An overview of metamorphic geology from central Indonesia : Importance of South Sulawesi, Central Java and South-West Kalimantan metamorphic terranes

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Article

An overview of metamorphic geology from central Indonesia: Importance of South Sulawesi, Central Java and South-West Kalimantan metamorphic terranes

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Abstract

Various metamorphic rocks expose in the central part of Indonesia including Java, Kalimantan and Sulawesi islands. This paper explains results of the compilation of all relevant data regarding to the study of petrological, geochemical and geochronological investigations of metamorphic rocks from Bantimala and Barru Complexes in South Sulawesi, Luk Ulo Complex in Central Java, Meratus Complex in South Kalimantan, and Nangapinoh area of Schwaner Mountains in West Kalimantan.

High-pressure and very high-pressure metamorphic rocks crop out in the Bantimala Complex and experienced peak metamorphic condition to eclogite-facies. High-pressure metamorphic rocks also expose in the Luk Ulo Complex in Central Java with peak metamorphic condition in the eclogite-facies. From the South Kalimantan, the P-T condition of metamorphic rocks were estimated from Mg-rich chloritoid that recrystallized at pressure of ~1.8 GPa. The K-Ar dating of metamorphic rocks from South Sulawesi, Central Java and South Kalimantan were on the same range of Early Cretaceous that have a possibility of separated parts derived from a single subduction complex. Metamorphic rocks exposed in Schwaner Mountains from West Kalimantan are metatonalite and local contact metamorphism with the variety of hornfelsic rocks. No reliable P-T condition has been estimated from these metamorphic rocks. The LA-ICP-MS U-Pb zircon dating of metatonalite from Schwaner Mountains yields magmatic ages of Late Triassic that are older than the K-Ar granitoids ages from Schwaner Mountains (Late Jurassic to Cretaceous) but still in range of K-Ar granitoids ages from northwest Kalimantan (Carboniferous to Triassic). This evidence might indicate that magmatism of granitoids of the several parts in Schwaner Mountains were contemporaneous with northwest Kalimantan domain.

On the basis of whole rock chemistry, the protolith of basic metamorphic rocks from South Sulawesi and Central Java are basaltic to andesitic igneous rocks derived from tectonic environment generating MORB or within-plate signature. From the overview, it is confirmed that South Sulawesi, South Kalimantan and Central Java have possibility to be formed a part of a single subduction complex. From West Kalimantan, whole-rock chemistry analyses suggested that the metatonalites and granitoids are derived from a volcanic arc tectonic environment.

Keywords: metamorphic rocks, South Sulawesi, Central Java, South Kalimantan, West Kalimantan, geochemistry

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1. INTRODUCTION

High-pressure metamorphic rocks, particularly blueschist have tectonic significance as markers of fossil subduction zones. This rocks stored regarding processes at consuming plate boundaries, as controlled by the thermal history of the evolving earth (Maruyama et al., 1996). Late Mesozoic and Cenozoic orogenic activity at the margins of the Pacific plate has resulted in the accumulation, deformation, metamorphism and emplacement of accretionary complex throughout the circum-Pacific region. Among these rock assemblages, the occurrence of blueschists and associated high-pressure metamorphic rocks characterize diagnostic of a subduction zone environment.

Java, Kalimantan and Sulawesi are three main islands that are geographically located in the central Indonesia. The southeastern margin of Eurasian continent (Sundaland) is located in between these islands. Accretionary and metamorphic rocks expose in the Central Java, South Kalimantan and South-Central Sulawesi. Northwesterly-directed Cretaceous subduction beneath Sundaland was suggested responsible to build these formations (Fig. 1a) (Sukamto, 1982; van Leeuwen and Muhardjo, 2005; van Leeuwen et al., 2007). High-pressure metamorphic rocks exposing in South Sulawesi, Central Java and South Kalimantan are eclogite, garnet-glaucophane rock, garnet-glaucophane schist, garnet-jadeite-quartz rocks and glaucophane bearing metasedimentary rocks (e.g. Sukamto, 1982; Miyazaki et al., 1996, 1998; Parkinson, 1998; Setiawan, 2012).

From the West Kalimantan, metatonalite expose in the Schwaner Mountains area. Setiawan et al. (2011) determined the magmatic age of metatonalite by LA-ICP-MS U-Pb zircon dating as Triassic that imply the different tectonic event of Late Cretaceous in Schwaner Mountains (K-Ar by Williams et al., 1988). Moreover, contact metamorphic rocks expose in the Nangapinoh area, West Kalimantan, which was formed by the intrusion of subduction-related granitoids (Schwaner Mountains) in the low-grade metamorphic rocks during Early Cretaceous (Williams et al., 1988).

Hence, the occurrences of metamorphic terranes in the central Indonesia provide a very important key for understanding the tectonic and metamorphic evolutions in the margin of southeastern Asia. In this context, we explain compilation of all relevant data regarding to the study of petrological and geochemical and geochronological investigations of metamorphic rocks from Bantimala and Barru Complexes in South Sulawesi, Luk Ulo Complex in Central Java, Meratus Complex in South Kalimantan and Nangapinoh area of Schwaner Mountains in West Kalimantan. Field occurrences, petrographical observations, whole-rock chemistry and age references are discussed related to the metamorphic and magmatic activity. Mineral abbreviations in this paper follow Whitney and Evans (2010).

2. GEOLOGICAL OUTLINE

Indonesia is a geologically complex region that is situated in the southeastern edge of Eurasian continent. It is bounded to the south and west by the Indo-Australian Plate, and to the east by the Philippine Sea and Pacific Plates. Indonesian archipelago was formed by reassembly of fragments rifted from the Gondwana supercontinent that arrived at the Eurasian subduction margin (Hall, 2002). The present-day geology of Indonesia is broadly the result of Cenozoic subduction and collision at this margin (Hall, 2002). Central Indonesia consists of three main islands, which are Java, Kalimantan and Sulawesi. Accretionary and metamorphic complexes regarded as Cretaceous subduction complex of Indonesia are expose in Central Java, South-Central Sulawesi, and South Kalimantan (Sukamto, 1982; van Leeuwen and Muhardjo, 2005; van Leeuwen et al., 2007) (Fig. 1a). The complexes are predominantly composed of chaotic occurrence of sandstone, shale, chert, basalt, ultramafic rocks, serpentinite, low- and high-pressure metamorphic rocks (Sukamto, 1982; Wakita et al., 1994; Miyazaki et al., 1996). Before the opening of Makassar Strait, these complexes may have constituted a single subduction complex (Hamilton, 1979) and northwesterly-directed Cretaceous subduction beneath Sundalandis inferred to build these complexes (Sukamto, 1975; van Leeuwen and Muhardjo, 2005; van Leeuwen et al., 2007). The subduction ceased in Late Cretaceous and the subsequent collision of the micro-continents derived from west Australian margin is recorded on the eastern part of Sulawesi (Hamilton, 1979; Hall and Wilson, 2000; Hall, 2002).

In West Kalimantan, southward-directed subduc-

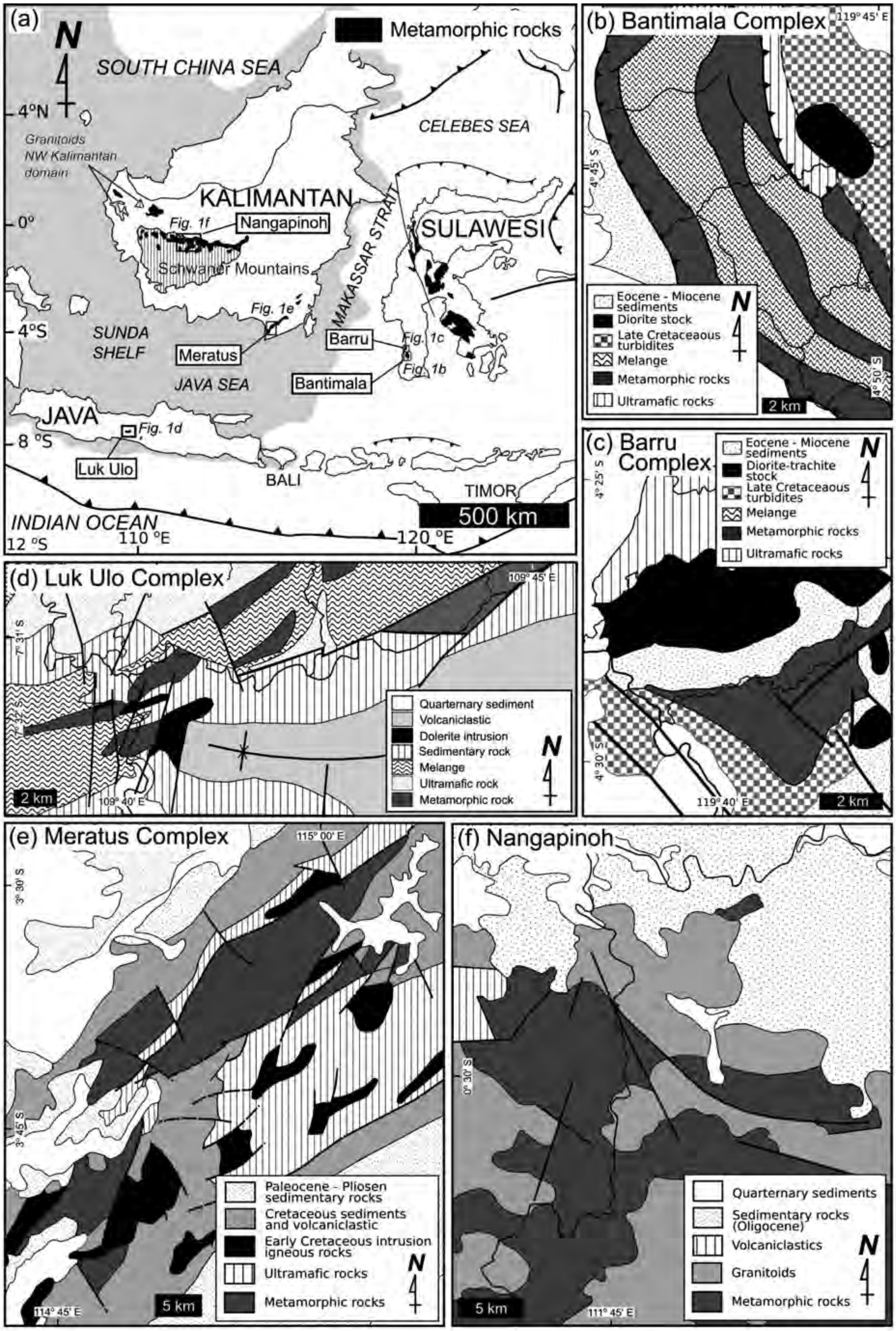

Figure 1. (a) Distribution of metamorphic rocks in central Indonesia region. Simplified geological map of (b) Bantimala Complex in South Sulawesi, (c) Barru Complex in South Sulawesi, (d) Luk Ulo Complex in Central Java, (e) Meratus Complex in South Kalimantan, and (f) Nangapinoh area in West Kalimantan.

tion during Early Jurassic to Early Cretaceous is considered to be granitoid plutons of Schwaner Mountains (Haile et al., 1977; Williams et al., 1988; Amiruddin and Trail, 1993) (Fig. 1a). The granitoids compose of tonalite and granodiorite with minor mafic rocks. The granitoids intrude low-grade metamorphic rocks and constructed contact metamorphic rocks during Early Cretaceous (Williams et al., 1988). The granitoids formed a belt of 200 km wide and at least 500 km long extending in an approximately E-W directions (Fig. 1a). Chemical analyses of typical rocks from the Schwaner Mountains indicate the I-type calc-alkaline nature of the suite (Williams et al., 1988). K-Ar ages of biotite and hornblende from the granitoids in Schwaner Mountains are ranging from 77 to 157 Ma (Late Jurassic-Late Cretaceous), while in the northwest Kalimantan block are from 204 to 320 Ma (Early Carboniferous-Late Triassic) (Fig. 1a) (Haile et al., 1977; Williams et al., 1988; Amiruddin and Trail, 1993).

3. METAMORPHIC ROCKS RELATED TO THE CRETACEOUS SUBDUCTION COMPLEX OF SOUTH SULAWESI, CENTRAL JAVA AND SOUTH KALIMANTAN

3.1. Metamorphic rocks in South Sulawesi

The metamorphic rocks related to the Cretaceous subduction system in South Sulawesi are recorded on the restricted area namely Bantimala and Barru Complexes (Fig. 1a). Detailed geology of this area was described by Sukamto (1982), Wakita et al. (1994, 1996, 2000), Miyazaki et al. (1996) and Parkinson et al. (1998).

3.1.a. Bantimala Complex

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 the age ranging from Jurassic to middle Cretaceous (Wakita et al., 1996) (Fig. 1b). The tectonic slices of the complex are elongated with the strike NW-SE. The metamorphic rocks are intercalated with mélange deposits and bounded on the south by thrust fault of Eocene-Miocene sediments while on the north bounded by ultramafic rocks and intruded by diorite stocks (Sukamto, 1982). Metamorphic rocks in this location mainly consist of high-pressure metabasites and low-pressure metapelites of Cretaceous age (Wakita et al., 1994, 1996; Parkinson et al., 1998). The mélange includes clasts and blocks of chert, sandstone, basalt, limestone and schist embedded within a sheared shale matrix (Wakita et al., 1996).

Setiawan et al. (2011, 2012) reported high-pressure metamorphic rocks in the Bantimala Complex crop out along the courses of Pangkajene, Bontorio, Cempaga, Pateteang and Bantimala Rivers. Mafic rocks (omphacite bearing garnet-glaucophane rock, eclogite and glaucophanite) (Figs. 2a, b) are much more common in this area than pelitic lithologies such as garnet-glaucophane-phengite-quartz schist. Rarely garnet-jadeite-quartz rock crops out in Bantimala River (Fig. 2c). Representative petrographical properties of these rocks in which reported by Setiawan et al. (2011, 2012) are given in Table 1.

The eclogite and garnet-glaucophane rock display-granoblastic or poikiloblastic texture and comprise garnet, omphacite, Na-Ca amphibole, epidote, phengite, and rutile, with or without quartz, hematite, apatite and titanite (Figs. 3a, b). Some eclogites have small amounts of glaucophane in the matrix. Omphacite, epidote, phengite and rutile grains are commonly 1-5 mm in diameter. Titanite occurs encloses rutile. Garnet commonly has medium-coarse grained (~2-10 mm in diameter) but some eclogites have fine- and coarse-grained garnet. The garnet richly contains mineral inclusions in the core and mantle portions, but is relatively free of inclusions in the rim portion. Random oriented inclusions of quartz, omphacite, rutile, epidote, phengite, chlorite and glaucophane, with or without 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 from the petrographic observation. Thin layer of actinolite occurs as the outermost rim in the Na-Ca amphibole and glaucophane. Secondary chlorite and albite commonly appear pseudomorph after garnet, glaucophane and omphacite.

Pelitic schists in the Bantimala Complex mainly consist of garnet, quartz, phengite, glaucophane, epidote, rutile, with secondary chlorite and albite (Fig. 3c). Quartz, glaucophane, epidote and phengite are ubiquitous in matrix. The schistosity is defined by

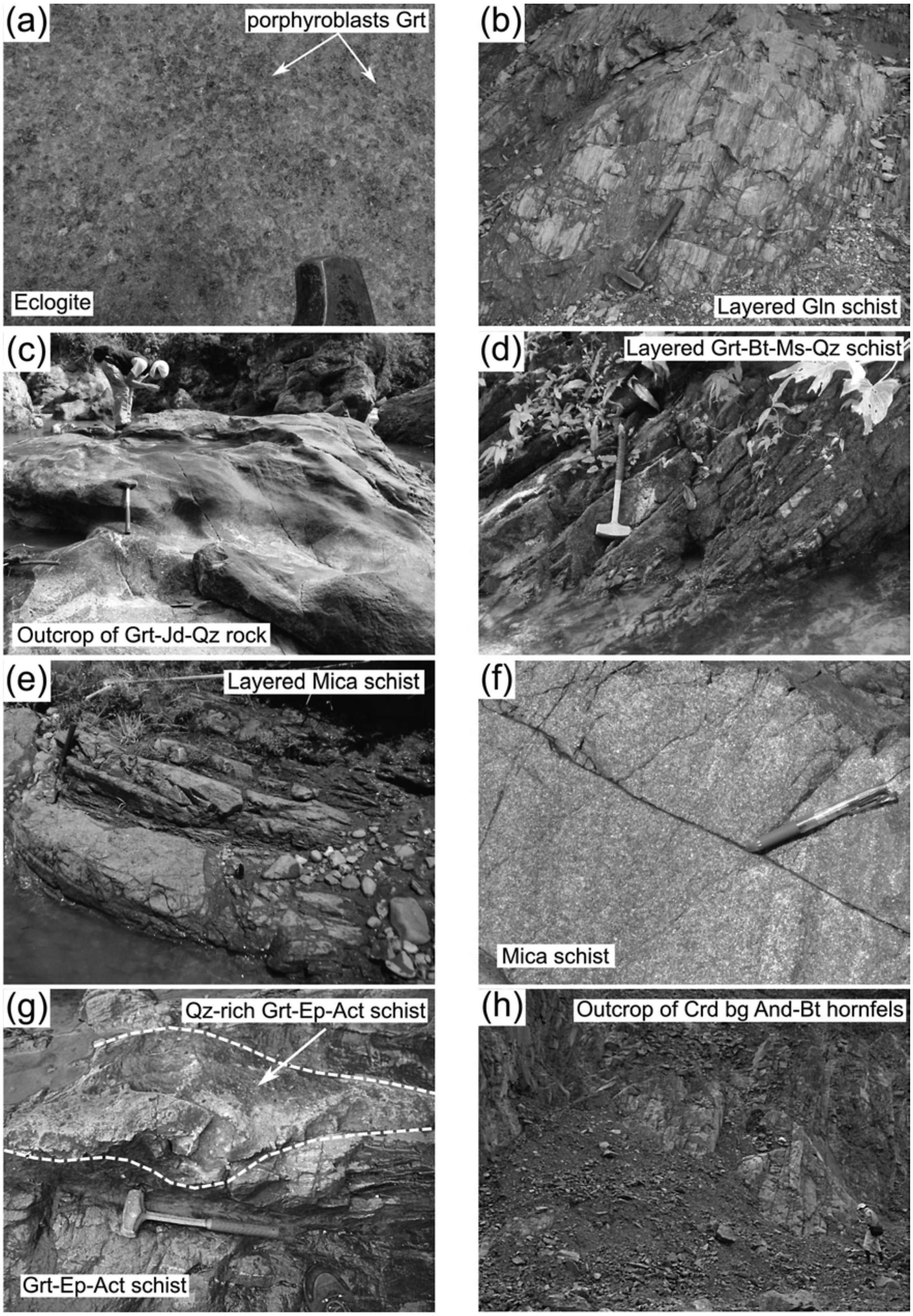

Figure 2. Modes of occurrence of metamorphic rocks in central Indonesia; (a) close up of eclogite that rich of porphyroblastic garnet in Cempaga River of Bantimala Complex, (b) outcrop of layered glaucophane schist in Batupute River of Bantimala Complex, (c) exposure of garnet-jadeite-quartz rock in Pateteang River of Bantimala Complex, (d) outcrop of layered garnet-biotite-muscovite-quartz schist in Dengedenge River of Barru Complex, (e) outcrop of layered mica schist from Loning River in Luk Ulo Complex, (f) close up mica schist from Luk Ulo Complex, (g) outcrop of garnet-epidote-actinolite schist with variation layer of quartz-rich in Aranio River of Meratus Complex and (h) outcrop of cordierite bearing andalusite-biotite hornfels in Nangapinoh area.

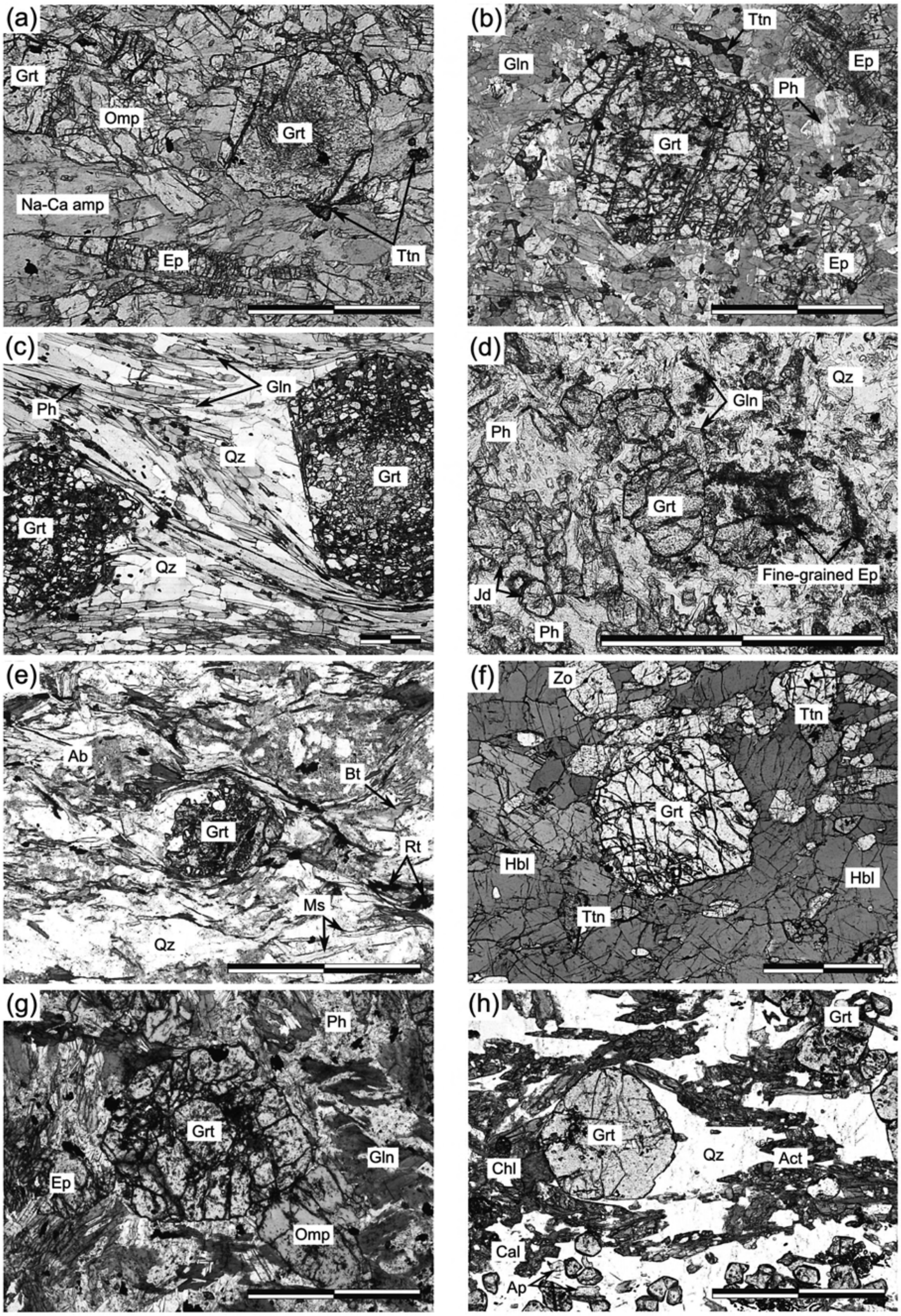

Figure 3. Photomicrographs of metamorphic rocks in central Indonesia. Scale-bars correspond to 1 mm. (a) Eclogite, (b) garnet-glaucophane rock, (c) garnet-glaucophane-phengite-quartz rock, and (d) garnet-jadeite-quartz rock from Bantimala Complex. (e) Garnet-biotite-muscovite-quartz rock from Barru Complex. (f) Garnet amphibolite, (g) eclogite, and (h) garnet-actinolite-quartz schist from Luk Ulo Complex.

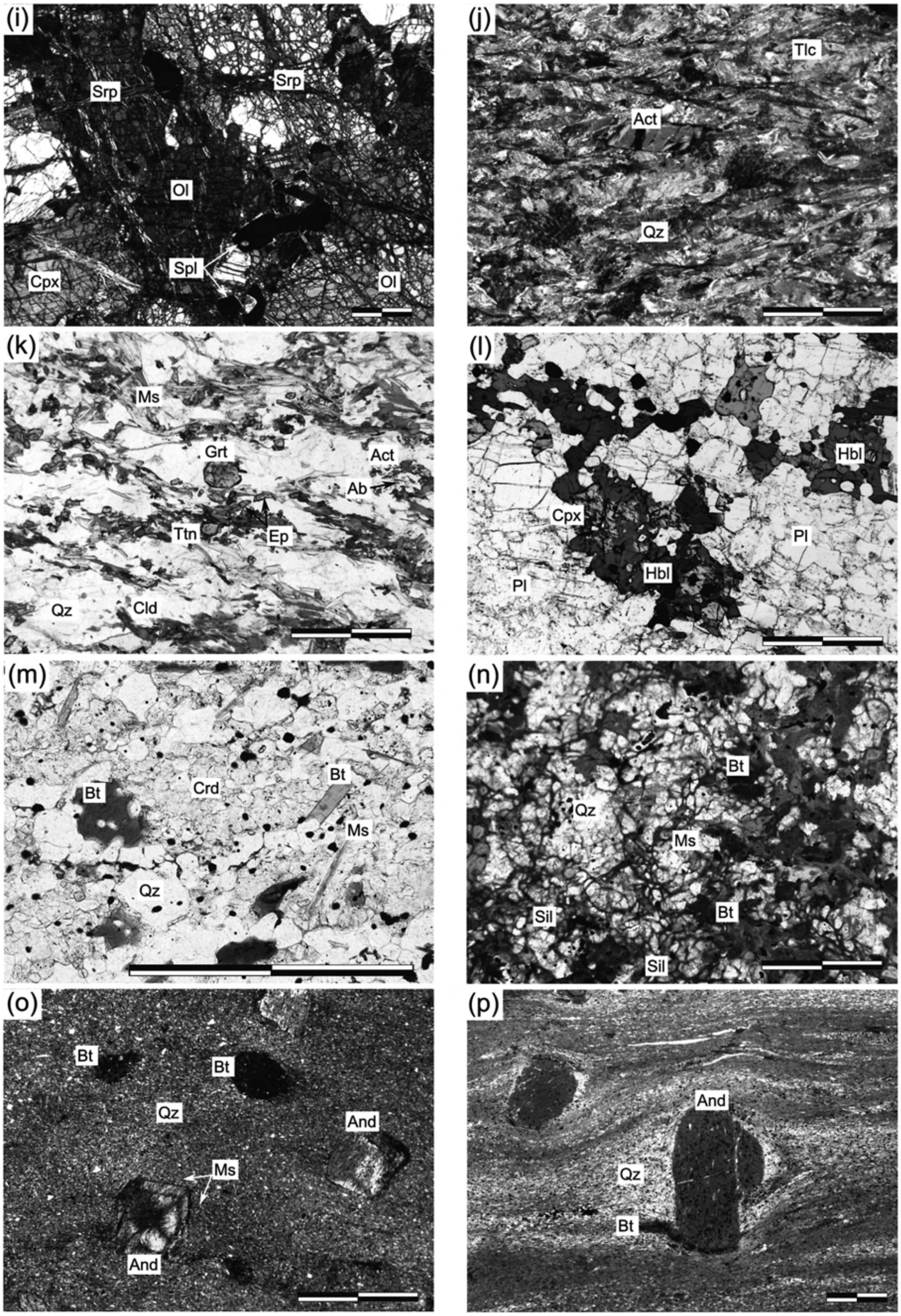

Figure 3. Photomicrographs of metamorphic rocks in central Indonesia (continued). Scale-bars correspond to 1 mm. (i) Serpentinite, (j) actinolite-talc schist, and (k) garnet-epidote-actinolite schist from Meratus Complex. (l) Metatonalite, (m) cordierite-andalusite-biotite hornfels, (n) silimanite (fibrolite) bearing cordierite-andalusite-biotite hornfels, (o) andalusite-biotite hornfels, and (p) andalusite-biotite schist from Nangapinoh area of West Kalimantan.

Table 1. Mineral assemblages of representative metamorphic rocks from central Indonesia.

Location	Rock Name	Major Mineral																		Minor Mineral								Secondary	Remark
		Grt	Omp	Gln	Jd	Ph	Bt	Qz	Crd	And	Sil (Fi)	Ms	Hbl	Ep /Zo	Na-Ca amp	Pl/ Ab	Srp	Act	Tlc	Cld	Rt	Ttn	Ap	Hem	Spl	Chl	Ilm		
Bantimala,	Eclogite	Δ	Δ	±	–	Δ	–	±	–	–	–	–	–	□	O	–	–	–	–	–	□	±	±	±	–	±	–	Act, Chl, Ab	
South Sulawesi	Grt-Gln rock	Δ	±	O	–	Δ	–	±	–	–	–	–	–	□	±	–	–	–	–	–	□	□	±	±	–	±	–	Act, Chl, Ab	
	Grt-Ph-Qz schist	Δ	–	–	–	O	–	O	–	–	–	–	–	Δ	–	–	–	–	–	–	□	□	±	□	–	–	–	Ab, Chl	
	Grt-Jd-Qz rock	Δ	–	□	Δ	Δ	–	O	–	–	–	–	–	O	–	–	–	–	–	–	□	□	–	–	–	–	–	Ab, Chl	
	Glaucophanite	–	±	O	–	Δ	–	±	–	–	–	–	–	Δ	–	–	–		–	–	□	□	±	±	–	–	–	Ab, Chl, Act	
	Gln-Ph-Qz schist	–	±	O	–	Δ	–	O	–	–	–	–	–	Δ	–	–	–	–	–	–	□	□	±	±	–	–	–	Act, Ab, Chl	
Barru, South Sulawesi	Grt-Bt-Ms-Qz schist	Δ	–	–	–	–	Δ	O	–	–	–	Δ	–	Δ	–	Δ	–	–	–	–	□	±	–	±	–	–	–	Chl	
Luk-Ulo, Central Java	Eclogite	Δ	□	Δ	–	O	–	Δ	–	–	–	–	–	□	–	–	–	–	–	–	□	Δ	–	–	–	–	–	Ab, Chl	
	Grt amphibolite	Δ	–	–	–	Δ	–	±	–	–	–	–	O	Δ	–	–	–	–	–	–	–	□	–	–	–	–	–	Chl	
	Grt-Gln schist	Δ	–	⊙	–	Δ	–	□	–	–	–	–	–	Δ	–	–	–	–	–	–	±	Δ	–	±	–	–	–	Ab, Chl	
	Grt-Ms-Qz schist	Δ	–	–	–	–	–	⊙	–	–	–	O	–	□	–	–	–	±	–	–	□	Δ	±	±	–	±	–	Ab, Chl	
	Grt-Act-Qz schist	Δ	–	±	–	–	–	O	–	–	–	Δ	–	Δ	–	–	–	O	–	±	±	±	±	±	–	Δ	–	Cal, Chl	
	Gln-Ep-Qz schist	–	–	O	–	Δ	–	O	–	–	–	–	–	⊙	–	–	–	–	–	–	–	Δ	–	–	–	–	–	Cal, Chl	
Meratus,	Grt-Ep-Act schist	Δ	–	–	–	–	–	⊙	–	–	–	O	–	Δ	–	–	–	O	–	±	–	Δ	–	–	–	Δ	–	Cal	
South Kalimantan	Cld schist	±	–	–	–	–	–	⊙	–	–	–	O	–	O	–	Δ	–	–	–	O	–	□	□	–	–	Δ	–	Cal	
	Act-Tlc schist	–	–	–	–	–	–	□	–	–	–	□	–	–	–	–	–	Δ	O	±	–	–	–	–	–	–	–	Cal	
	Serpentinite	–	–	–	–	–	–	±	–	–	–	–	–	–	–	–	O	–	–	–	–	–	–	–	Δ	–	–	–	Relict of Cpx and Ol
Nangapinoh,	Metatonalite	–	–	–	–	–	Δ	□	–	–	–	□	Δ	□	–	O	–	–	–	–	–	□	□	–	–	–	□	Ser	Relict of Cpx
West Kalimantan	Amphibolite	±	–	–	–	–	Δ	Δ	–	–	–	□	O	Δ	–	–	–	–	–	–	–	□	±	–	–	–	–	Ser	
	Crd-And-Bt hornfels	–	–	–	–	–	O	O	O	Δ	±	□	–	–	–	–	–	–	–	–	–	–	±	–	–	–	±	Ser	
	And-Bt hornfels	–	–	–	–	–	Δ	O	±	O	–	O	–	–	–	–	–	–	–	–	–	–	±	–	–	–	±	Ser, Chl	
	And-Bt schist	±	–	–	–	–	Δ	O	±	O	–	O	–	–	–	–	–	–	–	–	–	–	±	–	–	–	–	Ser, Chl	

⊙ Abundant, O rich Δ moderate □ poor – absent, ± occur only in some samples.

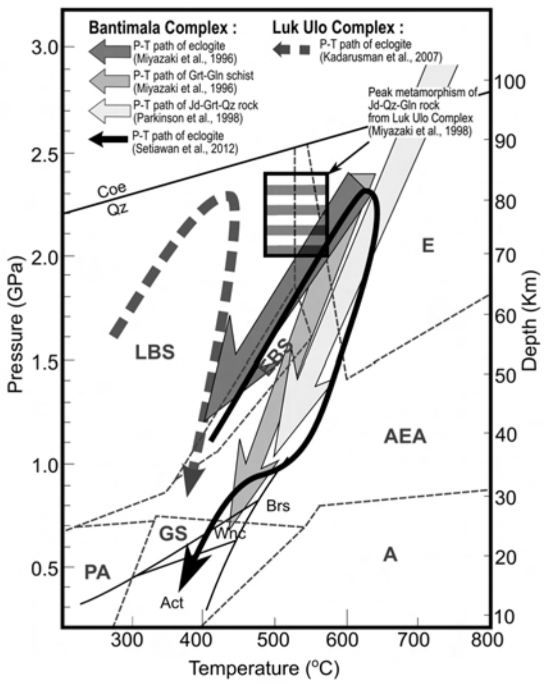

Figure 4. Compiled *P-T* conditions of metamorphic rocks from central Indonesia. The petrogenetic grids are based on Evans (1990). Abbreviations of facies names: E, eclogite; LBS, lawsonite-blueschist; EBS, epidote-blueschist; AEA, albite-epidote-amphibolite; GS, greenschist; PA, pumpellyite-actinolite; A, amphibolite.

alignment of pale glaucophane, phengite and green chlorite. Lepido-nematoblastic glaucophane grains are commonly zoned from the petrographic observation by its interference colour. Chlorite partially or completely replaces garnet, indicating the secondary stage.

The garnet-jadeite-quartz rock is rarely found in the Bantimala Complex. This rock comprises fine-grained garnet, jadeite, quartz, epidote, phengite, amphibole, hematite, apatite and rutile (Fig. 3d). Subidioblastic garnet grains (<1 mm in diameter) occur with mineral inclusions of epidote, phengite, quartz, jadeite and sodic-calcic amphibole. Subidioblastic fine-grained glaucophane (<0.05 mm) occurs together with fine-grained aggregates of epidote, quartz, phengite and jadeite that are ubiquitous in matrix. Moreover in this rock, large mass of fine-grained epidote occurs sporadically and is visible with naked eye. Phengite and albite are present as outer rim in jadeite indicate secondary phases. Chlorite replace garnet along cracks, this is interpreted as secondary phases.

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 ℃ and retrogressed to near 1.0 GPa at 350 ℃ and 0.5 GPa at 350 ℃ from eclogite and garnet-glaucophane rock, respectively (Miyazaki et al., 1996). Very high-pressure metamorphic condition was also reported from this area, in garnet-jadeite-quartz rock that experienced peak metamorphism at >2.7 GPa on 720–760 ℃ and retrogressed to near 1.0 GPa on 500 ℃ (Parkinson et al., 1998) (Fig. 4). Moreover, Setiawan et al. (2012) reported the first clockwise *P-T* path of eclogite from this area, which started from blueschist-facies to the peak *P-T* at 2.2–2.4 and 580–650 ℃ GPa estimated from pseudosection analysis and retrogressed to the glaucophane-stability field before passed through in the actinolite-stability field (Fig. 4). This retrograde *P-T* path probably relates to the rapid exhumation from the greater depth to the crustal level during the earlier stage and slower exhumation following cessation of rapid uplifting on the later stage (Zhang et al., 1995). The K-Ar ages of phengite for these rocks are ranging from 113 ± 6 Ma to 137 ± 3 Ma and interpreted as metamorphic age in Early Cretaceous (Wakita et al., 1994, 1996; Parkinson et al., 1998).

3.1.b. Barru Complex

The Barru Complex is located approximately 30 km north of the Bantimala area (Figs. 1a, c). Detailed geology of this area has been described by Sukamto (1982), Wakita et al. (1994) and Parkinson et al. (1998). 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 (Fig. 2d) and serpentinized peridotite (Wakita et al., 1994). The foliation recorded from the *in-situ* outcrop of garnet-mica schist in Dengedenge River varies from N 78 ° W to N 28 ° E with a dip of strata ranging from 28 to 56 ° E (Setiawan et al., 2011).

Setiawan et al. (2011) describe the garnet-biotite-muscovite-quartz schist is the most common metamorphic rock in this area (Fig. 3e). This rock mainly is composed of garnet, biotite, muscovite, epidote, quartz, rutile, chlorite, hematite and plagioclase. Subidioblastic-xenoblastic garnet (~0.3 mm) have helical inclusions of quartz and epidote (Fig. 4e). The schistosity is defined by alignments of muscovite and biotite. In the secondary stage, rutile is commonly rimmed by titanite and chlorite replace garnet. Representative petrographical observation of this rock is given in Table 1. The reliable *P*-*T* condition of the metamorphic rocks in the Barru Complex has not been reported. Wakita et al. (1994) reported phengite K-Ar age from quartz-mica schist of 106 ± 5 Ma as Early Cretaceous.

3.2. Metamorphic rocks in Central Java

In Central Java, the most significant metamorphic rocks of the Luk Ulo Complex expose in the Karangsambung area (Fig. 1d), although small area east of Yogyakarta also crops out very low-grade metamorphic rocks without eclogite. Luk Ulo Complex consists of shale, sandstone, chert, basic to ultrabasic rocks, limestone, conglomerate and metamorphic rocks (Miyazaki et al., 1998, Asikin et al., 2007, Kadarusman et al., 2007). The tectonic slices of the complex have a trend of ENE-WSW and the metamorphic rocks bounded with mélange deposits (Asikin et al., 2007). The metamorphic rocks occur along the Loning, Muncar and Lokidang River (Setiawan et al., 2011). This complex includes high-pressure metabasites (eclogite, garnet-glaucophane schist, blueschist), medium-grade low-pressure metabasites (amphibolite, garnet amphibolite) and pelitics chists (mica schist, garnet-mica schist) (Setiawan et al., 2011) (Figs. 2e, f). Pelitic schists are more dominant in this area. The occurrence of high-pressure jadeite-quartz-glaucophane rock was reported by Miyazaki et al. (1998). Representative petrographical properties of these rocks are given in Table 1.

Setiawan et al. (2011) describe the petrographic overview of the common metamorphic rocks from Luk Ulo Complex. Garnet amphibolite has granoblastic texture with garnet as porphyroblast and other minerals are hornblende, zoesite, phengite and titanite (Fig. 3f). Eclogite has porphyroblastic garnet (0.5-1 mm), in which mineral inclusions are abundant in the core and mantle portions but relatively free in the rim portion. Quartz, glaucophane and omphacite are inclusion minerals in the garnet that can be identified under a polarization microscope. Omphacite, glaucophane, epidote, phengite, rutile and quartz occur in the matrix (Fig. 3g). Titanite present in the matrix commonly encloses rutile. Porphyroblastic omphacite (0.5-1 mm) and nematoblastic glaucophane (0.1-0.5 mm) in the matrix are commonly zoned in color. Chlorite and albite occur as interstitial phase along the cracks of the garnet and other minerals.

Pelitic schists in this area are garnet-phengite-quartz schist, garnet-actinolite-quartz schist and glaucophane-epidote-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 presents as secondary stage replacing garnet and other minerals. The garnet-actinolite-quartz schist mainly consists of garnet, actinolite and quartz in the matrix with subordinate of chloritoid and apatite (Fig. 3h). Calcite and chlorite are present as interstitial phase in the other minerals. Glaucophane-epidote-quartz schist is characterized by abundance of glaucophane, epidote and quartz with schistosity texture defined by phengite and chlorite.

The *P*-*T* conditions of the metamorphic rocks in Central Java have been reported by Miyazaki et al. (1998) and Kadarusman et al. (2007). Miyazaki et al. (1998) estimated the peak condition of jadeite-quartz-glaucophane rock at 2.2 ± 0.2 GPa and 530 ± 40 ℃ (Fig. 4). Meanwhile, Kadarusman et al. (2007) estimated metamorphic evolution of eclogite by clockwise *P*-*T* path and divided into three stages of prograde as follows; stage I: 1.5–2.1 GPa at 283–415 ℃, stage II: 1.6–2.2 GPa at 329–442 ℃, and stage III: 1.8–2.2 GPa at 359–442 ℃. The later retrograde stage is on the *P*-*T* condition of 0.8–1.0 GPa at 350–400 ℃ (Fig. 4). K-Ar dating of muscovite from quartz-mica schist yielded 110 ± 6 Ma and 115 ± 6 Ma that interpreted as metamorphic age in Early Cretaceous (Miyazaki et al., 1998), while the dating of phengite in jadeite-glaucophane-quartz rock yielded older age of 119 ± 2 Ma and 124 ± 2 Ma that interpreted as metamorphic age in Early Cretaceous (Parkinson et al., 1998).

3.3. Metamorphic rocks in South Kalimantan

Metamorphic rocks in South Kalimantan are located in the Meratus Mountains. The basement rocks crop out in this area namely as Meratus Complex with a trend of NE-SW (Fig. 1e) (Sikumbang and Heryanto, 2009). The Meratus Complex consists of metamorphic rocks, ultramafic rocks and mélange including clasts of chert limestone and basalt within shale matrices (Wakita et

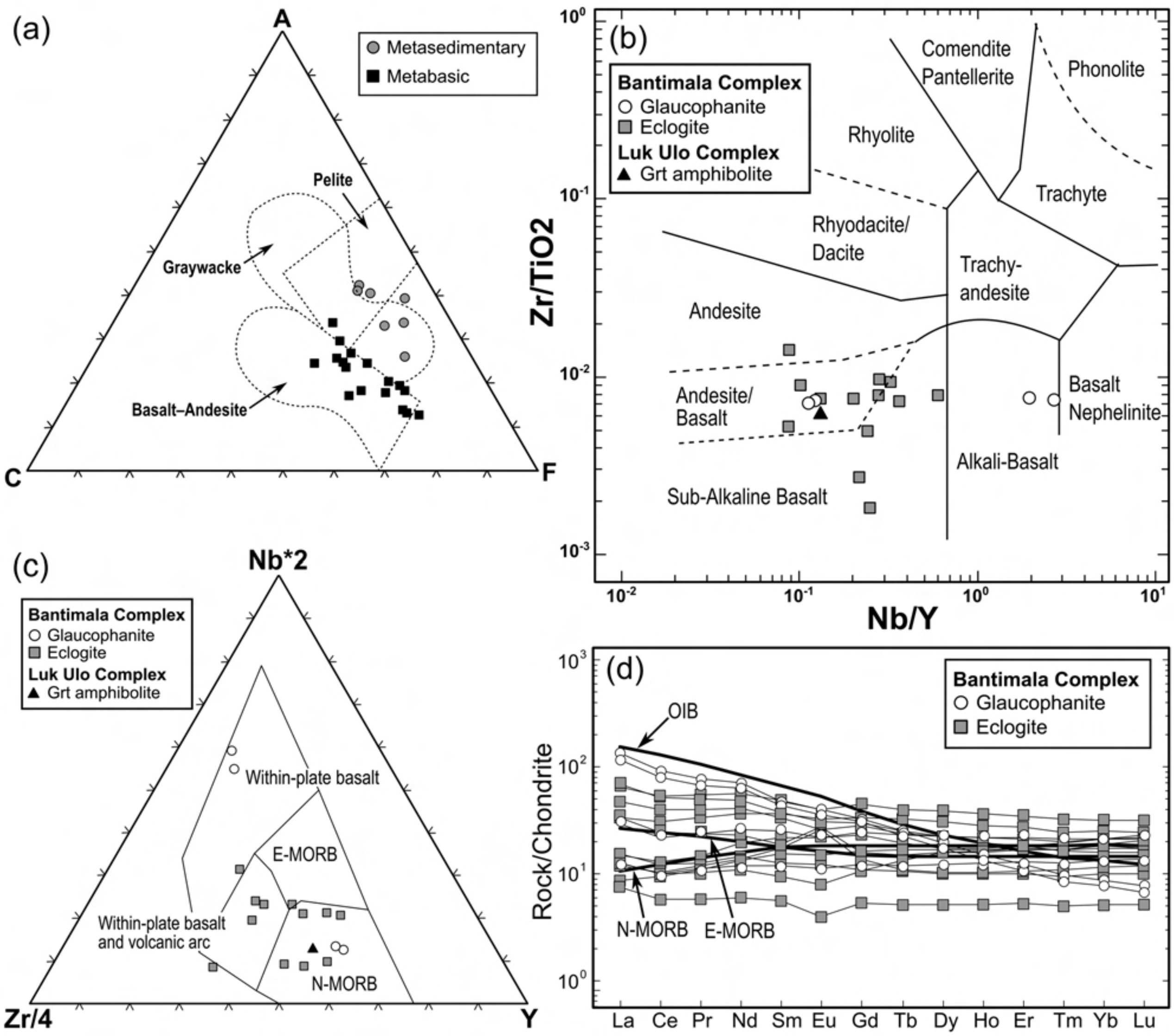

Figure 5. Discriminant diagrams of metamorphic rock from South Sulawesi and Central Java (Setiawan et al., 2013). (a) ACF diagram (Winkler, 1979) showing the distribution of metabasic on the basalt andesite field and metasedimentary rock on the pelite and greywacke fields. (b) Metabasic rocks plotted on the andesite and basalt field of discriminant diagram from Winchester and Floyd (1977) with parameters of Nb/Y and Zr/TiO_2. (c) Metabasic rocks ploted on the Nb-Zr-Y tectonomagmatic discriminant diagram from Meschede (1986) showing N-MORB and within-plate basalt or volcanic arc. (d) C1 chondrite normalized from McDonough and Sun (1995) REE pattern of metabasic rocks from Bantimala Complex showing MORB-type and OIB-type.

al., 1998). The dominant lithologies in this complex are serpentinized peridotite and pyroxenite, gabbro intrusion and various low-grade schists (Setiawan et al., 2012).

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 (Parkinson et al., 1998; Sikumbang and Heryanto, 2009). The metamorphic rocks predominantly found in this location are garnet-epidote-actinolite schist, which crops out on the Aranio River (Fig. 2g), and serpentinite. Other metamorphic rocks are chloritoid schist and actinolite-talc schist. Representative petrographical properties of these rocks are given in Table 1. Parkinson et al. (1998) reported the occurrence of glaucophane- and kyanite-bearing quartz schist in this location.

Setiawan et al. (2012) describe the petrographic and field observation of the common metamorphic rocks from Meratus Complex. Serpentinite are abundant in the Meratus Complex. This rock has mesh texture and almost entirely is made up of serpentine

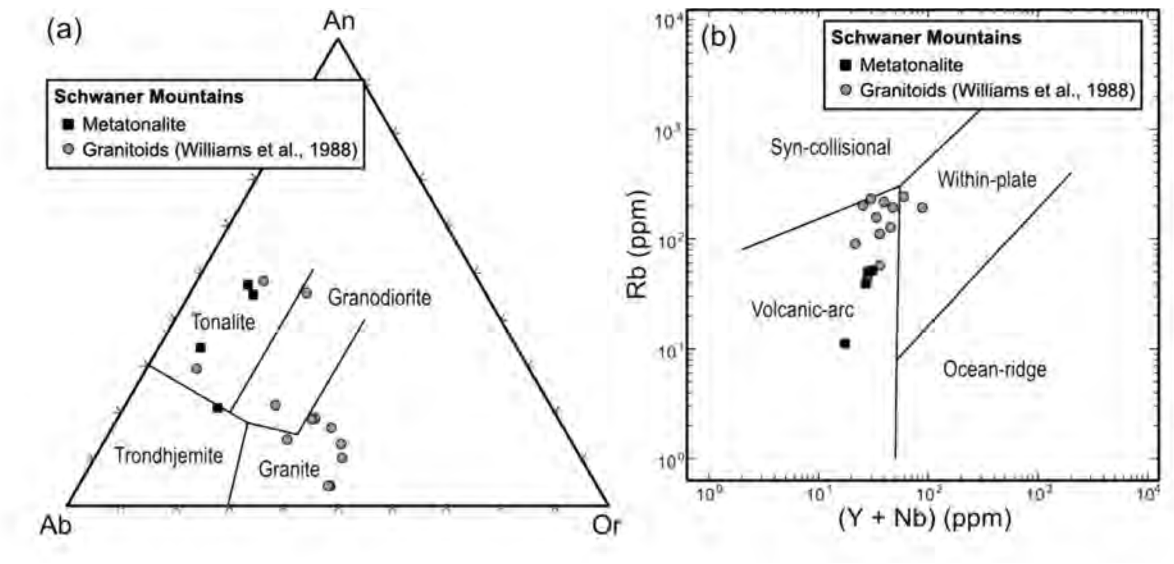

Figure 6. Discriminant diagrams for metatonalite and granitoids from Schwaner Mountains, West Kalimantan (Setiawan et al., 2013). (a) Mineral compositions plotted on the tonalite, granodiorite and granite fields of classification of granitic rocks from Barker (1979). (b) Diagram of Y + Nb versus Rb from Pearce et al. (1984) showing volcanic-arc environment.

together with spinel, hematite grains and several goethites stained. Some of the rocks still preserved relict minerals of olivine and clinopiroxene (Fig. 3i). Rarely actinolite-talc schist is also found in this area. Nematoblastic talc grains (0.5–1.5 mm) are abundant with spotted actinolite and interstitial quartz grains present in the matrix (Fig. 3j). 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 or without chloritoid (Fig. 3k). The variety of this rock has abundant of chloritoid namely as garnet-chloritoid schist.

Parkinson et al. (1998) suggested that the presence of Mg-rich chloritoid may have recrystallized at pressure of ~1.8 GPa or higher. The K-Ar dating of various mica schists yielded ages in the range of 110–119 Ma and interpreted as metamorphic age in Early Cretaceous (Sikumbang and Heryanto, 2009; Wakita et al., 1998).

4. METAMORPHIC ROCKS IN WEST KALIMANTAN

In Nangapinoh area in the northern part of Schwaner Mountains, West Kalimantan (Figs. 1a, f), the granitoids including of biotite-hornblende tonalite and granodiorite intruded the metamorphic rocks in Early Cretaceous (Amiruddin and Trail. 1993; Haile et al., 1977; Williams et al., 1988). Strike of cleavage and schistosity of metamorphic rocks generally ranges from E-W to NE-SW (Amiruddin and Trail, 1993). The metamorphic rocks in this area are dominated by contact metamorphic rocks such as andalusite-biotite hornfels and cordierite-andalusite-biotite hornfels (Fig. 2h). Metapelites also found in this location, and has schistosity texture, which characterizes andalusite-biotite schist.

Foliation also developed in the tonalite in contact with metamorphic rocks, named as metatonalite (Amiruddin and Trail. 1993). Several samples of metatonalite from this area collected by Geological Research and Development Centre of Indonesia were also analyzed in this study. Representative petrographical properties of these rocks are given in Table 1.

Setiawan et al. (2012) describe the petrographic and field observation of the common metamorphic rocks from Schwaner Mountains. Metatonalite predominantly compose of plagioclase, hornblende, biotite with small amounts of quartz, muscovite, and titanite. Weak-foliation texture is recognized from hornblende (0.5–2 mm) that encloses relict clinopyroxene (Fig. 3l). The cordierite-andalusite-biotite hornfels are characterized by spotted texture of cordierite (~0.5 mm) and andalusite (0.5–1 mm) (Fig. 3m). Other mineral assemblages are biotite, muscovite, quartz and apatite. Some of these rocks have fibrous silimanite (fibrolite) in the matrix (Fig. 3n). The secondary minerals present in these rocks are sericite, pinite and chlorite. The andalusite (0.5–1 mm), has a characteristic pattern of graphite inclusions on the core portion (Fig. 3o). Other minerals present in the groundmass are quartz, chlorite, biotite, and muscovite. Several andalusite-biotite-bearing metamorphic rocks also have schistosity texture (Fig. 3p). Large poikiloblasts of andalusite (1–2 mm) embedded in the biotite, quartz, and muscovite groundmass. The reliable *P*-*T* condition of the metamorphic rocks in this area has not been reported.

Setiawan et al (2011) reported the age determination by LA-ICP-MS U-Pb zircon dating of metatonalite from Schwaner Mountains yielded magmatic ages of 233 ± 3 Ma.

5. WHOLE-ROCK CHEMISTRY

Whole-rock analyses were conducted by Setiawan et al. (2013). Based on the petrographical observations and SiO_2 contents, these metamorphic rocks are grouped into two categories, which are metabasic (SiO_2: 40–53 wt%) and metasedimentary rocks (SiO_2: >53 wt%). The bulk chemical compositions of the metabasic rocks from South Sulawesi and Central Java distribute in the basalt-andesite field of ACF diagram of Winkler (1979), and metasedimentary rocks are in the pelite and greywacke fields (Fig. 5a) (Setiawan et al., 2013). Moreover, metabasic rocks (eclogite, glaucophanite and garnet amphibolite) were plotted on the discriminant diagram of Winchester and Floyd (1977) with the parameter of Nb/Y and Zr/TiO_2. In this diagram, all of the metabasic rocks are on the variety of andesite and basalt fields (Fig. 5b) (Setiawan et al., 2013). Therefore, the protolith of the metabasic and metasedimentary rocks are inferred to be mafic or intermediate igneous rocks and sedimentary rocks, respectively (Setiawan et al., 2013).

In the Nb-Zr-Y triangular discriminant diagram of tectonic environment from Meschede (1986), most of the basic metamorphic rocks are plotted on the N-type mid oceanic ridge basalt (N-MORB) and within-plate basalt or volcanic arc (Fig. 5c) (Setiawan et al., 2013). Furthermore, the C1 chondrite normalized REE patterns (McDonough and Sun, 1995) show that most of the metabasic rocks have a MORB-type flat REE pattern with two samples of glaucophanites have a pattern enriched with heavy REEs similar to OIB-type (Fig. 5d) (Setiawan et al., 2013). In summary, the protolith of the basic metamorphic rocks from South Sulawesi and Central Java might be derived from MORB and within-plate basalt or OIB-type (Setiawan et al., 2013).

Whole-rock chemistry of 4 metatonalites from Schwaner Mountains is shown on the discriminant diagrams (Figs. 6a, b) (Setiawan et al., 2013). Moreover, whole-rock chemistry of 12 selected granitoids of Williams et al. (1988) is also plotted on the same diagrams for comparison. All of the metatonalites are plotted on the tonalite field of An-Ab-Or triangular diagram from Barker (1979), while the granitoids of Williams et al. (1988) are plotted on the granite, granodiorite and tonalite fields (Fig. 6a) (Setiawan et al., 2013). In the Y + Nb versus Rb discriminant diagram of tectonic environment from Pearce et al. (1984), all of the samples are on the volcanic-arc field (Fig. 6b) (Setiawan et al., 2013). Hence, it might be concluded that the Schwaner Mountains granitoids composed of granite, granodiorite and tonalite was derived from volcanic-arc tectonic environment (Setiawan et al., 2013).

6. DISCUSSION AND CONCLUSION

Based on the geochemical signature, metamorphic rocks from Bantimala Complex, South Sulawesi are dominated by high-pressure metabasic with protolith of alkali basalt or sub-alkalic andesite to basalt derived from the MORB and within-plate basalt tectonic environment (Setiawan et al., 2013). The metamorphosed sedimentary rocks were derived from pelite to greywacke (Setiawan et al., 2013). Estimated peak *P*-*T* condition of eclogite by Setiawan et al. (2012) (2.2–2.4 GPa at 580–650 °C) corresponds to the crust subduction depth of 80–85 km for the formation of this rock. However, 30 km north of the Bantimala Complex (Barru Complex), no high-pressure metamorphic rocks were found in that area, and the K-Ar age of the rocks are relatively younger than the Bantimala Complex (Bantimala Complex: 113–137 Ma, Barru Complex: 106 Ma) (Wakita et al., 1994, 1996; Parkinson et al., 1998). Further study about metamorphic conditions in this area is required in order to understand the tectonic relations with Bantimala Complex.

The most abundant rock type in the Luk Ulo

Complex, Central Java is pelitic schists than basic metamorphic rocks. However, high-pressure metamorphic rocks were also found in this area; e.g., eclogite and blueschist. Estimated peak *P-T* condition from jadeite-quartz-glaucophane rock and eclogite are 2.2 ± 0.2 GPa at 530 ± 40 ℃ and 1.8–2.2 at 359–442 °C, respectively (Miyazaki et al., 1998; Kadarusman et al., 2007). The protolith of basic metamorphic rock tend to be basaltic or andesitic igneous rock derived from MORB and within-plate basalt tectonic environment (Setiawan et al., 2013). K-Ar ages in this area were contemporaneous with the Bantimala Complex (110–124 Ma) (Parkinson et al., 1998; Miyazaki et al., 1998). While the metamorphic rocks in the Meratus Complex, South Kalimantan are dominated by low-pressure medium-grade metamorphic rocks and serpentinite. However, Parkinson et al. (1998) reported the occurrence of glaucophane- and kyanite-bearing quartz schist that correspond to medium-pressure metamorphism were occurred in this location. K-Ar ages in this area are 110–119 Ma (Sikumbang and Heryanto, 2009; Wakita et al., 1998), also contemporaneous with Bantimala and Luk Ulo Complexes. From these evidence, it is confirmed that South Sulawesi, South Kalimantan and Central Java have a possibility of separated parts derived from single subduction complex.

Whole-rock chemistries shown in the discriminant diagrams suggest that the metatonalites and granitoids from West Kalimantan are tonalitic, granodioritic and granitic in composition, derived from volcanic arc tectonic environment (Setiawan et al., 2013). These agree with the results from previous researchers (Haile et al., 1977; Williams et al., 1988; Amiruddin and Trail, 1993). LA-ICP-MS U-Pb zircon dating of metatonalite from Schwaner Mountains yields magmatic ages of 233 ± 3 Ma (Setiawan et al., 2011) that are older than the reported K-Ar granitoids ages from Schwaner Mountains (77–157 Ma) (Haile et al., 1977; Williams et al., 1988; Amiruddin and Trail, 1993) but still in a range of the K-Ar granitoids ages from northwest Kalimantan (204–320 Ma; Williams et al. 1988). This evidence might indicate that magmatism of granitoids of several parts in Schwaner Mountains was contemporaneous with the northwest Kalimantan domain.

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インドネシア中央部の変成岩：概説—スラウェシ島南部，ジャワ島中央部，カリマンタン島南部・西部に分布する変成帯の重要性

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日本語要旨

インドネシア中央部に位置するジャワ，カリマンタン，スラウェシ各島には変成岩類が分布している．本論文では，スラウェシ島南部・バンティマラ岩体およびバルー岩体，ジャワ島中央部・ルクウロ岩体，カリマンタン島南部・メラトゥス岩体および西部・シュワナ山地域に分布する変成岩類に関する岩石学的，地球化学的および年代学的データについてまとめ，これらの地域に関するこれまでの研究例をまとめた．

バンティマラ岩体には，エクロジャイト相に達する高圧変成岩類が分布している．同様の変成条件を示す変成岩はルクオロ岩体からも報告されている．カリマンタン島南部の変成岩からも，Mgに富むクロリトイドの存在から～1.8GPaの高圧の変成条件が報告されている．これらの高圧変成岩からは前期白亜紀のK-Ar年代が報告されていることから，スラウェシ島南部，ジャワ島中央部，カリマンタン島南部は一連の沈み込みによって形成された可能性が示唆される．カリマンタン島西部・シュワナ山地域には，変成トーナル岩とホルンフェルスを含む接触変成岩が分布しているが，詳細な変成条件の解析はなされていない．変成トーナル岩からは，後期トリアス紀の火成年代がLA-ICP-MSを用いたジルコンU-Pb年代測定によって明らかにされている．この年代は，後期ジュラ紀から白亜紀のK-Ar年代を示すシュワナ山地域の花崗岩類より古いが，カリマンタン北東部に分布する花崗岩類が示すK-Ar年代（石炭紀から白亜紀）の範囲内である．このことは，シュワナ山地域における花崗岩類の火成活動は，カリマンタン島北西部と同時期であったことを示している．

全岩化学組成からは，スラウェシ島南部およびジャワ島中央部の塩基性変成岩は，中央海嶺あるいはプルームに関連するテクトニクスで形成された玄武岩と安山岩を起源物質とする．そのため，これらの地域は一連の沈み込みによって形成されたものである可能性が高い．カリマンタン島西部に関しては，変成トーナル岩や花崗岩類は，火山弧に関連するテクトニクスに由来することが示唆される．

キーワード：変成岩，スラウェシ島南部，ジャワ島中央部，カリマンタン島南部，カリマンタン島西部，全岩化学組成分析