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Geochemical Evidence of Island-Arc Origin for Sumatra Island; A New Perspective based on Volcanic Rocks in Lampung Province, Indonesia

Bukti Geokimia Pulau Sumatra Asal-Busur Kepulauan; Sebuah Pandangan Baru berdasarkan Batuan Vulkanik di Provinsi Lampung, Indonesia

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Abstract

Since decades, Sumatra Island is considered as the Eurasia continental margin where the Indian Ocean plate has been subducted oblique beneath the continental plate of Sumatra. But, the occurrences of volcanic rocks in almost all areas of Lampung Province in the southernmost of Sumatra Island, as the presence of the Quaternary Tanggamus Volcano in the western part of the province together with the Quaternary Rajabasa Volcano in the eastern area cannot be justified using the consideration. Spider diagrams of trace and rare earth elements of volcanic rocks from the western and eastern areas of the province reveal that the rocks come from three different tectonic settings, namely island-arc, active continental margin (ACM), and intra continental plate. All basalt and one dacite of western volcanic rocks show a character of island-arc origin, while the eastern volcanic rocks are reflecting characters of ACM and intra continental plate. Plot of the rocks in the diagram of Ta/Yb *versus* Ce/P and in Ta/Yb *versus* Th/Yb confirmed the tectonic environments and specifically classify the intra continental plate into Within Plate Volcanic Zone (WPVZ). The island-arc group is characterized by Ta/Yb ratio of less than 2.0 and Ce/P less than 1.8. The ACM group is recognized having Ta/Yb ratio between 2 and 4 with Ce/P more 1.8, while the WPVZ group is defined as a group having Ta/Yb more than 6 and Ce/P more than 1.0. The result indicates that the western part of Sumatra is an island-arc fragment and the eastern part belongs to the Eurasia continental margin. The concentration of volcanics having ACM character from areas around the Sumatra Fault System to the east indicates that the collision zone between the Sumatra island-arc fragments with the Eurasia continental margin is probably located along the SFS. More statistical data is still needed from other Sumatra volcanics to confirm this conclusion.

Keywords: Eurasia continental margin, volcanic rocks, Lampung Province, island-arc, active continental margin, intra continental plate, Within Plate Volcanic Zone

Sari

Sejak beberapa dekade yang lalu, Pulau Sumatra dianggap sebagai tepi Benua Eurasia, tempat menunjamnya Lempeng Samudra Hindia secara miring di bawah lempeng benua Sumatra. Tetapi keterdapatan batuan vulkanik di hampir semua wilayah Provinsi Lampung, di bagian paling selatan Pulau Sumatra, seperti keberadaan Gunung api Tanggamus di sebelah barat provinsi ini bersama dengan Gunung api Rajabasa di sebelah timur yang sama-sama berumur Kuarter, tidak dapat dijelaskan dengan anggapan tersebut. Diagram laba-laba unsur jejak dan unsur tanah jarang batuan vulkanik yang dikumpulkan dari daerah barat dan timur provinsi ini mengungkapkan bahwa batuan tersebut berasal dari tiga lingkungan tektonik yang berbeda, yaitu busur kepulauan, tepian benua aktif, dan antar lempeng benua. Semua batuan basal dan satu batuan dasit dari batuan vulkanik daerah barat menunjukkan karakter busur kepulauan, sementara batu-

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batuan sebelah timur mencerminkan karakter tepian benua aktif (TBA) dan antar lempeng benua. Hasil plot batu-batuan tersebut dalam diagram Ta/Yb vs Ce/P and Ta/Yb vs Th/Yg mengkonfirmasi lingkungan tektonik tersebut dan secara spesifik mengklasifikasikan antar lempeng benua menjadi zona vulkanik di dalam lempeng (ZVDL). Kelompok busur kepulauan dicirikan oleh rasio T/Yb kurang dari 2,0 dan Ce/P kurang dari 1,8. Kelompok TBA dikenali memiliki rasio Ta/Yb antara 2 dan 4 dengan Ce/P lebih besar daripada 1,8, sedangkan kelompok ZVDL dicirikan oleh rasio Ta/Yb yang lebih besar daripada 6 dan Ce/P lebih besar daripada 1. Hasil tersebut mengindikasikan bahwa bagian barat Sumatra adalah fragmen busur kepulauan dan bagian timur termasuk tepian Benua Eurasia. Konsentrasi batuan vulkanik berkarakter TBA dari zona patahan Sumatra ke arah timur mengindikasikan bahwa zona tumbukan antara fragmen busur kepulauan Sumatra dengan tepian Benua Eurasia kemungkinan besar terdapat sepanjang zona patahan Sumatra. Masih diperlukan banyak data statistik dari batuan vulkanik di Sumatra untuk mengkonfirmasi kesimpulan ini.

Kata Kunci: *tepian benua Eurasia, batuan vulkanik, Provinsi Lampung, busur kepulauan, tepian benua aktif, antar lempeng benua, zona vulkanik dalam lempeng.*

Introduction

All geologists or earth scientists that ever conducted geological researches or tectonic assessments about Sumatra Island in the western part of Indonesia, always classify the island as the margin of Eurasia continent or it belongs to an active continental margin tectonic setting (Hamilton, 1979; Curray., 1989; Barber, 2000; Barber and Crow., 2003; Crow, 2005). It is well understood that there is an oblique subducted Indian Ocean Plate beneath the continental plate of Sumatra along the western offshore of the island. The understanding is also used to describe or to determine many geological aspects on the island such as the genesis of gold mineralization along the west flank of Barisan Mountain or mechanism controlling the formation of volcanic chains along the west side of the island and also tectonic history of the island. Of course, the understanding also becomes a basic frame in revealing potential earthquake hazard in the area. The understanding is valid since decades.

According to Tatsumi and Eggins (1995), a subduction system in which an oceanic plate is subducted beneath a continental plate usually will form a pair of volcanic chain. One of them will be located nearer to the trench and called as the trench-side volcanic chain and the other will be situated nearer to back-arc and called as back arc-side volcanic chain. The trench-side volcanic is controlled by magma generation through partial melting of the subducted slab at around 110 km depth, while the back arc-side volcanic is controlled by partial melting of the subducted slab at around 180 km depth (Figure 1). The difference of the magma source for

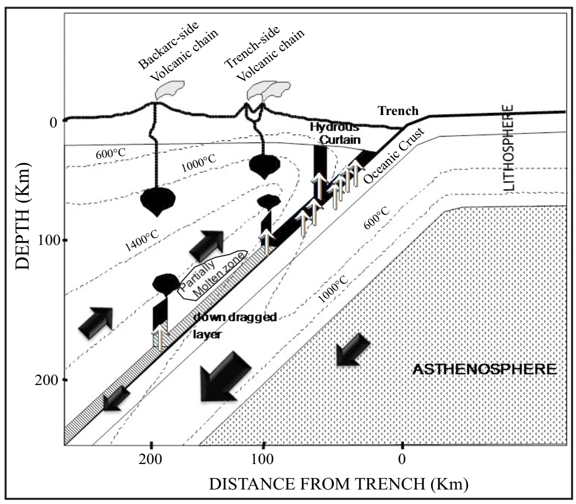

Figure 1. Subduction system controlling formation of a pair volcanic chain with magma generation at 110 and 180 km depth (after Tatsumi and Eggins, 1995).

both volcanics should also be reflected in composition of their volcanic products. The mixing or assimilation of the shallower magmas with thinner mantle wedge during their ascending to the surface will produce volcanic products with intermediate composition compared to the deeper magmas. In another word, the products of back arc-side volcanics will range from basic to intermediate in composition, while the trench-side volcanic products will be intermediate to acid in composition. This postulate is already proofed in North Sulawesi area, where the volcanic products of trench-side volcanoes (Tagulandang, Siau, and Awu Volcanoes) are composed of andesitic rock, while the volcanic products on Manado Tua Island are representing the back arc-side volcano consisting of basalt to basaltic andesite (Zulkarnain, 2001).

In Lampung Province, the most southern province of Sumatra, volcanic products spread from the western side of the island (around Tanggamus Volcano), through areas around Semangko Bay and continue to the east to Rajabasa Volcano and Plateau Basalt in Sukadana area. From the above model point of view, volcanic products in this province seem to represent the occurrences of the trench-side volcanics in the west (Tanggamus Volcano) and back arc-side volcanic in the east (Rajabasa Volcano). However, although the both volcanoes are of the same age (Quaternary), the volcanic products around the volcanoes are older than them ranging from Plio-Pleistocene in the east to Oligo-Miocene in the west (Figure 2).

The occurrences of both Quaternary volcanoes in two different places with significant different distances from the subduction front are found only in Lampung, although distribution of volcanic products from the west to the east is also recognized in the North Sumatra Province. Meanwhile, other volcanoes on this island are concentrated only along the west coast of the island that is indicated by the location of volcanic rock distribution on the island (Figure 3). In term of the above model, their rock composition should also be different where the eastern volcanic products should be more basic compared to the western ones. The difference should also be identified on the pattern of their trace and rare earth elements. But the important one is the pattern of their trace and Rare Earth Elements that should clearly show their tectonic setting origin. The aim of this paper is to find out the tectonic setting of the Sumatra Island based on the geochemical character of the volcanic products distributed in the Lampung Province.

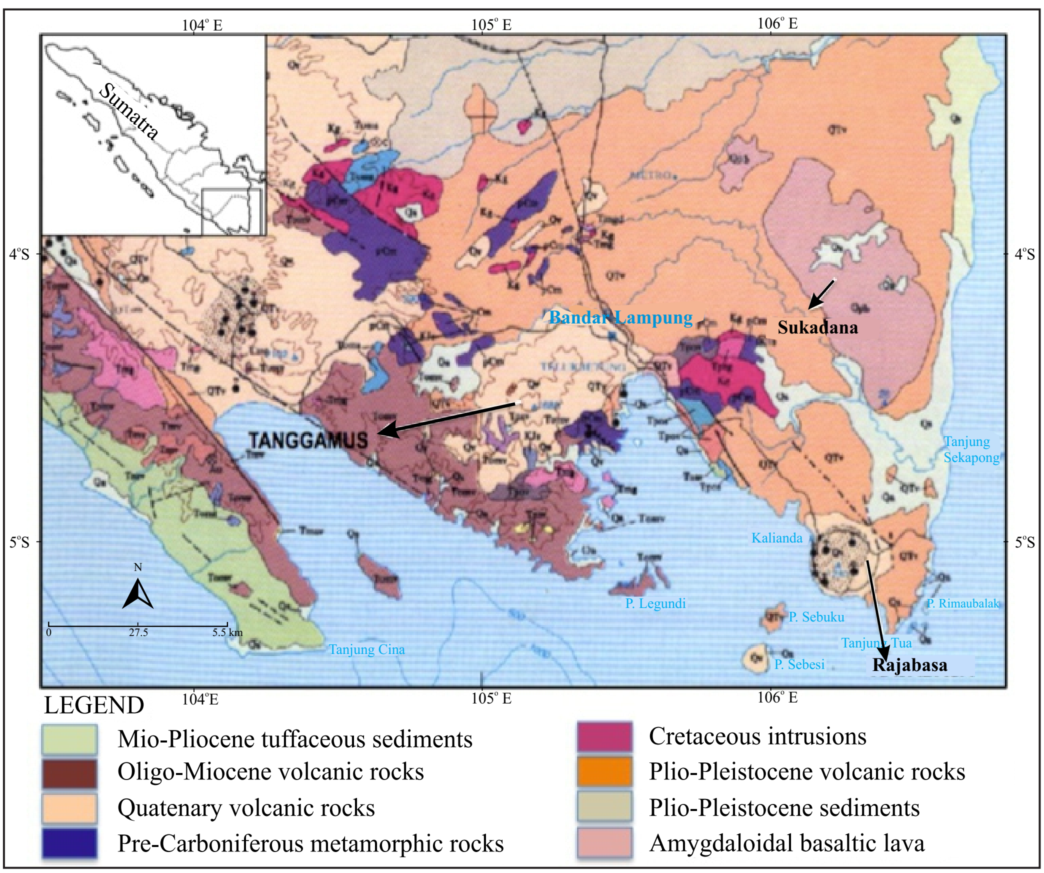

Figure 2. Geological map of Lampung Province (after Gafoer *et al*., 1992).

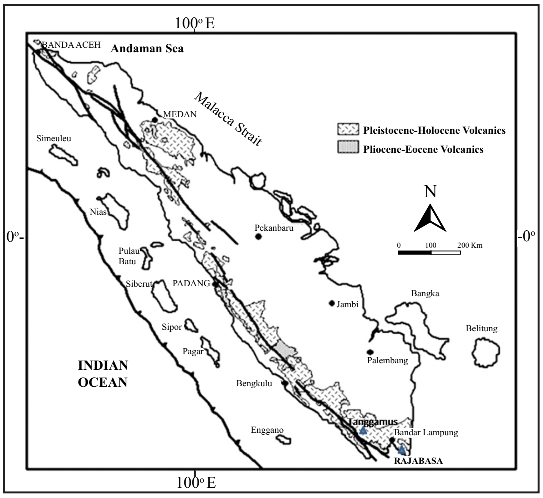

Figure 3. Distribution of volcanics on Sumatra that is mostly concentrated along the west coast of the island with exception in Lampung and North Sumatra Provinces (after Zulkarnain, 2007).

Geological Setting

Most of the area on the Lampung Province is covered by volcanic rocks, ranging from Oligo-Miocene to Quaternary in age (Figure 3). Quaternary volcanic products of the Tanggamus Volcano and Oligo-Miocene volcanic rocks of the Hulusimpang Formation dominate the western part of the province up to the central part, while the Plio-Pleistocene volcanic products cover almost all areas from the central part of the province to the east (Gafoer *et.al*, 1992). Among the volcanics in the eastern part, there is also Quaternary amygdaloidal basalt spreading as black boulders throughout a wide area in Sukadana District and Quaternary Rajabasa Volcano in the south. At certain locations along the border of both volcanic products, there are several spotted outcrops of older rocks identified as Pre-Carboniferous metamorphic rocks and Cretaceous intrusion. Besides the above-mentioned lithology, the area is also covered by sediments distributed in the most western part, parallel to the coast, and in the northern part. The western area is dominated by Mio-Pliocene tuffaceous sediments, while Plio-Pleistocene terrestrial sediments cover the northern area.

In more detail, the Tanggamus products (Quaternary volcanic rocks) in the west are composed of lava, breccia, and tuff with basaltic to andesitic composition. Meanwhile, the Hulusimpang Formation (Oligo-Miocene volcanic rocks) consists generally of green or greenish grey lava, breccia, and tuff with andesitic to basaltic composition and sometimes shows sandstone intercalations. In some locations, they are prophyllitized and mineralized. The Plio-Pleistocene volcanic products in the eastern part of the province are lava, breccia, and tuff ranging from rhyolitic, through dacitic to andesitic in composition. Generally, they spread with pumice and sometimes they contain carbonaceous material within. The pre-Carboniferous metamorphic rocks consist of mica-chlorite-quartz-graphite schist, gneiss, phyllite, quartzite, marble, and slate, while the intrusions are granitic and granodioritic in composition with several dykes of basalt and aplite. The sediments in the western part occur as tuffaceous sandstone and mudstone, tuff, and conglomerate containing mollusca, while the terrestrial sediments in the northern area consist of pumiceous epiclastic sediments, tuff, sandy tuff, and tuffaceous sandstone with silicified plant.

Major geological structures in the province are faults, which belong to the Sumatra Fault System, mainly in the western part parallel to the coast. Several minor faults are concentrated in the locations where the oldest rocks crop out.

Sample Location and Analytical Method

Around 40 relatively fresh rock samples were collected from the western and eastern parts of the Lampung Province and twelve of them were analyzed for their major, trace, and rare earth elements. The chemical analysis was carried out by Activation Laboratories in Canada under analysis code 4Litho. They have developed a lithium metaborate/tetraborate fusion ICP Whole Rock Package and a trace element ICP/MS package that are unique for scope of elements and detection limits. The two packages are combined for Code 4Litho and Code 4Lithoresearch.

Seven samples were collected from the western area representing the Oligo-Miocene Hulusimpang Formation and the Tanggamus Quaternary products, while five samples were collected from the eastern area consisting of two samples from Quaternary Rajabasa Volcano products and three samples of basalt from Sukadana and Tamiyang areas (Figure 4). The various ages of the volcanic products in this province reflect that they were derived from different magmatic activities and it would be used to reveal the history of their tectonic setting.

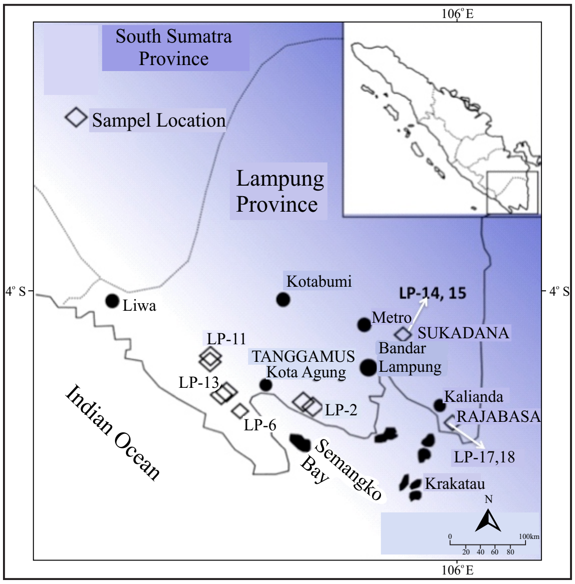

Figure 4. Sample location map showing most of analyzed samples were collected from the western area.

Results

The analytical result of the twelve samples will be described and demonstrated systematically from major elements, through trace elements, and finally the Rare Earth Elements.

Major Elements

The chemical results of major elements for the twelve samples collected in Lampung Province are given in Table 1.

It is shown in the Table 1 that the western volcanic rocks contain SiO_2 from 51 to around 65 %weight, while the SiO_2 content of eastern volcanic rocks ranges from 51 to around 57 % weight. Their TiO_2 content is almost similar varying from 0.67 to 1.28 %weight, but the western volcanic rocks have a wider range and are richer in Al_2O_3 than those of eastern part, as well as P_2O_5 content. Based on their SiO_2 content, the western volcanic rocks are classified as basalt (belongs to Oligo-Miocene Hulusimpang Formation) and dacite (belongs to Quaternary Tanggamus products), while the eastern ones are composed of basalt (from Sukadana and Tamiyang areas) and andesite (products of Quaternary Rajabasa Volcano). Most of them belong to Medium-K type, although one sample is plotted in the upper part of Low-K zone and another sample in the lower part of High-K zone (Figure 5). Their trend cannot be taken into account due to too small amount of samples and difference of age and origin, especially for eastern volcanics where two samples come from a volcano eruption (Rajabasa samples), while basalts from Sukadana and Tamiyang areas are reported as plateau in origin (Gafoer *et al*.,1992). On the above table, it is also seen that basalts from the eastern part (from Sukadana with sample No. L-15A and 15B, and from Tamiyang with sample No. LP-14) contain high MgO (around 7 % weight), while the basalts of the western volcanic contain lower MgO (around 4 % weight). However, the western basaltic rocks show higher CaO content (around 9 % weight), whereas the eastern basalts contain slightly lower

Table 1. Chemical Analyses for Major Elements of Volcanic Rocks from Lampung Province

	Western Volcanics						Eastern Volcanics				
	LP 02A	LP 02B	LP 06	LP 11C	LP 13	LP 13D	LP 14	LP 15A	LP 15B	LP 17	LP 18A
$Si0_2$	52.39	61.76	51.96	51.12	64.79	63.81	51.58	51.1	51.66	58.19	56.91
$Ti0_2$	0.947	0.672	0.877	1.282	1.025	0.572	1.28	1.262	1.278	0.751	0.887
Al_20_3	19.05	16.39	19.09	17.58	15.01	15.77	17.02	16.39	16.67	17.58	17.32
Fe_20_3	7.7	5.75	8.78	11.36	5.61	5.35	10.63	10.29	10.33	6.88	8.58
Mn0	0.151	0.103	0.169	0.184	0.028	0.115	0.136	0.124	0.132	0.138	0.161
Mg0	2.8	2.6	3.88	4.76	2.22	1.88	7.06	7.04	7.2	2.75	2.82
Ca0	7.55	5.15	9.59	9.17	2.78	4.67	8.59	8.5	8.44	5.63	5.8
Na_20	3.05	3.84	2.15	2.73	4.48	3.49	3.55	3.42	3.39	3.95	3.87
K_20	1.3	1.73	0.65	0.9	1.02	1.98	0.5	0.56	0.49	2.4	2.09
P_20_5	0.21	0.13	0.18	0.32	0.32	0.13	0.16	0.17	0.17	0.21	0.31
$L0_1$	4.93	1.73	2.7	0.79	2.81	2.21	-0.01	0.71	0.34	1.44	1.32
TOTAL	**100.1**	**99.85**	**100**	**100.2**	**100.1**	**99.99**	**100.00**	**99.56**	**100.10**	**99.93**	**100.06**

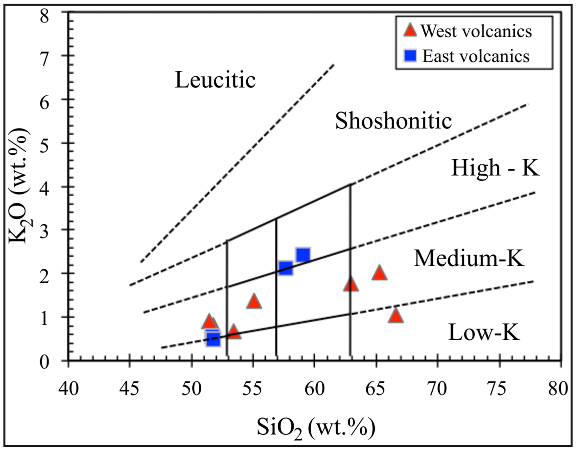

Figure 5. Correlation diagram of SiO_2 *vs.* K_2O showing almost all samples are classified as Medium-K type.

CaO (around 8 % weight). For Fe_2O_3 content (total Fe is calculated as Fe_2O_3), basalts from Sukadana and Tamiyang show consistent Fe_2O_3 content (about 10.3 % weight), but the western basalts show various Fe_2O_3 content ranging from 8.7 to 11.3 % weight.

Plot of all samples in the classification diagram of Miyashiro (1974) shows that basalts of western volcanic rocks are classified as tholeiitic type, while the dacites from this area are plotted in the calc-alkaline field (Figure 6). It indicates that the dacites of Quaternary Tanggamus volcanic products were derived from magma that significantly depleted on Fe_2O_3 compared to the Oligo-Miocene basalts of Hulusimpang Formation. In contrast, the basalts from the eastern part of the area (Sukadana and Tamiyang basalts) together with one andesitic sample from Rajabasa Volcano belong to calc-alkaline type, while another andesitic sample from the Rajabasa Volcano is plotted in the tholeiitic field, but very near to the separating line.

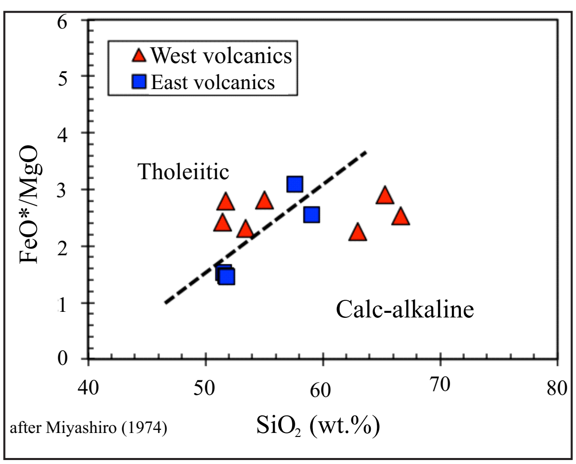

Figure 6. Classification diagram for volcanic rocks affinity (after Miyashiro, 1974).

Trace Elements

The twelve samples were also chemically analyzed for their trace elements and the result is given in Table 2.

The analytical results show that all rocks have higher Ba, Rb, Sr, Th, and K as well as Ti and Ce relatively compared to MORB. It ranges from 113 to 331 ppm of Ba for the western volcanics and from 95 to 431 ppm for the eastern volcanic rocks. Rb content of the western volcanic is higher, ranging from 26.7 to 74.9 ppm, than the eastern volcanic rocks, varying from 11 to 69.6 ppm. For Sr content, the western volcanic rocks contain lower Sr, ranging from 200 to 486 ppm, than the eastern volcanic rocks varying from 393 to 448 ppm. Meanwhile, their Th content is almost similar, ranging from 2 to 8.1 ppm for the western volcanic and from 1.3 to 9.9 ppm for the eastern volcanic rocks. For Potassium, the basalts of western volcanic rocks contain higher of K varying from 5394 to 10787 ppm, while those from eastern volcanic rocks ranging from 4066 to 4646 ppm. The intermediate and acid rocks from both areas have K content from 8463 to 19915 ppm. In contrast with the K-content, Ti-content as well as Ni-content of the western basalts are relatively low (5257 to 7684 ppm for Ti and from 0 to 46 ppm for Ni), while the eastern basalts show higher Ti-content (7564 - 7672 ppm) and Ni content (160 to 170 ppm). The pattern is found also for Cr and Co where the eastern basalts contain higher Cr and Co compared to the western ones.

All samples are characterized by selective enrichment of incompatible elements of low ionic potential (Sr, K, Ba, Rb, and sometimes Th), and low abundances of elements of high ionic potential (Ta, Nb, Ce, P, Zr, Hf, Sm, Ti, Y, and Yb). All samples are plotted in spider diagrams after normalized the elements content to MORB according to Pearce (1983). There are three different patterns of the rocks in spider diagrams. The first pattern is characterized by a significant enrichment on the incompatible elements (Rb and Th are enriched from around 20

Table 2. Trace Elements Concentration in Twelve Volcanic Rocks from Lampung Province

	Western Volcanics							Eastern Volcanics				
	LP 02A	LP 02B	LP 06	LP 11	LP 11C	LP 13	LP 13D	LP 14	LP 15A	LP 15B	LP 17	LP 18A
In ppm												
Ba	200.6	323.6	113.1	171.2	176.7	162.8	331.6	95.1	106.7	106.9	431.5	327.3
Rb	37.6	61.8	73.9	26.7	28.9	36.6	74.9	11.1	11.0	12.2	69.6	51.3
Th	3.5	6.4	2.6	2.0	2.7	3.4	8.1	1.3	1.4	1.4	9.9	5.4
K	10787	14355	5394	6721.3	7468.1	8463.8	16429.8	4148.9	4646.8	4066.0	19915	17343
Nb	2.4	3.2	1.7	2.7	3.3	2.6	3.9	6.9	7.7	7.8	6.3	6.1
Ta	0.2	0.3	0.1	0.1	0.2	0.2	0.3	0.4	0.4	0.4	0.5	0.4
La	12.9	14.3	8.8	11.5	13.9	12.0	18.1	6.4	7.2	7.9	24.8	22.9
Ce	26.8	32.9	19.6	26.5	31.2	29.4	36.1	14.0	15.5	15.5	51.4	50.8
Sr	486.5	345.4	280.8	373.7	346.9	200.7	288.0	393.8	428.1	422.1	434.5	448.8
Nd	15.7	15.0	10.2	15.3	18.6	17.6	14.3	9.6	10.2	10.7	22.6	26.2
P	916.9	567.6	785.9	916.9	1397.2	1397.2	567.6	698.6	742.3	742.3	916.9	1353.5
Sm	4.2	3.5	2.8	4.0	5.0	5.1	3.2	3.2	3.3	3.4	4.9	6.3
Zr	98.4	98.1	59.0	91.7	119.4	110.1	118.5	64.3	61.1	61.8	150.2	197.3
Hf	2.8	2.9	1.7	2.5	3.3	3.1	3.2	1.8	1.7	1.7	4.0	5.1
Ti	5676.3	4028.0	5257	6731.3	7684.3	6143.8	3428.6	7672.3	7564.4	7660.3	4501.5	5316.7
Tb	0.7	0.5	0.5	0.7	0.9	0.9	0.5	0.5	0.5	0.5	0.7	0.9
Y	22.7	19.0	15.3	22.2	33.0	31.4	16.7	12.6	13.0	14.2	20.9	27.4
Tm	0.3	0.3	0.3	0.4	0.5	0.5	0.3	0.2	0.2	0.2	0.4	0.5
Yb	2.1	2.1	1.6	2.3	3.0	3.3	1.9	1.1	1.1	1.2	2.3	2.9
Ni	-20	-20	-20	46	38	-20	-20	177	170	161	-20	-20
Cr	-20	-20	21	74	72	-20	-20	306	323	315	-20	-20
Co	11	14	25	28	36	14	12	46	47	44	19	16

to more than 50 times MORB) and having slightly lower content on Ta and Nb compared to MORB and then slightly enriched on Ce and P (marked by trough on Ta and Nb). The enrichment on Ce and P ranges from 1.5 to 3 times MORB and shows a slightly variation on other compatible elements (Figure 7). This pattern is very similar to spider diagram pattern of island-arc basalts (Wilson, 1989). All basalts of the western volcanic rocks and one dacite sample of Hulusimpang Formation (LP-13) show this pattern.

The second pattern seems to be similar with the first one, but they are enriched on incompatible elements and differ in Ta and P contents. The pattern has higher content of Ta (higher than MORB) and similar content of P with MORB (Figure 8). This pattern is very similar with spider diagram of Active Continental Margin or ACM (Wilson, 1989). Two

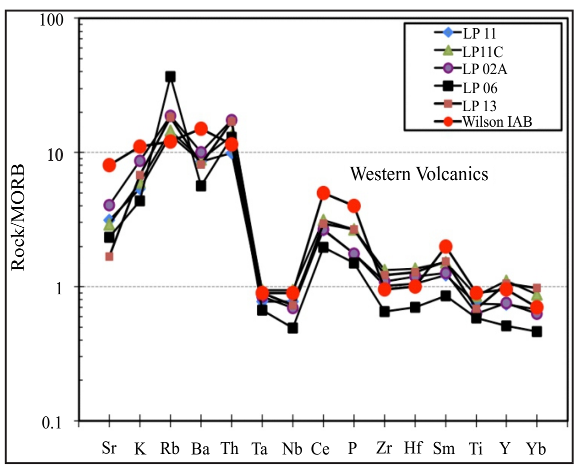

Figure 7. Pattern of spider diagram of trace elements of western volcanic rocks showing similarity with those of island-arc origin (IAB, Wilson, 1989).

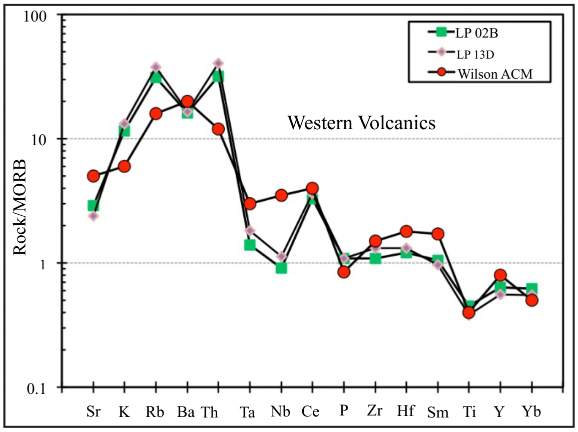

Figure 8. Pattern of spider diagram of western volcanic rock showing similarity with those of Active Continental Margin (ACM) origin (Wilson, 1989).

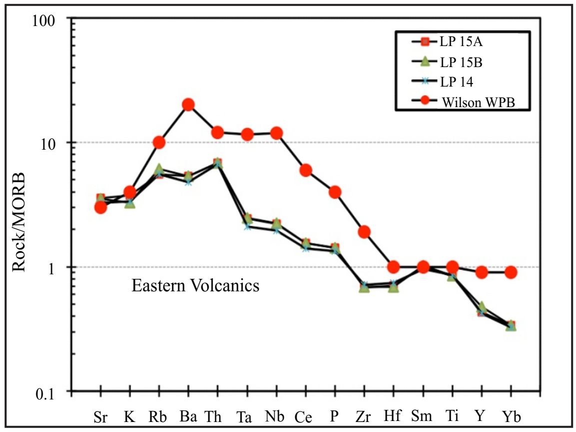

Figure 10. Pattern of spider diagram of eastern volcanics showing a similarity with those of intra-continental plate or Within-Plate Basalt (WPB).

dacites of western volcanic rocks (LP-02B from Tanggamus and LP-13D from Hulusimpang Formation) and two andesites of eastern volcanic rock (LP-17 and LP-18A) belong to this pattern (Figures 8 and 9). But, andesites of the eastern volcanics show higher content of Ta and Nb (around two times of

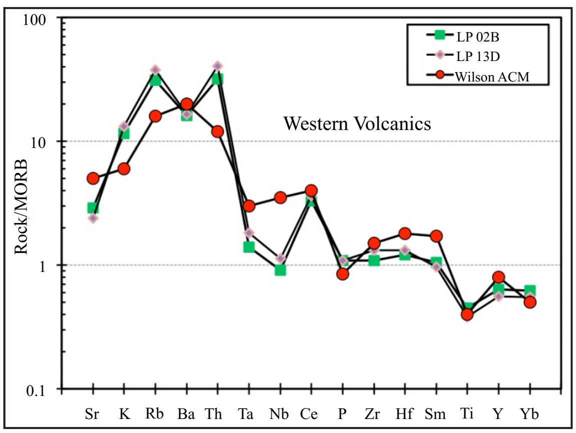

Figure 9. Pattern of spider diagram of eastern volcanic rock showing a similarity with those of ACM origin (Wilson, 1989).

MORB) than dacites of the western volcanics. The third pattern is characterized by slightly enrichment on incompatible elements (Rb and Th are enriched up to 8 times of MORB content) and showing flat decreasing towards Ta, Nb, Ce, and P. They are generally depleted on the compatible elements such as Zr, Hf, Sm, Ti, Y, and Yb (Figure 10). This pattern shows a similarity to spider diagrams of intra-continental plate basalts (Wilson, 1989). All basalt samples of eastern volcanics (from Sukadana and Tamiyang areas) represent this pattern.

Rare Earth Elements

Rare earth elements (REE) are also analyzed for the twelve samples from Lampung Province and the result is given in the Table 3.

All REE concentrations of the samples are plotted in spider diagrams after normalizing the contents to chondrite according to Sun & McDonough (1989). Consistently, three different patterns that found in the spider diagrams of their trace elements are also recognized in the REE spider diagrams of the samples. The western volcanic rocks having island-arc character represent the first REE pattern (Figure 11). This pattern is characterized by moderate enrichment on light rare earth elements (LREE), where La content ranges from 30 to 60 times of chondrite, and shows a relatively constant slope of decreasing elements content towards heavy rare earth elements (HREE). Meanwhile, two dacites of western volcanics (Figure 12) together with two other andesites of eastern volcanics (Figure 13) that have an ACM character represent the second pattern. This second pattern is characterized by high enrichment of LREE (La content ranges from 60 to more than 100 times of chondrite) and decreases towards HREE with steeper slope than those of island-arc (Figure 12). It shows kick points on Eu and Ho and their HREE

Table 3. Concentration of REE in the Volcanic Rocks from Lampung Province

	Western Volcanics							Eastern Volcanics				
In ppm	LP 02A	LP 02B	LP 06	LP 11	LP 11C	LP 13	LP 13D	LP 14	LP 15A	LP 15B	LP 17	LP 18A
La	12.9	14.3	8.8	11.5	13.9	12.0	18.1	6.4	7.2	7.9	24.8	22.9
Ce	26.8	32.9	19.6	26.5	31.2	29.4	36.1	14.0	15.5	15.5	51.4	50.8
Pr	3.5	3.9	2.5	3.5	4.2	3.9	3.9	1.9	2.1	2.2	5.8	6.3
Nd	15.7	15.0	10.2	15.3	18.6	17.6	14.3	9.6	10.2	10.7	22.6	26.2
Sm	4.2	3.5	2.8	4.0	5.0	5.1	3.2	3.2	3.3	3.4	4.9	6.3
Eu	1.2	1.0	0.9	1.3	1.4	1.6	0.9	1.1	1.1	1.2	1.3	1.6
Gd	4.0	3.1	2.8	4.1	5.3	5.4	2.8	3.0	3.2	3.3	4.0	5.6
Tb	0.7	0.5	0.5	0.7	0.9	0.9	0.5	0.5	0.5	0.5	0.7	0.9
Dy	3.8	3.3	2.8	4.1	5.3	5.6	2.9	2.6	2.7	2.7	3.8	5.2
Ho	0.7	0.7	0.6	0.8	1.1	1.2	0.6	0.5	0.5	0.5	0.8	1.0
Er	2.3	2.2	1.8	2.6	3.5	3.7	1.9	1.4	1.4	1.5	2.4	3.2
Tm	0.3	0.3	0.3	0.4	0.5	0.5	0.3	0.2	0.2	0.2	0.4	0.5
Yb	2.1	2.1	1.6	2.3	3.0	3.3	1.9	1.1	1.1	1.2	2.3	2.9
Lu	0.3	0.3	0.2	0.3	0.4	0.5	0.3	0.2	0.2	0.2	0.3	0.4

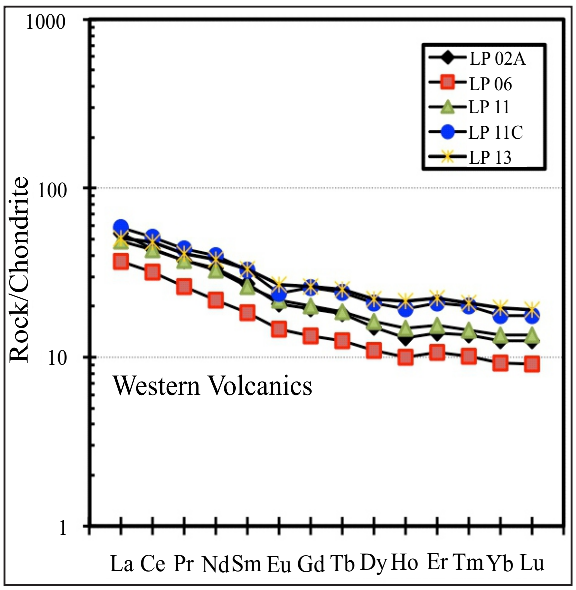

Figure 11. Pattern of REE spider diagram of volcanic rocks having island-arc characters.

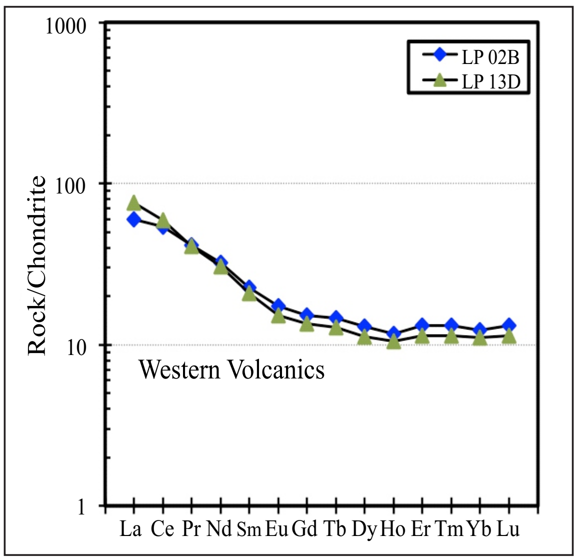

Figure 12. Pattern of REE spider diagram of rocks having ACM character shows high enrichment on LREE with a steeper slope decreasing than those of island-arc.

almost similar or slightly enriched than 10 times of chondrite. The andesites of eastern volcanic rocks show slightly higher content of LREE and HREE than dacites of western volcanics (Figure 13).

The third pattern representing volcanic rocks having Within-Plate Basalt (WPB) shows a different REE spider diagram pattern from the two previous patterns. This last pattern shows slightly enrichment on LREE (about 30 times of chondrite) and decreases gradually towards HREE. The HREE content consisting of Ho, Er, Tm, Yb, and Lu becomes lower and lower below 10 times of chondrite (Figure 14).

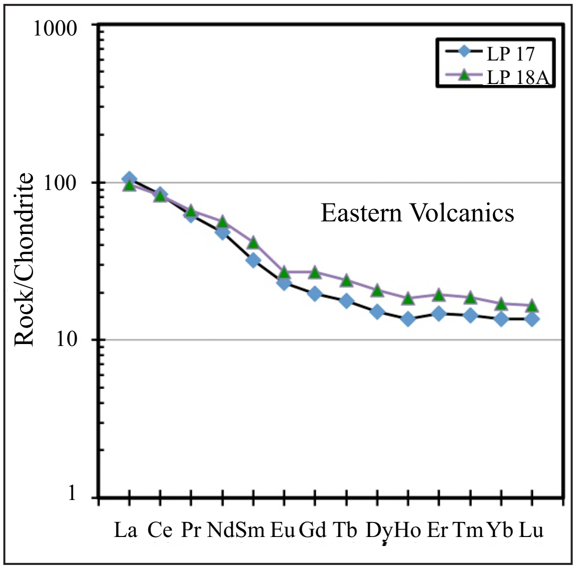

Figure 13. Pattern of REE spider diagram of eastern volcanic showing an ACM character.

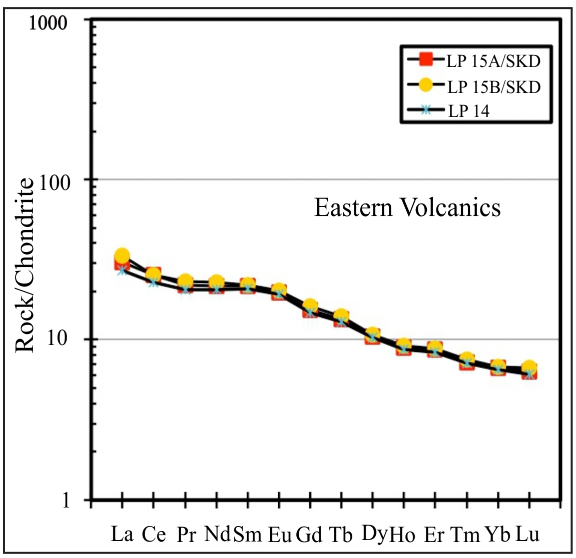

Figure 14. Pattern of REE spider diagram of eastern volcanics having WPB character that shows slightly enrichment on LREE and decreases gradually towards HREE until below 10 times of chondrite.

Discussion

The analyzed samples were collected from two different areas (west and east) in Lampung Province, in order to find out the changing or variation of tectonic environment of the volcanic products. The variation of their tectonic environment will reflect the history of the Sumatra Island itself. In the western areas, the samples were collected from Oligo-Miocene Hulusimpang Formation and from the Quaternary Tanggamus volcanic products. The Hulusimpang Formation samples consist of basalt and dacite, while the Tanggamus products are only dacites. Meanwhile, in the eastern areas, the samples were taken from Quaternary Rajabasa Volcano products (andesite) and from Sukadana basalt plateau that is also Quaternary in age.

Plot of the volcanic rocks in the SiO_2 *versus* K_2O correlation diagram (Le Bas *et al*., 1986) classifies most of the rocks as medium K type, although there is one sample is located in the upper part of Low-K zone and another one is in the lower part of High-K zone (Figure 5). The trend of the point distribution could not be taken into account, because they have different age (for western volcanics) and different origin (for eastern volcanics). The unclear trend is confirmed by plotting the samples on the Miyashiro diagram showing distribution of the western samples in two different affinities where the basalts are classified as tholeiitic and the dacites belong to calc alkaline affinity (Figure 6). It indicates that the western volcanic rocks were derived from two different conditions where the dacites were crystallized from magma depleted on iron compared to their basalts.

Comparing the composition of the Rajabasa volcanic products with the Tanggamus products having similar age, it is found that the Rajabasa volcanics has more basic composition (andesite) than the Tanggamus volcanics (dacite). In term of Tatsumi and Eggin's model, the fact indicates that both volcanic activities were derived from the recent subduction system which places them as trench-side volcanics (Tanggamus) and back-arc volcanics (Rajabasa).

Plot of trace elements of the volcanic rocks from western areas in spider diagrams shows two different patterns. According to Wilson, 1989, all basalt and one dacite samples show a pattern that is similar to that of island-arc rocks (Figure 7), while the other two dacites of this group show another pattern in spider diagram that is similar to that of Active Continental Margin or ACM (Figure 8). The second pattern is actually not fully fit to the ACM pattern from Wilson (1989) and it is more as a combined pattern between the pattern of island-arc and the ACM. The samples still show lower content of Ta and Nb like an island-arc character, but they show significant decreasing on P like the ACM pattern. However, the ACM pattern is really not a fix pattern because it is very influenced by how much continental material that mixed into the magma. Therefore, the second pattern of the western volcanic rocks is believed to be formed through mixing of the island-arc magma with Eurasia continental crust with low intensity.

Plot of trace elements of the volcanic rocks from eastern areas in spider diagrams results also in two different patterns. The first pattern shown by the andesites is very similar to the dacite of western rocks showing a pattern of ACM character, but they have higher content of Ta and Nb than the western rocks (Figure 9). It probably indicates that the ACM samples of the eastern group were derived from magma containing more continental material than the western ones. In an other word, the island-arc magma has been contaminated by more continental materials during its ascent to the surface. The second pattern represents a pattern that is similar to the pattern of intra-continental plate or Within-Plate Basalt (WPB). But in this case, the rock pattern is not fully fixed with the WPB pattern, because the rocks show lower concentration of all trace elements, except Sr and Sm (Figure 10). This pattern probably represents the rocks were derived from basaltic magma that is very little influenced by continental materials during its ascent to the surface.

The three different patterns representing three different tectonic environments during their generation that are recognized through their trace elements spider diagrams can also be found in their REE spider diagrams. The island-arc type rocks are characterized by moderate enrichment of La (up to 60 times of chondrite) and decrease in constant slope to HREE (with Lu about 10 times of chondrite). The western rocks with island-arc character show different fractionation stages indicated by constant increasing of their REE ratio to chondrite (Figure 11). Meanwhile, the western and eastern volcanic rocks having ACM character are characterized by high enrichment of La (60 to 100 times of chondrite) and decrease with steeper slope than the island-arc towards Ho and continue to Lu with almost constant ratio with chondrite for Er Tm and Yb (Figure 12 and 13). The high enrichment of LREE of these rocks indicates that the magma was mixed with continental materials which were rich on elements of LREE. The ACM patterns of western and eastern volcanic rocks reveal that the eastern rocks are derived from more contaminated magma than the western ones. It is indicated by the higher ratio of LREE and HREE to chondrite of the eastern rocks compared to the western ones. The rocks having WPB character show also a certain pattern where the rocks are enriched insignificantly on LREE (with La up to 30 times of chondrite). The LREE decrease almost constantly towards HREE with Ho, Er, Tm, Yb and Lu less than 10 times of chondrite (Figure 14).

The above results are partly confirmed by plotting all of the rocks in the Ta/Yb versus Th/Yb diagram (Gorton & Schandl, 2000). The plot of the rocks in the diagram classifies them into types of oceanic-arc, ACM and Within Plate Volcanic Zone (Figure 15). Almost all of the western rocks

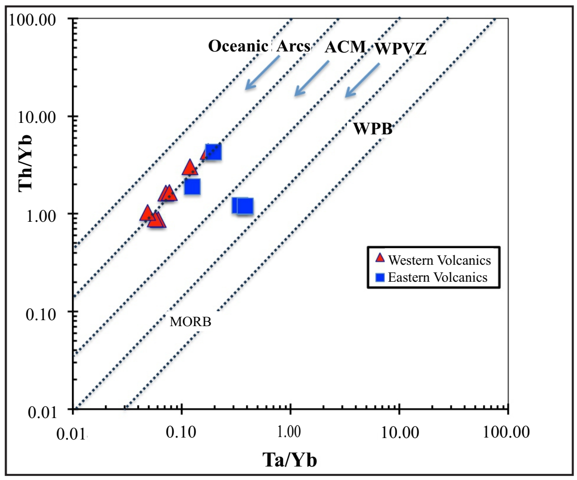

Figure 15. Plotting the rocks in Ta/Yb *versus* Th/Yb diagram classifying them into oceanic-arc, ACM and WPVZ (after Gorton & Schandl, 2000).

with island-arc character are plotted along the line separating oceanic-arc and ACM as well as the western and eastern rocks showing ACM character. It indicates that the diagram cannot be separated clearly between island-arc and ACM rocks, but it can clearly distinguish between WPB with Within Plate Volcanic Zone (WPVZ). This classification can explain why the REE spider diagrams pattern of eastern volcanic rocks does not fix the WPB pattern.

Besides that, the plotting of the rocks in the diagram indicates that the elements Ta, Th, and Yb are not sensitive enough to be used as variables for discriminating the tectonic environments.

Based on the similarity and different pattern of the island-arc and ACM characters that are found on the above spider diagrams, the rocks are plotted in the Ta/Yb *versus* Ce/P. The result can be clearly separating the three different tectonic environments (Figure 16). The island-arc group is characterized by Ta/Yb ratio less than 2.0 and Ce/P less than 1.8. The ACM group is recognized having Ta/Yb ratio between 2 and 4 with Ce/P more than 1.8, while the WPVZ group is defined as a group having Ta/Yb more than 6 and Ce/P more than 1.0.

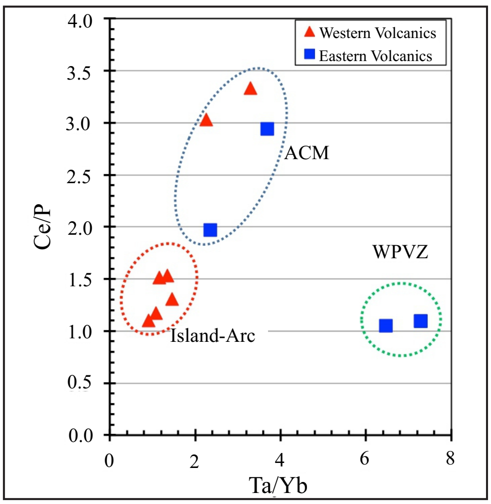

Figure 16. Plot of the rocks in the Ta/Yb *versus* Ce/P diagram showing clear three different tectonic environments

The fact shows that two dacites of western volcanic rock (samples belong to Oligo-Miocene Hulusimpang Formation and to Quaternary Tanggamus volcanics) are ACM, which indicates that there was a subduction system that continues from Oligo-Miocene to recent time in the western part of Sumatra (probably close to the Sumatra Fault System/SFS) as a collision result between an island-arc fragment with the Eurasia continental margin. However, there is a basalt sample of the Tanggamus Volcano product that represents an island-arc character. It indicates that probably the SFS is the zone where the Sumatra island-arc fragment collided with the Eurasia continental margin. More statistically data from the other volcanic products towards the north are still needed to confirm that the western part of Sumatra Island does not belong to Eurasia continental margin, but it is actually an island-arc in origin.

Conclusions

The geochemical analysis using major, trace, and Rare Earth Elements of volcanic rocks from the Lampung Province gives evidences that the Sumatra Island is not pure part of Eurasia continental margin. Their geochemical characters reveal that the western part of the Lampung Province is an island-arc in origin, whereas the eastern part is definitively showing active continental margin characters. In an other word, the western part is an island-arc and the eastern part is the margin of the Eurasian Plate. Based on the distribution of samples with two different tectonic characters around the SFS zone, it is interpreted that the collision zone between the Sumatra island-arc fragment with the Eurasia continental margin is probably located along the SFS zone. It is still needed to get more geochemical characters of the volcanic rocks along the western coast of Sumatra in order to confirm the island-arc origin of this island.

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