ORIGIN OF CRETACEOUS HIGH MAGNESIAN ANDESITES FROM SOUTHEAST KALIMANTAN

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Abstract

High magnesian andesites are found in the Cretaceous Haruyan volcanics in Southeast Kalimantan. The rocks have Mg$^{\#}$ 67 – 69, but low concentrations of Ni (44 – 60 ppm), Cr (37 – 411 ppm) and, except two samples of 95UH23C and 96UH23, ratios of Sr/ Y are also low. Geochemical and tectonic studies show that the high magnesian andesites were originated from a subduction zone-type magma similar to that of the most “normal” Haruyan volcanics. Two possible origins of the Cretaceous high magnesian andesites are proposed. First, melting of the mantle wedge above the slab to produce a basaltic magma followed by crystal fractionation, especially olivine and pyroxene, during magma ascent to the surface resulted in a derivative magma with low Ni and Cr concentrations. A collision between the pre-Mesozoic Paternoster platform (microcontinent ?) and the Sundaland continent in the Upper Cretaceous-Lower Miocene might cause the magma ascent to pool immediately in the lower crust-upper mantle boundary. The impending magma then reacts with hot mantle peridotite to produce the high magnesian andesites. Secondly, the high magnesian andesite may resulted from a reaction between silicic magma and hot mantle peridotite. The collision may also cause lower crust melting resulted in granitic magma (? The Hajawa Granite), which then reacts with hot mantle peridotite to produce the adakite-type high magnesian magma, such as samples 95UH23C and 96UH23.

Keywords : high magnesian andesites, Southeast Kalimantan, origin

Sari

Andesit magnesium tinggi dijumpai di Haruyan volcanics berumur Cretaceous di Kalimantan Tenggara. Batuan ini mengandung Mg$^{\#}$ 67 – 69, tetapi konsentrasi Ni dan Cr rendah, masing-masing (44 – 60 ppm) dan (37 – 411 ppm) dan perbandingan Sr/ Y juga rendah, kecuali percontoh 95UH23C and 96UH23. Hasil kajian geokimia dan tektonik menunjukkan bahwa andesite magnesium tinggi ini berasal dari magma hasil penunjaman seperti umumnya “normal”Haruyan volcanics. Dua kemungkinan kejadian andesit magnesium tinggi yang diusulkan. Pertama, peleburan baji mantel di atas slab menghasilkan magma basal, yang kemudian mengalami fraksinasi kristalisasi, terutama olivine dan piroksen, selama magma naik ke permukaan dan menghasilkan magma dengan kandungan Ni dan Cr rendah. Tumbukan antara Paternoster platform (microcontinent ?) yang berumur pra-Mesozoik dan kontinen Sunda pada Kapur Akhir-Miosen Bawah mengakibatkan magma yang naik ini terbendung di batas antara mantel bawah-kerak atas. Magma yang tertahan ini kemudian bereaksi dengan mantel peridotit yang panas dan menghasilkan andesit magnesium tinggi. Kedua andesit magnesium tinggi dihasilkan dari reaksi antara magma asam dan mantel peridotit panas. Tumbukan sangat boleh jadi juga mengakibatkan peleburan kerak bawah, menghasilkan magma granitik (? Granit Hajawa), yang kemudian bereaksi dengan mantel peridotit menghasilkan magnesian magma bertipe adakit, seperti percontoh 95UH23C dan 96UH23.

Kata kunci : andesit magnesium tinggi, Kalimantan Tenggara, asal-muasal

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Introduction

A magmatic activity in subduction zone environments is the key for understanding arc tectonics, the formation of continental crusts, and the characteristics of crust-mantle geochemical systems. Among the important aspects of subduction zone magmatism that continuous to be of interest are the origin, including the source/ or sources of arc magmas, the process by which magma rise from the source to the surface, and the origin of the subduction geochemical signature. Andesite is the most common rock occur in orogenic tectonic and its origin has attracted continuous attention of petrologists. The most popular hypothesis of the origin of andesite is that andesite has been derived from mantle derived basaltic primary magmas by crystallization

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differentiation (*e.g.* Crawford *et al*., 1987; Woodhead, 1988; Eggins, 1993). However recently, some andesites in several arcs are believed to be originated from melting of crustal materials, either subducted oceanic crusts or lower crust. Arc related andesitic rocks, called adakite (*e.g.*, Defant and Drummond 1990; Defant and Kepezhinskas, 2001, Hartono and Suyono, 2006;) and high Mg andesite (*e.g.*, Yogodzinski and Kelemen, 1998; Kelemen, 1995; Tatsumi and Ishizaka, 1982) are believed to be originated from crustal melting or at least some crustal materials are significantly involed in the petrogenesis.

It has long been known that unusually high-Mg andesite occur in several arcs, such as in Mariana arc (Crawford *et al*., 1981), Setouchi volcanic belt, Japan (Tatsumi and Ishizaka, 1982), Far Western Aleutian arc (Yogodzinski *et al*., 1994), North Fiji back arc basin (Danyushevsky *et al*., 2006), the Cenozoic volcanic and subvolcanic rocks from the Meratus Range (Hartono *et al*., 1999), and many others. High-magnesian andesites are distinctive in their relatively high MgO contents at a given SiO_2 compared to normal arc andesites. Several petrologists (*e.g.*, Kuroda *et al*., 1978; Meijer, 1980) suggested that the significantly high-magnesian andesites (called boninite) are derived from andesite primary magmas generated by partial melting of the depleted mantle peridotite. However Crawford *et al*. (1981) believed that boninite in West Philippine-Mariana regions might be formed in an island arc-back arc basin system. The generation of the boninite series magma appears to occur at the point when arc volcanism ceases and back-arc spreading is initiated.

The high-Mg andesites of Cretaceous age are also found in the Meratus Mountains and Pulau Laut, Southeast Kalimantan (Fig. 1). The presence of these high-Mg andesites have been reported by Hartono *et al.* (1997). The rocks were found in association with other normal andesite of the Cretaceous (Haruyan and Paau) volcanics in those two above areas. However, their origin has never been discussed. This paper discusses the origin of this Cretaceous magnesian andesite in Southeast Kalimantan mainly based on geochemical characteristics of the rocks. As arc magmatism is a direct response to tectonic and chemical process operating in subduction zone environments, knowledge of the origin of the Cretaceous Haruyan Mg-andesites is a key for better understanding of the tectonic and geological history of Kalimantan area. The magnesian andesite discussed in this paper is defined as andesite containing MgO > 4wt % with magnesium-number ($Mg^{\#} = 100Mg^{+2} / (Mg^{+2} + Fe^{+2}) > 67$ and silica contents 54 – 59wt%.

Samples and Analytical Procedures

Field works and rock samplings were carried out in 1994-1995 as a part of the research on Magmatic Evolution in South Kalimantan. The research was financed by the *Proyek Kajian dan Informasi Geologi Tematik*, the Indonesian Geological Research and Development Centre (now the Centre for Geological Survey). The very dense vegetation and highly weathered volcanic formations make it difficult to collect the fresh samples. In order to get the best samples, most of the samples were taken from big boulders or river floats. Twenty nine representative samples were analyzed. Major and trace element analysis were done at the University of Tasmania, Australia by the first author and Tsukuba University, Japan. Weathered surfaces were removed before rock samples were crushed into coarse-grained gravels in a steel jaw crusher. About 50-80 gram of selected fresh grains were then ground in a tungsten-carbide swing mill. Major elements were measured from glass discs, which were prepared with 0.7 gram sample powder, 3.75 gram lithium borate flux, and 0.05 gram lithium nitrate (Norris and Chappel, 1967), using an automated Phillips PW 1480 X-Ray fluorescence spectrometer. Trace elements are also analyzed using the same spectrometer in the University of Tasmania, which were measured from pressed powder pills backed by boric acid. Volatile components (loss on ignition) were determined by heating 1 – 1.5 gram sample powder to 1000°C for over night. Rare earth elements (REE) were determined using an ion-exchange technique. The detailed procedure followed for determining the REE is presented by Robinson *et al*. (1986). Accuracy and precision were monitored using a variety of national standard and international standard rocks.

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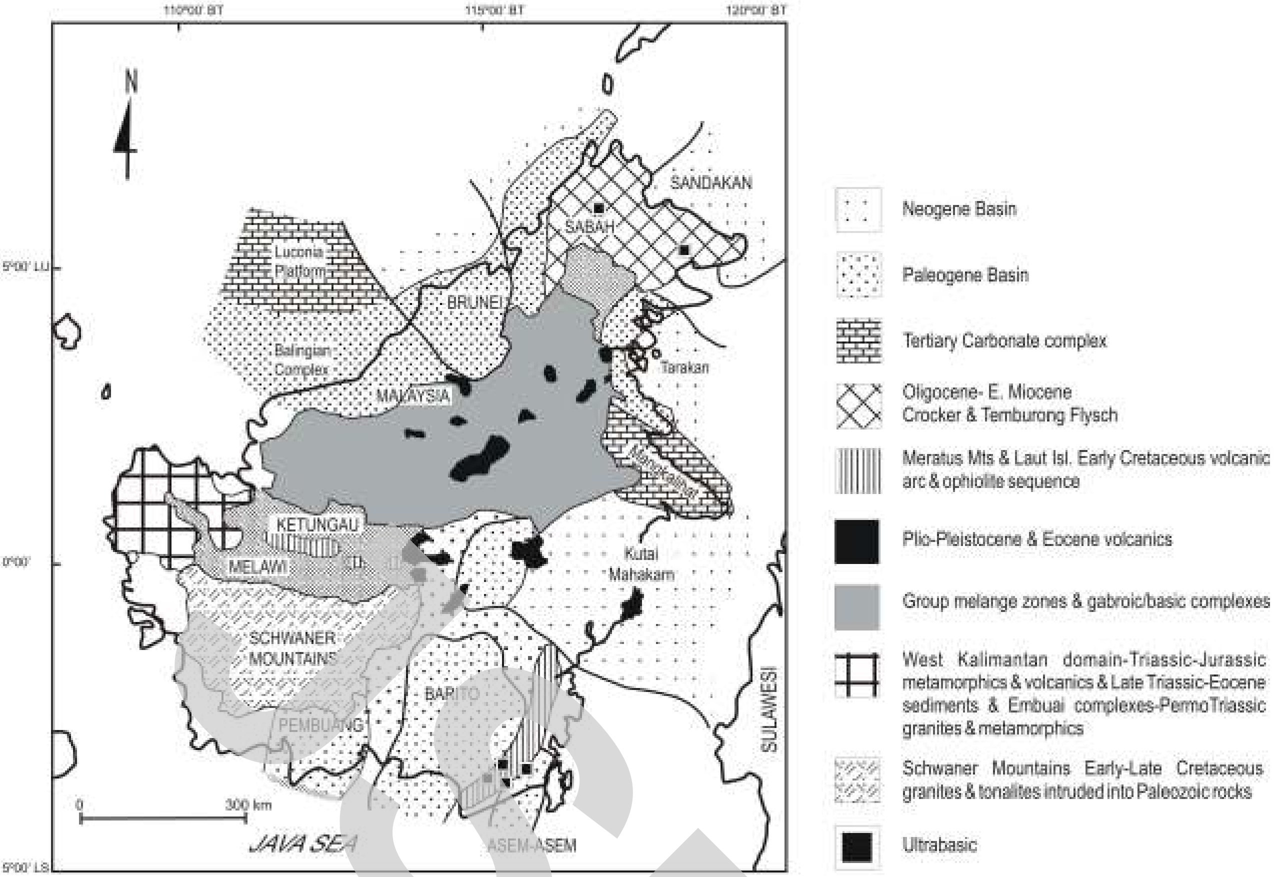

Figure 1. Schematic figure of Sotheast Kalimantan tectonic setting simplified from Darman and Sidi (eds) (2000). Also shown the Meratus Mountains and Pulau Laut as the study area.

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Regional Geology of Southeast Kalimantan

The study area belongs to the Meratus Mountains and Pulau Laut, Southeast Kalimantan. Geology of the area (Fig. 2) have been studied by Koolhoeven (1935), Sikumbang (1986), Sumarsono (1987), Sikumbang and Heryanto (1994), Heryanto and Sanyoto (1994), Supriatna *et al*. (1994), Rustandi *et al*. (1994), and Krol (1920). The following discussion of the regional geology of Southeast Kalimantan is largely based on these reports.

The Meratus Mountains (or Meratus High) separates the Barito and Kutai Basins from the Kintap Basin which lies to the southeast (Fig. 1). The high consists of ophiolite nape overtrust (together with group of metamorphic rocks) on the Cretaceous volcanics (the Haruyan and Paau volcanics of Sikumbang and Heryanto, 1994). The ophiolite comprises hazburgite, peridotite, serpentinite and gabbro, while the metamorphic unit is composed of hornblende schist, mica schist, epidote schist, glaucophane schist and amphibolite. The Cretaceous Haruyan volcanics are subducted related volcanics (Hartono et al., 1997, 1999) consisting of andesitic breccias, tuffs, lavas, minor dykes and basaltic lavas. The volcanic might have been formed at 82 my ago based on K-Ar data (Permanadewi *et al*., 1996). Cretaceous clastic (the Pitap Formation) and carbonate (the Batununggal Limestone) sediments unconformably overlay the ophiolite and metamorphic basement. The Pitap Formation, which is made up of sandstone, claystone, chert with limestone intercalations containing *Radiolaria*, was possibly deposited in a fore-arc region (Heryanto and Sanyoto, 1994). The formation may be interfingering with the Cretaceous Haruyan Volcanics. The Cretaceous sediments and volcanics have been intensively folded with steeply dipping and faulted resulting NE-SW trending direction. The Batununggal Limestone consists of massive, well-bedded limestone containing fossils of *Orbitolina* of Early Cretaceous and was deposited in the fore-reef environment (Heryanto ande Sanyoto, 1994). Early-Late Cretaceous subducted related granitoids (Hartono *et al*., 1999) may intruded the basement rocks, but the contact has not been found. Tertiary fluviatile to shallow marine sediments of the

Tanjung, Berai, Warukin, and Dahor Formations (of the Barito basin) unconformably overlie the pre-Tertiary rocks. Tertiary arc related andesitic to basaltic volcanic and subvolcanic rocks occur in spotted areas along strike-slip faults, which have been developed to normal faults (Hartono *et al*., 1997). The Cretaceous high magnesian andesite discussed in this paper are found within the Haruyan and Paau volcanics of volcanics.

Petrographic Summary

The Cretaceous Meratus volcanic reported in this paper, in which the high magnesian andesite occurred, belongs to the Pitanak Group of Sikumbang and Heryanto (1994), which consists of Haruyan volcanics (or Haruyan Formation of Heryanto and Sanyoto, 1994) and Paau volcanics (or Paau Formation of Sikumbang and Heryanto, 1994). The Haruyan volcanic is well exposed both in the western and eastern flank of the Meratus Mountains and in Pulau Laut (Fig. 2). The volcanic comprising interbedded andesitic to basaltic lava, minor dacite, breccia and tuff. On the other hand the Paau volcanic is only exposed in the Meratus Mountains and dominated by well to poorly bedded volcaniclastic sediments and tuff ("reworked pyroclastics"). Comagmatic dykes or subvolcanics are found locally. Petrographic descriptions presented below are based on a report by Hartono (1997).

The andesitic to basaltic lavas are usually hipocrystalline, porphyritic (45 – 65% phenocrysts), with plagioclase and pyroxene phenocrysts set up in a groundmass of lath-like and or microlite plagioclase, microcrystalline pyroxene and magnetite, and glass partly devitrified. Minor basaltic lava with pillow structures was found locally (Hartono, 1997) indicating a submarine environment. Trachytic basalt and adesite are characterized by trachytic textures, especially the groundmass, and the presence of K-feldspard as phenocrysts and groundmass in the samples. The dacite is fine-grained, hypocrystalline, porphyritic, with dominant plagioclase, minor pyroxene, and magnetite phenocrysts set up in a groundmass of devitrified glass, microcrystalline feldspard, and magnetite. The volcanic breccia is usually weathered, with angular to subangular basaltic andesite to andesite fragments. The tuffs are fine- to medium-grained crystal tuff, consisting of plagioclase, pyroxene, magnetite, minor rock fragment, and devitrified glass.

The crystal rich and porphyritic texture of Meratus Cretaceous volcanics and those alternating deposition between fined- to medium-grained pyroclastics and lava are very common in subduction related volcanisms.

Geochemistry

About 29 samples have been analyzed for major and trace elements and the result is shown in several figures and diagrams. 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). In SiO_2 vs K_2O+Na_2O diagram (Fig. 3) of LeBas *et al*. (1986), the data show that the volcanic is dominated by an intermediate composition of basaltic andesite and andesite to basaltic trachyandesite to trachyandesite and only few basaltic and dacitic composition. It is consistent with the rocks derived from magma in an arc tectonic setting. Hartono *et al*. (1999) reported the Haruyan and Paau volcanics are mostly calc-alkaline, the only rocks that formed in subduction zone environments and not in other tectonic settings. The subduction related magmatism is also supported by trace element data (Fig. 4). The Cretaceous volcanic from the Meratus Mountains is characterized by high concentration of large ion lithophile elements (LILE: Ba, K, Rb, Sr), and light rare earth elements (LREE : La, Ce), but depletion in high field strength elements (HFSE Nb, Ti, Zr). The depletion Nb relative to K and La is characteristic of the magma produce in subduction zone environments.

However, some samples show anomalously high in having MgO content (Fig. 5). The high magnesian concentration is more clearly when the data are compared to "normal arc" andesite and basalt from Wilis and Lawu Volcanoes, East Java (Fig. 6). The Wilis and Lawu volcanoes are Quaternary volcanoes resulted from a subduction of the Indian oceanic plate beneath the east Java crust. The subduction produced a series of basaltic to dacitic volcanics in the Wilis volcano and from basaltic to andesitic in the Lawu volcano (Hartono, 1994). The high magnesian andesite occurred together with potassic rocks (evidenced by the presence of trachybasalt and trachyandesite) is significant phenomenon and will be discussed in the following session.

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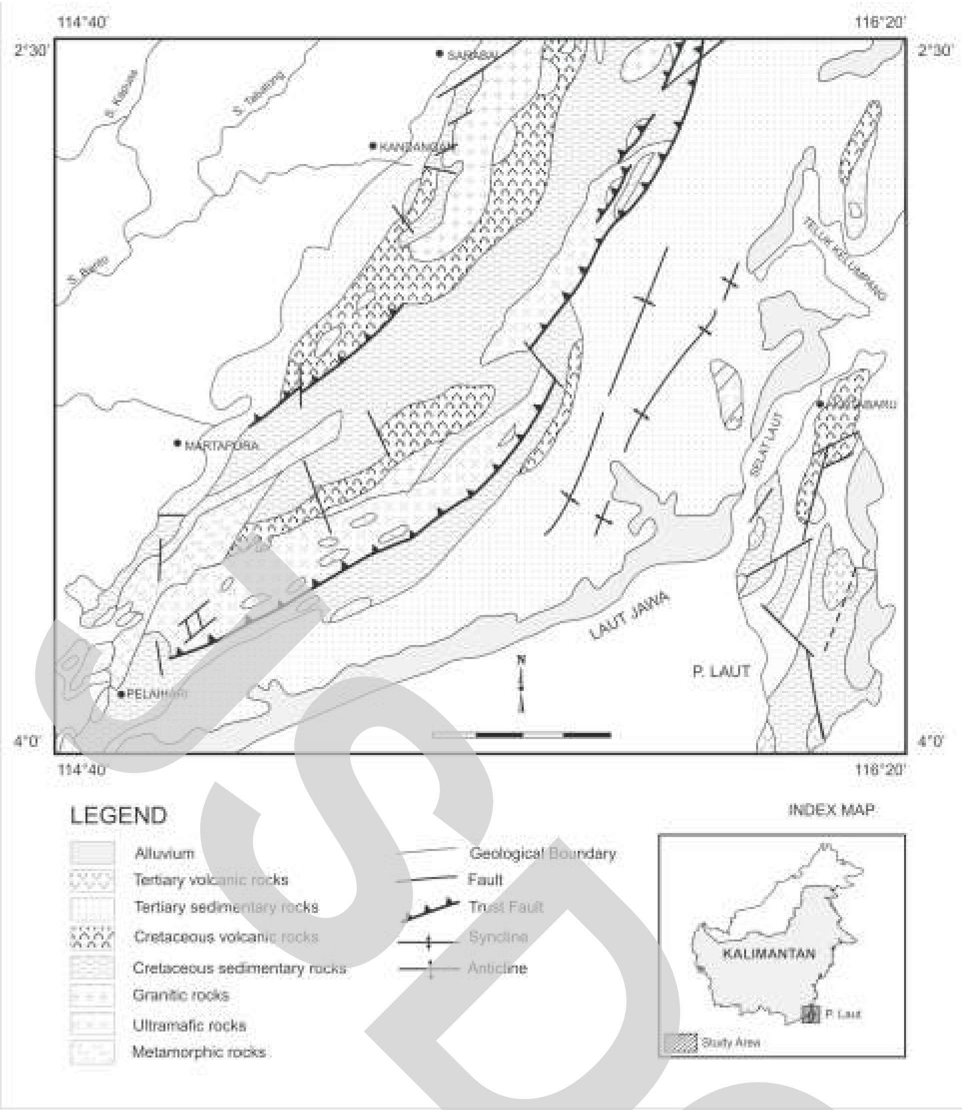

Figure 2. Schematic geological map of the Meratus Mountains (simplified from Supriatna *et al*., 1994) showing the distribution of the Cretaceous volcanics.

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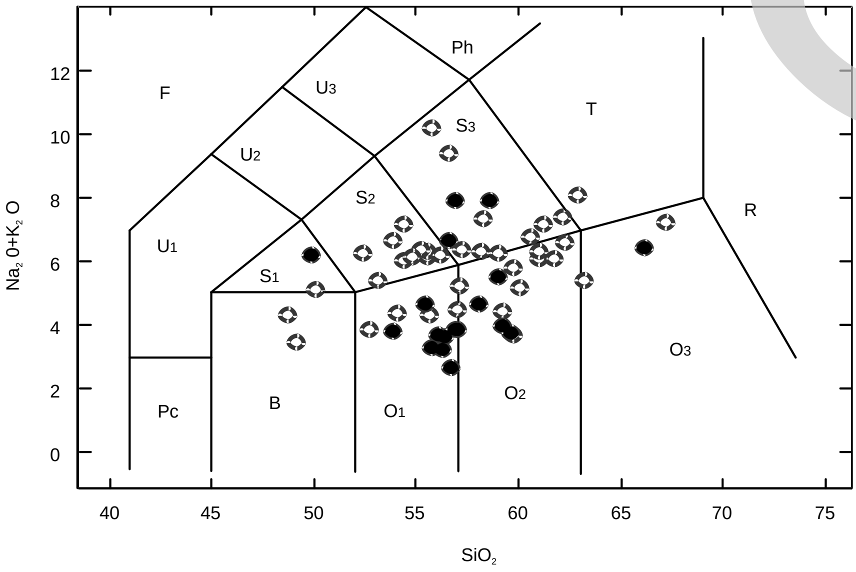

Figure 3. SiO$_2$vs K$_2$O + Na$_2$O of the Cretaceous volcanics from the Meratus Mountain. Black filled circles are high magnesian andesite and red open circles are "normal" basalt-andesite-dacite.

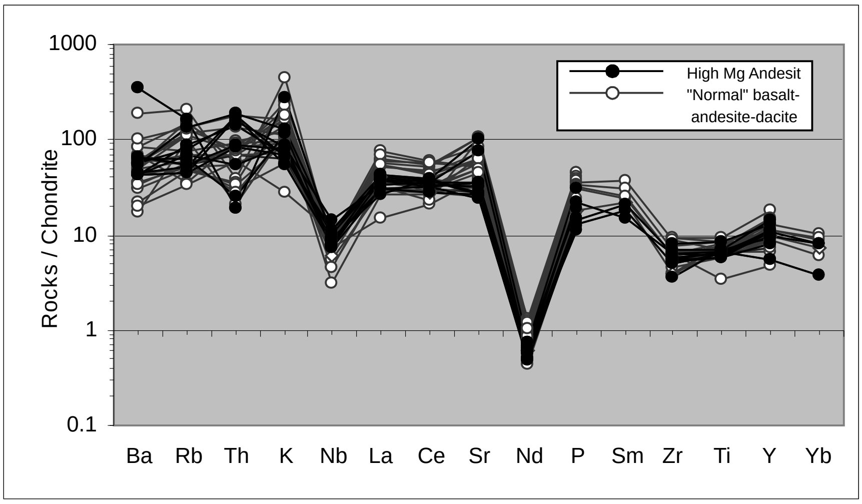

Figure 4. Chondrite-normalized trace elements of the Cretaceous volcanics from Southeast Kalimantan, including the high magnesian andesite.

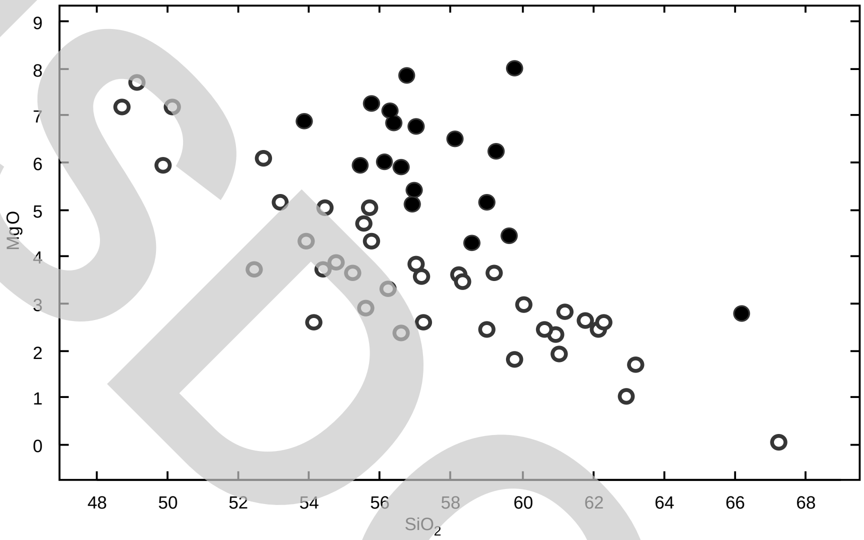

Figure 5. SiO_2 vs MgO the Cretaceous volcanics from the Meratus Mountain. Black filled circles are high magnesian andesites and red open circles are “normal” basalt-andesite-dacite.

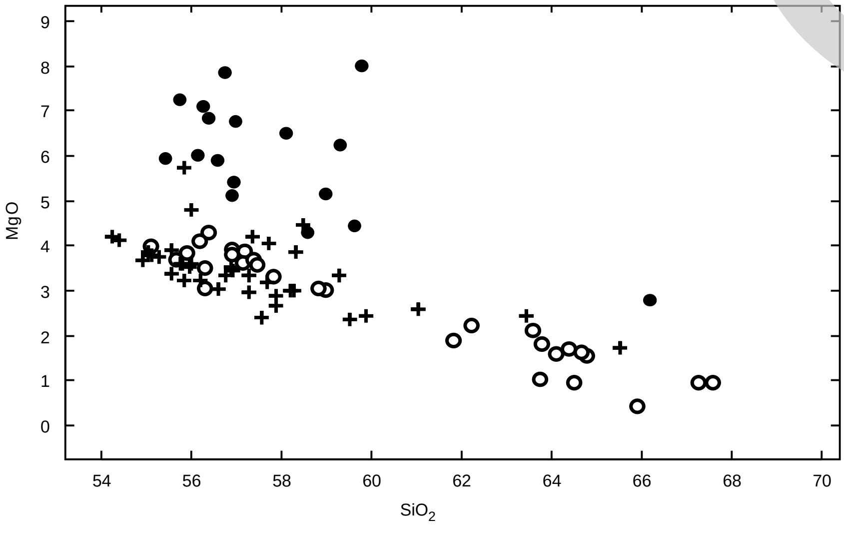

Figure 6. Cretaceous high magnesian andesite and basalt form the Meratus Mountain (filled circles) plotted on SiO_2 vs MgO. Show for comparisons are andesite and basalt of “normal arc rocks” from the Wilis Volcano (open circles) and Lawu volcano (crosses). The data of the Wilis and Lawu volcanoes are from Hartono (1994).

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Discussion

Petrogenesis

The presence of high magnesian andesites in subduction zones is a significant phenomenon, and their origin is widely discussed among petrologists. Several experimental studies (*e.g.*, Grove and Kinzler, 1986; Sisson and Grove, 1993) show that high magnesian andesite can not be produced by direct partial melting of mantle peridotite. Many magnesian andesite have $Mg^{\#}$ and Ni concentrations too low to be in equilibrium mantle olivine (Kelemen, 1995). Grove and Kinzler (1986) and Sisson and Grove (1993) suggested that high magnesian andesites might be a result of crystal fractionation from basaltic magma. They show calc-akaline differentiation trend having 55 to 65 wt% SiO_2 and $Mg^{\#}$ more 30 can be produced by differentiation of basaltic magmas at high pressures.

However, some high magnesian andesites have composition $Mg^{\#} > 60$ and $Ni > 100$ ppm, which are consistent with equilibration of mantle olivine ± ortho- and clinopyroxene, and thus they could represent mantle-derived liquids. Experimental studies by Nicholls and Ringwood (1973) and Nicholls (1974) show that magmas more silicic than basaltic andesite may result from melting of water-saturated pyrolitic mantle at depth less than 35 km and the $Mg^{\#}$ are similar to those of basalts. Tatsumi (1982), in his study on natural rocks from Setouchi volcanics, reported that high magnesian andesite is in equilibrium with olivine + two pyroxenes with mantle compositions even under water-undersaturated condition. Two types of high magnesian andesite were recognized, these are the opx-high magnesian andesite which is produced by higher degree of partial melting than the cpx-high magnesian andesite.

The presence of an arc trace element signature of the Cretaceous Haruyan and Paau volcanics from the Meratus Mountain (Fig. 4) is consistent with the calc-alkaline affinity of the rocks (Hartono *et al*., 1999) and with the crystal-rich porphyritic texture and mineralogy of the acid rocks. Those characteristics indicate that the volcanics were originated from magma formed in a subduction zone environment. It is widely believed that andesite in arc systems is produced by crystal fractionation from a basaltic magma parent. Figure 5 shows that the distribution of most andesites and basalts of the Cretaceous volcanics from the Meratus Mountain may represent liquid line of decent, it means the andesite might be originated from basaltic parent magma by a process of fractionation. However the high magnesian andesites are sitting outside of the basalt-andesite straight line.

The Cretaceous high magnesian andesites from the Meratus Mountain have $Mg^{\#}$ 67 – 69, but Ni and Cr concentrations are low, (44 – 60 ppm) and (37 – 411 ppm) respectively (Table 1), suggesting not in equilibrium with mantle olivine ± two pyroxenes. Assuming that the partition coefficient (K_D) between olivine and liquids is ? 0.3 (Roeder and Emslie, 1970) and the olivine from the upper mantle has $Mg/(Mg+Fe^{+2}) > 0.88 – 0.95$ (Gurney and Harte, 1980), primary magma in equilibrium with such upper mantle olivine have $Mg^{\#} \geq 69$. This number would increase up to 75 if the value of K_D between olivine and liquids is taken as 0.4 (Nicholls, 1974). The primary magma should have $Mg^{\#}$ 69 – 75, $FeO^{*}/MgO < 1$ (Tatsumi *et al*., 1983), Ni 235 – 400 ppm (Sato, 1977) and Cr 500 – 600 ppm (Perfit *et al*., 1980).

If the magnesian andesite of the Cretaceous volcanics from the Meratus Mountain does not represent primary magma in equilibrium with mantle olivine, alternatively the magnesian andesite magma may be derivative liquid from basaltic magma as suggested by Grove and Kinzler (1986) and Sisson and Grove (1993). The absence of or only few olivine phenocrysts in the rocks (see the petrographic summary) may also be consistent with derivative magma from a more basaltic parent magma that has undergone olivine fractionation. However, it is clear in Fig. 5 that the magnesian andesite seems not to be derived from the most basic Cretaceous Haruyan volcanics. The rocks are too high in MgO content and, as mentioned, are not sitting in the basalt-andesite straight line.

Two types of high magnesian andesites were recognized in modern arcs (Yogodzinski and Kelemen, 1998). The first type is a high magnesian andesite that has a “normal” subducted related characteristic in term of enrichments in LILE and LREE. This type of

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high magnesian andesites is believed to be derived from melting of the mantle wedge above the slab. The second type is that in association with adakites as broadly defined by Defant and Drummond (1990). Such high magnesian andesites are characterized by > 500 ppm Sr, and Sr/Yb values > 400, La/Yb > 10, and Yb < 1 ppm at Mg# > 70 (Danyushevsky et al., 2006). The rocks are believed to be originated from melting of subducted slab followed by reaction with very depleted mantle wedge.

Table 1. Representative Analysis of High Magnesian Andesites From South Kalimantan

Sample No	**95UH2**	**95UH10B**	**95UH10H**	**95UH16**	**95UH19**	**95UH22C**	**96UH5**	**95UH23C**	**96UH23**	**96RH37**
Major Elements (wt%)										
SiO2	57	54.63	54.93	57.35	55.42	54.41	54.14	56.61	55.6	54.1
TiO2	0.59	0.65	0.68	0.63	0.67	0.89	0.61	0.72	0.7	0.72
Al2O3	15.3	15.71	15.89	16.41	16.01	16.02	16.68	16.79	16.71	15.7
Fe2O3	6.95	7.49	7.43	6.69	6.94	8.08	7.34	6.35	5.75	8.19
MnO	0.14	0.14	0.14	0.12	0.14	0.14	0.16	0.12	0.09	0.18
MgO	5.97	6.6	6.91	6.41	6.57	5.8	4.85	4.13	4.85	5.11
CaO	6.95	8.76	9.1	7.04	8.27	8.63	4.34	4.59	5.67	7.99
Na2O	2.81	2.44	2.15	2.67	2.53	2.75	5.8	3.69	4.04	2.38
K2O	0.98	1.02	0.97	1.87	1.21	0.79	1.68	3.93	1.15	1.24
P2O5	0.12	0.14	0.16	0.15	0.13	0.2	0.23	0.33	0.23	0.16
Loss	0.12	1.69	2.33	0.84	1.74	1.92	4.59	2.4	4.71	3.48
Total	96.93	99.27	100.69	100.18	99.63	99.63	100.42	99.66	99.5	99.25
Mg#	67	67	68	69	69	63	61	60	66	59
Trace Elements (ppm)										
Ba	295	300	309	375	389	300	438.8	2447.7	454.1	289.3
Rb	30	16	18	47	28	16	21.95	57.2	18.85	23.75
Th	5.8	3.5	7.4	7.8	6.6	7.2	1.05	<1	3.65	2.25
Nb	3.6	3.1	4	4	4.9	2.8	2.7	3.2	3	2.6
La	13	10	12	14	11	14	11.9	8.7	13.1	9.9
Ce	29	28	32	32	31	34	27.4	33.4	30.7	23.6
Sr	382	287	330	321	422	308	412.5	1198.3	889.5	308.6
Nd	16	12	15	15	16	19	17.1	18.9	14.8	13
Zr	98	88	99	112	101	147	93.1	122.4	111.5	65
Y	21	20	21	21	23	26	16.5	28	11.2	18.8
Ni	44	57	60	45	58	72	24.7	36.8	54	30.2
Cr	411	245	301	394	306	214	97.6	37.1	176.1	71.7
V	150	175	158	124	145	212	253.7	175.5	187	285.3
Sc	28	27	26	23	25	26	26.7	17.3	20.1	31.7
Pb	13	10	17	24	15	23	6.95	2.8	8.5	8.1
U	<1.5	<1	<1.5	<1.5	1.9	<1.5	0.85	0.2	1.15	0.3
Rare Earth Elements (ppm)										
La		11.6		15.7					13.16	
Ce		25.7		34.7					27.76	
Pr		3.37		4.3					3.56	
Nd		14.4		18					15.07	
Sm		3.76		4.2					3.02	
Eu		0.84		0.89					0.88	
Gd		3.61		3.83					2.26	
Dy		3.03		3.13					1.77	
Er		1.91		1.94					0.094	
Yb		1.74		1.76					0.84	

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Except samples 95UH23C and 96UH23, the Cretaceous high magnesian andesites have low Sr concentration (287 – 412 ppm), low Sr/Y 12 – 25 or Sr/Yb 165 – 182 indicating that these rocks are unlikely derived from magma from subducted slab melting, but more possibly derived from upper mantle. The high magneisan andesites from the Meratus Mountain are comparable in having Sr/Yb ratios and TiO2 contents to the Piip volcano, western Aleutian (Yogodzinski *et al*., 1994) and the Hunter ridge, North Fiji (Danyushevsky *et a.l*, 2006) (Fig. 7 and 8). In these two areas, the high magnesian andesites were believed to be derived from melting of the mantle. The TiO_2 concentrations of the Meratus high manesian andesites is also comparable to the mantle derived high magnesian andesites from Setouchi volcanic belt, Japan (Fig. 8), which was formed from a mantle peridotite melting magma (Tatsumi, 1982). Compared to the normal intraoceanic arc lava of Tonga-Tofua arc (Danyushevsky *et al*., 2006), the Meratus high magnesian andesites have higher Sr/Yb ratios, but these ratios are lower than that of Baja California high magnesian andesites (Fig. 7). The Baja high magnesian andesites are known as rocks with strong adakite signatures that developed in a nonintraoceanic setting. However, few samples of the Meratus high magnesian andesites are sitting in the area of Baja, suggesting cructal origin.

The trace element distribution of the Meratus high magnesian andesites (Fig. 9) is also similar to that of the Setouchi volcano, which has “normal” arc characteristics derived from mantle origin (Tatsumi, 1982). There is a different in LILE (Ba, Rb, Th) enrichments when the Meratus high magnesian andesites compared to the Piip volcano, Far Western Aleutian (Yogodzinkski *et al*., 1994). The difference might be caused by different in their tectonic setting, although they have come from a similar souruce (*i.e*., the mantle sources). Yogodzinkski *et al*. (1994) proposed that the high magnesian andesites from the Piip volcano was a result of a reaction between mantle derived magma and hot mantle peridotite in the mantle-lower crust boundary due to a transpresional tectonic since Middle Miocene. Different from the other high magnesian andesites in the Meratus Mountain, sample 96UH23 shows a moderate slope in the most compatible elements (from P to Yb). The pattern is similar to the high-Al TTDs, which are the rocks resulted from magma derived from subducted oceanic crust melting (Drummond and Defant, 1990).

The REE pattern (Fig. 10) is also consistent with the trace element signatures. Two samples of the Meratus high magnesian andesites show a moderate slope from the LILE to HREE, while the 96UH 23 has a deeper slope, indicating different in a petrogenetic history. The first may be consistent with the rocks derived from magma originated from a mantle source similar to normal andesite of the Medicine Lake volcano (Grove *et al*., 1982), and the second could possibly indicate a subducted oceanic crust source similar to the high-Al TTDs. The strong enrichment in LREE and depleted in HREE of sample 96UH 23 could indicate the role of garnet and/ or amphibole in the petrogenesis of the rock in a high pressure condition. Plagioclase fractionation would drive magmatic liquids toward high Y and low Sr based on the partition coefficient between minerals and melt. Although amphibole fractionation could cause depletion in HREE, the absence of amphibole phenocrysts in the Meratus high magnesian andesite suggests that amphibole fractionation is unlikely. Pyroxene is the other phase that could lower the HREE, as pyroxene is present in the phenocryst phase. However as long as plagioclase fractionates during the fractionation of amphibole and pyroxene, magma with low Y and high Sr and high Al_2O_3 will not be produced. Other significant characteristic is the absence of Eu anomaly. This supports the argument that the rock could not be a result of low pressure fractionation involving plagioclase, because plagioclase fractionation would cause a negative anomaly in the REE pattern.

The possibility that some of the Meratus high magnesian andesite (and to some extend the “normal” andesite) originated from crustal origin may also be indicated by Sr and Y concentrations. Plot of Sr/Y ratio versus Y content of the rocks (Fig. 11) shows that some of the samples are sitting in the adakite field of Drummond and Defant (1990). The scattered distribution of the Meratus high magnesian andesites (Fig. 5) also suggests the rocks may not come from single magnesian basaltic magma parent.

Relation to Tectonics

There are two possible crustal origin of adakite and its associate high magnesian andesites, these are subducted oceanic crust (*e.g*., Drummond and Defant, 1990; Drummon and Defant, 1990; Cosky *et al*., 2005) and lower crust (*e.g*, Peacock *et al*., 1994; Chung *et al*., 2003; Petford and Atherton, 1996)

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melting. Experimental studies (*e.g.*, Defant and Drummond, 1990; Peacock *et al.*, 1994; Cosky *et al.*, 2005) show the role of slab melting in the generation of arc magmas found in several subduction zones (*e.g.*, Cascade, western Mexico, southern Chile), in which a young, hot, oceanic crust is being subducted. However, in the area in which young oceanic crust is not being subducted, melting of underplated mafic lower crust, *e.g.*, Southern Tibet (Chung *et al.*, 2003), Peru (Petford and Atherton, 1996) or previously subducted oceanic crust, *e.g.*, Baja California and New Guinea (Peacock *et al.*, 1994) may also be suggested. The geochemical data and modeling suggest that the high magnesian andesite, and to some extend the “normal” andesite, of the Cretaceous Haruyan volcanics might not come from single source, but could possibly derive from mantle and crustal melting magmas. Because of limited data, especially for the REE, the crustal magma origin is not yet known of whether caused by a subducted oceanic crust melting as a model suggested by *e.g.*, Drummond and Defant (1990) or lower crust melting as proposed by *e.g.*, Peacock *et al.* (1994).

However, a young oceanic crust was not present in Kalimantan at Cretaceous time, so a subducted oceanic crust melting magma is unlikely. Dirk and Amiruddin (2009) reported the granitoid rocks exposed in the Meratus Mountain ranging in age from Late Carboniferous-Early Permian (the Lumo Granite) to Late Cretaceous (the Hajawa Granite) are calc-alkaline volcanic arc granite. Amiruddin (*in prep.*) further suggested that those granitoid rocks resulted from northward subduction of the Indian oceanic plate beneath Eurasian (Kalimantan) continent. This scenario indicates that the age of the Indian oceanic plate is old, and unlikely to be the source of the adakitic magma. As a consequence, the Haruyan high magnesian andesite could not be produced by reaction between ascending subducted oceanic crust derived magma and mantle peridotite. It is consistent with the geochemical data that most of the Haruyan high magnesian andesite, except sample 95UH23C and 96UH23, are mantle origin. Several hypotheses may be suggested for the generation of the Haruyan high magnesian andesite: (1) direct partial melting of previously depleted, then metasomatized, amphibole peridotite; (2) reaction between silicic magma and mantle peridotite in the upper mantle-lower crust boundary; and (3) reaction between basaltic magma and mantle peridotite.

The hypothesis (1) was proposed by Kelemen (1995) explaining that, direct partial melting of previously depleted, then metasomatized, amphibole peridotite may be capable of producing high magnesian andesite. This hypothesis is not applicable for the Haruyan high magnesian andesite at least for two reasons. First, the process could not account for the high abundance of LILE and other incompatible elements in the rocks (Fig. 4) and second, the Haruyan high magnesian andesite is not primary magmas as evidenced by low concentration of Ni and Cr. Reaction between silicic magma and mantle peridotie in lower crust (the hypothesis 2) is possible mechanism in producing the Haruyan high magnesian andesite. If the Haruyan high magnesian adakitic-type rocks (95UH23C and 96UH23) is not a subducted oceanic crust melting magma (discussed before), one possible alternative is the magma originated from melting of the basaltic lower crust. Amiruddin (*in prep*) envisaged that the Aptian-Upper Cretaceous granitic rocks in the Meratus Mountain (? The Hajawa Granite) may be a product of crustal anatexis. It is possible that reaction between this granite and upper mantle peridotite resulted in adakitic-type magma with high magnesium ($Mg^{\#}$) concentration. Although the original model by Kay (1978) proposing reaction between a slab derived silicic melt and mantle peridotite, an experimental study of Carroll and Wyllie (1989) support this mechanism. The study shows that dissolution of olivine, caused by a reaction olivine + SiO_2 = orthopyroxene, would cause decreasing silica content and sharp increase in magnesium concentration (and $Mg^{\#}$) in the derivative liquids. This model could explain the origin of the Haruyan high magnesian andesite with adakitic signatures (the high magnesian adakitic-type rocks) such as sample 95UH23C and 96UH23.

The hypothesis (3), explaining reaction between basaltic magma and mantle peridotite, might be the more dominant process in the generation of the Haruyan high magnesian andesite, as the geochemical data show a mantle derived magma. There are two possible mechanisms of reaction, *i.e.*, reaction between basaltic liquid and upper mantle peridotite during magma ascend from the source or the reaction occurred in the upper mantle-lower crust boundary. Based on the geochemical data (*i.e.*, low content of Ni and Cr), the first mechanism may not be valid. Although dissolution of pyroxenes from mantle peridotite in olivine-saturated would produce a

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substantial increase in SiO_2 content and Mg ($Mg^{\#}$) value, the Ni concentration remain high because "buffered" by exchange reactions with olivine (Kelemen, 1995). In fact Ni and Cr concentrations are low in the Haruyan magnesian andesite. In the case of reaction occurred in the upper mantle-lower crust boundary, the basaltic melt has undergone fractionation (olivine and other ferromagnesian minerals) during ascend from the magma source resulted in decreasing Ni and Cr concentration. Fisk (1986) and Kelemen (1986, 1990) suggested that primitive andesites and basaltic andesites may also form through the low-pressure reaction of basaltic melts and peridotite, even under unhydrous condition. At high pressures basaltic magmas are saturated in olivine, two pyroxenes, and chromian spinel and will become increasingly undersaturated in pyroxene as they rise to lower pressures. A reaction could occur when such basalts pool within the warm upper mantle, and they will produce primitive silica-oversaturated melts and refractory peridotites (Kelemen, 1990). Yogodzinski *et al*. (1994) envisaged that formation of thick arc crust could create a density barrier, impending magma ascent from the mantle into the crust, and leading an extensive reaction between liquid and peridotite. In Kalimantan a thickened crust may happen during collision between the pre-Mesozoic Paternoster platform (microcontinent ?) and the Sundaland continent in Upper Cretaceous-Lower Miocene (Hartono, 2003), and the delaminating melting process may resulted in the Upper Cretaceous granite, which then reacts with warm upper mantle peridotite to produce the Haruyan high magnesian adakite-type magma explained in hypothesis (2).

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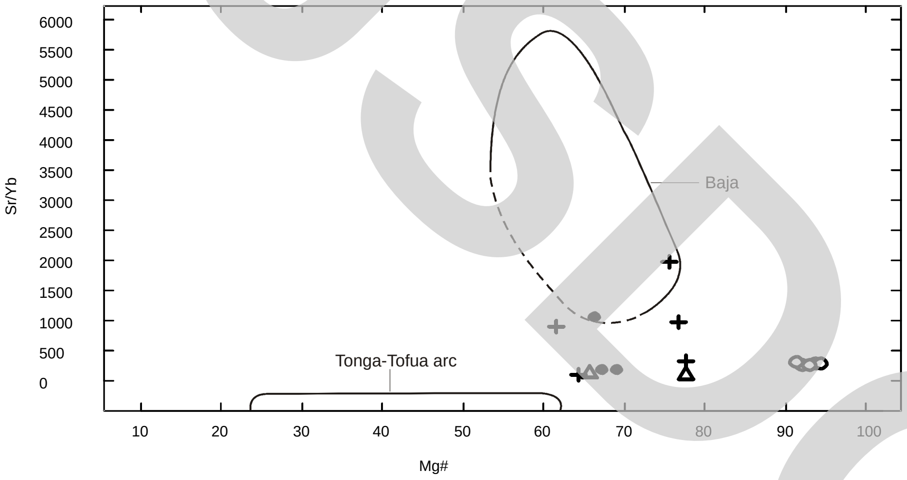

Figure 7. Plot of $Mg^{\#}$ vs Sr/Yb ratios for the Cretaceous high magneisan andesite from the Meratus Mountain (filled circles) compared to that of the Piip volcano (open circles: Yogodzinkski *et al*., 1994), Hunter rift (crosses) and Hunter ridge (open triangles) (Danyushevsky *et al*., 2006). Also shown the field of Tonga-Tofua intraoceanic arc lavas and Baja California (Danyushevsky *et al*., 2006). See text for the discussion.

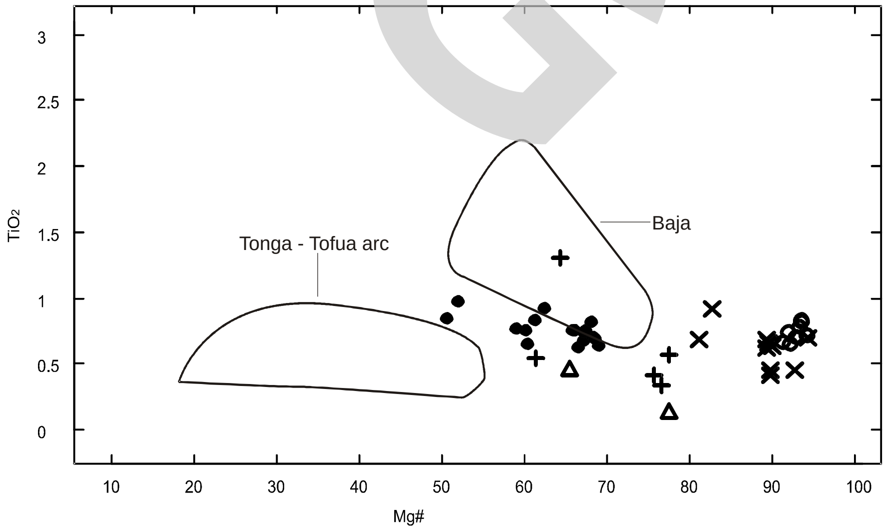

Figure 8. Plot of $Mg^{\#}$ vs TiO_2 for the Cretaceous high magneisan andesite from the Meratus Mountain (filled circles) compared to that of the Piip volcano (open circles: Yogodzinkski *et al*., 1994), Hunter rift (crosses) and Hunter ridge (open triangles) (Danyushevsky et al., 2006) and the Setouchi, Japan (x : Tatsumi, 1982). See text for the discussion.

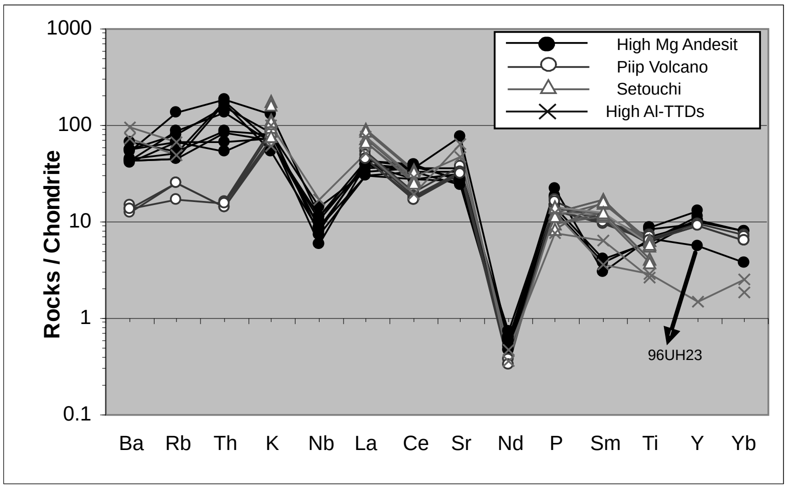

Figure 9. Chondrite-normalized trace elements of the Meratus high magnesian andesites compared to that of the Piip (Yogodzinkski *et al*., 1994) and Setouchi Tatsumi, 1982) volcanoes and the high-al TTDs (Drummond and Defant, 1990). See text for the discussion.

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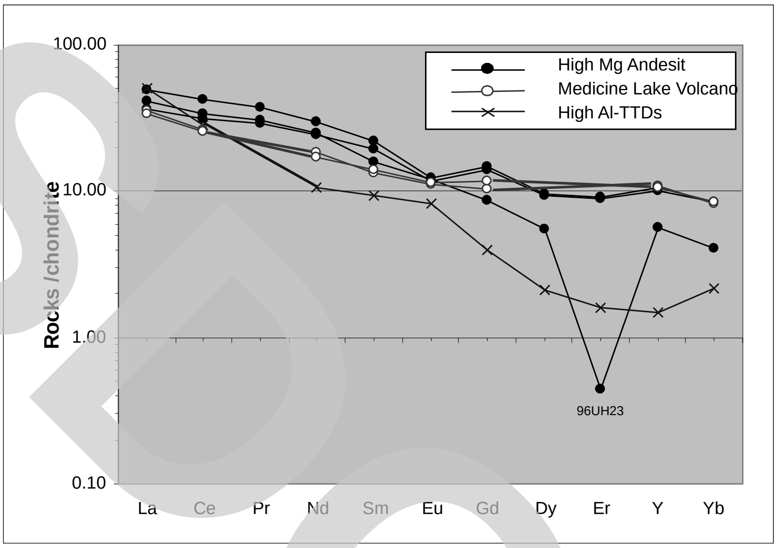

Figure 10. Chondrite-normalized REE of the Meratus high magnesian andesites compared to that of the Piip volcano (Yogodzinkski *et al*., 1994) and high-Al TTDs ((Drummond and Defant, 1990). See text for the discussion.

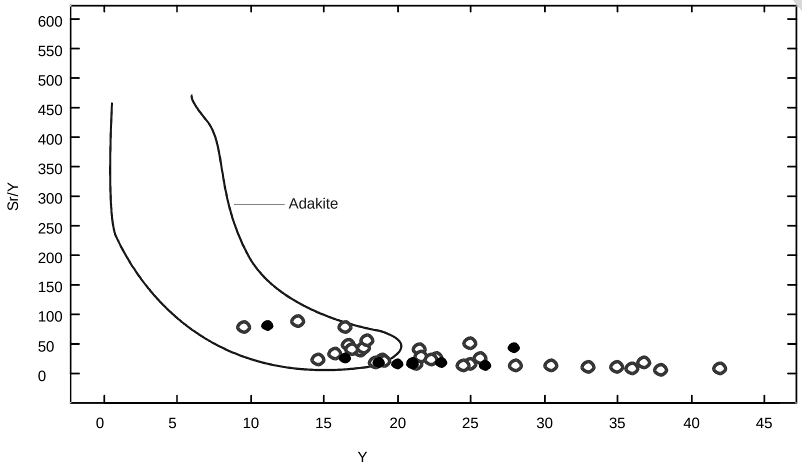

Figure 11. Plot of Sr/Y vs Y of the high magnesian andesite (black filled circles) and "normal" basalt-andesite-dacite (red open circles) compared to that of adakite field of Drummond and Defant (1990). See text for the discussion.

Conclusions

The geochemical data of the Cretaceous high magnesian andesite from the Haruyan volcanics, Southeast Kalimantan indicate the rock was originated from magma in a subduction zone environment same as the "normal" Haruyan volcanics. However, the high magnesian andesite might not be derived from basalt of "normal" Haruyan volcanics by process of fractionation. The trace and rare earth element signatures combined with tectonic condition suggest that most of the high magnesian andesites are mantle origin. A primary basaltic magma produced by melting of the mantle wedge above the slab, then undergone fractionation (especially olivine) to produce derivative magmas with low concentrations of Ni and Cr. A tectonic collision in the Upper Cretaceous may cause part of the mantle derived basaltic magmas to pool immediately below the arc crust. The pooled basaltic magma then reacts with hot upper mantle peridotite to produce the high magnesian andesite. The tectonic collision might also cause an anaxtesis of the lower crust resulting in the Upper Cretaceous granite (such as the Hajawa Granite), which reacts with hot mantle peridotite in the lower crust-upper mantle boundary to produce the high magnesian adakite-type magma, such as samples 95UH23C and 96UH23.

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