GEOCHEMICAL CHARACTERISTIC OF METAMORPHIC ROCKS FROM SOUTH SULAWESI, CENTRAL JAVA, SOUTH AND WEST KALIMANTAN IN INDONESIA

Nugroho Imam Setiawan[1], Yasuhito Osanai[2], Nobuhiko Nakano[3], Tatsuro Adachi[4], Kazuhiro Yonemura[5], Aya Yoshimoto[6], Lucas Donny Setiadji[7], Kaharuddin Mamma[8], and Joko Wahyudiono[9]

[1,2,3,4,5,6] Division of Earth Sciences, Faculty of Social and Cultural Studies, Kyushu University, Fukuoka, Japan, e-mail: nusetiawan@gmail.com

[1,7] Geological Engineering Department, Faculty of Engineering, Gadjah Mada University, Yogyakarta, Indonesia

[8] Geological Engineering Department, Faculty of Engineering, Hasanuddin University, Makassar, Indonesia [9] Geological Research and Development Centre of Indonesia, Bandung, Indonesia

Received Date: December 18, 2012

Abstract

Various metamorphic rocks are exposed in the central part of Indonesia, including the islands of Java, Kalimantan and Sulawesi. Metamorphic complexes, regarded as products of Cretaceous subduction of Indonesia outcrop in Central Java, South Kalimantan, and South Sulawesi. The lithology in these locations is predominantly composed of high-pressure metamorphic rocks. Moreover, metatonalite is exposed in the Schwaner Mountains of West Kalimantan. This study describes the geochemical character of the metamorphic rocks to consider the original rock composition and ascertain their relationship to the tectonic environments in the area.

The geochemical characteristics suggest that protolith of the metamorphic rocks from South Sulawesi, Central Java and South Kalimantan can be categorized as metabasic and metamorphosed sedimentary rocks (pelite to greywacke). The origin of the metabasic rocks from South Sulawesi and Central Java is considered as alkali basalt or sub-alkali andesite to basalt. The protolith is characterized by signatures pointing to N-MORB, E-MORB and within-plate basalt settings with a tholeiitic nature. Eclogites and blueschists from South Sulawesi contain both MORB and within-plate basalt signatures that might indicate several ocean islands existed and subducted together with oceanic floor composed of MORB during the Cretaceous. Meanwhile, eclogites and blueschists from Central Java mostly show within-plate basalt signatures, whereas amphibolites and garnet amphibolites are characterized by MORB. These results suggest several possibilities: a different component between the upper- and lower-oceanic crusts; a difference in the metamorphic ages between eclogite- and amphibolite-facies metamorphism; and a change of the subduction angle between the two metamorphisms.

Metatonalites from the Schwaner Mountains are calc-alkaline rocks derived from volcanic-arc tectonic environments. Two samples indicate adakitic nature. One sample of adakitic metatonalite has the age of 233 ± 3 Ma (Late Triassic) that could be divided from the major Cretaceous non-metamorphosed granite event in the same region. These might imply that the subduction mechanism and felsic magma genesis changed between the Early Triassic and the Cretaceous. Some metatonalites show similar signature to the Cretaceous granite, indicating that subsequent metamorphism occurred during the Cretaceous subduction system.

Keywords: Adakite, Central Java, Geochemistry, Metamorphic rocks, South Kalimantan, South Sulawesi, West Kalimantan

Introduction

Indonesia is a geologically region situated in the southeastern edge of the Eurasian continent. It is bounded to the south and the west by the Indo-Australian Plate and to the east by the Philippine Sea and Pacific Plates. The Indonesian archipelago was formed by reassembly of fragments rifted from the Gondwana supercontinent that arrived at the Eurasian subduction margin [1]. The present-day geology of Indonesia is broadly the result of Cenozoic subduction and collision at this margin.

Java, Kalimantan and Sulawesi are three main islands that are geographically located in the central part of Indonesia. Accretionary and metamorphic complexes are exposed in Central Java, South Kalimantan, and South–Central Sulawesi. Northwesterly-directed Cretaceous subduction was suggested to be the tectonic event responsible to build these formations [2, 3]. The metamorphic complexes are predominantly composed of high-pressure metabasic and metapelitic rocks. Metatonalites also outcrop in the Nangapinoh area, West Kalimantan, which are associated with a later granitoid event. The granitoids were generated by the intrusion related to the southward-directed subduction during the earlier Jurassic to Early Cretaceous [4].

The geochemical characteristics of the metamorphic rocks from South Sulawesi, Central Java, South Kalimantan, and West Kalimantan have remained obscure. Previous studies of metamorphic rocks from South Sulawesi and Central Java have been shown that the metabasic rocks correspond in composition to tholeiite basalts with a MORB-like affinity [5, 6]. The signature of OIB-like affinity from greenschist-facies rocks of the Bantimala Complex was also reported by [7]. But this conclusion was based on the limited number of analyses and short descriptions of the geochemical characteristics. Consequently, the regional distribution of the protolith for the high-pressure metabasic rocks, as well as the relationship between the protolith and their metamorphic grades, has so far not been well considered. Furthermore, there is almost no previous research that describes the geochemical characters of metatonalites in the Schwaner Mountains. [8] determined the magmatic age of metatonalite by LA-ICP-MS U-Pb zircon dating as 233 ± 3 Ma that implies a different tectonic event prior to the Late Cretaceous (77–157 Ma) granitoids of the Schwaner Mountains [4, 9]. To address these deficiencies, this paper provides a detailed geochemical study of the high-pressure metabasic rocks and metatonalites from the Bantimala and Barru Complexes of South Sulawesi, the Luk Ulo Complex of Central Java, the Meratus Mountains of South Kalimantan and the Schwaner Mountains in West Kalimantan. Mineral abbreviations in this paper follow [10].

Geological Outline

Metamorphic Rocks Related to the Cretaceous Subduction of Indonesia

Accretionary and metamorphic complexes, regarded as part of the Cretaceous subduction complex in Indonesia, are exposed in Central Java, South–Central Sulawesi, and South Kalimantan (Figure 1a). The complexes are predominantly composed of a chaotic occurrence of sandstone, shale, chert, basalt, ultramafic rocks, serpentinite, and low- and high-pressure metamorphic rocks. Before the opening of the Makassar Strait, these complexes may have constituted a single subduction complex [11]. Northwesterly-directed Cretaceous subduction beneath the Sundaland was suggested responsible for building this formation [2, 3]. The subduction ceased in Late Cretaceous, and the following collision of the microcontinents derived from the west Australian margin is recorded on the eastern part of Sulawesi [1, 11].

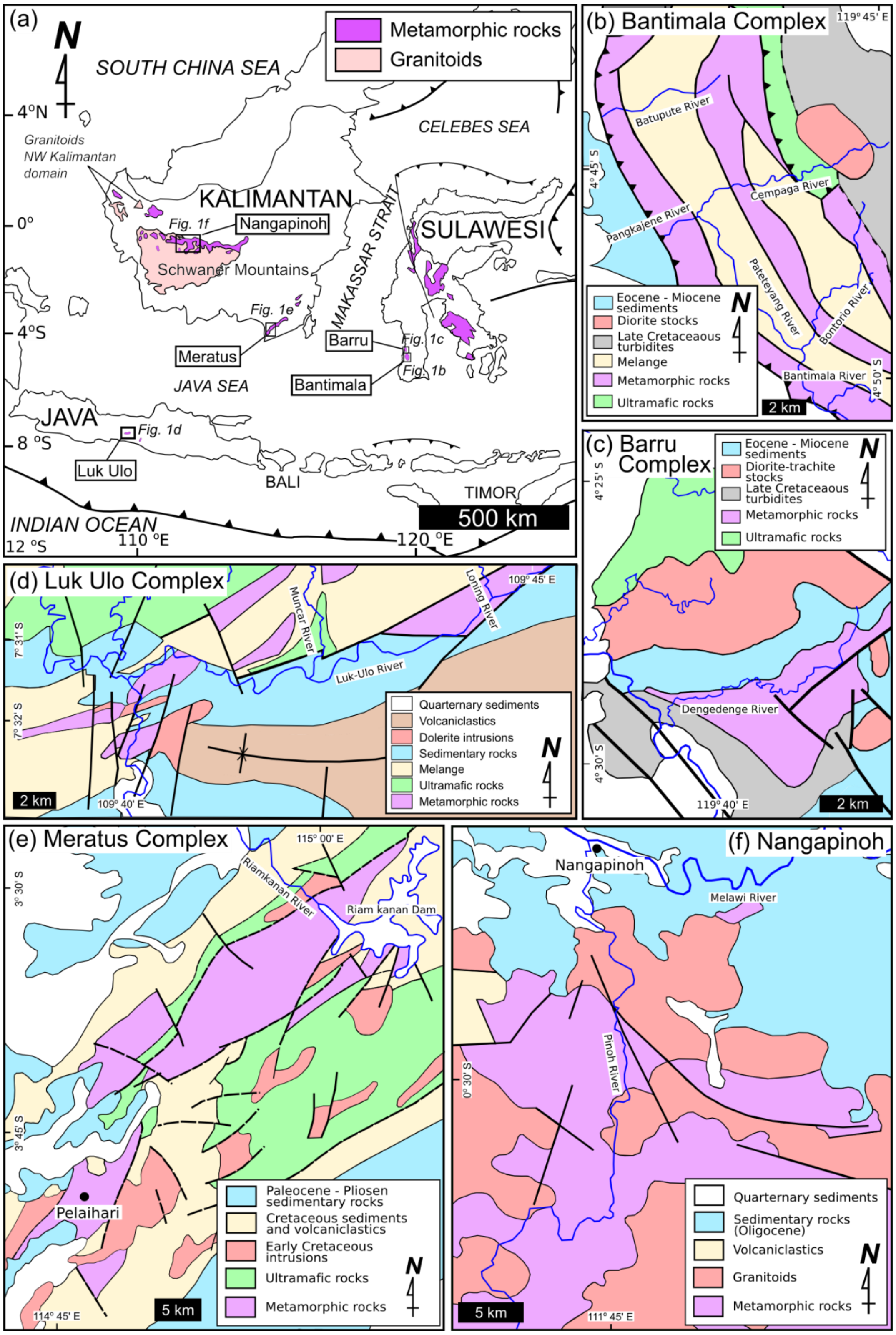

Figure 1. Distribution of metamorphic rocks in the central Indonesia region (a). Simplified geological map of the Bantimala Complex (b) and the Barru Complex in South Sulawesi (c) (modified from [2]), the Luk Ulo Complex in Central Java (d) (modified from [20]), the Meratus Complex in South Kalimantan (e) (modified from [22]), and the Nangapinoh area in West Kalimantan (f) (modified from [9])

Metamorphic Rocks in South Sulawesi

The metamorphic rocks related to the Cretaceous subduction system in South Sulawesi are restricted to the areas of the Bantimala and Barru Complexes (Figure 1a). Detailed geology of these areas were described by [2, 12, 13, 14, 15, 16].

The Bantimala Complex is a tectonic assemblage of slices and blocks consisting of sandstone, shale, conglomerate, chert, siliceous shale, basalt, ultramafic rocks, schist and schist breccia with ages ranging from Jurassic to middle Cretaceous [13] (Figure 1b). The tectonic slices of the complex are elongated with the strike in the NW–SE direction [2]. The metamorphic rocks are intercalated with mélange deposits and bounded on the south by a thrust fault of Eocene–Miocene sediments, whereas on the north they are bounded by ultramafic rocks and intruded by diorite stocks [2]. Metamorphic rocks in this location mainly consist of high-pressure metabasic and low-pressure metapelitic rocks of Cretaceous age [13]. Metamorphic rocks in the Bantimala complex consist of glaucophane-schist, albite-actinolite-chlorite schist, chlorite-mica schist, garnet-glaucophane-quartz schist, garnet-chloritoid-glaucophane-quartz schist, serpentinite, garnet-glaucophane rock and eclogite [15]. The predominant lithology is glaucophane schist. The garnet-glaucophane schist is interlayered with either the garnet-chloritoid-glaucophane-quartz schist or garnet-glaucophane-quartz schist [15]. The eclogite and the garnet-glaucophane rocks occur as tectonic blocks within the sheared serpentinite [15].

Peak metamorphic conditions of the high-pressure metamorphic rocks from Bantimala Complex, South Sulawesi have been reported to be 1.8–2.4 GPa at 580–640 ºC and retrogressed to near 1.0 GPa at 350 ºC and 0.5 GPa at 350 ºC from eclogite and garnet-glaucophane rock, respectively [15]. Very high-pressure metamorphic conditions were also reported in this area from garnet-jadeite-quartz rock that experienced peak metamorphism at >2.7 GPa on 720–760 ºC and retrogressed to near 1.0 GPa on 500 ºC [16]. Moreover, [17] reported the first clockwise *P-T* path of eclogite from this area, which started from blueschist- to eclogite-facies with the peak *P-T* at 2.2–2.4 GPa and 580–650 ºC (estimated from pseudosection analysis), and retrogressed to the actinolite-stability field and passed through glaucophane-stability field. This retrograde *P-T* path probably relates to the rapid exhumation from greater depths to crustal levels during the earlier stage and slower exhumation following cessation of rapid uplifting on the later stage [18]. The K-Ar ages of phengite for these rocks are ranging from 113 ± 6 Ma to 137 ± 3 Ma (Early Cretaceous) [12, 13, 16].

The Barru Complex is located approximately 30 km north of the Bantimala area (Figures 1a, c). Metamorphic rocks in this area are bounded in the north with ultramafic rocks and in the south with Late Cretaceous sedimentary rocks. The most common lithologies in this area are variably of garnetiferous quartz-mica schist and serpentinized peridotite. The reliable *P-T* condition of the metamorphic rocks in this area has not been reported previously. [12] reported the phengite K-Ar age of the quartz-mica schist to be 106 ± 5 Ma.

Metamorphic Rocks in Central Java

In Central Java, the most significant metamorphic rocks are exposed on the Luk Ulo Complex in Karangsambung area (Figure 1d), although very low-grade metamorphic rocks also crop out in small areas at the northeast of Yogyakarta (Jiwo Hills). Detailed geology of this area was described by [19, 20, 21]. The Luk Ulo Complex consists of shale, sandstone, chert, basic to ultrabasic rocks, limestone, conglomerate and metamorphic rocks. The tectonic slices of the complex have a trend of ENE–WSW [20]. Most of the metamorphic rocks in the Luk Ulo Complex are pelitic schists in which albite, quartz, and muscovite are abundant [19]. The epidote amphibolite in which barroisite, garnet, epidote, albite, biotite and phengite are present, is intercalated with garnet- bearing pelitic schists [19]. Small amounts of garnet amphibolite, eclogite, glaucophane rock and jadeite-quartz-glaucophane rock occur as tectonic blocks in sheared serpentinite [19]. Compared to the Bantimala Complex, the garnet amphibolite and amphibolite in the Luk-Ulo Complex are considered to be the low-*P-T* metamorphic rocks. These rock types could not be found in the Bantimala Complex.

The *P-T* conditions of the metamorphic rocks have been reported by [19, 21]. [19] estimated the peak condition of jadeite-quartz-glaucophane rock at 2.2 ± 0.2 GPa and 530 ± 40 ºC. Meanwhile, [21] estimated the metamorphic evolution of eclogite that experienced clockwise *P-T* path with the peak *P-T* at 1.8–2.2 GPa and 359–442 ºC. The later *P-T* condition of the retrograde stage is 0.8–1.0 GPa and 350–400 ºC. The *P-T* estimation of relatively low-pressure metamorphic rocks of amphibolites and garnet amphibolites have not been reported.

K-Ar dating of muscovite from quartz-mica schist yielded ages of 110 ± 6 Ma and 115± 6 Ma [19], whereas the dating of phengite in the jadeite-glaucophane-quartz rock yielded older ages of 119 ± 2 Ma and 124 ± 2 Ma [16]. These ages of the sedimentary and metamorphic rocks are very similar to those on the Bantimala Complex [13].

Metamorphic Rocks in South Kalimantan

Metamorphic rocks in South Kalimantan are located in the Meratus Mountains. The basement rocks, known as the Meratus Complex, crop out in this area in a NE–SW trend [22] (Figure 1e). The Meratus Complex consists of metamorphic rocks, ultramafic rocks and mélange with clasts of chert, limestone, and basalt within shale matrices [14, 22]. The dominant lithologies in this complex are serpentinized peridotite and pyroxenite, gabbro, and various low-grade schists [22].

The metamorphic rocks are distributed in the southwestern part of the Meratus Mountains. They occur as wedge-shaped tectonic blocks in fault contact with ultramafic rocks and Cretaceous sediments [22]. Moreover, [22] reported metamorphic rocks of quartz-muscovite schist, micaceous metaquartzite, barroisite-epidote schist, and metagabbro. [16] reported the occurrence of glaucophane- and kyanite-bearing quartz schist in this location and suggested that the presence of Mg-rich chloritoid imply recrystallization at a pressure of ~1.8 GPa or higher. The K-Ar dating of various mica schists yielded ages in the range of 110–119 Ma, which are in the same range with the metamorphic rocks in South Sulawesi and Central Java [14, 21].

Metamorphic Rocks in West Kalimantan

In West Kalimantan, southward-directed subduction during the Early Jurassic to Early Cretaceous is responsible for the formation of the Schwaner Mountains granitoid plutons [4] (Figure 1a). The granitoids are composed of biotite-horblende tonalite and granodiorite with minor mafic rocks and granite. These rocks intruded into the low-grade metamorphic rocks during the Early Cretaceous and resulted in contact metamorphism [4]. Strikes of schistosity of the metatonalites generally range from E–W to NE–SW [9]. The granitoids formed a belt 200 km wide and at least 500 km long, extending in an approximately E–W direction (Figure 1a). Chemical analyses of typical rocks from the Schwaner Mountains indicate the I-type calc-alkaline nature of the suite [4]. K-Ar ages of biotite and hornblende from the granitoids in the Schwaner Mountains range from 77 to 157 Ma, while the northwest Kalimantan block ages are from 204 to 320 Ma (Figure 1a) [4, 9, 23]. Moreover, [8] reported the magmatic age of metatonalite from Schwaner Mountains by LA-ICP-MS U-Pb zircon dating as 233 ± 3 Ma.

Field Occurrence and Petrography

The Bantimala Complex in South Sulawesi

High-pressure metamorphic rocks in the Bantimala Complex crop out along the courses of Pangkajene, Bontorio, Cempaga, Pateteang and Bantimala Rivers (Figure 1b). In these areas, mafic rocks (omphacite-bearing garnet-glaucophane rock, eclogite, and glaucophanite) are more common than pelitic metamorphic rocks such as garnet-glaucophane-phengite-quartz schist. Garnet-jadeite-quartz rock also crops out in Bantimala River, but exposures are rare.

The eclogite and garnet-glaucophane rock display granoblastic or poikiloblastic texture with the composition mainly consisting of garnet, omphacite, Na–Ca amphibole, epidote, phengite, and rutile, with occassional quartz, hematite, apatite, and titanite (Figures 2a, b). Some eclogites have small amounts of glaucophane in the matrix. Omphacite, epidote, phengite, and rutile grains are commonly 1–5 mm in diameter, whereas titanite occurs as inclusions in rutile. Garnet is commonly medium–coarse grained (~2–10 mm in diameter), but some eclogites have fine- and coarse-grained garnet. The garnet contains many mineral inclusions in the core and mantle portions, but relatively free from inclusions in the rim portion. Randomly oriented inclusions of quartz, omphacite, rutile, epidote, phengite, chlorite and glaucophane, with occasional paragonite are present in the garnet core and mantle portions. In the matrix of garnet-glaucophane rock and glaucophanite, nematoblastic glaucophane grains are commonly zoned. Secondary chlorite and albite commonly appear as pseudomorphs after garnet, glaucophane and omphacite. Moreover, actinolite is present as a secondary phase in the outermost rims of the Na–Ca amphibole and glaucophane.

Pelitic schists in the Bantimala Complex mainly consist of garnet, quartz, phengite, glaucophane, epidote, rutile, with secondary chlorite and albite (Figure 2c). Quartz, glaucophane, epidote and phengite are ubiquitous in the matrix. The schistosity is defined by alignment of pale glaucophane, phengite and green chlorite. Lepido-nematoblastic glaucophane grains are commonly zoned. Chlorite is partially or completely forming pseudomorphs after garnet, which may indicate the secondary phase.

The garnet-jadeite-quartz rock is rarely found in the Bantimala Complex. This rock has compositions of fine-grained garnet, jadeite, quartz, epidote, phengite, amphibole, hematite, apatite and rutile (Figure 2d). Subidioblastic garnet grains (<1 mm in diameter) occur with mineral inclusions of epidote, phengite, quartz, jadeite, and Na–Ca amphibole. Subidioblastic fine-grained garnet (<0.05 mm) occurs together with fine-grained aggregates of epidote, quartz, phengite and jadeite that are ubiquitous in matrix. Moreover, large masses of fine-grained epidote, visible with naked eye, occur sporadically in the rock. Phengite and albite are present in the outer rims of jadeite, which may indicate secondary stage. Chlorite is present as an interstitial mineral in the cracks of garnet and also indicates secondary stage.

The Barru Complex in South Sulawesi

Metamorphic rocks in the Barru Complex crop out in the Dengedenge River (Figure 1.c). The foliation recorded from the outcrop of the garnet-mica schist varies from N 78° W to N 28 °E with a dip of strata ranging from 28 to 56 °E.

Garnet-biotite-muscovite-quartz schist is the most common metamorphic rock in this area. This rock is mainly composed of garnet, biotite, muscovite, epidote, quartz, rutile,

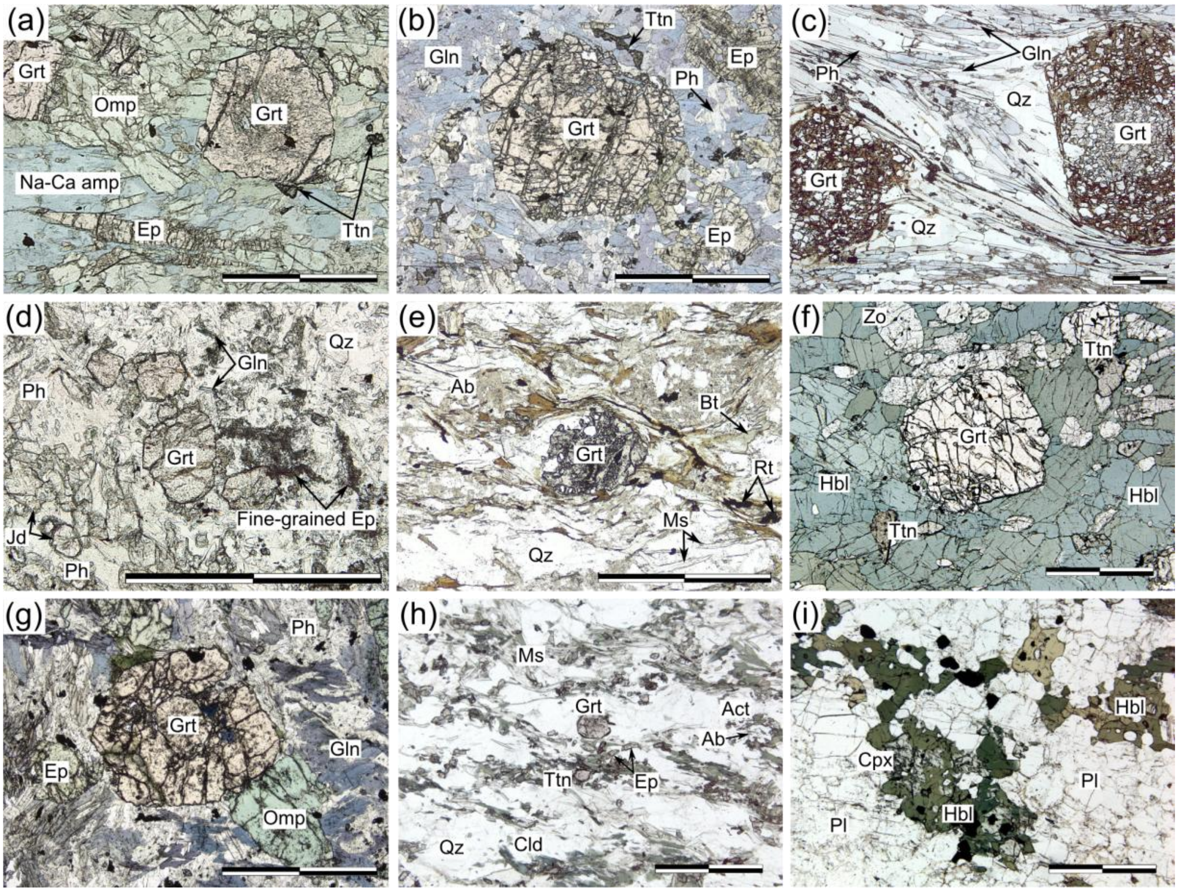

Figure 2. Photomicrographs of metamorphic rocks. Scale-bars correspond to 1 mm. (a) Omphacite, garnet, Na-Ca amphibole, and epidote as major minerals in eclogite, (b) porphyroblast garnet embed in the glaucophane rich matrix of garnet-glaucophane rock, (c) the schistosity defined by phengite, glaucophane and quartz in garnet-glaucophane-phengite-quartz schist, and (d) fine-grained aggregate epidote in garnet-jadeite-quartz rock from Bantimala Complex. (e) Helical texture of garnet in garnet-biotite-muscovite-quartz schist from Barru Complex. (f) Garnet, zoesite, and titanite embed in matrix hornblende from garnet amphibolite. (g) Garnet, omphacite, glaucophane, epidote and phengite defined the eclogite from Luk Ulo Complex. (h) Garnet-epidote-actinolite-quartz schist from Meratus Complex. (i) Hornblende encloses clinopyroxene in metatonalite from Schwaner Mountains.

chlorite, hematite and plagioclase. Subidioblastic–xenoblastic garnet (~0.3 mm) have helical inclusions of quartz and epidote (Figure 2e). The schistosity is defined by alignments of muscovite and biotite. The rutile is commonly rimmed by secondary titanite and chlorite. Furthermore, secondary albite is observed to replace garnet.

The Luk Ulo Complex in Central Java

The metamorphic rocks occur along the Loning, Muncar, and Lokidang Rivers and include high-pressure metabasic rocks (eclogite, garnet-glaucophane schist, and glaucophane schist), medium-grade low-pressure metabasic rocks (amphibolite, Grt amphibolite) and pelitic schists (muscovite schist, garnet-muscovite schist).

Garnet amphibolite has granoblastic texture containing porphyroblast garnet embeded in the matrix that consists of hornblende, zoesite, titanite and phengite (Figure 2f). Eclogite has porphyroblastic garnet (0.5–1 mm), in which mineral inclusions are abundant in the core and mantle portions but only few in the rim portion. Quartz, glaucophane and omphacite are inclusion minerals in the garnet. Omphacite, glaucophane, epidote, phengite, rutile and quartz occur in the matrix (Figure 2g). Titanite is present in the matrix and commonly encloses rutile. Porphyroblastic omphacite (0.5–1 mm) and nematoblastic glaucophane (0.1–0.5 mm) in the matrix are commonly zoned. Chlorite and albite occur as interstitial phase along the cracks of the garnet and other minerals. Garnet-glaucophane schist is characterized by modally abundant of glaucophane. Garnet porphyroblasts are embedded in the matrix of glaucophane. Glaucophane schist is differentiated from garnet-glaucophane schist by the presence of garnet in the matrix. Significant amounts of phengite and epidote are also found in the matrix and define the schistocity of the rock. Quartz, rutile, and titanite occur rarely in the matrix.

The most common pelitic schists in this area are garnet-muscovite-quartz schist and epidote-glaucophane-quartz schist. Garnet-muscovite-quartz schist mainly consists of fine-grained garnet (0.1 mm in diameter), muscovite, and quartz. Small amounts of chloritoid and apatite occur in the matrix. Chlorite is present as secondary stage replacement of Grt and other minerals.

The Meratus Complex in South Kalimantan

Serpentinite is abundant in the Meratus Complex. This rock has mesh texture and almost entirely made up of serpentine together with spinel, iron oxide grains and several stained hematites. Some of the rocks were able to preserve relict minerals of olivine. Actinolite-talc schist is also observed in a few exposures in this area. Nematoblastic talc grains (0.5–1.5 mm) are abundant with spotted actinolite and interstitial quartz grains present in the matrix. The garnet-epidote-actinolite schist from Aranio River has fine-grained garnet (0.1–0.5 mm) together with epidote, actinolite, titanite, quartz, and muscovite, with occasional chloritoid (Figure 2h). The variety of the rock with abundant chloritoid is classified as garnet-chloritoid schist.

The Nangapinoh Area in West Kalimantan

Metatonalites are exposed in the Nangapinoh area in the northern part of the Schwaner Mountains, West Kalimantan (Figures 1a, f). The metatonalite predominantly contains plagioclase, hornblende, clinopyroxene, biotite with small amounts of quartz, muscovite, and titanite. Weak foliation texture is recognized from hornblende (0.5–2 mm) that encloses relict clinopyroxene (Figure 2i). Moreover, local contact metamorphism is developed in this location. The cordierite-andalusite-biotite hornfels are characterized by spotted texture of cordierite (~0.5 mm) and andalusite (0.5–1 mm). Other mineral assemblages are biotite, muscovite, quartz and apatite. Some of these rocks have fibrous silimanite (fibrolite) in the matrix. The andalusite (0.5–1 mm) has characteristic patterns of graphite inclusions on the core portion. Other minerals present in the groundmass are quartz, chlorite, biotite, and muscovite.

Whole-Rock Chemistry

Analytical Methods and Samples

Major, trace, and rare-earth elements composition of the metamorphic rock samples were analyzed by X-ray fluorescence spectrometry (XRF) using Rigaku ZSX Primus II and by laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) with an Agilent 7500cx quadrupole ICP-MS with a New Wave Research UP-213 laser at Kyushu University, Japan on a fused glass disk (sample:flux ratio 1:2). The detailed analytical

Table 1. Representative Major (wt%), Trace and Rare-Elements (ppm) Value of Metamorphic Rocks from the South Sulawesi, Central Java, South Kalimantan and West Kalimantan.

Locality	Bantimala Complex										Barru Comp.	Meratus Complex	
Rock Type	Eclogite			Grt-Gln rock	Grt-Gln schist	Grt-Gln schist	Glaucophanite			Grt-Gln-Ph-Qz schist	Grt-Bt-Ms-Qz schist	Grt-Ep-Act-Qz schist	
Sample No	310T03A2	310T03C	310T03F	310T02D	311T01P	310T03G	311T01Z	313T01Q	313T01I	313T02H	31202A	31601A	31701
SiO_2	49.80	48.43	50.90	48.36	53.07	50.50	51.81	48.73	52.03	58.54	71.72	70.27	49.98
TiO_2	1.23	2.54	1.04	2.03	1.03	0.48	2.50	2.78	0.14	1.08	0.63	0.57	2.14
Al_2O_3	12.99	15.30	8.98	15.67	17.44	8.33	11.41	11.38	6.85	15.10	13.49	10.99	12.69
Fe_2O_3*	11.41	11.33	10.19	10.61	11.72	9.08	11.21	11.73	13.29	9.64	5.05	6.28	14.72
MnO	0.11	0.16	0.33	0.14	0.26	0.18	0.15	0.18	0.09	0.18	0.06	0.38	0.22
MgO	7.48	7.61	16.25	5.18	3.93	18.04	8.74	9.13	15.33	4.46	1.61	2.63	6.22
CaO	9.71	9.48	8.84	10.63	7.56	7.64	5.25	9.53	8.62	3.31	1.86	2.50	9.66
Na_2O	5.82	3.91	2.21	3.44	2.89	2.01	4.28	2.93	2.63	2.74	2.74	1.23	2.34
K_2O	0.19	0.22	0.39	1.61	0.34	0.44	1.09	1.46	0.18	1.87	1.79	2.39	0.11
P_2O_5	0.00	0.07	0.01	0.22	0.21	0.01	0.46	0.49	0.01	0.13	0.11	0.12	0.18
LOI	1.11	0.78	1.17	1.27	1.32	2.54	2.18	1.87	1.11	2.72	1.48	1.65	1.62
TOTAL	99.85	99.81	100.31	99.15	99.76	99.25	99.08	100.22	100.28	99.77	100.55	99.02	99.90
V	471.30	232.35	201.38	282.06	358.02	145.66	151.97	187.53	100.06	194.65	99.82	114.31	395.41
Cr	163.43	339.99	684.74	391.85	87.75	1222.37	578.58	717.25	1091.95	213.80	139.79	100.30	107.09
Ni	117.90	138.64	484.67	110.81	44.65	859.36	124.05	137.22	953.22	86.54	37.71	54.39	54.76
Rb	6.15	5.27	8.63	36.46	5.22	7.80	23.91	34.38	2.46	50.96	72.55	58.40	0.07
Sr	34.75	294.81	32.59	316.28	266.99	20.62	191.10	390.51	11.19	275.10	218.97	38.56	191.51
Y	15.41	18.34	18.96	54.91	3.78	26.35	20.98	25.21	3.99	23.65	20.89	27.85	50.57
Zr	92.79	200.43	50.83	147.60	91.73	37.14	184.50	210.09	n.d.	120.92	188.14	103.64	144.34
Nb	1.68	18.63	3.88	10.36	2.41	1.98	45.68	45.42	0.23	6.78	6.49	4.20	5.15
Ba	64.73	38.37	52.05	208.45	82.43	57.81	64.26	229.84	13.54	163.09	265.05	237.04	18.54
La	n.d.	10.26	n.d.	1.77	2.99	6.43	26.39	31.85	0.48	11.15	17.50	16.29	5.52
Ce	2.85	31.78	4.28	18.96	24.26	3.55	55.82	57.95	n.d.	24.81	38.07	36.65	15.20
Nd	6.24	22.24	5.02	16.77	18.52	2.70	28.99	32.05	0.88	14.00	19.23	19.18	14.78
Sm	6.67	5.56	5.59	5.44	5.00	0.83	13.73	9.11	2.56	7.41	12.59	4.69	5.20
Pb	1.29	5.01	1.17	3.27	6.18	0.42	6.81	9.75	1.42	6.55	12.26	3.78	1.14
Th	6.17	1.43	3.59	0.88	2.89	0.23	8.33	6.42	2.68	3.80	6.95	5.04	0.92
Eu	1.45	1.71	0.45	1.83	1.45	0.22	2.02	2.27	0.09	1.06	0.73	1.09	1.77
Gd	2.73	6.02	2.08	6.74	5.55	1.05	6.07	6.55	0.55	4.21	3.27	4.99	7.27
Tb	0.39	0.90	0.48	1.17	0.86	0.19	0.81	0.90	0.13	0.68	0.52	0.80	1.30
Yb	1.85	2.58	3.03	4.10	3.37	0.83	1.24	1.38	0.22	2.58	2.13	3.06	5.58
Lu	0.30	0.39	0.50	0.60	0.52	0.13	0.16	0.19	0.03	0.40	0.34	0.48	0.83
Hf	2.76	5.21	2.22	4.96	3.66	1.01	4.21	4.51	0.20	3.44	5.04	3.22	4.13
Ta	0.17	1.24	0.43	0.82	0.27	0.12	2.45	2.44	0.10	0.46	0.64	0.88	0.30
U	0.04	0.24	0.11	0.17	0.54	0.03	0.57	0.74	0.00	0.41	0.86	0.58	0.24

Table 1. (*continued*)

Locality	Luk Ulo Complex									Schwaner Mountains			
Rock Type	Eclogite	Grt-Gln schist		Gln schist		Grt amphibolite		Amphibolite	Grt-Ms-Qz schist	Metatonalite			
Sample No	317T01A	318T02D	318T02B	318T03G	318T01AC	318T02G	318T03E	318T03I	318T01Q	327GM01	84BH236A	84MS89A	84U221A
SiO_2	48.31	48.62	48.13	49.56	51.95	50.49	49.99	51.12	60.11	60.27	71.12	58.02	59.00
TiO_2	2.78	3.34	2.61	1.70	2.16	1.62	1.64	2.16	0.82	0.66	0.50	0.65	0.90
Al_2O_3	17.59	13.22	13.82	11.50	11.08	13.86	13.51	8.67	17.04	18.00	14.54	18.96	17.47
Fe_2O_3*	12.25	14.16	12.03	12.36	14.03	12.67	13.86	13.43	6.88	5.30	3.46	6.30	6.98
MnO	0.10	0.20	0.11	0.33	0.27	0.17	0.18	0.17	0.11	0.08	0.06	0.06	0.14
MgO	4.73	7.93	6.61	10.30	1.63	6.90	6.54	12.18	2.32	1.80	0.90	2.00	2.86
CaO	5.04	6.90	9.66	8.07	13.32	10.76	10.03	5.42	2.73	6.68	2.75	7.62	7.42
Na_2O	3.34	4.18	4.24	3.45	1.60	2.75	2.44	4.27	2.89	5.00	4.51	5.18	3.27
K_2O	4.17	0.51	0.77	0.87	0.03	0.09	0.07	0.75	2.41	1.35	1.80	0.96	1.28
P_2O_5	0.54	0.17	0.49	0.15	0.21	0.14	0.14	0.13	0.14	0.26	0.11	0.24	0.18
LOI	2.02	1.50	1.25	1.59	2.81	0.85	0.91	1.66	4.36	0.17	0.72	0.33	0.66
TOTAL	100.87	100.72	99.71	99.87	99.09	100.31	99.30	99.97	99.81	99.56	100.47	100.33	100.15
V	180.63	218.25	261.65	289.73	365.91	323.08	320.38	177.41	144.77	81.19	39.39	101.29	175.51
Cr	195.21	308.55	518.69	234.88	197.74	143.14	145.16	109.75	71.64	85.79	88.77	70.64	116.36
Ni	71.96	146.37	167.30	176.45	94.45	51.25	63.53	221.93	20.22	21.99	n.d.	2.23	24.49
Rb	104.76	6.36	12.15	13.55	n.d.	1.36	n.d.	11.76	85.71	18.57	51.76	11.30	49.61
Sr	348.50	139.58	411.99	482.26	591.07	154.70	133.77	15.25	108.81	873.20	228.84	1216.73	382.83
Y	33.42	35.53	26.39	32.00	38.36	37.77	40.53	19.85	26.20	17.62	24.31	11.94	22.56
Zr	249.62	280.79	215.73	111.59	140.26	111.02	114.97	193.48	148.95	154.20	178.41	70.62	123.17
Nb	41.59	38.36	29.83	18.46	12.12	3.38	4.24	26.92	6.30	7.72	6.78	5.26	5.77
Ba	684.54	67.71	140.00	113.79	11.90	26.40	39.75	92.67	299.81	312.31	436.88	608.26	195.10
La	37.39	32.06	23.86	11.38	8.88	4.23	6.14	24.67	12.81	19.59	19.93	11.49	13.24
Ce	71.09	68.18	49.30	22.59	20.93	11.37	12.08	41.46	30.42	43.54	40.05	25.26	28.59
Nd	34.24	38.86	28.13	18.72	16.46	11.48	13.64	33.27	15.72	22.36	19.60	15.72	16.15
Sm	7.09	8.70	6.45	5.21	5.09	3.98	4.45	7.22	3.88	4.48	4.26	3.42	4.00
Pb	3.86	1.17	3.03	5.63	5.18	0.45	0.61	0.46	10.53	8.77	40.49	1.53	21.88
Th	3.36	3.08	1.95	0.55	0.74	0.26	0.27	1.88	5.63	12.74	10.34	1.39	5.80
Eu	2.48	2.81	2.25	1.75	1.62	1.46	1.53	2.01	1.02	1.33	0.93	1.21	1.22
Gd	6.90	8.55	6.08	5.53	6.25	5.52	5.76	5.89	3.97	3.83	4.22	3.04	4.12
Tb	1.01	1.23	0.89	0.92	1.05	0.98	1.02	0.82	0.66	0.54	0.67	0.42	0.65
Yb	2.56	3.15	1.94	3.43	3.90	4.10	4.08	1.75	2.48	2.07	3.00	1.24	2.31
Lu	0.36	0.44	0.26	0.49	0.58	0.60	0.58	0.26	0.37	0.34	0.48	0.19	0.36
Hf	5.46	7.04	4.72	2.97	3.71	2.89	2.80	4.49	3.82	4.61	5.86	1.87	3.63
Ta	2.77	2.90	1.94	0.55	0.74	0.26	0.25	1.99	0.68	1.46	1.31	0.56	0.91
U	0.70	0.64	0.59	0.49	0.41	0.08	0.06	0.35	1.31	3.59	2.23	0.32	1.80

Fe2O3*, total Fe as Fe2O3. LOI and n.d. means loss-on-ignition and non detection, respectively.

conditions and procedures are given in [24]. In total, 84 metamorphic rock samples were analyzed as follows: 34 samples from South Sulawesi (13 eclogites, 9 garnet-glaucophane schists, 5 glaucophanites, 5 garnet-glaucophane-phengite-quartz schists, and 2 garnet-biotite-muscovite-quartz schists), 21 samples from Central Java (1 eclogite, 6 garnet-glaucophane schists, 3 glaucophane schists, 4 garnet amphibolites, 2 amphibolites, and 5 garnet-muscovite-quartz schists), 3 garnet-epidote-actinolite-quartz schists from South Kalimantan, and 4 samples of metatonalites from West Kalimantan. Representative data of the major, trace, and rare-earth elements are presented in Table 1.

Major Element Concentration

Based of the petrographic observations and the analysis of chemical characeristics, metamorphic rocks from South Sulawesi and Central Java are grouped into two categories: metabasic rocks and metasedimentary rocks. The bulk chemical compositions of the metabasic rocks are distributed in the basalt-andesite field of ACF diagram from [25], and metasedimentary rocks plot in the pelite and greywacke fields.

The SiO_2 content of metabasic rocks range from 37.28 to 53.10 wt% (Figure 3). Although SiO_2 concentrations of most metabasic rock range from 45 to 55 wt%, others yielded values less than 45 wt% (Figure 3). However, considering the petrographical observations and other element concentrations (e.g., MgO = 1.63–18.04 wt%, Mg# = 0.22–0.58, Ni = 48.34–943.32 ppm, and Cr = 41.73–1222.37 ppm), these rocks are not likely ultramafic rocks. Hence, in this paper, we regard these rocks containing low-SiO_2 content as metabasic rocks. The TiO_2 compositions are mostly clustered in the range 0.84 to 4.01 wt%, with the exception of one sample containing up to 9 wt% TiO_2 (Figure 3). The $A1_2O_3$

compositions have a wide range between 8.53 and 19.45 wt% (but mostly 11–17 wt%; Figure 3). The Fe_2O_3 concentration has a range of 9.08–20.72 wt%, with most of the rocks concentrated within 8–15 wt% (Figure 3). The MnO, MgO, and CaO compositions also have wide ranges of 0.09–0.63, 1.63–18.04, and 5.04–14.05 wt%, respectively. Similarly, Na_2O, K_2O, and P_2O_5 contents have wide ranges of 0.51–4.87, 0.01–4.17, and 0.01–0.86 wt%, respectively (Figure 3). Although all the metabasic rocks show tholeiitic basalt signatures on the AFM ternary diagram (Figure 4) [26], these scattered values for major elements suggest the elemental migration from protolith due to later metamorphism and fluid-assisted alteration that the rocks have undergone.

The SiO_2 contents of metatonalites range from 58.02–71.12 wt%, with 3 samples likely to be clustered at 58–60 wt% (Figure 3). The elements TiO_2, Fe_2O_3, MnO, MgO, K_2O, and P_2O_5 show ranges of 0.50–0.90 wt%, 3.11–6.28 wt%, 0.06–0.14 wt%, and 0.96–1.80 wt%, respectively (Figure 3). Slightly wide ranges were observed in Al_2O_3, CaO, Na_2O, K_2O, and P_2O_5: 14.54–18.96 wt% , 2.75–7.62 wt%, 3.27–5.18 wt%, and 0.90–2.86 wt%, respectively (Figure 3). All of the rocks plot on the tonalite field in the CIPW normative An-Ab-Or classification diagram [27], and are classified as calc-alkaline rocks on the AFM ternary diagram (Figure 4) [26].

Trace and Rare-Earth Element Concentrations

In this section, we describe the trace and rare-earth element (REE) characteristics of the metamorphic rocks, based on the normalized patterns and discrimination diagrams, to identify the tectonic settings of the protolith formation. During medium- to high-grade metamorphism, the large ion lithophile elements (LILE) such as K, Rb, Sr, and Ba as well as Th and U have probably been mobilized. However, the elements with high field-strength elements (HFSE; Ti, Zr, Y, V, Cr, Ni) and REE are interpreted to have been effectively immobile, and are therefore suitable for determining protoliths [31]. As already described

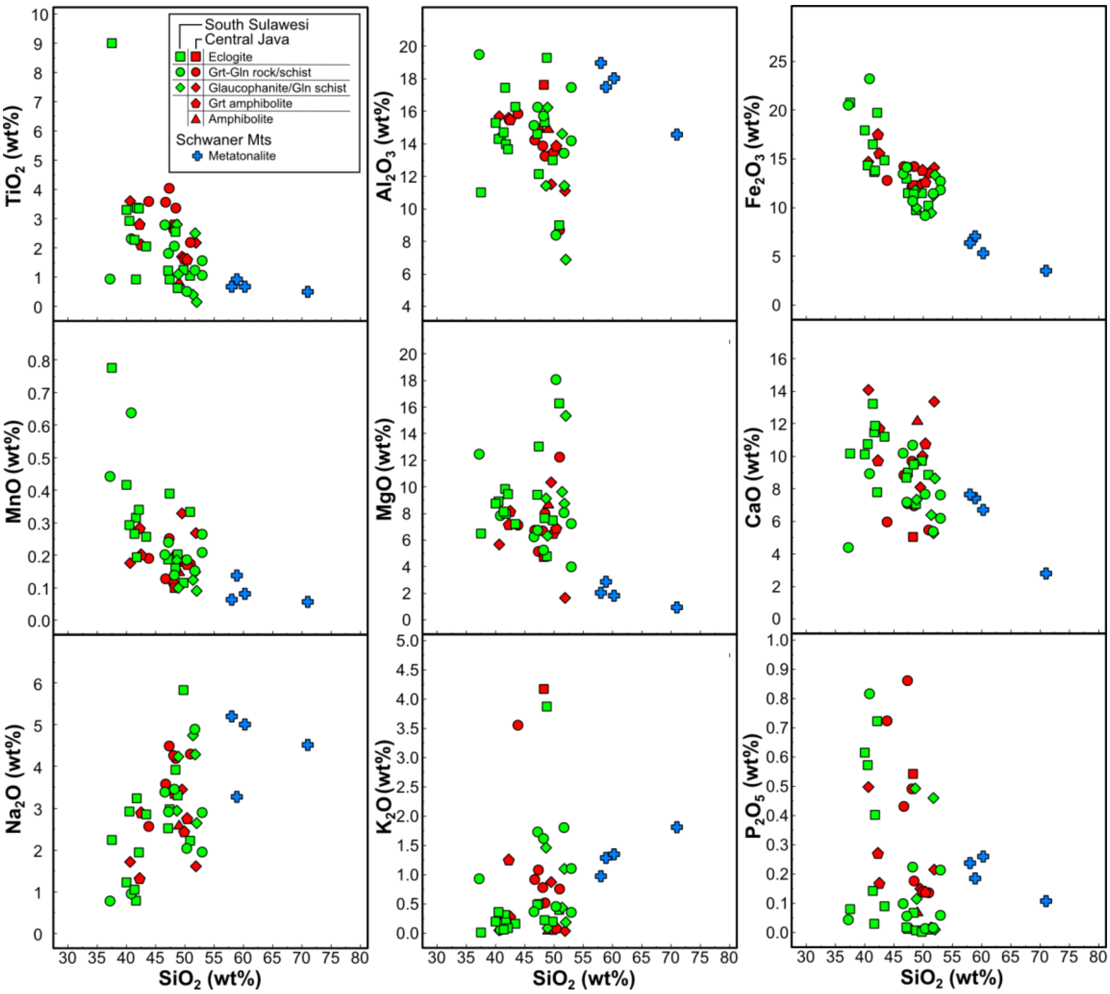

Figure 3. Harker diagrams of metabasic rocks from South Sulawesi and Central Java and metatonalite from Schwaner Mountains. Further description see on the text

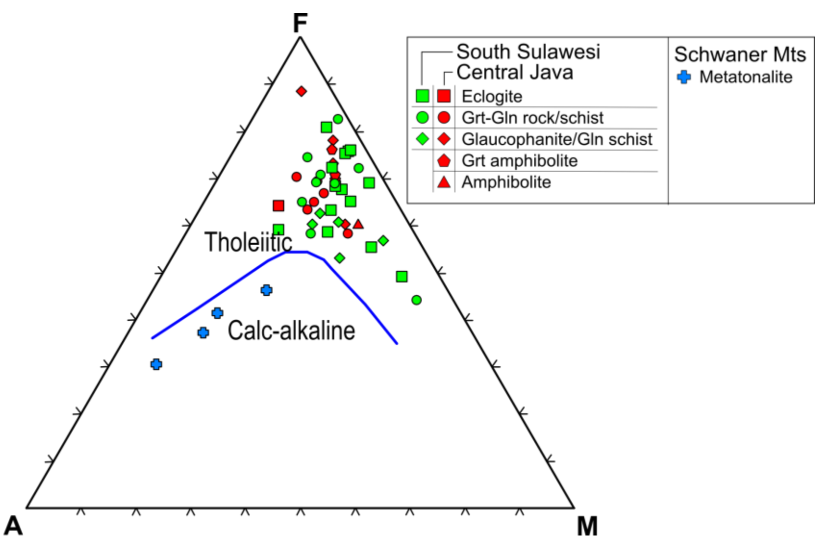

Figure 4. All of the metabasic rocks from South Sulawesi and Central Java are plotted on the tholeiitic field, whereas metatonalite from Schwaner Mountains are plotted on the calc-alkaline field

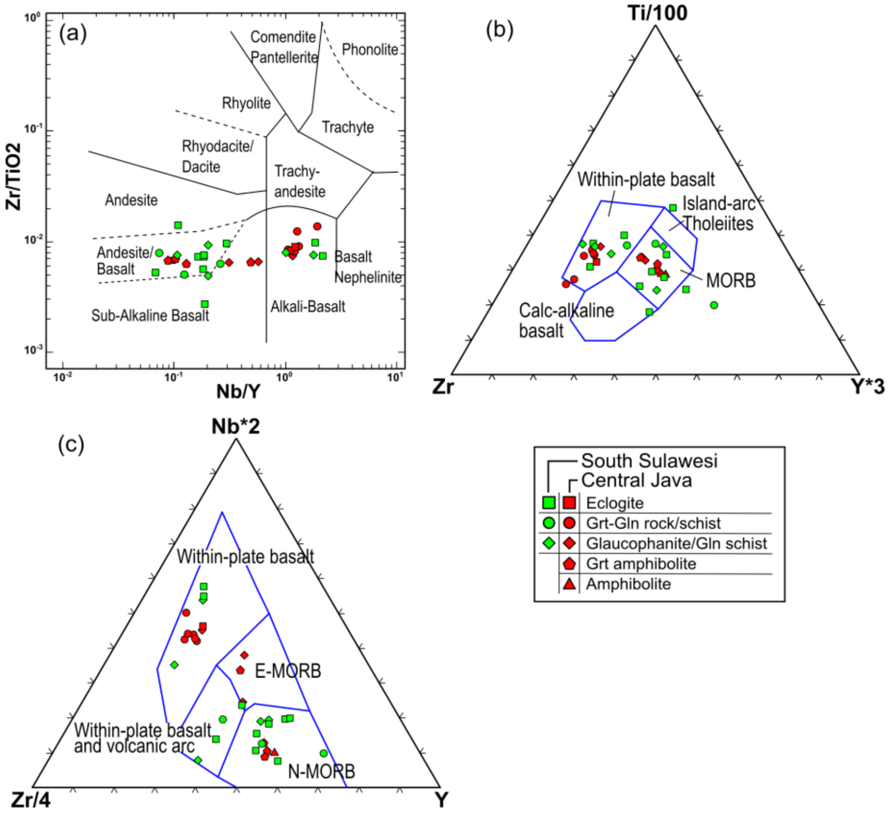

Figure 5. Discrimination diagrams of metabasic rocks from South Sulawesi and Central Java. (a) Metabasic rocks on Zr/TiO_2 and Nb/Y discrimination diagram [28] plot on the alkali basalt or sub-alkali andesite to basalt fields. (b) Metabasic rocks on the Ti-Zr-Y discrimination diagram [29] plot on the MORB and within-plate basalt fields. (c) Metabasic rocks on the Nb-Zr-Y discrimination diagram from [30] plot on the N-MORB, E-MORB and within-plate basalt or volcanic arc fields

above, the major element concentrations of metabasic rocks are significantly scattered, whereas HFSE and REE contents and ratios preserve their consistency. Therefore, these elements should be useful in understanding the chemical features of the protolith prior to the metamorphism.

The trace element composition of basic metamorphic rocks from the Bantimala Complex in South Sulawesi and the Luk Ulo Complex in Central Java were plotted on the discrimination diagram of [28] with the parameter of Zr/TiO_2 and Nb/Y (Figure 5a). In this diagram, all of the metabasic rocks are divided into two, plotted on either the alkali basalt or sub-alkali andesite to basalt fields. In the Ti-Zr-Y diagram [29], most of the metabasic rocks plot in the within-plate basalt and mid oceanic ridge (MORB) fields (Figure 5b). The Nb-Zr-Y triangular discrimination diagram suggested by [30] also reflects similar results to the Ti-Zr-Y diagram [29], whereas several samples are scattered in the enrichment-type of mid oceanic ridge basalt (E-MORB) and within-plate basalt and volcanic arc (Figure 5c).

The C1 chondrite normalized REE patterns [32] could be clustered into three types of tectonic environments as indicated by discriminant diagrams, which are the within-plate basalt including oceanic island basalt (OIB), normal-type mid oceanic ridge basalt (N-MORB) and E-MORB (Figure 6). The OIB-type patterns show light REE (LREE) enrichment relative to heavy REE (HREE). The E-MORB-type patterns show slight enrichment in LREE and flat HREE. Meanwhile, the N-MORB-type pattern shows slightly depleted LREE and flat HREE. The eclogites, garnet-glaucophane rocks, and

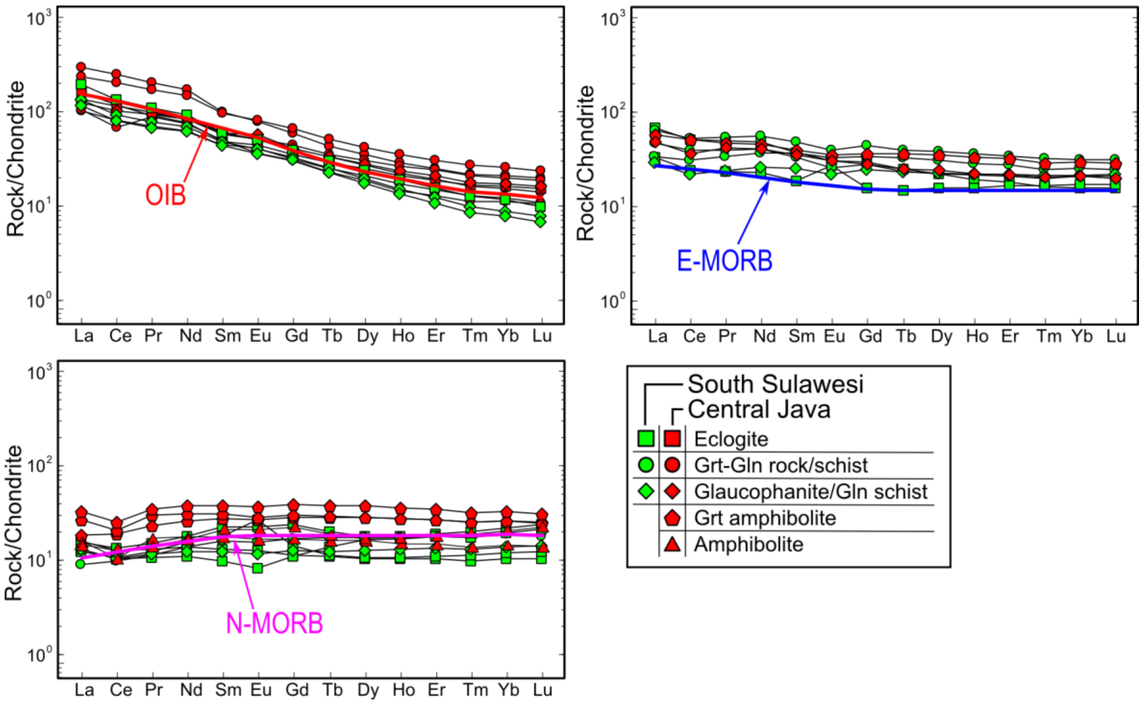

Figure 6. REE patterns of metabasic rocks from South Sulawesi and Central Java. Eclogite, garnet-glaucophane rock and schist, and glaucophanite from South Sulawesi have both OIB-type and MORB-type patterns. The eclogite and garnet-glaucophane schist from Central Java have OIB-type pattern. Garnet-amphibolite and amphibolite from Central Java have MORB pattern. REE's reference for OIB, E-MORB, N-MORB, and C1 chondrite normalization follow [32]

glaucophanites from South Sulawesi have both OIB-type and MORB-type patterns. The eclogite and garnet-glaucophane schist from Central Java have OIB-type patterns. Garnet-amphibolites and amphibolites from Central Java have MORB-type patterns.

The N-MORB normalized trace elements patterns [33] of metatonalites obviously show negative anomalies of Nb and Ti as well as positive anomaly of Pb (Figure 7a). These signatures are usually observed in subduction- and collision-related granitoids. In the Rb versus Yb + Ta discrimination diagram of tectonic environments of [34], the metatonalites plot on the volcanic-arc granitic field (Figure 7b). The primordial mantle normalized REE pattern from [33] shows slight enrichment LREE relative to HREE with negative Eu anomaly on the sample 84BH236A (Figure 7c). On the adakite discrimination diagram using the Sr/Y and Y proposed by [35], most metatonalites are plotted on island arc andesite–dacite-rhyolite field together with Cretaceous granitoids from Schwaner Mountains [4]. However, two samples fall into adakite field area (Figure 7d).

Discussion

This paper reports a large number of geochemical data from the metamorphic rocks that showed several protoliths. On the metamorphosed sedimentary rocks, we reported the geochemical signatures (pelite to greywacke) from a small number of samples (n = 15) in this study. However, more analyses including geochemical data, detrital zircon U-Pb geochronological data, and P-T evolution should provide much more critical insights into the tectonic evolution in the studied area, which will be published elsewhere in the future. Here, we mainly discuss the significance of the geochemical data obtained from metabasic rocks and metatonalites.

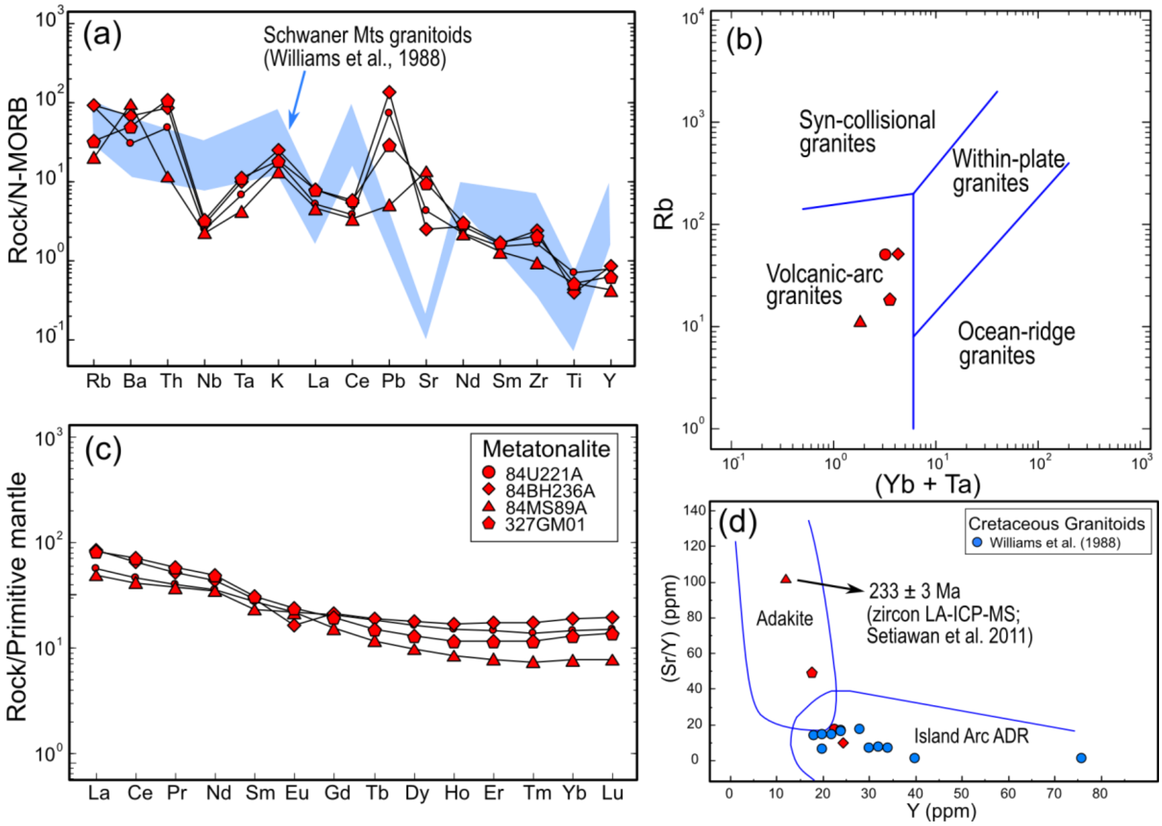

Figure 7. (a) N-MORB normalized [33] trace element diagram of metatonalite from the Schwaner Mountains showing subduction signature compared with the granitoids data from [4]. (b) The metatonalites plot on the volcanic-arc environment in the discrimination diagram Rb versus Yb + Ta [34]. (c) The primordial mantle normalized REE pattern [33] shows slightly enrichment of LREE relative to HREE. (d) On the discrimination diagram Sr/Y versus Y [35], two metatonalites samples fall on the adakite field

Implications for Component of Subducted Oceanic Plate

The metabasic rocks from South Sulawesi and Central Java analyzed in this study are considered to have experienced high-pressure metamorphism with peak pressure condition on the eclogite-facies. The *P-T* evolution of high-pressure metamorphic rocks from the Bantimala Complex in South Sulawesi experienced a clockwise *P-T* path with peak condition of 1.8–2.4 GPa and 580–650 ºC from eclogite and garnet-glaucophane rock [15, 17]. Very high-pressure metamorphic conditions were also reported from this area in the coesite-bearing garnet-jadeite-quartz rock that experienced peak metamorphism of >2.7 GPa and 720–760 ºC [16]. The K-Ar ages of phengite for these rocks range from 113 ± 6 Ma to 137 ± 3 Ma (Early Cretaceous) [12, 13, 16]. From the Barru Complex, the K-Ar age from the quartz-mica schist yielded 106 ± 5 Ma (Early Cretaceous). The peak *P-T* conditions of the metamorphic rocks from Central Java were estimated as 2.2 ± 0.2 GPa and 530 ± 40 ºC from jadeite-quarz-glaucophane rock and 1.8–2.2 GPa and 359–442 ºC from eclogite [19, 21]. The K-Ar dating of muscovite in the quarz-mica schist and phengite in the jadeite-glaucophane-quartz rock range from 110 to 124 Ma (Early Cretaceous) [16, 19]. These data strongly suggest that the subduction of oceanic plate and the high-*P-T* metamorphism occurred during the Cretaceous period.

Based on the trace and rare-earth element analyses in this study, the protoliths of the basic metamorphic rocks from the Bantimala Complex in South Sulawesi and the Luk Ulo Complex in Central Java were derived from MORB and within-plate basalt with tholeiite

Table 2. Summary of the Protolith for Metabasic Rocks from South Sulawesi and Central Java

Locality	Rock Type	OIB	N-MORB	E-MORB	(*n*)
South Sulawesi	Eclogite	⦿	⦿	⦿	13
	Grt-Gln rock/schist	–	–	⦿	9
	Glaucophanite	⦿	⦿	⦿	5
Central Java	Eclogite	⦿	–	–	1
	Grt-Gln schist	⦿	–	–	6
	Gln schist	⦿	–	⦿	3
	Grt amphibolite	–	⦿	⦿	4
	Amphibolite	–	⦿	–	2

⦿: present, – : absent

nature (Figures 4, 5) Although previous studies reported that the protolith of the high-pressure metabasic rocks in these regions are of MORB-like affinity [5, 6], the current study reveals that within-plate basalt is widely distributed together with MORB. It is worth noting that the rocks from the Bantimala Complex in South Sulawesi contain both MORB and within-plate basalt signatures, even though the analyzed samples show similar high-*P/T* gradient (eclogite and blueschist) (Table 2). This might indicate that several hot spots existed and formed ocean islands that subducted together with the oceanic floor composed of MORB during the Cretaceous.

In contrast, the eclogite and blueschist from the Luk Ulo Complex in Central Java mostly show within-plate basalt signatures, whereas protolith of relatively low-*P-T* metamorphic rocks of amphibolites and garnet amphibolites are characterized by MORB (Table 2). The results suggest several possibilities: different component between upper and lower oceanic crusts; difference of the metamorphic age between eclogite- and amphibolite-facies metamorphism; and change of the subduction angle between two metamorphic events. These results strongly recommend detailed age determinations of both protoliths (MORB and within-plate basalt) and both metamorphisms (blueschist–eclogite and amphibolite). These data should also be compared with high-pressure metamorphic rocks from the South Sulawesi to better understanding the Mesozoic history in this region, although the geology of these regions have been explained by the single subduction system as suggested by previous studies [1, 2, 3, 11, 16, 21].

Implications for Subduction-Related Felsic Magmatism during the Mesozoic

Based on the trace element normalized patterns (Figure 7a), discrimination diagrams (Figure 7b), and the calc-alkaline rock signatures, it is no doubt that the protolith of the studied metatonalites from the Schwaner Mountains was derived from volcanic-arc tectonic environments. In the Sr/Y versus Y discrimination diagram from [35], two samples indicate adakite nature (Figure 7d). These are also confirmed by the characteristics of major element concentrations of SiO_2>56 wt%, high Al_2O_3 (>15 wt%), high Na_2O contents (3.5≤Na_2O≤7.5 wt %), correlated low K_2O/Na_2O (~0.42), Y (<5 ppm), and Yb (<1.9 ppm), and high Sr content (>400 ppm) without Eu anomaly as proposed adakite characteristics [35, 36, 37]. The magma genesis of adakitic magma is still controversial and could be any of the following possibilities: slab melting due to the young (hot) oceanic plate; ridge subduction; and magma differentiation [36]. However, the magma genesis is different from that of non-adakitic rocks. In this study, we found two samples showing adakitic signatures from Schwaner Mountains that can be completely differentiated from the Cretaceous non-metamorphosed granite in the same region [4]. The magmatic age of adakitic metatonalite was reported by [8] by LA-ICP-MS U-Pb zircon as 233 ± 3 Ma. The chemical characteristics and the determined age strongly suggest that the subduction mechanism and felsic magma genesis changed between the Early Triassic and Cretaceous. Some metatonalites, excepting adakite rock, show similar signature to Cretaceous granite (Figure 7d), indicating that the subsequent metamorphism occurred during the Cretaceous subduction system. At the present stage, it is difficult to consider the tectonic evolution of this area. However, this study proposes that the Schwaner Mountains, composed of metamorphic and granitic complexes, were not formed by a consecutive subduction system. Much more geochemical data for metatonalites, age determination for each protolith with the *P-T* evolution, and the age of metamorphism are highly significant to determine the Mesozoic tectonic evolution in this region.

Acknowledgements

We thank the editor and two anonymous reviewers for their constructive comments, which helped us to improve the manuscript. We would like to thank staff members of the Geological Engineering, Hasanuddin University and Gadjah Mada University, Indonesian Institute of Science (LIPI) Karangsambung, and Geological Research and Development Centre of Indonesia for their assistance during the field survey in Indonesia, sample arrangements and valuable discussions. This work is a part of the PhD study supported by JICA AUN/SEED-Net scholarship, and was supported by Grants-in-Aid for Scientific Research (No. 21253008 and 22244063 to Y. Osanai) from the Ministry of Education, Culture, Sports, Science and Technology, Japan.

References

[1] R. Hall, "Cenozoic geological and plate tectonic evolution of SE Asia and the SW Pasific: computer-based reconstructions, model and animations," *Journal of Asian Earth Sciences,* Vol. 20, pp. 353-431, 2002.

[2] R. Sukamto, *Geological map of Pangkajene and western part of Watampone quadrangle, Sulawesi,* Scale 1:250.000, Geological Research and Development Centre, Indonesia, 1982.

[3] T. van Leeuwen, and Muhardjo, "Stratigraphy and tectonic setting of the Cretaceous and Paleogene volcanic-sedimentary successions in northwest Sulawesi, Indonesia:

Implications for the Cenozoic evolution of Western and Northern Sulawesi," *Journal of Asian Earth Sciences*, Vol. 25, pp. 1-27, 2005.

[4] P.R. Williams, C.R. Johnston, R.A. Almond, and W.H. Simamora, "Late Cretaceous to Early Tertiary structural elements of West Kalimantan," *Tectonophysics*, Vol. 148, pp. 279-297, 1988.

[5] C.D. Parkinson, "The origin and significance of metamorphosed tectonic blocks in mélanges: Evidence from Sulawesi, Indonesia," *Terra Nova*, Vol. 8, pp. 312-323, 1996.

[6] A. Kadarusman, H. Permana, H.J. Massonne, H.V. Roermund, Munasri, and P. Bambang, "Contrasting protoliths of Cretaceous metamorphic rocks from the Luk Ulo accretionary wedge complex of Central Java, Indonesia," *The 39th IAGI Annual Convention and Exhibition*, 2010.

[7] A. Maulana, D. Ellis, A. Christy, K. Watanabe, A. Imai, and Purwanto, "Rare-earth element in greenschist facies rock from Bantimala Complex South Sulawesi Indonesia," *The 36th HAGI and 40th IAGI Annual Convention and Exhibition*, 2011.

[8] N. Setiawan, Y. Osanai, and J. Wahyudiono, "A preliminary view of metamorphic rocks in Indonesia region," *Abstracts with Programs of 2011 Annual Meeting of Japan Association of Mineralogical Sciences*, No. SGC008-P08, 2011.

[9] Amiruddin, and D.S. Trail, *Geological map of the Nangapinoh Quadrangles, Kalimantan*, Scale 1:250.000, Geological Research and Development Centre, Indonesia, 1993.

[10] D.L. Whitney, and B.W. Evans, "Abbreviations for names of rock-forming minerals," *American Mineralogist*, Vol. 95, pp. 185-187, 2010.

[11] W. Hamilton, "Tectonics of the Indonesia region," *U.S. Geological Survey Professional Paper*, Vol. 1078, pp. 345, 1979.

[12] K. Wakita, Munasri, J. Sopaheluwakan, I. Zulkarnain, and K. Miyazaki, "Early Cretaceous tectonic events implied in the time-lag between the age of radiolarian chert and its metamorphic basement in the Bantimala area, South Sulawesi, Indonesia," *The Island Arc*, Vol. 3, pp. 90-102, 1994.

[13] K. Wakita, J. Sopaheluwakan, K. Miyazaki, I. Zulkarnain, and Munasri, "Tectonic evolution of the Bantimala Complex, South Sulawesi, Indonesia," In: R. Hall and D.J. Blundell, eds., *Tectonic Evolution of Southeast Asia*, Geological Society of London Special Publication, Vol. 106, pp. 353-364, 1996.

[14] K. Wakita, K. Miyazaki, I. Zulkarnain, J. Sopaheluwakan, and P. Sanyoto, "Tectonic implications of new age data for the Meratus Complex of South Kalimantan, Indonesia," *The Island Arc*, Vol. 7, pp. 202-222, 1998.

[15] K. Miyazaki, I. Zulkarnain, J. Sopaheluwakan, and K.Wakita, "Pressure-temperature conditions and retrograde paths of eclogites, Grt-Gln rocks and schists from South Sulawesi, Indonesia," *Journal of Metamorphic Geology*, Vol. 14, pp. 549-563, 1996.

[16] C.D. Parkinson, K. Miyazaki, K. Wakita, A.J. Barber, and A. Carswell, "An overview and tectonic synthesis of the pre-Tertiary very-high-pressure metamorphic and associated rocks of Java, Sulawesi and Kalimantan, Indonesia," *The Island Arc*, Vol. 7, pp. 184-200, 1998.

[17] N.I. Setiawan, Y. Osanai, N. Nakano, T. Adachi, K. Yonemura, and A. Yoshimoto, "Metamorphic evolution of high-pressure metamorphic rocks from Bantimala and Barru Complex in South Sulawesi, Indonesia," *Abstracts with Programs of 2012 Annual Meeting of Japan Association of Mineralogical Sciences*, No. R8-05, 2012.

[18] R.Y. Zhang, J.G. Liou, and W.G. Ernst, "Ultrahigh-pressure metamorphism and decompressional P-T paths of eclogites and country rocks from Weihai, eastern China," *The Island Arc*, Vol. 4, pp. 293-309, 1995.

[19] K. Miyazaki, J. Sopaheluwakan, I. Zulkarnain, and K. Wakita, "A jadeite-quartz-glaucophane rock from Karangsambung, central Java, Indonesia," *The Island Arc*, Vol. 7, pp. 223-230, 1998.

[20] S. Asikin, A. Handoyo, A. Busono, and S. Gafoer, *Geological map of the Kebumen Quadrange, Jawa,* Scale 1:100.000, Geological Research and Development Centre, Indonesia, 2007.

[21] A. Kadarusman, H.J. Massonne, V.H. Roermund, H. Permana, and Munasri, "P-T evolution of eclogite and blueschists from Luk Ulo Complex of Central Java, Indonesia," *International Gelogy Review*, Vol. 29, pp. 329-356, 2007.

[22] N. Sikumbang, and R. Heryanto, *Geological Map of the Banjarmasin Quadrangle, Kalimantan,* Scale 1: 250.000, Geological Research and Development Centre, Indonesia, 2009.

[23] N.S. Haile, M.W. McElhinny, and I. McDougall, "Palaeomagnetic data and radiometric ages from the Cretaceous of West Kalimantan (Borneo), and their significance in interpreting regional structure," *Journal of the Geological Society of London*, Vol. 133, pp. 133-144, 1977.

[24] N. Nakano, Y. Osanai, T. Adachi, K. Yonemura, A.Yoshimoto, and N. Setiawan, "Rapid techniques for quantitative determination of major, trace and rare earth elements in low dilution glass bead using XRF and LA-ICP-MS," *Bulletin of the Graduate School of Social and Cultural Studies Kyushu University,* Vol. 18, pp. 81-94, 2012.

[25] H.G.F. Winkler, *Petrogenesis of Metamorphic Rocks*, Springer-Verlag, New York, 1979.

[26] T.N. Irvine, and W.R.A. Baragar, "A guide to the chemical classification on the common volcanic rocks," *Canadian Journal of Earth Sciences*, Vol. 8, No. 5, pp. 523-548, 1971.

[27] F. Barker, and J.G. Arth, "Trondhjemite: Definition, environment and hypotheses or origin," In *Trondhjemites, Dacites, and Related Rocks*, F. Barker, ed.: Elsevier, New York, pp. 1-12, 1979.

[28] J.A. Winchester, and P.A. Floyd, "Geochemical discrimination of different magma series and their differentiation products using immobile elements," *Chemical Geology*, Vol. 20, pp. 325-343, 1977.

[29] J.A. Pearce, and J.R. Cann, "Tectonic setting of basic volcanic rocks determined using trace element analyses," *Earth and Planetary Science Letters*, Vol. 19, pp. 290-300, 1973.

[30] M. Meschede, "A method of discriminating between different types of mid-ocean ridge basalts and continental tholeiites with the Nb-Zr-Y diagram," *Chemical Geology*, Vol. 56, pp. 207-218, 1986.

[31] Y. Osanai, K. Shiraishi, Y. Takahashi, H. Ishizuka, Y. Tainosho, N. Tsuchiya, T. Sakiyama, and S. Kodama, "Geochemical characteristics of metamorphic rocks from the central Sør Rondane Mountains, East Antartica," In: Y. Yoshida, K. Kaminuma, and K. Shiraishi, eds., *Recent Progress in Antarctic Earth Science*, TERRAPUB, Tokyo, pp. 17-27, 1992.

[32] W.F. McDonough, and S.S. Sun, "The composition of the Earth," *Chemical Geology*, Vol. 120, pp. 223-253, 1995.

[33] S.S. Sun and W.F. McDonough, "Chemical and isotopic systematics of oceanic basalts: Implications for mantle composition and processes," In: A.D. Saunders and M.J. Norry, eds., *Magmatism in the Ocean Basins*, Geological Society Special Publication, No. 42, pp. 313-345, 1989.

[34] J.A. Pearce, N.B.W. Harris, and A.G. Tindle, "Trace element discrimination diagrams for the tectonic interpretation of granitic rocks," *Journal of Petrology*, Vol. 25, pp. 956-983, 1984.
[35] M.J. Defant, and M.S. Drummond, "Derivation of some modern arc magmas by melting of young subducted lithosphere," *Nature*, Vol. 347, pp. 662-665, 1990.
[36] P.R. Castillo, "An overview of adakite petrogenesis," *Chinese Science Bulletin*, Vol. 51, No. 3, pp. 257-268, 2006.
[37] A. Kamei, K. Horie, M. Owada, M, Yuhara, N. Nakano, Y. Osanai, T. Adachi, Y. Hara, M. Terao, S. Teuchi, T. Shimura, K. Tsukada, T. Hokada, C. Iwata, K. Shiraishi, H. Ishizuka, and Y. Takahashi, "Late proterozoic juvenile arc metatonalite and adakitic intrusions in the Sør Rondane Mountains, eastern Dronning Maud Land, Antartica," *Precambrian Research* (article in press), 2012.