

Geochemical Signature of Mesozoic Volcanic and Granitic Rocks in Madina Regency Area, North Sumatra, Indonesia, and its Tectonic Implication

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ABSTRACT

Five samples consisting of two Permian-Triassic basalts, two Triassic-Jurassic granitic rocks, and a Miocene andesite were collected from the Madina Regency area in North Sumatra that is regionally situated on the West Sumatra Block. Previous authors have proposed three different scenarios for the geological setting of West Sumatra Permian Plutonic-Volcanic Belt, namely an island-arc, subduction related continental margin arc, and continental break-up.

Petrographic analysis of the Mesozoic basaltic samples indicates that they are island-arcs in origin; however their trace element spider diagram patterns (Rock/MORB ratio) also show the character of back-arc marginal basin, besides the island-arc. Furthermore, their REE spider diagram patterns (Rock/Chondrite ratio) clearly reveal that they were actually generated in a back-arc marginal basin tectonic setting. Meanwhile, the two Mesozoic granitic rocks and the Miocene andesite reflect the character of an active continental margin. Their spider diagram patterns show a significant enrichment on incompatible elements, usually derived from fluids of the subducted slab beneath the subduction zone. The high enrichment on Th makes their plots on Ta/Yb versus Th/Yb diagram are shifted to outside the active continental margin field. Although the volcanic-plutonic products represent different ages, their La/Ce ratio leads to a probability that they have been derived from the same magma sources.

This study offers another different scenario for the geological setting of West Sumatra Permian Plutonic-Volcanic Belt, where the magmatic activities started in a back-arc marginal basin tectonic setting during the Permian-Triassic time and changed to an active continental margin during Triassic to Miocene.

The data are collected through petrographic and chemical analyses for major, trace, and REE including literature studies.

Keywords: Mesozoic, volcanic-granitic rocks, back-arc marginal basin, active continental margin, magma sources

SARI

Lima percontoh batuan yang terdiri atas dua basal berumur Perem-Trias, dua batuan granitik berumur Trias-Jura, dan satu andesit berumur Miosen telah diambil dari daerah Kabupaten Madina, Sumatra Utara, yang secara regional terletak pada Blok Sumatra Barat berumur Perem. Para peneliti terdahulu mengusulkan tiga skenario yang berbeda untuk kondisi geologi pembentukan Sabuk Vulkanik-Plutonik Sumatra Barat tersebut, yakni suatu busur kepulauan, busur tepian benua yang berhubungan dengan penunjaman/subduksi, dan "pecah"nya benua.

Analisis petrografi percontoh basal berumur Mesozoikum tersebut mengindikasikan bahwa mereka berasal dari lingkungan tektonik busur-kepulauan, tetapi pola diagram laba-laba unsur jejaknya (untuk rasio Rock/MORB), juga menunjukkan karakter tepian cekungan busur-belakang, di samping lingkungan busur-kepulauan. Lebih jauh lagi, pola diagram laba-laba unsur REE-nya (untuk rasio Rock/Chondrite) mengungkapkan bahwa sebenarnya mereka terbentuk pada lingkungan tepian cekungan busur-belakang. Sementara itu, dua batuan granitik berumur Mesozoikum dan satu batuan andesit berumur Miosen mencerminkan karakter tepian benua aktif. Pola diagram laba-labanya menunjukkan pengayaan yang signifikan terhadap unsur inkompatibel yang kemungkinan besar disebabkan oleh proses-proses kontaminasi selama perjalanan magma menuju permukaan. Tingginya pengayaan pada

unsur Th telah menyebabkan hasil plot batuan tersebut dalam diagram Ta/Yb versus Th/Yb menjadi bergeser keluar areal tepian benua aktif. Meskipun produk-produk vulkanik dan plutonik tersebut mewakili umur yang berbeda-beda, namun rasio La/Ce nya bermuara pada suatu kemungkinan bahwa mereka berasal dari sumber magma yang sama.

Studi ini menawarkan satu skenario lain yang berbeda untuk kondisi geologi Sabuk Vulkanik-Plutonik Sumatra Barat yang menyatakan bahwa aktivitas magmatik telah dimulai pada kondisi cekungan busur-belakang selama Perem-Trias dan kemudian berubah menjadi lingkungan tepian benua aktif sejak Trias hingga Miosen.

Semua data didapat dari hasil analisis petrografi dan kimia untuk unsur utama, jejak, dan unsur tanah jarang, termasuk studi literatur.

Kata kunci: Mesozoikum, batuan vulkanik-granitik, cekungan busur-belakang, tepian benua aktif, sumber magma

INTRODUCTION

Sumatra has experienced long magmatic processes during its geological history since Paleozoic or Mesozoic up to the present time. The presence of metavolcanics in the Kuantan Formation (Gafoer & Purbo-Hadiwidjojo, 1986; Silitonga & Kastowo, 1975, 1995), that is Carboniferous (Early or Mid to Late Visean) in age (Fontaine & Gafoer, 1989), indicates that the volcanic activities already took place in Sumatra before the deposition of the formation. The track of the Carboniferous volcanism is also noted by Cameron *et al.* (1982a) through the discovery of green metavolcanics within the Alas Formation, in the Medan Quadrangle that may be of Visean age, like the associated limestone.

The Permian volcanism is reported on both East and West Sumatra Blocks. It is marked on the Eastern Block by Katili (1973) on the basis of Rb-Sr age determinations on feldspars of Setiti batholiths giving ages of 298 ± 30 Ma (brecciated granite) and 276 ± 10 Ma (sheared granite). Furthermore, Suwarna *et al.* (1991) indicate that the volcanic Condong Member of the Mentulu Formation near Tigaluluh Mountains (Simanjuntak *et al.*, 1991) is also of Permian age. On the Western Block, Lower - Middle Permian volcanic and sediments and several associated granitic plutons crop out and form a discontinuous belt, much disrupted by strike-slip movements along the Sumatra Fault Zone, parallel to the west coast of the island (Crow, 2005). The products of Permian volcanism on the Western Block are listed as Sibolga granite (Aspden *et al.*, 1982b), Silungkang Formation (Katili, 1969; Fontaine & Gafoer, 1989; Silitonga & Kastowo, 1975),

Palepat Formation (Fontaine & Gafoer, 1989) and Kuantan Formation (Silitonga & Kastowo, 1975). The Madina Regency area is situated in the West Sumatra Block.

Three different geological settings for the West Sumatra Permian Plutonic-Volcanic Belt have been proposed, namely an island-arc, subduction related continental margin arc and continental break-up (Crow, 2005). The West Sumatra Permian Plutonic-Volcanic Belt is referred to as the "Palepat Terrane" by McCourt *et al.* (1996) who discuss the suggestion by Wajzer *et al.* (1991) that the Palepat Terrane represents an allochthonous oceanic arc which collided with Sumatra in the Late Permian or Early Triassic. This interpretation was adopted by Metcalfe (2000). This hypothesis is denied by Barber (2000) based on the reason that oceanic volcanic and ophiolite have not been identified, nor is the Palepat Terrane bounded along its eastern boundary by thrust (Katili, 1970), as had been supposed previously. Cretaceous ophiolite outcrops shown within Early Permian sediments in the Solok Quadrangle by Gafoer *et al.* (1992a) are basaltic lavas interbedded within phyllites and quartzite of the Phyllite and Shale Member of the Kuantan Formation (Silitonga & Kastowo, 1975). These basalts are now considered to be an outlier of the Calcareous Member of the Silungkang Formation and are not associated with ultrabasic rocks. Thus, their ophiolite association is not established.

The second geological setting was proposed by Katili (1969, 1972, 1981) that interpreted the Volcanic Member of the Silungkang Formation, the Palepat Formation, and the associated granite suite, as relicts of a continent margin magmatic arc of a

subduction origin. This interpretation is supported by the presence of tholeiitic and calc-alkaline trends in these volcanics (Suwarna *et al.*, 2000). The location of this magmatic arc in the palaeogeographic reconstruction would have been on the southern margin of the Cathaysian supercontinent, where it might have been related to a contemporary Permian magmatic arc in the Indochina Block of East Malaysia Peninsula described by Cobing *et al.* (1992). The third alternative was proposed by Suparka & Asikin (1981) who assumed that volcanics represent igneous activity associated with a passive continent margin. Charlton (2001), on the palaeogeographic term, has indicated that the West Sumatra Permian volcanics were related to the break-up at the Gondwana-Cathaysia interface. In this hypothesis, the volcanism was associated with the thermal uplift of the Gondwana margin (Veevers & Tewari, 1995) which coincided in the Asselian with the conclusion of the Gondwana glaciations and the start of the sea-floor spreading in Meso-Tethys. Crow (2005) indicated, based on timing and chemistry of the west Sumatra Permian Plutonic-Volcanic Belt, that it was linked both with subduction and continent margin faulting/seafloor spreading, but the chemical data do not discriminate which process was dominant at any particular time.

For the granitic rocks on Sundaland, there are two hypotheses through which the granites were produced. They have developed through two contrasting geological cycles, a Carboniferous-Permian cycle of convergence and collision followed by a younger Triassic-Early Jurassic cycle in which a new subduction zone was formed along the southwestern margin of the new continent (Hutchison, 1994; McCourt *et al.*, 1996). During the first mechanism, the different accreted terrains were host rocks to granites which, because of their contrasting geochemical and isotopic characters seemed to mirror the lower crustal regions from which they were derived (Cobbing, 2005). These terrains are distinguished most clearly in Malaysia and Thailand Peninsulas as contrasting belts which are additionally characterized by stanniferous S-type and generally non-stanniferous I-type granites (Beckinsale, 1979). The second cycle generated granites having a wide compositional range from diorite to monzogranite were associated with the development of a Late Triassic-Early

Jurassic volcanic arc along the southern margin of Sundaland. McCourt *et al.* (1996) indicated that the two cycles were overlapped in Sumatra.

The aim of this paper is to discuss the geological setting of Sumatra Permian Plutonic-Volcanic Belt based on the rock chemistry of Mesozoic volcanic and plutonic rocks collected on an area near Panyabungan, Kotanopan, and Muara Sipongi, in the Madina Regency area. Although the analyzed samples are limited, the data are considered to be helpful in order to improve the understanding about petrogenesis of the Sumatra Pre-Tertiary Plutonic-Volcanic Belt.

Geological Setting

The Madina Regency area is covered by various types of lithology and age (Figure 1). The oldest one is the Kuantan Formation that is Permian-Carboniferous in age, consisting of Limestone (meta-limestone) and Pawan Members (composed of metalimestone and basic schistose metavolcanics). They are comparable to the Kluet Formation that belongs to the Tapanuli Group which crops out mostly in the northern part of Sumatra. On the Padangsidempuan Quadrangle Sheet to the north, the change from the Kluet to Kuantan Formations was set arbitrarily where there is a break in the outcrop at 99° E longitude (Aldiss *et al.*, 1983). The outcrop of the Kuantan Formation extends along the core of the Barisan Mountains from Padangsidempuan to the latitude of Padang. Silitonga & Kastowo (1975) distinguished a Lower Member dominated by quartzite and quartz sandstone, rarely conglomeratic, with interbedded shales usually metamorphosed to slates or phyllites.

In contact with the Kuantan Formation, there are several Mesozoic magmatic bodies that crop out as the Panyabungan Batholith and Muara Sipongi granitic intrusions. The Panyabungan Batholith shows a wide range composition from granite, microgranite, leucogranite, and micadiorite where some are distinctly foliated to gneissose and others are sheared (Rock *et al.*, 1983). The batholith is probably Permian-Triassic in age and it has experienced metamorphism as well as the Tapanuli Group. K/Ar age determination on a cataclased biotite granodiorite, which was taken from floats in a river East of Panyabungan, gives an age of 121 ± 1 Ma (Rock *et*

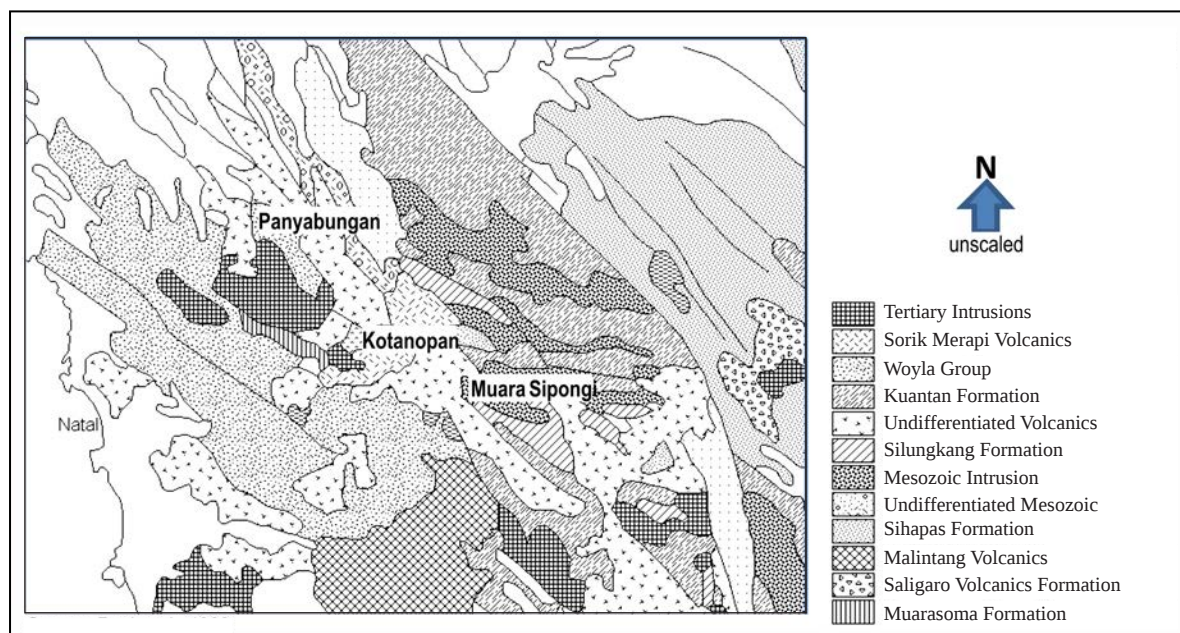


Figure 1. Geological sketchmap of the Madina Regency area (after Rock *et al.*, 1983).

et al., 1983). The Muara Sipongi intrusions have also a widely variation in composition from granite, granodiorite until diorite and often carrying basement xenoliths. Stephens *et al.* (1987) reported, based on sample taken from Batang Gadis area, that the intrusions show calc-alkaline granitoids character and exhibit $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratios greater than 1.0 and low to zero normative corundum. Trace element patterns are entirely typical of orogenic granitoids and match with the type of island or immature continental arcs (Brown *et al.*, 1984). The salient features being comparable Ba and Rb enrichment, no Sr depletion and low Nb. K/Ar ages for biotite separates show a range from 181 to 142 Ma. A single K/Ar mineral age of 197 Ma was reported by Rock *et al.* (1983), but for this case the material dated is not specified and the sample location is in doubt. The rocks were also analyzed for Rb-Sr isotopes and the whole rock isochrons give an age of 158 ± 23 Ma for the emplacement of Muara Sipongi Batholith. Hehuwat & Sopaheluwakan (1978) through K/Ar determination got an age of 196.7 ± 2.4 Ma for the Muara Sipongi intrusions.

In association with the Panyabungan or Muara Sipongi intrusions, several outcrops of the Silungkang Formation can be observed. It belongs to the Peusangan Group that is Permian-Triassic in age.

The formation consists of limestone, metalimestone, basic metavolcanics, metatuffs, and volcanoclastic sandstones.

Eastwards from the batholiths, the area is covered largely by the Sihapas Formation consisting of the Kanan and Cubadak Members of Early Tertiary in age. They are composed of sediments such as clean quartz, sandstones, carbonaceous shales, siltstones, and conglomerates. On the western part, the area is dominated by the Woyla Group Melange (Jurassic in age) consisting of greenstone, metawackes, metatuffs, metalimestone, serpentine, various coloured cherts, and talcose schist. The area between the batholiths and the Woyla Group Melange is mostly covered by undifferentiated volcanics that are Miocene in age. They are dominantly stratiform volcanics and their volcanic centre are not traceable any more. Among all the previously mentioned lithology, Tertiary intrusions occur mostly towards the west coast of the island. There are two episodes of the Tertiary intrusions, namely during Oligocene-Eocene producing the Manunggal Batholith, Air Bangis and Kanaikan intrusions, and during the Late Miocene-Pliocene including the Timbahan and Parlampungan intrusion, and Binail microgranites. The first period intrusions show a narrower variation in composition ranging from granite, adamellite, and granodiorite,

while the second period intrusions have a wider range in composition from granite, granodiorite to diorite. Westwards from Kotanopan, there stands the Sorik Merapi Volcano that cover its surrounding area with its Quarternary volcanic products as well as for the Malintang Volcano in the south.

SAMPLE LOCATION AND ANALYTICAL METHOD

More than forty rock samples were collected from the Madina Regency area, but only five samples analyzed for major, trace, and rare earth elements. Two of them are intrusive granitoid rocks and the rest three others are volcanics. The intrusion samples are represented by samples PYB-15A and KNP-7 that were taken from the Panyabungan Batholiths and sample MS-16 collected from the Muara Sipongi intrusions (Figure 2), while the volcanic samples are PYB-3 and MS-14. The sample labelled MS-14 belongs to the Silungkang Formation (Permian-Triassic) that crops out on the Muara Sipongi River, while the samples PYB-3 represents the undifferentiated volcanic unit (Miocene).

The chemical analysis was done by Activation Laboratories in Canada under the analysis code 4Litho. They have developed a lithium metaborate/

tetraborate fusion ICP Whole Rock Package and a trace element ICP/MS package which is unique for the scope of elements and detection limits. The two packages are combined for Code 4Litho and Code 4Lithoresearch.

RESULTS

Petrography

Two samples collected from the Panyabungan area, namely PYB-3 and PYB-15A, represent two different lithologies and age. The first sample (PYB-3) is pyroxene andesite in composition, representing the undifferentiated volcanic rock type that is Miocene in age. It was collected near the road from Panyabungan to Natal (Figure 2). Petrographically, the rock shows a porphyritic texture and a flow structure with their phenocryst is up to 4 mm in size, embedded in a groundmass of around 0,01mm in average. The phenocrysts comprise plagioclase, ortho- and clinopyroxene, and a minor amount of olivine and magnetite. They are invariably already replaced by chlorite and some parts have been oxidized. The plagioclase is labradorite and andesine types, while the pyroxene is identified as hypersthene and augite showing pleochroism. The ground

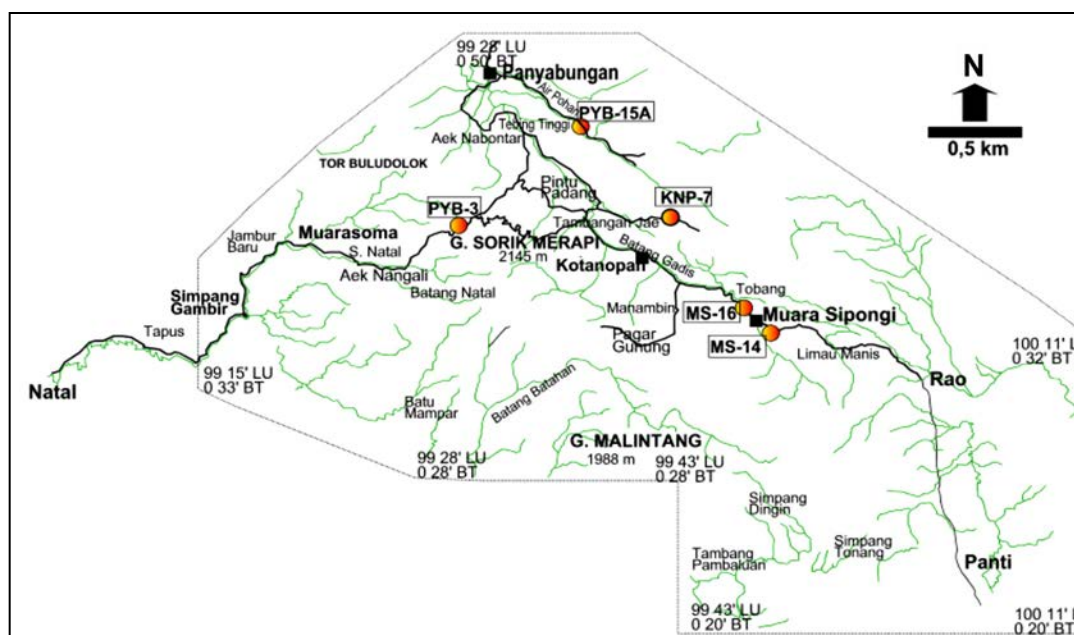


Figure 2. Sample location map around Panyabungan, Kotanopan, and Muara Sipongi in the Madina Regency area.

mass is dominated by volcanic glass and microlath plagioclase in which the glass shows a devitrification partly into chlorite and carbonate. A minor amount of secondary silica was found as a filling material for its vesicular structure. The magnetite and olivine are present only in a few amounts.

The second sample (PYB-15A) belongs to the Panyabungan Batholiths and was collected in the Panyabungan area, northeastward from Panyabungan Town (Figure 2). It is granitic in composition and Permian-Triassic in age. The rock shows inequigranular texture, holocrystalline character and intergrowth structure between orthoclase and quartz. It consists of K-feldspar that is identified as orthoclase, quartz, biotite, hornblende, albite, and minor amount of muscovite and opaque. The crystals vary from 0,05 to 8,0 mm in size, averaged around 4 to 5mm. The quartz and K-feldspar usually show undulating extinction, while the biotite and hornblende occur as green subhedral prismatic crystals showing strong pleochroism. Among the mentioned minerals, many small grained clinozoisite and a small amount of epidote are present together with grains of opaque, while the hornblende and biotite have been altered partly into chlorite. The rock is classified as metagranite.

The only one sample collected near Kotanopan that was analyzed chemically for major, trace, and rare earth elements of the whole rock is the KNP-7 sample. This sample is identified as metagabbro that its presence is never reported before. It was found in association with the Panyabungan Batholith. The rock shows a relatively equigranular texture and it is composed dominantly of plagioclase, green antophyllite, and grained magnetite. The plagioclase occurs as euhedral to subhedral prismatic crystals in a big size (up to more than 4 mm) and it is sometimes found as inclusions in the antophyllite. In some crystals, they are changed into carbonate in a small amount along their twinning line. The antophyllite is believed to be derived from pyroxenes showing strong pleochroism, and in some cases they are present as aggregates in association with chlorite, carbonate and epidote. The magnetite spreads usually in association with antophyllite. Some carbonate veinlets are observed cutting the thin section.

There are two analyzed samples that were taken from an area near Muara Sipongi, namely

MS-14 and MS-16. They have different composition and age where the MS-14 sample represents a volcanic product within the Silungkang Formation (Permian-Triassic), while the MS-16 represents the Muara Sipongi intrusion. The MS-14 sample cropping out in the Muara Sipongi River is identified as pyroxene basalt that should belong to the metavolcanic member of the formation. It shows an intergranular texture with size ranging from 0.05 to 4.0 mm. The rock comprises plagioclase, ortho- and clinopyroxene, olivine, and magnetite, while the space among the crystals is filled by volcanic glass and plagioclase laths. The plagioclase occurs as euhedral to subhedral prismatic crystals, up to 2 mm in size and some crystals show multiple twinings. Some of them have been changed in a small part into carbonate. The pyroxene is distinguished into augite and hypersthene and they have in some parts already changed into carbonate, clinozoisite, epidote, and chlorite. Some augites are present as big crystals, up to more than 5 mm.

Another sample collected near Muara Sipongi is labeled with MS-16. The rock is identified as hornblende granodiorite. It shows inequigranular with interlocking texture and holocrystalline character. The rock is composed of plagioclase, green hornblende, orthoclase, albite, quartz, and magnetite with the crystal size up to 3 mm. The plagioclase is found as subhedral to euhedral prismatic crystals that are interlocking with the hornblende. They contain some dots of carbonate within. The hornblende, showing a strong pleochroism and already altered in a small part into chlorite, is green in colour. Sometimes, they contain small grained magnetites within. Orthoclase and quartz is observed as an interstitial mosaic. Among the coarser crystals, a significant amount of fine-grained clinozoisite and epidote spread throughout the thin section. Beddoe-Stephens *et al.* (1987) described about the Muara Sipongi Batholiths that petrographically consist predominantly of hornblende-bearing quartz diorites and granodiorites that are relatively uniform in appearance on all outcrops. They are nonporphyritic and formed by interlocking laths of medium-grained euhedral to subhedral hornblende crystals with plagioclase. Biotite is common in more granodioritic variants, occasionally in a modal abundance equal to that of hornblende. Quartz is invariably present in varying amounts and usually associated with feldspars as an

interstitial mosaic. Magnetite with minor ilmenite are abundant up to 3 %, while apatite, sphene, and zircon occur as accessories phases. An alteration to varying degrees is ubiquitous with phyllic and propylitic types indicated by a sericitization of feldspar and a replacement of hornblende by fibrous actinolite, chlorite, and epidote. Similarly, biotite often shows a partial to complete replacement by chlorite. There is no evidence of a potassic-style alteration.

Rock Chemistry

As mentioned above, the five samples were analyzed for major, trace, and rare earth elements and the chemical data are given in Table 1 below. Four samples are Mesozoic in age (PYB-15A, KNP-7, MS-14 and MS-16), while the rest one sample is of Miocene age (PYB-3).

Major Elements

The rocks range from basaltic/gabbroic through andesitic to granitic in composition with SiO_2 content varying from 46.28 to 68.57 wt.% (Table 1). All rocks contain low LoI, except sample MS-14 (LoI=3.09 wt.%), indicating that the rocks are relatively free from alteration processes, although mineralogically they are already metamorphosed into greenschist facies. The samples KNP-7 and MS-14 have a similar SiO_2 content, but coarser grain minerals in the meta-gabbro (KNP-7) are more difficult to be changed by the metamorphism process compared to smaller grain minerals in the basalt (MS-14). Therefore, the hydroxyl bearing-metamorphic minerals were formed more abundant in the sample MS-14 and causing its higher LoI value.

The granitic samples (PYB-15A and MS-16) show the highest SiO_2 content ranging from 61.04 to 68.57 wt.% indicating the composition of granodiorite and granite, while the sample of the Silungkang Formation (MS-14) has 48.42 wt.% SiO_2 representing the basaltic composition. The sample PYB-3 representing the undifferentiated volcanic unit has an andesitic composition with 57.31 wt.% SiO_2 , while the meta-gabbro sample (KNP-7) contains 46.28 wt.% SiO_2 . The sample KNP-7 has the most basic composition with the highest total Fe content of 14.37 wt.%, CaO up to 11.15 wt.%, and the lowest total alkali content of 2.54 wt.%.

K_2O content of the basaltic samples (KNP-7 and MS-14) is very low ranging from 0.63 to 0.23 wt.%, while the Panyabungan granitic sample (PYB-15A) has that in significant high content up to 5.24 wt.%. Therefore, the Panyabungan granite is classified as shoshonitic rock, while the sample MS-14 belongs to low K rock and the rest three samples fall into the medium-high K rocks (Figure 3 left). Furthermore, the two basaltic samples contain high total Fe, varying from 14.37 to 12.49 wt.%, compared to the other three samples, and they are classified into tholeiitic affinity and the other three samples into calc-alkaline type (Figure 3 right).

Trace Elements

The andesite and granitic samples contain higher incompatible elements (Ba, Rb, K), Th, and P than the two basaltic samples, and also enriched on High Field Strength Elements (HFSE) such as Zr, Nb, Hf, and Ta, except for Ti (Table 1). They have a lower content on Sr and Ti.

The plot of the basalts on the spider diagrams, after normalizing the elements to MORB according to Pearce (1983), gives two different patterns. Sample KNP-7 shows a slightly enrichment on incompatible elements and has a spike on Rb with value around 10 times to MORB. But, it is depleted on almost all less incompatible elements (including their HFSE). It has almost a similar concentration on Ti with MORB. This pattern, except the higher Ti content, is also observed among samples of back-arc basin basalts from the East Scotia Sea (Saunders and Tarney, 1979) and for typical tholeiitic basalt from the associated South Sandwich island-arc (Pearce, 1983) (Figure 4, left). Meanwhile, the MS-14 sample shows a different pattern where it is also slightly enriched by Ce, P, and Sm compared to MORB, besides the incompatible elements. It shows spikes on Ba, Ce, and Sm. The pattern shows a similarity with the pattern for island-arc calc-alkaline basalt, where it shows peaks on Ba, Ce, and Sm with troughs on Ta, Nb, and Zr (Figure 4 right; taken from Wilson, 1989). The data indicate that the tectonic environment could be changed from an island-arc to a back-arc basin tectonic setting. The interpretation is based on the tectonic development in an island-arc setting where the island-arc can be developed to the back-arc basin through a penetration of the magma plume (Wilson, 1989).

Table 1. Chemical Analysis Result of Samples from Madina Regency Area

Wt %	PYB-3	PYB-15A	KNP-7	MS-14	MS-16
SiO ₂	57.310	68.570	46.280	48.420	61.040
Al ₂ O ₃	17.150	13.850	17.400	17.050	15.370
Fe ₂ O ₃ (T)	7.490	3.430	14.370	12.490	6.690
MnO	0.139	0.081	0.221	0.188	0.099
MgO	3.900	1.000	5.360	5.930	3.180
CaO	7.350	3.390	11.150	5.870	5.890
Na ₂ O	2.950	2.750	1.910	5.310	3.360
K ₂ O	1.670	5.240	0.630	0.230	1.730
TiO ₂	0.647	0.457	1.288	1.092	0.555
P ₂ O ₅	0.130	0.120	0.080	0.109	0.130
LoI	0.840	0.840	0.740	1.160	1.640
Total	99.570	99.620	99.850	99.850	99.690
In ppm					
Ba	316.00	1020.00	131.00	160.00	366.00
Rb	56.00	193.00	20.00	4.00	59.00
Sr	349.00	247.00	372.00	814.00	371.00
Y	23.00	33.00	14.00	22.00	24.00
Zr	110.00	266.00	26.00	53.00	84.00
Nb	4.00	17.00	1.00	2.00	3.00
La	16.50	62.30	2.60	8.40	11.40
Ce	32.50	109.00	5.80	17.70	23.60
Pr	4.31	13.20	0.93	2.71	3.34
Nd	17.10	44.80	4.90	12.50	13.80
Sm	3.80	7.80	1.50	3.30	3.30
Eu	1.02	1.59	0.60	1.15	0.82
Gd	3.60	6.20	2.00	3.40	3.20
Tb	0.70	1.00	0.40	0.60	0.60
Dy	3.80	5.70	2.40	3.90	3.90
Ho	0.80	1.10	0.50	0.80	0.80
Er	2.40	3.20	1.40	2.30	2.50
Tm	0.36	0.48	0.21	0.35	0.39
Yb	2.40	3.20	1.30	2.30	2.50
Lu	0.36	0.44	0.20	0.33	0.38
Hf	3.20	7.20	0.90	1.70	2.70
Ta	0.30	1.40	< 0.10	< 0.10	0.20
Th	7.60	28.70	0.70	1.30	3.80

Spider diagrams of the andesite (PYB-3) and the two granitic rocks (PYB-15A and MS-16) show a significant enrichment on the incompatible elements and less on the HFSE, but depleted on Ti (Figure 5). The pattern looks like a variant of spider diagrams of magmatic rocks on an active continental margin although the spider diagrams of the rocks from the active continental margin show different spikes on

Ba and Hf but the same troughs on Ta, P and Ti (Wilson, 1989). The enrichment on Rb and Th (PYB-15A and PYB-3) or only on Rb (MS-16) probably took place during partial melting and fractional crystallization processes.

The plot of the basalts on spider diagrams of Rock/Chondrite ratio, after the elements being normalized according to Thompson *et al.* (1984),

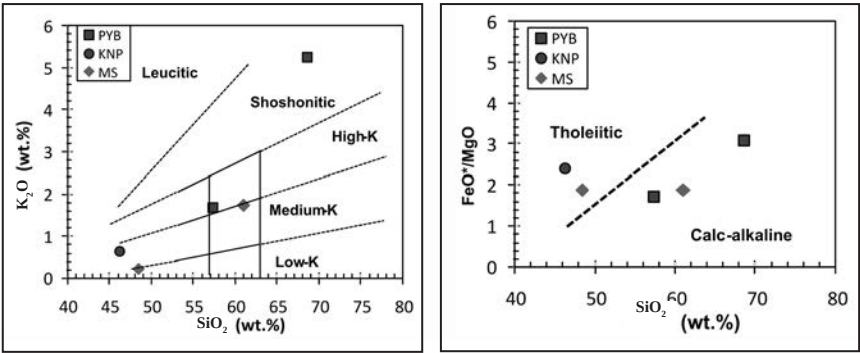


Figure 3. Plots of the Madina samples on the SiO_2 versus K_2O diagram (after Le Bas, 1986) distinguishing them into low-, medium- and high-K and shoshonitic rocks, and (right) showing tholeiitic and calc-alkaline affinities of the samples (after Miyashiro, 1974).

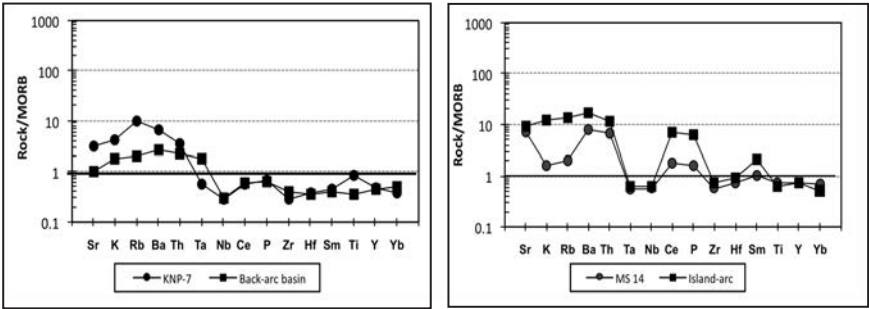


Figure 4. Spider diagrams of two Permian-Triassic basaltic rocks from the Madina Regency area showing two different characters, namely back-arc basin and island-arc. (Data for back-arc basin samples are taken from Saunders and Tarney, 1979; data for island-arc samples are taken from Wilson, 1989).

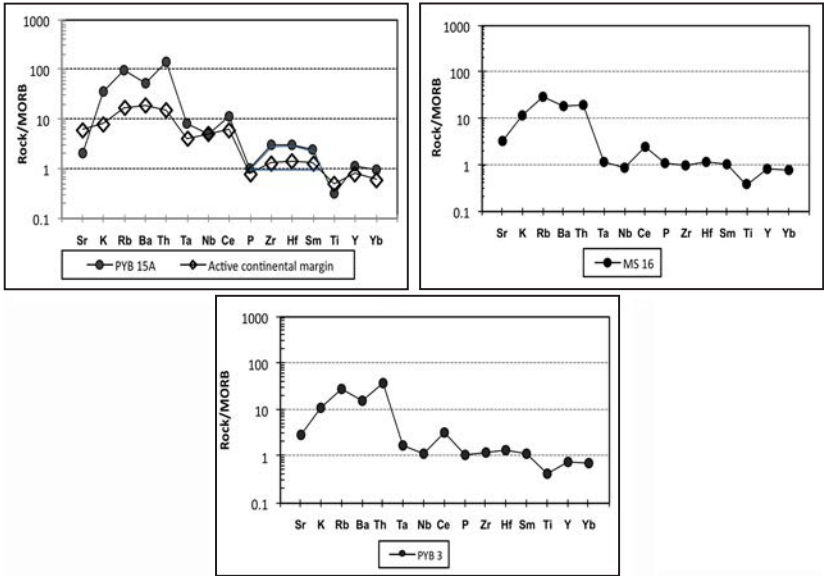


Figure 5. Spider diagrams of two granitic rocks and andesite from the Madina Regency area showing variation patterns of magmatic rocks in the active continental margin. The legend is like those above. (Data for the active continental margin were taken from Wilson, 1989).

shows a very similar pattern on less- to compatible elements with small different on incompatible elements, where the sample KNP-7 has spikes on Rb and K, while the sample MS-14 show spikes on Th (Figure 6 left). The pattern similarity should reflect that both rocks were derived from the same tectonic environment, either from an island-arc or back-arc marginal basin environment. The enrichment on Ta for sample KNP-7 (Ta higher than Nb on Figure 6 left) indicates that its magma has experienced some

contamination (Wilson, 1989) and accompanied by decreasing Th. On Figure 6 (right), plots of the andesitic and granitic rocks show a very similar pattern reflecting they also came from the same tectonic environment. They are enriched significantly on incompatible elements, on HFSE, and on other less incompatible elements. The enrichments are considered to be caused by contamination processes during the magma ascending, where it is in line with their higher Ta compared to Nb.

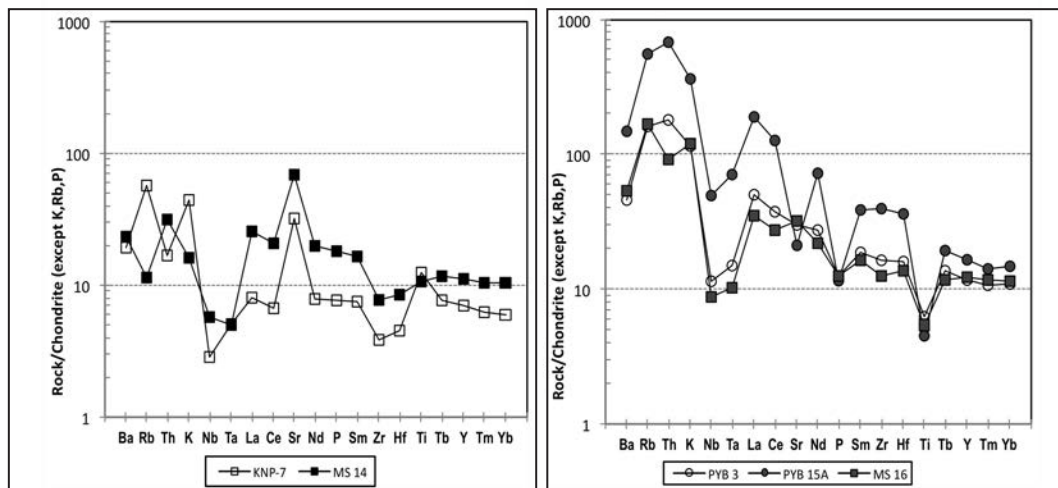


Figure 6. (Left) Spider diagrams of Madina basalts showing a very similar pattern indicating that they should come from the same tectonic environment. (Right) Spider diagrams of andesitic and granitic rocks from the Madina area that are enriched significantly on incompatible elements and other less- and compatible elements due to probably contamination processes.

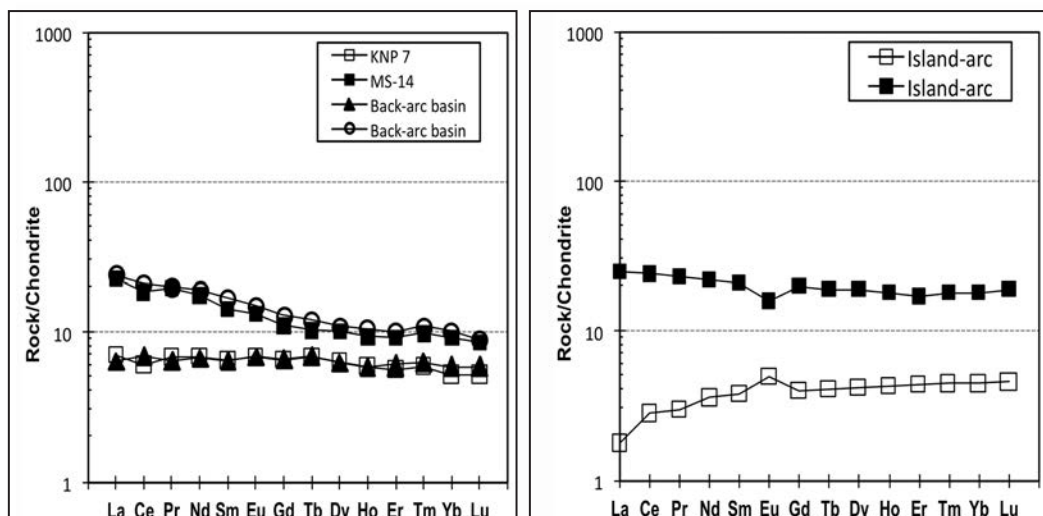


Figure 7. (Left) REE spider diagram of the Madina basalts shows the similar pattern with the marginal basin basalt from East Scotia Sea, and (Right) REE spider diagram for the island-arc basalt in South Sandwich Island arc shows an anomaly on Eu. (Data for East Scotia Sea and South Sandwich were taken from Hawkesworth *et al.*, 1977).

Rare Earth Elements

Plot of the REE of basaltic samples in the spider diagrams after the elements being normalized according to Sun and McDonough (1989), results in two different pattern (Figure 7, left). Sample KNP-7 shows a flat pattern for all elements, while sample MS-14 was enriched slightly on Light REE (LREE). Both patterns were observed exactly on basalt from the associated marginal basin in the East Scotia Sea (Hawkesworth *et al.*, 1977). For comparison, the island-arc basalt patterns also show two different patterns with the low pattern indicating the increase of rock/chondrite ratio from La to Lu. The rock/chondrite ratio has the wider area than the back-arc marginal basin basalts. But, the difference between both tectonic settings is the occurrence of Eu anomalies on the island-arc patterns (Figure 7, right) that are not available on spider diagrams of the marginal basin type.

Figure 8 demonstrates the plot of REE of the andesitic and granitic rocks of the Madina area showing the similar pattern with the active continental margin magmatic product. They can be distinguished into tholeiitic, calc-alkaline, and high-K calc-alkaline affinities. The negative anomaly on Eu indicates that it has fractionally crystallized plagioclase.

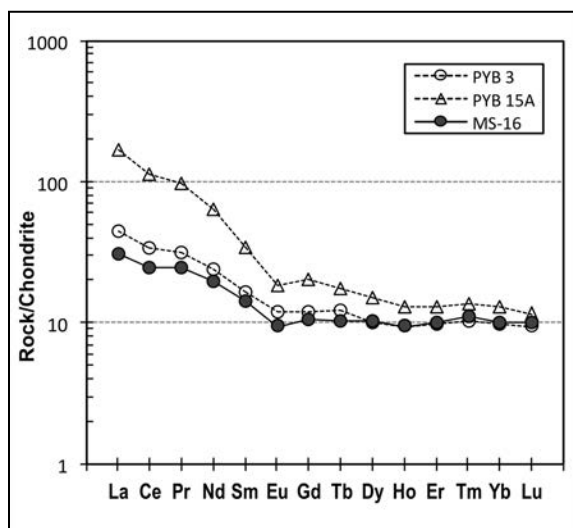


Figure 8. REE spider diagram of Madina andesite and granitic rocks showing a pattern of an active continental margin that can be distinguished into tholeiitic, calc-alkaline, and high-K calc alkaline affinities.

DISCUSSION

As mentioned previously, there are three scenarios proposed to explain the Pre-Tertiary volcanic-plutonic belt on Sumatra, namely an island-arc, a subduction related continental margin arc, and a continental break-up (Crow, 2005). The data of this study offer another scenario, where the Mesozoic tectonic setting of the area seems to have been a back-arc marginal basin that changed in to an active continental margin since Jurassic until Recent. For the Permian-Triassic volcanic rock represented by the two basaltic samples (KNP-7 and MS-14), they are classified as volcanics having tholeiitic affinity (Figure 3) and the plot of their trace elements in spider diagrams for ratio rock/MORB results in two different patterns that similar to back-arc and island-arc basalts (Figure 4). But their pattern in the spider diagrams for ratio Rock/Chondrite (Figure 6 left) are very similar leading to a conclusion that actually they should belong to the same tectonic environment, either back-arc marginal basin or island-arc environment. The enrichment on Ta of sample KNP-7 (higher Ta than Nb on Figure 6, left) indicates that its magma was already partly contaminated (Wilson, 1989). In fact, the petrography of the rocks also includes island-arc characters, such as strong pleochroism and the presence of two types of pyroxene. It seems that all data lead to a character of island-arc tectonic setting. But, their pattern on REE spider diagram on rock/chondrite ratio shows clearly a character of the back-arc basin origin for both basalts (Figure 7, left). It can be concluded that both basalts from the back-arc basin and island-arc environment may show a similar character on petrography and trace element pattern, but they can be separated through their REE pattern. The difference between the back-arc basin and island-arc basalts is essentially on the occurrence of Eu anomalies, where the island-arc basalts show positive and negative Eu anomalies while the back-arc basin basalts without Eu anomalies (Figure 7). Based on those data, it can be concluded that the Permian-Triassic volcanism in Sumatra was related to a back-arc tectonic environment, because the development of a back-arc marginal basin is usually generated through ascending diapirs of asthenospheric mantle rise beneath an island-arc environment. Thus, the geochemical signature of the island-arc may still be observed

in spider diagrams of the back-arc basin basalts. Therefore, in the tectonic classification they will be commonly plotted in an oceanic island-arc field (Figure 9, left). It seems that the diagram cannot be used effectively to distinguish between the island-arc and back-arc basin tectonic setting. But, based on their Y content and ratio of Nb/Zr, all samples of the Madina area are classified as volcanics having a back-arc side character (Figure 9, right).

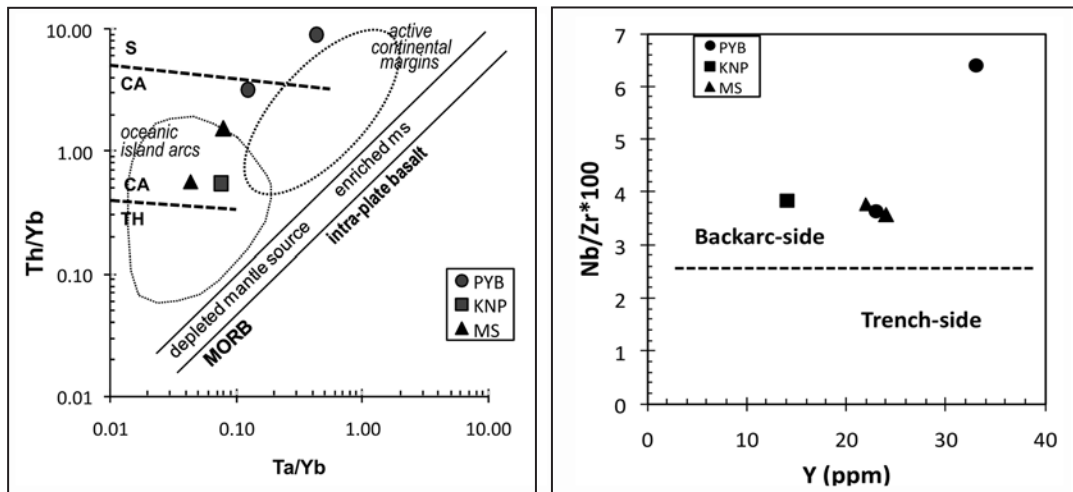


Figure 9. (Left) Plot of samples from the Madina area in Ta/Yb versus Th/Yb (after Pearce, 1982) gives an island-arc character for basaltic samples although they actually belong to back-arc marginal basin, and (Right) the plot of them in Y versus Nb/Zr*100 (after Zulkarnain, 2001). TH = tholeiite; CA=calc-alkaline; S=shoshonitic.

The Triassic-Jurassic granitic rocks and Miocene andesite from the Madina area are classified as shoshonitic and high-K rocks which are typical for an active continental margin environment (Figure 3). Their spider diagram patterns for trace elements in ratio of rock/MORB are also matched generally with a character of magma in the active continental margin (Figure 5). They show a significant enrichment on incompatible elements, particularly shoshonite (PYB-15A) and depleted on Ti. Interestingly, the spider diagram of granodiorite from Muara Sipongi (MS-16) and andesite (PYB-3) samples from Panyabungan area shows exactly the same pattern with a small difference only on Th. They reflect a significant enrichment on incompatible elements and Ce, and depleted on Ti. It seems that the granodiorite should be derived from the andesitic magma through fractional crystallization or differentiation

processes. But in fact, both samples are very different in age. However, it indicates that the magmas for the magmatic activities since Triassic-Jurassic until Miocene in this area may have come from the same sources. Furthermore, it also indicates that the volcanic-plutonic activities in Sumatra had taken place consistently in an active continental margin tectonic setting from Triassic-Jurassic until Miocene. The conclusion is also confirmed by the

spider diagram of Triassic-Jurassic granitic rock from Panyabungan (PYB-15A) that also shows the similar pattern with the other two samples.

The magmas in the active continental margin have commonly been enriched significantly by the incompatible elements. It can occur through the contamination by subduction fluids and or by the lower continental crust that probably occurred during the magma ascending. Contaminated magmas are usually marked by an increase of Ta which changes the trend line from Nb to Ta in the trace element spider diagram from downline to upline (Wilson, 1989). For the Madina case, the contamination seems to be the proper process that takes responsibility for the enrichment of the incompatible elements in the rocks (Figure 6). The Nb-Ta line pattern of the three samples in Figure 6 (right) and KNP-7 reflects the contamination effect of MORB by amphibolites or

granulite in the lower continental crust of Sumatra. The REE spider diagrams of the three samples are in line with the conclusion, where they show a significant enrichment on Light-REE and have the calc-alkaline to high-K calc-alkaline affinity (Figure 7, right). The negative anomaly of Eu reflects the fractionation of plagioclase. Although magmas in an active continental margin almost always experience contamination processes, in the case of Madina samples, it seems that the significant Th enrichment occurred and tends to change their Th/Yb ratio. It makes their plot shift to an area outside an active continental margin field (Figure 9, left).

The ratio of very incompatible REEs is usually used as a diagnostic indicator to know whether two magmatic rocks came from the same source or not, because they should not be fractionated. Therefore, the ratio of La/Ce can still be used in the Madina

is represented by the Kotanopan basalt KNP-7 (it is in line with its lowest SiO_2 content) and followed by basalt and granodiorite from Muara Sipongi, and the end member are the andesite and shoshonite from Panyabungan. The last two samples are interpreted as the most contaminated products. All data and analysis above lead to a conclusion that the magmatic activities in the Madina area during Triassic-Jurassic had been changed from a back-arc basin tectonic setting to an active continental margin, but probably they had come from the same magma sources.

Concerning the granitoid batholiths or intrusions in the area, it seems that they were emplaced when the tectonic environment had already changed into an active continental margin forming a volcanic arc in Sumatra. It is marked by the distribution of samples in the field Volcanic Arc Granite (VAG) (Figure 10, right).

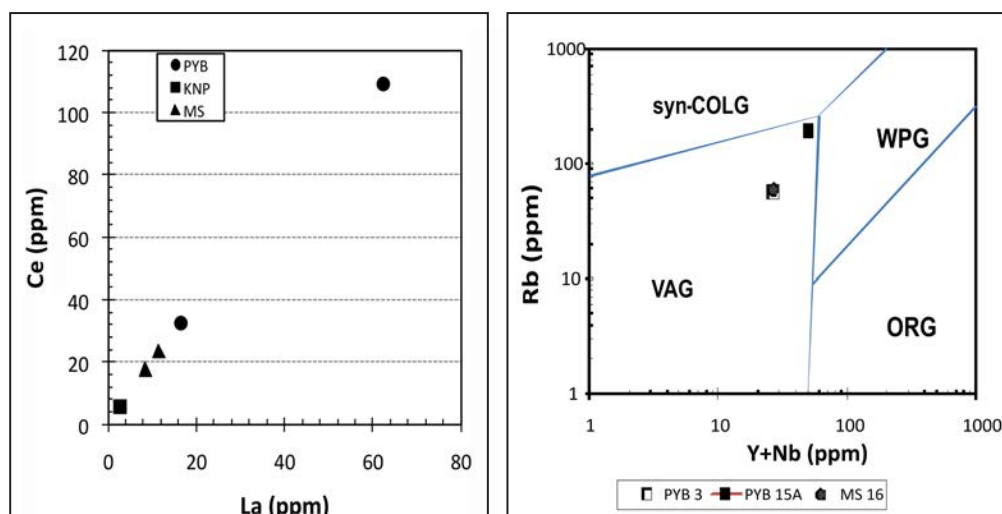


Figure 10. (Left) Plot of the samples from Madina area in La versus Ce diagram showing a clear and good trend line. It indicates that all samples with different age probably had come from the same magma sources. (Right) The plot of the granitic and andesitic samples on granite tectonic classification diagram that is confirmed the granites as Volcanic Arc Granite (VAG).

case, although some samples have shown the effect of contamination. The La/Ce ratios of all samples that different in age are relatively similar ranging from 0.45 to 0.57, and they show a clear and good trend line (Figure 10, left). It indicates that all products of volcanism and intrusion since Permian until Miocene in the Madina area, had probably come from the same magma sources. Figure 10 also shows that the primitive magma composition

CONCLUSION

The Permian-Triassic basalts from Kotanopan and Muara Sipongi, in the Madina Regency are classified as low-K rocks having tholeiitic affinities. Their spider diagram patterns on both Rock/MORB and Rock/Chondrite ratios indicate that they are products of the volcanism in a back-arc marginal basin tectonic setting. One of the basalts (KNP-7)

seems to be derived from contaminated magmas that is marked by an increase of Ta compared to Nb in its trace element spider diagram. Generally, all samples show also the significant enrichment on Th, so their geochemical signature is shifted to an area outside the island-arc and active continental margin fields. The granitic and andesitic rock data indicate that since Triassic-Jurassic until Miocene, the geological tectonic setting was changed from a back-arc basin environment to an active continental margin. The character is in line with the granitic rock type that belongs to the Volcanic Arc Granite (VAG). Although all of the rocks have different ages, probably they had come from the same magma sources with a different intensity of a fractional crystallization or lower crust contamination. All data lead to a conclusion that the magmatic activities in the Madina area during Triassic-Jurassic had been changed from a back-arc basin tectonic setting to an active continental margin, but probably they had come from the same magma sources. This conclusion offers an other different alternative besides three scenarios that were proposed by previous authors, namely island-arc, subduction related continental margin arc, and continental break-up.

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