GEOCHEMISTRY OF THE JELAI VOLCANICS FROM MOUNT RIAN EAST KALIMANTAN: Implications for the magma compositional gap

GEOKIMIA BATUAN VOLKANIK JELAI DI PEGUNUNGAN RIAN KALIMANTAN TIMUR: Implikasi perbedaan komposisi magma

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Abstract

The Jelai volcanics are exposed at Mount Rian and the surrounding area, northeastern part of Kalimantan. Major, trace and rare earth element data are presented. The volcanics consist of basalt to andesite with silica content ranging from about 52 to 63.5 wt%. Fractional crystallization involving olivine, pyroxene, plagioclas, and magnetite may resposible for the geochemical variation in the volcanics. However, there is a silica gap about 5wt% between basaltic andesite and andesite. Two trends of fractionation are observed, *i.e.,* the tholeiitic and calc-alkaline trends in the basaltic and andesitic magmas respectivelly. Precipitation of magnetite, as a new phase, in the andesitic magma might change the fractionation from tholeiitic to calc-alkaline trends. Initial crystallization of Fe-Ti magmentite, pyroxene and plagioclase, that produce a rapid compositional change in the residual basaltic andesite to andesite liquids over a small temperature interval would cause a compositional gap.

Keyword : Mount Rian volcanics, geochemistry, compositional gap

Abstrak

Batuan volkanik Jelai tersingkap di Gunung Rian dan sekitarnya di bagian timur-laut Kalimantan. Data unsur utama, jejak dan tanah jarang disajikan di makalah ini. Batun volkanik ini terdiri dari basalt sampai andesit dengan kandungan silika berkisar dari sekitar 52 sampai 63,4%. Fraksional kristalisasi yang melibatkan olivin, piroksen, plagioklas, dan magnetit bertanggung jawab pada variasi geokimia batuan. Namun demikian ada jeda komposisi sekitar 5wt% silika di antara basaltik andesit dan andesit. Dua arah fraksinasi terlihat, yaitu toleitik dan kalk-alkalin masing-masing di batuan basaltik dan andesitik. Kristalisasi magnetit, sebagai fase baru, di magma andesit akan merubah arah fraksinasi dari toleit ke kalk-alkali. Kristalisasi awal Fe-Ti magnetit, piroksen dan plagioklas yang menghasilkan perubahan komposisi larutan sisa secara cepat dari basaltik andesit ke andesit pada interval temperatur kecil akan menghasilkan jeda komposisi.

Kata kunci : Batuan volkanik Gunung Rian, geokimia, jeda komposisi

Introduction

The wide compositional variation of subduction zone magmas has led to the development of several controversial hypothesis of their genesis. The causes of compositional variation among arc basalts and their differences from mid-ocean ridge and oceanic island basalts are widely debated in petrological literatures. It is generally aggreed that the process of magma generation in orogenic environments is a multistage multisource phenomenon. The source of arc magmas may be of mantle (either MORB or OIB characters) or crust (lower crust or subducted oceanic crust including sediments), while the process might involve fractionation with or without assimilation/ contamination, and magma mixing (see Hartono and Sulistyawan, 2011 for recent review).

The Jelai Volcanics discussed in this paper are Tertiary volcanics exposed at Mount (G. = Gunung) Rian and the surrounding areas northeastern part of Kalimantan (Borneo) island (Fig. 1). Hartono (2012) introduces this volcanics as the Midle Miocene-Pliocene volcanics. The volcanic consists of basaltic to andesitic lava and pyroclastic rocks (Heryanto *et al*., 1995). Baharuddin (2011) suggested that the volcanics may result from arc magmas caused by subduction of the Palawan oceanic crust beneath the Kalimantan continent in the Middle Miocene. However their petrogenesis, particularly the cause of geochemical variation and the genetic relationship between basaltic and andesitic magmas, has never been discussed. This paper explores the geochemical characteristics of the Jelai Volcanics to discuss the petrogenesis. The presence of geochemical compositional gap (Hartono, 2012) may also have significant meaning in petrogenetic history and will be discussed in this paper.

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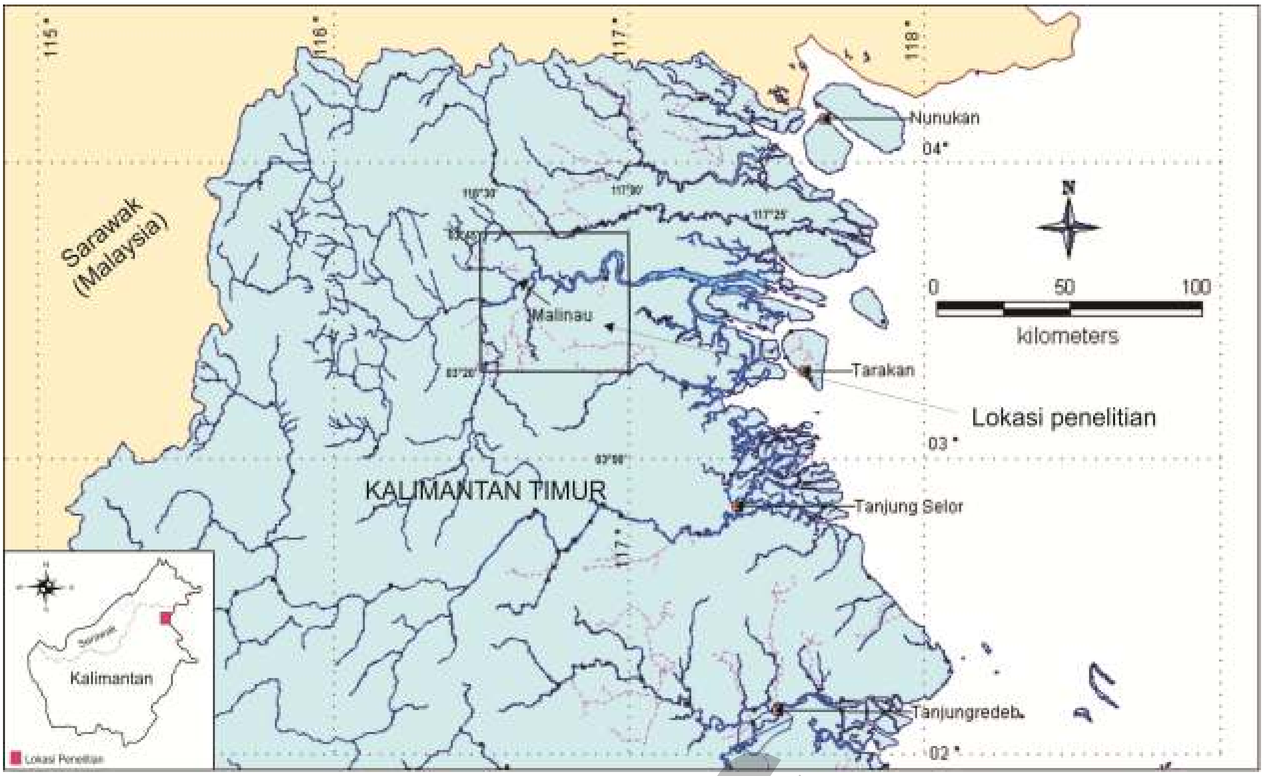

Figure 1. Location of the study area

Samples and Analytical Methods

Rock samples were collected from the field for petrographic and chemical study purposes. Although taken by hammer, a careful selection rocks has been done to ensure that they were as fresh as possible. Fifteen and nine samples were analyzed for petrographic and geochemical studies respectively, and the results are presented through this paper.

Weathered surfaces were removed before rock samples were crushed into coarse-grained gravels in a steel jaw crusher for geochemical analysis. Major, trace and rare earth element analysis were done in the Geolabs, Centre for Geological Survey, the Geological Agency in Bandung. Major elements were determined by an Automated X-Ray Fluorescence Thermo ARL advanced XP Spectrometer, while the trace and rare earth elements were analyzed using a Thermo Elemental ICP-MS.

Three samples were analyzed for K-Ar datings using plagioclase separation minerals. The mineral separation was prepared in the Geolabs in Bandung, while the isotopic analysis was done in AMDAL Australia.

Geology

On the basis of lithology and age, Carlile and Mitchell (1994) divided four magmatic belts in Kalimantan. The belts are referred to as the Cretaceous Meratus, Sunda Shelf, Schwaner, and the Tertiary Central Kalimantan-Northwest Borneo Belts. The Jelai volcanics, discussed in this paper, are part of the Tertiary Central Kalimantan-Northwest Borneo magmatic belt, exposed at Gunung Rian and the surrounding areas in Malinau Northeast Kalimantan (Fig. 1). Heryanto *et al*. (1995) envisaged the volcanics are Tertiary in age, consisting of volcanic breccia, tuff, lava breccia, and basaltic-andesitic lava flows. The presence of lavas indicates their distribution closed to eruption centre, and the Gunung Rian is supposed to be the old volcanic centre. In the study area, the volcanics are deposited unconformity above the Middle Miocene-Late Eocene shallow marine basal conglomerate, claystone, siltstone, and reef limestone of the Sebakung Formation. The Jelai volcanics are unconformably overlain by lacustrine sediments of white chalky tuff, conglomerate with 80% - 90% clayey sandstone and milky quarzt fragments in a coarse-grained sandstone matrix (the Langap Formation of Heryanto *et al*., 1995).

Heryanto *et al*. (1995) and Heryanto and Abidin (1995) reported that the Jelai Formation consists of intermediate to basaltic lava, lava breccia, volcanic breccia, and tuff, which are equivalent to the Sintang Intrusives. However there is no age data to support their interpretation. The andesitic and basaltic lava are porphyritic (the andesite is strongly porphyritic) with plagioclase, pyroxene (plus olivine in basalt) set up in a groundmass of microcrystalline plagioclase and minor pyroxene. Flow structures might be shown in some samples as a lath-like plagioclase groundmass (Baharuddin, 2011). The Jelai volcanics are calc-alkaline, with minor tholeiitic, volcanics originating from subducted related magmas (Baharuddin, 2011). He further reported that the basalt from the Jelai volcanic have been age dated as 16.1, 15.2, and 16.7 ma from basalts. The France Bureau de Recherches Geologiques et Minieres (DRGM) and the Indonesian Directorate of Mineral Resources (DRM) reported that the Jelai volcanics are ranging in age from16.3 ± 2.67 to 14.72 ±0.9 ma (Baharuddin, 2011). It is suggested that, the volcanics may belong to the Middle Miocene-Pliocene Rajang-Cagayan volcanic belt of Soeria-Atmadja *et al*. (1999), formed in relation to the subduction in the Palawan trench. The authors suggested the subduction might occur after collision of the Luconia Block to the Sundaland (Kalimantan) in the Middle Oligocene.

Geochemistry

Geochemical analysis, including major, trace and rare earth elements of the Jelai volcanics are presented in several diagrams. A complete result of the analysis have been presented by Baharuddin (2011: Table 1,2.3).

Major Elements

The major element analyses, both in quoted and plotted values, reported in this paper refer to analyses normalized to 100% volatile free, with Fe as FeO. The whole rock Mg# (Mg# = 100Mg/Mg+Fe+2) was calculated based on the adjustment of ferrous iron as FeO = 0.85 FeO* (Fudali, 1965). The Jelai volcanics are calc-alkaline basaltic to dacitic in composition with silica content various from about 52 wt% to 63 wt% (Fig. 2). Two samples (07EP09 an 07EP10) are within the tholeiitic field. However, there is a silica gap of about 5wt% between the basaltic and intermediate rocks of the calc-alkaline series. The gap may have a significant petrogenetic meaning, which will be discussed letter in this paper. The rocks are also characterized by low titanium ($TiO_2 <$ 1wt%), high aluminium ($Al_2O_3 >$ 15wt%). The Mg# vary from 77 in basalt to 48 in the dacitic rocks, but two samples of basaltic andesite and andesite has 70 and 68 respectively. On the AFM diagram (Fig. 3) most of the Jelai volcanics fall in the calc-alkalic serie, and only few are within tholeiitic field.

Trace Elements

The trace element data of the Jelai volcanics are presented in the chondrite-normalized abundance (Fig. 4). The data indicate that, for the calc-alkaline serie, there is an enrichment of the large ion lithophile elements (Rb, Th, K, and slightly Ba) and the light rare earth elements/ LREE (La, Ce, Sr, and Nd). Although not very significant, the high field strength elements/ HFSE (Nb, Zr, Ti) concentration is depleted. Compared to the rocks originated from subducted-related magmas, the Nb concentration is higher (the Nb abundances vary from 5 to 16 ppm. In contrast, the tholeiitic rock serie do not show the LILE enrichment depletion of Nb relative to K and La.

Rare Earth Elements

The rare earth element (REE) data of the Jelai volcanics are presented in the chondrite-normalized abundance (Fig. 5). The volcanics is characterized by moderate slope of REE patterns with $(La/Yb)_N$ vary from 5.59 in basalt to 7.13 in andesite. It is interesting to note that all samples show slightly Eu negative anomly.

Petrogenetic Discussion

Tectonic Settings

Combined data of rock association, petrographic characteristics, and geochemical characteristics of the Jelai volcanics are consistent with rocks originated from mgmas in subduction zones. The volcanics compose of alternating rocks of basaltic to andesitic lava, and pyroclastics (volcanic breccia and tuff) suggesting a stratovolcano volcanism, which is common in arc magmatic systems. The andesitic lavas are strongly porphyritic, while the basalts are less porphyritic, typical lavas in arc magmatism, consisting of plagioclase and pyroxene as dominant phenocryst phases as well as olivine as a minor phase in the basalt.

Table 1. Major, trace, and rare earth element analysis of the Jelai Volcanics Kalimantan (after Hartono, 2012)

Major Element

	07 SH 09A	07 NO 12	07 NO 13	07 NO 14	07 EP 10	07 NO 05	07 EP 15	07 EP 12	07 EP 09	07 JW 07
SiO2	50.36	53.46	52.92	58.7	58.78	52.32	59.22	61.38	53.9	53.16
TiO2	0.58	0.88	0.9	0.7	0.59	0.75	0.57	0.47	0.56	0.8
Al2O3	15.21	16.89	16.88	17.18	15.97	15.54	17.24	16.09	15.71	16.28
Fe2O3	7.88	9.62	9.31	7.49	4.97	8.73	6.72	6.13	9.53	9.44
MnO	0.14	0.31	0.17	0.14	0.07	0.14	0.12	0.11	0.13	0.15
MgO	11.31	4.32	4.97	3.66	4.53	8.6	3.43	2.47	7.15	5.93
CaO	8.1	8.13	8.25	6.77	9.32	8.82	6.46	5.56	8.1	7.98
Na2O	2.56	3.33	3.08	2.35	1.83	3.22	2.2	2.48	1.25	2.88
K2O	0.93	1.53	1.42	1.75	0.1	1.01	1.9	2.45	0.12	1.2
P2O5	0.1	0.21	0.2	0.21	0.11	0.14	0.13	0.08	0.09	0.15
Loss	1.91	0.81	1.37	1.5	2.49	0.74	2.01	1.91	2.62	1.2
Total	99.08	99.48	99.46	100.44	98.75	100.01	99.99	99.13	99.16	99.16
Total-Loss	97.17	98.67	98.09	98.94	96.26	99.27	97.98	97.22	96.54	97.96
Mg#	77	51	55	53	68	70	54	48	64	59
Trace Element										
Ba	243.20	273.90	257.50	277.30	62.17	173.60	276.80	324.10	47.88	188.70
Rb	42.52	48.00	44.98	64.60	4.83	26.37	82.49	105.63	6.37	42.55
Th	5.77	5.31	5.23	6.47	9.53	3.22	8.72	8.94	6.23	4.65
K	7720.38	12701.27	11788.11	14527.60	830.15	8384.50	15772.82	20338.64	996.18	9961.78
Nb	7.00	16.13	15.82	10.16	7.55	11.65	8.14	5.24	6.08	12.06
La	16.75	17.89	17.36	23.80	17.81	10.90	23.16	18.97	17.61	14.57
Ce	33.20	36.42	35.37	50.07	34.55	21.89	47.25	36.62	36.17	29.84
Sr	280.50	314.40	315.20	553.00	335.70	354.40	324.90	300.20	219.00	288.20
Nd	14.72	17.40	17.06	23.15	17.24	11.28	19.60	14.97	16.98	14.24
P	436.41	916.46	872.82	916.46	480.05	610.98	567.34	349.13	392.77	654.62
Sm	3.17	3.90	3.87	4.90	3.81	2.82	3.93	3.06	3.65	3.36
Zr	62.64	92.18	81.38	141.28	11.57	60.22	94.02	64.06	59.06	75.16
Ti	3477.10	5275.59	5395.49	4196.50	3537.05	4496.25	3417.15	2817.65	3357.20	4795.99
Y	20.17	24.42	23.91	27.92	18.66	17.88	21.68	19.08	20.62	21.59
Yb	2.01	2.27	2.25	2.65	1.72	1.68	2.18	1.94	2.08	1.98

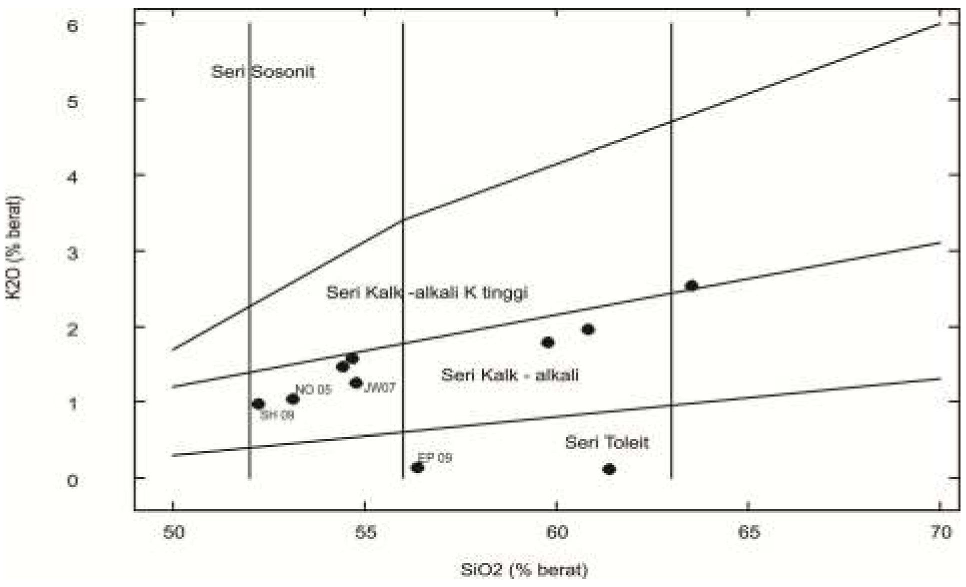

Figure 2. SiO2 vs K2O diagram (Peccerillo and Taylor, 1976) for the Jelai volcanics. Th: tholeiite, CA: calc-alkaline, HCA: high-K calc alkaline, and SH: shoshonitite.

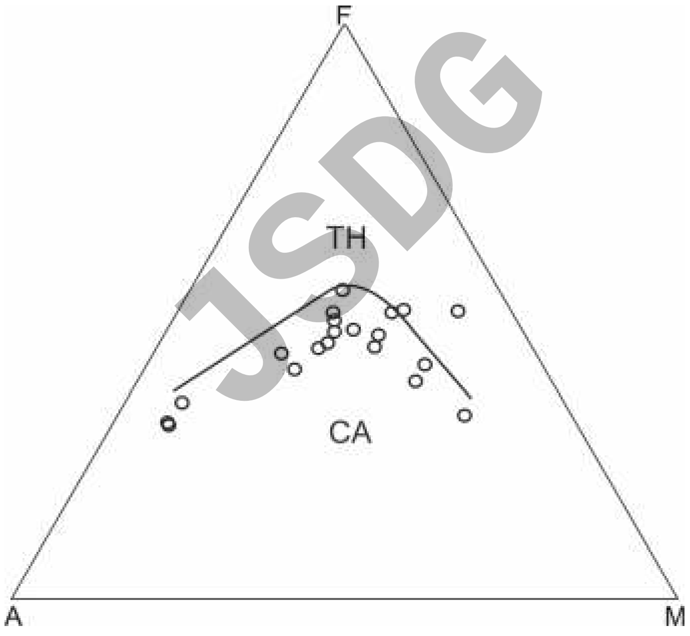

Figure 3. AFM Diagram for the tertiary volcanic rocks from Kalimantan. Symbols as for Fig 2. TH : Tholeiitic, CA : Calc Alkaline series

The dominant calc-alkaline rocks, with minor tholeiite (Fig. 2), present in the Middle Miocene-Pliocene volcanics is consistent with the rock originated from a subducted related magma. It is generally known that the calk-alkaline signature is the only affinity of magma formed in a subduction environment, and has never been originated in other tectonic settings. The orogenic-related rock is also indicated by lower concentration of TiO_2 (< 1wt%: Fig. 6).

Although the concentration of Nb in the Jelai volcanics is slightly higher than that in common arc rocks, the trace element distribution (Fig. 4) is similar. The calc-alkaline rocks show depletion in HFSE (Nb) relative to K and La, a characteristic of rocks originated from an orogenic magma. The Jelai volcanics may resulted from a subduction of the Palawan oceanic crust beneath the Sundaland continent in the middle Miocene time (Soeria-Atmadja *et al*., 1999; Baharuddin, 2011; Hartono, 2012). However this characteristic (depletion in Nb relative to K and La) is not shown in the tholeiitic rocks which contains low potasium concentration. The presence of tholeiitic rocks in the Jelai volcanics suggests the early stage of magmatisme in Miocene subduction in Kalimantan. The Jelai volcanics also contain low abundance of Ba, which is uncommon in the rock formed in a subduction zone environment.

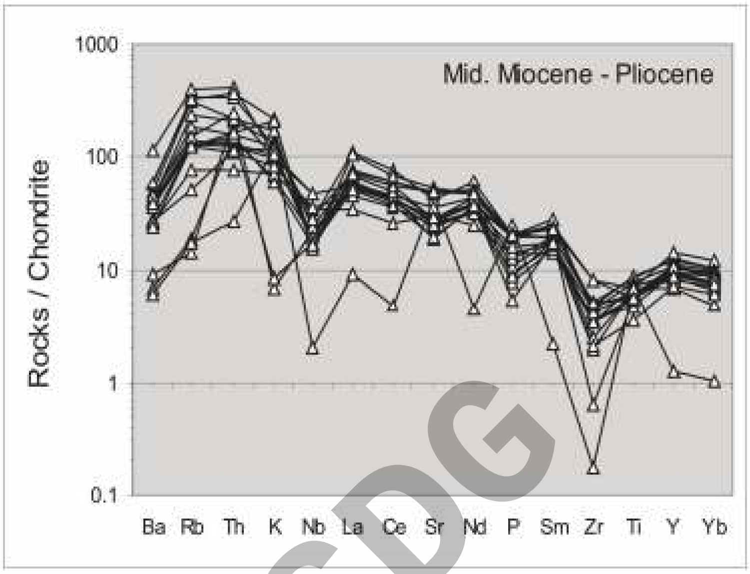

Figure 4. Chondrite-normalized trace element concenration of the Jelai volcanics.

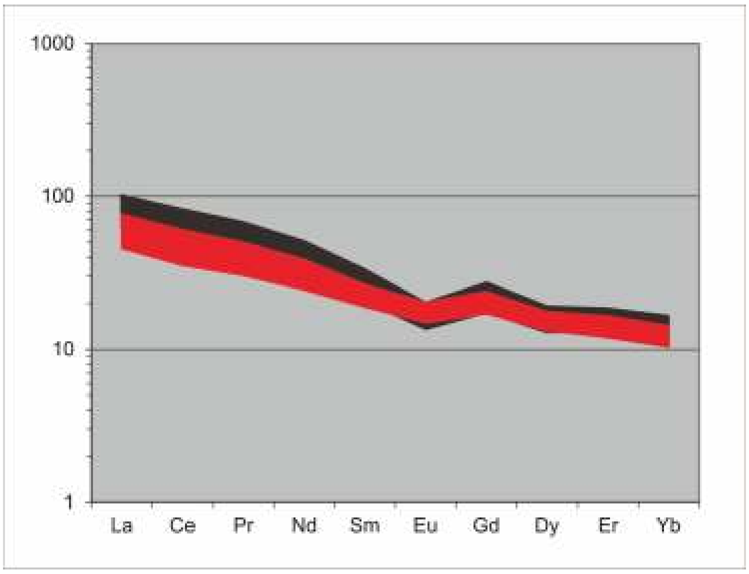

Figure 5. Chondrite-normalized rare earth alement abundance for the Jelai volcanics

This low concentration of Ba may indicate the small contribution of sediments in the source.

Magma Sources and Fractional Crystallization

The most basic rock from the Jelai volcanics is basalt 07SH09A (Table 1) with high MgO concentration ($Mg^{\#}$ 77). Although with high $Mg^{\#}$, we do not sugget the basalt 07SH09A represents a primary magma in equilibrium with the mantle olivine. There is no other data to support this interpretation, such as the concentraion of Ni and Cr. This high $Mg^{\#}$, including that in the andesite 07EP10 ($Mg^{\#}$ 68) and basaltic andesite 07NO05 ($Mg^{\#}$ 70) could be anomalies, and the origin is more complex (see for example Hartono and Sulistyawan, 2010 for recent review). However the high concentration of LILE, except Ba, and LREE (La,Ce,Nd) as well as depletion in HFSE (Nb, Zr) might indicate that the mantle source that has been enriched by LILE and LREE. As presented, the Nb content of the Jelai volcanics is anomalously higher than that in common arc magmas (Table 1), suggesting the involvement of a deep mantle (OIB) source.

by a process of, for example, magma mixing (e.g. Hartono, 2003). The low concentration of Ba may be caused by only small ammount sediments in the Palawan subducted oceanic crust beneath the Sundaland in the Middle Miocene time.

The distribution of major element data of the Jelai volcanics (Fig. 6) is not easy to be interprete. The geochemical variation, especially the basic rocks, seems to be inconsistent with the presence of phenocryst phases. The presence of plagioclase and pyroxene phenocrysts is not expresed by the Al_2O_3 and FeO* distribution respectively. The distribution of these elements shows positive correlation to the silica concentration, suggesting no plagioclase and pyroxene separation. Alternativelly, pyroxene may fractionate in a small amount causes decrease in MgO and slightly decrease in CaO. Decreasing MgO with increasing silica may aslo indicate olivine fractionation, as olivin presents in the basalt in a small ammount. The behaviour of FeO* might not be influenced by separation of pyroxene (becouse only small ammount of pyroxene precipitated), but could be strongly influenced by magnetite fractionation.

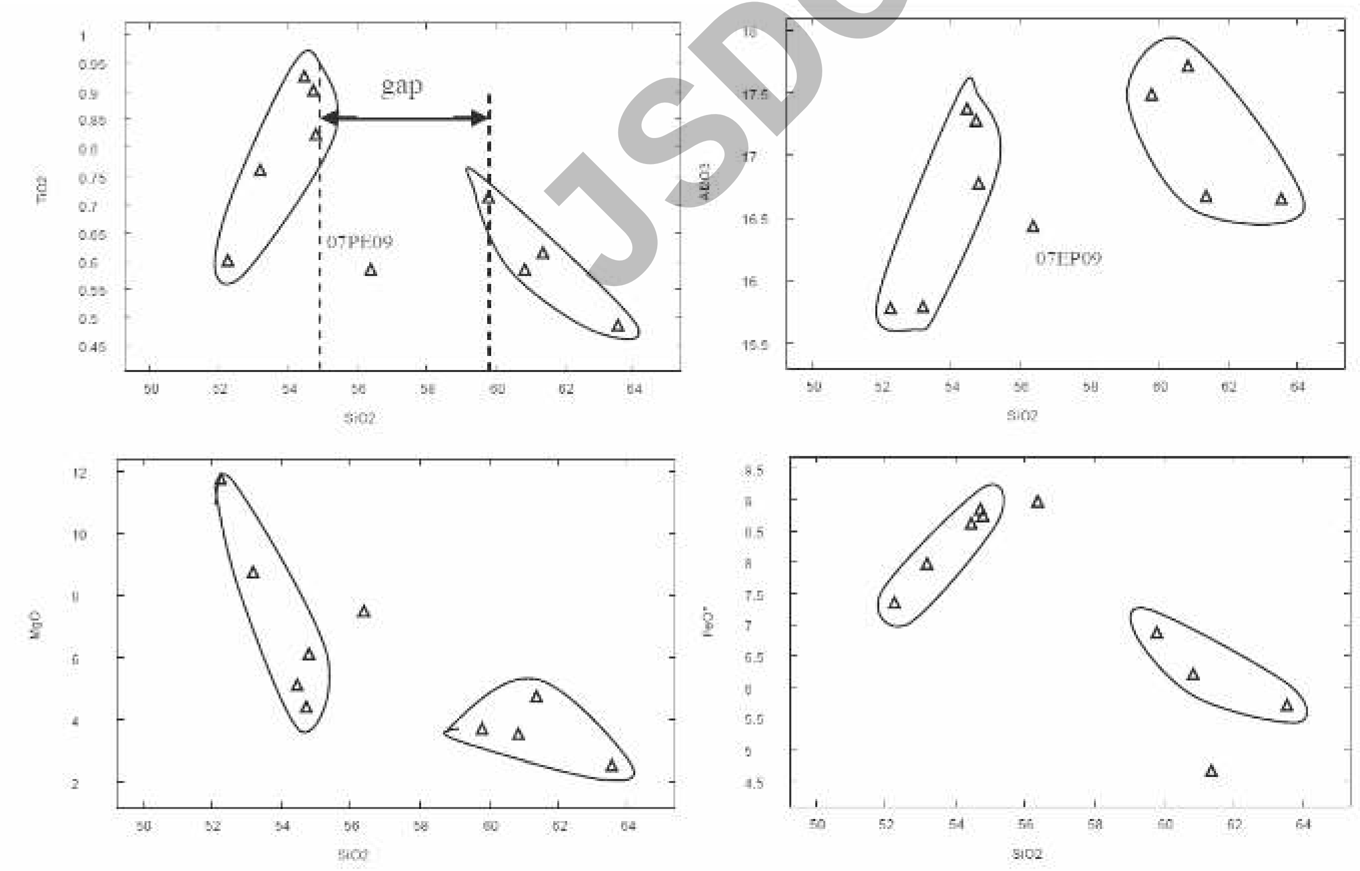

Figure 6. Major element Harker diagram for the Jelai volcanics. See the silica gap of about 5wt%. The closed-line indicate trend of element increases and decreases within the basaltic and andesitic rocks, which represent tholeiitic and calc-alkaline trends respectivelly.

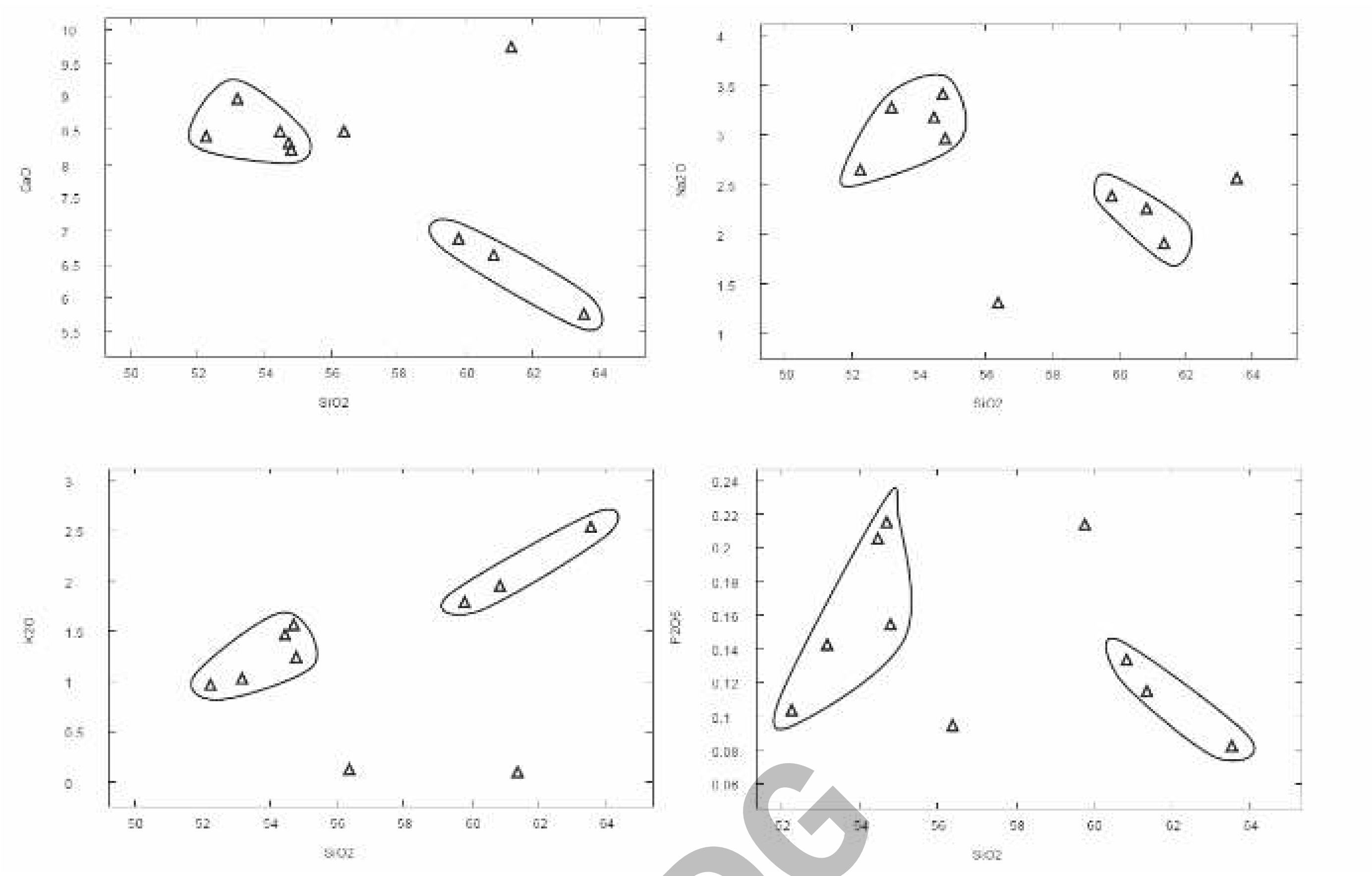

Figure 6. (Continued) Major element Harker diagram for the Jelai volcanics. See the silica gap of about 5wt%. The closed-line indicate trend of element increases and decreases within the basaltic and andesitic rocks, which represent tholeiitic and calc-alkaline trends respectivelly.

The tholeiitic fractionation trend of the basaltic magmas (Fig. 2) may support the interpretation. The distribution of TiO_2 and FeO* increases with increasing silica in the basaltic magma, suggesting absence of magnetite precipitation. Magnetite absence precipitation in the basaltic magma would result in Fe enrichment in the residual liquids and the tholeiitic differentiation trend will be maintained (Osborn, 1969). In contrast, Osborn (op cit) suggested the calc-alkaline fractionation trend is indicated by silica enrichment caused by magnetite fractionation. It is common in subduction zone magmatism that the early stage of tholeiitic fractionation will be followed by calc-alkaline fractionation trends.

The behaviour of Al_2O_3, which has positive correlation with the silica content is in contrast to the plagioclase penocrysts present in the basic rocks and the tholeiitic fractionation trend. In the early stage basaltic differentiation, olivine, pyroxene and plagioclasen would fractionate early. If plagioclase dominates fractionation the residual liquid would enriched in Fe concentration cause tholeiitic differentiation trend, but if pyroxene is the mineral phase dominate the trend of calc-alkaline will be formed (Grove and Baker, 1984). The basaltic rocks of the Jelai volcanics show tholeiitic fractionation trend and contain plagioclase phenocrysts, but the Al_2O_3 increases. The inconsistency between petrographic and geochemical data for the plagioclase phenocrysts is still open for discussion, and we leave it to the reader.

The correlation between petrographic and major element distribution is more clearly in the intermediate magma differentiation. Pyroxene separation is indicated by decreasing CaO, FeO* and MgO with increasing silica concentration. While decreasing CaO together with Al_2O_3 when silica increases suggest fractionation of plagioclase. Fe-Ti magnetite might starts to separate from the liquid, which is characterized by a negative correlation between silica concentration and FeO* and TiO_2 contents. However, there is a silca gap between basaltic and andesitic magmas, and will be discussed in the following section.

Na2O increases in the basaltic rocks and decreases in the andesitic rocks with increasing silica concentration might indicate Na-plagioclase crystallized in the andesitic magma. Apatite may crystallize in the andesitic magma as indicated by decreasing P_2O_5 with increasing silica content.

Possible Origin of Compositional Gap

A compositional gap may be formed during fractional crystallization processes (*e.g.,* Weaver, 1977; Clague, 1978; Grove and Donnelly-Nolan, 1986). Clague (1978) shows that a compositional gap found in oceanic basalt-trachyte suites is caused by the appearance of a new mineral phase in the crystallisation sequence. The gap was evident when some elements which were compatible with this new phase were used as compositional variables, but when elements that were incompatible with all of the crystallising phases were used the gap disappeared. Grove and Donnelly-Nolan (1986) proposed that the compositional gap present in the Medicine Lake lavas was caused by crystallisation of an amphibole-bearing assemblage that followed the early crystallisation of olivine, plagioclase and augite. They demonstrated that initial crystallisation of amphibole-plagioclase-orthopyroxene-magnetite-apatite resulted in a rapid compositional change in the residual andesitic liquid to rhyolite over a small temperature interval, and produced a compositional gap.

Although fractional crystalliztion is the main process caused the geochemical variation, (Fig.5 & 6) the major element distributions between basaltic and intermediate magmas of the Jelai volcanics suggest no a simple parent-daughter relationship.

As stated before, there is a compotional gap about 5wt% silica between the basaltic and intermediate rocks. As discussed, there is a change of fractionation trend from tholeiitic to calc-alkaline in the beginning of the andesitic magma formation. Crystallization of magnetite, which is indicated by decreasing FeO* and TiO_2 with increasing silica content (Fig. 6), might cause the trend of fractionation change from tholeiitic to calc-alkaline trends. An experimental work by Osborn (1969) suggests that Fe-Ti magnetite crystallizes in a magma chamber with high oxygen fugacity. He proposed the high oxygen fugacity of the calc-alkaline magma due to the dissociation of water that was incorporated into magmas as its process through the wet crust. In the Jeli volcnics, the incorporation of water in the basaltic magma may cause abrupt change the temperature, which may be steady during separation of olivine, pyroxene, plagioclase(?), and Fe-Ti magnetite (new phase) to produce the calc-alkaline andesitic magma. A rapid compositional change in the residual basaltic andesite to andesite liquids over a small temperature interval caused by intial crystallization of Fe-Ti magmentite, pyroxene and plagioclase would resulted in a compositional gap.

Conclussion

The geochemical variation of the calc-alkaline Jelai volcanics from G. Rian northeastern part of Kalimantan is caused by fractionation of olivine, pyroxene and plagioclase in the early stage of basaltic magma producing a tholeiitic fractionation trend. The trend of fractionation changes to calc-alkaline when Fe-Ti magnetite begin to crystallized to produce an andesitic magma. Initial crystallization of Fe-Ti magmentite together with pyroxene and plagioclase, that produce a rapid compositional change over a small temperature interval, might produce a silica gap. The minor low-K tholeiitic rocks present in the Jelai volcanics suggest an early stage magmatism in the Miocen subduction in Kalimantan.

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