012) and Andesitic Lava Weh at Column 2, 3, and 4. While at 5, 6, and 7 The Contents are Normalized to Chondite (Nakamura, 1974)

REE	Andaman		Weh	Andaman		Weh
	Andesite	Basalt		Andesite	Basalt	
				Normalized to Chondrite		
La	12.6	3.86	18.6625	38.57143	11.73252	56.72492
Ce	21.03	9.72	42.075	24.31214	11.23699	48.64162
Pr	2.67	1.45	4.8275	22.06612	11.98347	39.89669
Nd	11.01	7.67	18.3375	17.47619	12.1746	29.10714
Sm	2.57	2.42	4.0125	12.6601	11.92118	19.76601
Eu	0.9	0.88	0.925	11.68831	11.42857	12.01299
Gd	2.99	3.15	3.775	10.83333	11.41304	13.67754
Tb	0.45	0.55	0.505	9.574468	11.70213	10.74468
Dy	2.83	3.77	3.1875	8.250729	10.99125	9.293003
Ho	0.51	0.69	0.6375	6.538462	8.846154	8.173077
Er	2.98	4.08	1.825	13.24444	18.13333	8.111111
Tm	0.28	0.39	0.3	8.75	12.1875	9.375
Yb	1.75	2.47	1.8125	7.954545	11.22727	8.238636
Lu	0.28	0.39	0.30375	8.259587	11.50442	8.960177

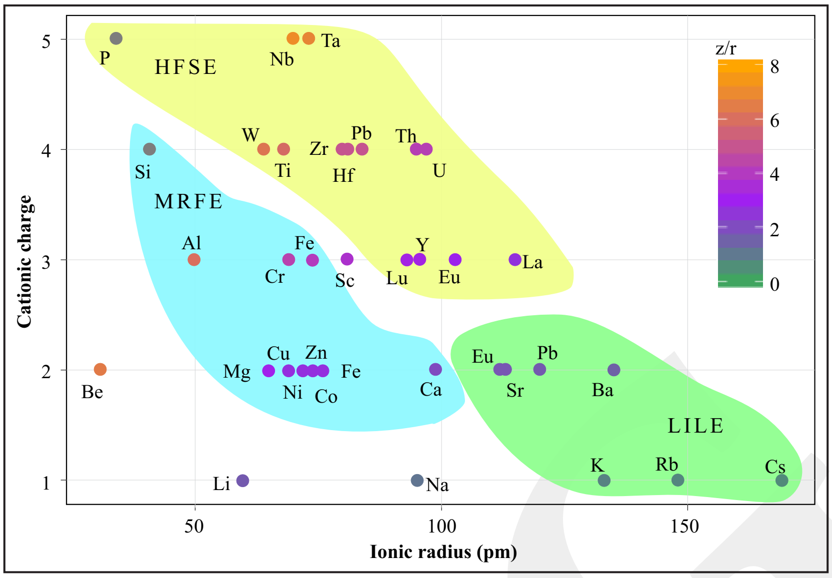

Figure 13. Large ion lithophile elements are characterized by large ionic radius and small cationic charge.

indeed larger than other cations. They are lithophile in the sense that they are incompatible and usually end up with enrichment in the crust (also lithosphere). Rare Earth Elements have been considered as LILE. The LILE are fluid - mobile and hydrothermal alteration that may change their contents in the studied rock. Thus, the LILE could be used for the study of alteration processes. If fresh rocks and anomalies in the LIL systematics are found, hydrothermal processes can be learnt which occurr in the mantle that would not otherwise be able to see. The following Table 7 demonstrates some LILE occur in andesitic volcanic rocks of Andaman, Weh, and Semangko. Along the Sunda volcanic belt, there is a change of tectonic regime of volcanoes from subduction related and strike - slip - fault from Sumatra to back - arc spreading in Andaman Sea in the north. Andaman also shows an orogenic tectonic regime that could possibly be related to the Himalaya orogenic belt in Asia mainland.

Table 7. Large Ion Lithophile Elements (LILE) of Andaman, Weh, and Semangko

Lile	Andaman	Weh	Semangko
Eu	0.9	0.922222	0.95333333
Ba	312.64	341.3333	370
K	12.600	16677.78	9500
Rb	44.29	91.92222	59.9166667

The area between North Sumatra and Andaman Islands shows no volcanism activities, instead it is replaced by active seismicity that would be an interesting subject to be studied further.

Conclusions

The characteristics of Sunda volcanic belt in Sumatra are revealed through each volcano discussed. In submarine volcano of Weh Island, trace and rare earth elements (REE) are produced by seafloor fumaroles, while sulphide minerals do not occur; and mineralization in marine environment is shown by the existence of barium (Ba).

REE are more distributed in shallow coastal water of high marine energy than at a deeper sea. The pattern of REE compared to Mid Oceanic Ridge Basalt (MORB), higher in light REE but low lower in heavy REE, shows the characteristic of subduction tectonic. The comparison of rare earth element contents from seafloor sediments, altered andesitic lava, tuff, unaltered lava and sediments closed to seafloor fumaroles demonstrates that the volcanism process causes REE enrichment either in the past or recent.

The geochemical characteristics of Tabuan Island in Semangko Bay reveal the occurrence of hydrothermal mineralization followed with pervasive occurrences of sulphide minerals in vein - type disseminations which is rich in Au, Ag, Zn, Pb, Cu, As, Sb, Ba, and Mn. While the geochemical characteristics of Andaman Islands reveal imprint of substantial subduction component in the form of sediment fluid and melt and fluid - induced subduction component derived from altered ocean crust.

Acknowledgments

The author would like to thank Marine Geology Institute (MGI) management for permission using geochemical data of the mentioned areas and also financial support to acquire the data. Thanks are also dedicated to colleagues in MGI for fruitful discussion until publication of this paper that could not be mentioned all. Special thanks to IJOG in facilitating the publication.

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