SPECULATIVE MODELS OF EXHUMATION ON HIGH-PRESSURE LOW-TEMPERATURE METAMORPHIC ROCKS FROM CENTRAL PART OF INDONESIA: AN IMPLEMENTATION OF CONCEPTS AND PROCESSES

Nugroho Imam Setiawan\textsuperscript{1}, Salahuddin Husein\textsuperscript{1}, and Muhammad Faqih Alfyan\textsuperscript{1}

\textsuperscript{1}Geological Engineering Department, Faculty of Engineering, Gadjah Mada University, Jl. Grafika 2, Bulaksumur, Yogyakarta 55281, Indonesia

Abstract

High-pressure low-temperature metamorphic rocks are considered as fossil subduction zones from the interpretation of progressive and retrogressive metamorphism, metamorphic facies series, protolith, role of fluid, geochronology of the various stages of metamorphism, $P$-$T$-$t$ path, and exhumation model during regional metamorphism. Worldwide discovery of these rock types (e.g., Kokchetav, Dabie Shan, Indonesia, Franciscan, and Sanbagawa) have received much attention from earth scientists to demonstrate the exhumation of the rocks that have been metamorphosed at great depths in subduction zones that are exhumed at the surface. High-pressure metamorphic rocks expose in the South Sulawesi, Central Java, and South Kalimantan, which considered as central part of Indonesia. Northwesterly directed Cretaceous subduction was suggested responsible to build these formations. Most of the metamorphic rocks occur in limited areas and are bounded by thrust fault with other units such as dismembered ophiolites, cherts, mélanges, and serpentinites. This contribution is implementation of published-exhumation concepts and processes, which are focus on the high-pressure metamorphic rocks in central part of Indonesia. The published-exhumation models on the high-pressure low-temperature metamorphic rocks in subduction zones suggest that buoyancy is the only effective force to exhume rocks from the deeply subducted levels to the base of the crust. Serpentinites are extremely buoyant with respect to the oceanic crust that has been transformed to eclogites during subduction and increasing their density, which are denser than average mantle rocks. Indeed, serpentinites have restricted $P$-$T$ limit in the subduction zone. However the general $P$-$T$ metamorphism of eclogites are within the range of serpentinites stability field. Thus, serpentinites might be counter-balancing the negative buoyancy, decouple, and facilitate exhumation of the high-pressure metamorphic rocks. Only rapid uplift accompanied by relatively low temperature rapid cooling maintains the high-pressure minerals in rocks. Furthermore, the presence of mélange units intercalated with high-pressure metamorphic rocks and chaotic occurrence of different metamorphic facies (e.g., eclogite, blueschist, greenschist) are typically formed in the subduction channel environment.

Keywords: Exhumation, Model, High-pressure metamorphic rocks, Subduction, Indonesia

Introduction

Recent updates of the progress study of the global high-pressure and ultrahigh-pressure metamorphic rocks from several publications provide important meaning of the global tectonics through continental subduction, collision, exhumation, mantle-lithospheric slab interactions, and geochemical recycling of subducted/exhumed rocks (Figure 1). Most high-pressure and ultrahigh-pressure metamorphic terranes in the world (e.g. Liou et al., 2009; Dobrzhinetskaya and Faryad, 2011) are resulted by orogenic metamorphism, which
occurs in convergent zones of the earth’s plate represented by the subduction zone and the collisional zone. In the boundary of the collision zone, crustal thickening or subduction takes place and several kinds of metamorphic rocks are newly formed. It is important for understanding their evolution, which are factors leading to such pressure-temperature metamorphic conditions, the duration of these conditions, and the events leading to subsequent exposure at the surface. The development of geochronological system, especially multiple isotopic geochronologies, changed our understanding of the metamorphic evolution from two dimensions (pressure-temperature path; \(P-T\)) to three dimensions (pressure-temperature-time path; \(P-T-t\)).

High-pressure and low-temperature metamorphic rocks are considered as fossil subduction zones from the interpretation of progressive and retrogressive metamorphism, metamorphic facies series, protolith, role of fluid, geochronology of the various stages of metamorphism, \(P-T-t\) path, and exhumation model during regional metamorphism. Such metamorphism results from cool rock material rapidly subducted to great depths, which reach >50 km that corresponds to pressure of 1.5 gigapascal (1 GPa = 10 kilobar) with temperature approximately 800–900 °C for subducted continental crust and shows lower temperature (200–500 °C) for young and warm oceanic crust (Frisch et al., 2011). Worldwide discovery of these rock types (e.g., Kokchetav, Dabie Shan, Indonesia, Franciscan, and Sanbagawa) have received much attention from earth scientists (e.g., Platt, 1993; Maruyama et al., 1996; Herman et al., 2000; Ernts, 2006; Agard et al., 2009; Maruyama et al., 2010) to demonstrate the exhumation of the rocks that have been metamorphosed at great depths in subduction zones that are exhumed at the surface. Commonly, high-pressure mineral associations are only preserved as relics because they adapt to decreasing pressure and temperature that accompany slow isostatic ascent. Only rapid uplift accompanied by relatively low temperatures or rapid cooling maintains high-pressure minerals in rocks (Platt, 1986). The study of high-pressure metamorphic rocks and their exhumation mechanism leads new point a view to understanding the evolution of global tectonics as well as geological processes under lower crust and upper mantle conditions. Finally, those important meaning of the study high-pressure metamorphic rocks and their exhumation mechanism will be applied in the central Indonesia metamorphic terranes.

Methods
This study is integration of many recent published and unpublished works of exhumation mechanisms on the high-pressure metamorphic rocks in central Indonesia metamorphic terranes including Central Java (Karangsambung Complex, Jiwo Hills), South Kalimantan (Meratus Complex), and South Sulawesi (Bantimala and Barru Complex). Main data are focused on the publications of metamorphic conditions (pressure, temperature, time) in those areas. Furthermore, new data of database metamorphic rocks are provided from Jiwo Hills area. Results of previous works and new data are integrated and synthesized to result a new models for exhumation mechanism in central Indonesia high-pressure metamorphic terranes.

Exhumation mechanisms in oceanic crust subduction
The exhumation mechanisms should be differed from the word of uplift. The uplift means the motion of rocks towards the earth’s surface, while exhumation mechanisms are likely to cause a decrease in surface elevation (Platt, 1993). Research on the exhumation of high-pressure metamorphic rocks mainly focused on the continental high- to ultrahigh-pressure metamorphic rocks (e.g. Platt, 1993; Ernts, 1997; 2006; Maruyama et al., 1996).
famous model of tectonic setting of exhumation in subduction zones is shown in Figure 2 (Agard et al., 2009). The model suggests during a period of oceanic subduction, the oceanic crust and the overlying sediments, part of which can be decoupled from the crust and accreted to form the accretionary wedge, are dragged at depth along the subduction plane into the so-called subduction channel. The exhumation of metamorphic rocks under high-pressure conditions may then take place in the wedge and/or in the channel. The exhumation situations of the continental rocks are different for the denser oceanic high-pressure metamorphic rocks. Agard et al. (2006) demonstrates during oceanic convergence, oceanic material was returned along the subduction plane (from depths ≥40–50 km back to depths ≤15–20 km) during short-lived time periods only that is discontinuously with respect to the subduction duration. Furthermore, Agard et al. (2009) compiled 17 different worldwide oceanic high-pressure subduction locality types (e.g. Chile, Fransiscan Complex, Iran, New Caledonia, Western Alp, etc.), which may consist of oceanic sediments and oceanic crust, for their geodynamic characteristic. The results suggest that 1) the oceanic crust (+mantle) appears to be exhumed episodically, that is only during restricted, specific time window. 2) The sedimentary exhumation appears to be a long process (e.g. >50 Ma for Chile, ~50 Ma for Franciscan) and return larger volume proportion (~80–90% and 30–50% for Cascades and West Alps, respectively) than oceanic crust (<5% for West Alps and <1% for Himalaya). 3) Oceanic crust material is almost systematically associated with serpentinites, either as lenses wrapped in a serpentinite rich mélanges or as dispersed, isolated blocks. Serpentinites possibly originate from the hydrated mantle wedge or from hydrothermally altered slab mantle, or both (Hermann et al., 2000). 4) Exhumation velocities range mainly between 1 and 5 mm/yr. 5) P-T gradients are in general ~8–10 °C/km, and in any case <15 °C/km. 6) P-T path essentially fall into two types; type 1 as cooling P-T path (e.g. Chile, Franciscan, Santa Catalina) and type 2 as nearly isothermal decompression path (e.g. W. Alps, Iran, Himalaya). 7) There have little or no influence on exhumation pattern with convergence velocities.

Tsujimori et al. (2006) suggests that the preservation of lawsonite eclogite (high-pressure, low-temperature) is possible if refrigerant conditions are maintained on exhumation. Continuous exhumation process is explained by incorporation of oceanic crust in the wedge and possibly enhanced by serpentinitization. While discontinuous (incidental) exhumation process only happened during specific time windows in response to the entrance of buoyant material in the subduction wedge (e.g. thinned continental margin, oceanic plateau), modification of the convergence setting (velocities, obliquity), or cessation of subduction (e.g. delamination of lower crust, slab-breakoff (Agard et al., 2009).

Hermann et al. (2000) proposed that the exhumation of oceanic crust was facilitated by their association with serpentinites, which would counter balance their negative buoyancy and enhance mechanical decoupling in the internal position of orogen. It is strongly supports by the stability field of antigorite (≤650 °C) that covers the subducted oceanic crust from the various setting (Herman et al., 2000). However, beyond depth ~70 km (>2.0–2.3 GPa), there are not enough serpentinites and/or not light enough to compensate the negative buoyancy of the crust (Agard et al., 2009). Those, suggest that the exhumation of UHP metamorphic rocks should be facilitate by the buoyancy of subducted sedimentary or continental crust.
Geological Background of Central Indonesia High-Pressure Metamorphic Terranes

The Cretaceous subduction complex, which is represented by the occurrence of accretionary unit such mélanges, pillow basalts, dismembered ophiolites, cherts, serpentinites, high-pressure metamorphic rocks, and occasionally granulites and garnet lherzolite, are sporadically exposed in the central Indonesia region through the Java, Kalimantan, and Sulawesi Islands (Sukamto, 1982; Wakita et al., 1994a, 1994b, 1996, 1998; Miyazaki et al., 1996, 1998; Parkinson, 1998a, 1998b; Wilson and Moss, 1999; Kadarusman and Parkinson, 2000; Kadarusman et al., 2005). The distribution of the accretionary units and metamorphic rocks are shown in Figure 3. Most of the metamorphic rocks exposing in the complexes occur in a limited areas and is bounded by the thrust fault with other units such as dismembered ophiolites, cherts, mélanges, and serpentinites (Sukamto, 1982; Asikin et al., 2007; Sikumbang and Heryanto, 2009; Figure 4). In the Java Island, metamorphic rocks are exposed in the central part, namely as Luk Ulo Complex in Karangsambung area, although small area east of the Yogyakarta (Jiwo Hills) and western part of Java Island (Bayah Complex) also crops out very low-grade metamorphic rocks. Meanwhile in Sulawesi Island, the accretionary and metamorphic complexes occupied more widely compared to the other islands. In this island, the complexes expose in the southern and central part of Sulawesi Island. In the South Sulawesi, the metamorphic rocks crop out in the restricted area namely as Bantimala and Barru Complexes (Figs. 4a, b). While in the Central Sulawesi, the accretionary and metamorphic rocks expose more widely in the Pompanegeo, Palu, and Malino Complexes. Cenozoic tectonic activities made these main complexes separate 500 to 1000 km of each other. Northwesterly-directed Cretaceous subduction beneath the Sundaland was suggested to be responsible to build the formation of metamorphic rocks from Central Java, South Kalimantan, South Sulawesi, and Central Sulawesi (Sukamto, 1982; van Leeuwen and Muhardjo, 2005; van Leeuwen et al., 2007). Furthermore, Hamilton (1979) and Parkinson et al. (1998b) considered that these complexes might have derived from a single subduction complex that extending ~1500 km wide.

K-Ar ages of phengite from high-pressure metamorphic rocks in the Bantimala Complex of South Sulawesi are ranging from 113 Ma to 137 Ma (Wakita et al., 1994a, 1996; Parkinson et al., 1998) and interpreted as exhumation age. Meanwhile, the radiolarian assemblages from chert in this area yielded middle Cretaceous (late Albian to early Cenomanian) age (Wakita et al., 1994a, 1996). From Barru Complex, 30 km north of Bantimala area, Wakita et al. (1994a) reported K-Ar age from mica schist yield 106 Ma. In the Pompanegeo Complex of Central Sulawesi, Parkinson (1998a) reported the K-Ar age of phengite from pelitic and metabasic rocks as 108 Ma to 114 Ma. From the Luk Ulo Complex in Central Java, K-Ar age from quartz mica schist is 110 Ma to 115 Ma (Miyazaki et al., 1998) and 119 Ma to 124 Ma from jadeite-glaucophane-quartz rock (Parkinson et al., 1998). The radiolarian assemblage from chert in this area gave the ages of early to late Cretaceous (Wakita et al., 1994b). In the Meratus Complex of South Kalimantan, K-Ar isotopic composition from mica schists yielded 110 Ma to 180 Ma with the radiolarian chert gave the ages of early-middle Jurassic to late-early Cretaceous (Wakita et al., 1998).

Distribution, Modes of Occurrence, and General Petrography

This section briefly describes the distribution, modes of occurrence, and representative general petrography of the metamorphic rocks from central Indonesia region that mainly
described in detail by Setiawan (2013). Summary of metamorphic rock types found in these areas is presented in Table 1.

The Bantimala and Barru Complexes in South Sulawesi

In the Bantimala Complex, high-pressure metamorphic rocks crop out along the courses of Bantimala, Pateteang, Cempaga, Pangkajene, and Batupute Rivers (Figure 4a). Along these rivers, exposures of glaucophane schist are abundant with the foliation orientation N 50 W and dipping 52º to the South, while other metamorphic rocks (e.g. eclogites and garnet-glaucophane schists) mostly occur as a river boulder (Setiawan, 2013). Most of the metamorphic rocks occurring in this area are as a tectonic blocks and are surrounded by mélange units and intercalated with chert. The foliation of glaucophane schist is defined by the layers of epidote-rich glaucophane schist and sometimes epidote-chlorite schist. Garnet-jadeite-quartz rock rarely occurs in this area. Mafic rocks (eclogite, garnet-glaucophane schist, and epidote-glaucophane schist) are much more common in this area than pelitic lithologies (garnet-glaucophane-quartz schist or garnet-phengite-quartz schist). The eclogite blocks composed of omphacite-rich and omphacite-poor layers (omphacite-bearing garnet-glaucophane rock or garnet-glaucophane rock; Setiawan, 2013). The variation of high-pressure mafic rocks are phengite-rich garnet-glaucophane rock and phengite-rich epidote-glaucophane schist. The ultramafic rocks are mostly serpentinite. Miyazaki et al. (1996) reported that the eclogite and the garnet-glaucophane rock occur as tectonic blocks within sheared serpentinite. Other type of metamorphic rocks found in this area are hematite schist, piemontite schist, graphite schist, muscovite schist, and albite-chlorite schist. The petrographical observation reveals that metabasic rock types have several variations of barroisite-bearing and barroisite-free, garnet-glaucophane schist, epidote-glaucophane schist, garnet-barroisite schist, and barroisite schist (Setiawan, 2013). Pelitic rocks that observed in this area are garnet-glaucophane-quartz schist, garnet-jadeite-quartz rock, glaucophane-quartz schist, garnet-phengite schist, muscovite schist and piemontite schist. In particularly metabasic rocks, experienced metamorphism in eclogite- and blueschist-facies.

The exposures of the metamorphic rocks in the Barru Complex are well preserved along the Dengedenge River (Figure 2b). The most common lithologies are pelitic rocks of garnet-biotite-muscovite schist (Setiawan, 2013). Furthermore, Wakita et al. (1994) reported the occurrences jadeite-quartz-glaucophane rock in this complex. Well exposed of the garnet-muscovite schist found along the Loning River with the addition of serpentinite, chert, and mélange units were also found in this area (Setiawan, 2013).

The Luk Ulo Complex and the Jiwo Hills of Central Java

Metamorphic rocks in the Luk Ulo Complex occur along the Muncar and Loning Rivers (Figure 4c). Setiawan (2013) confirms that high-pressure metamorphic rocks including eclogite-, blueschist-, and amphibolite-facies are abundant in this complex, which includes high-pressure metabasites (eclogite, garnet-glaucophane schist, and glaucophane schist), medium- to low-pressure metabasites (amphibolite, garnet amphibolite) and pelitic schist (garnet-muscovite schist, muscovite schist). Pelitic rocks are more dominant in this area, in which quartz, albite, and muscovite minerals are abundant, compared to metabasic rocks. The abundant of medium- to low-pressure metabasites (amphibolite, garnet amphibolite) is not similar with the lithologies in Bantimala Complex (Setiawan, 2013). Miyazaki et al. (1998) reported the occurrences jadeite-quartz-glaucophane rock in this complex. Well exposed of the garnet-muscovite schist found along the Loning River with the addition of serpentinite, chert, and mélange units were also found in this area (Setiawan, 2013).
Kadarusman et al. (2007) reported that high-pressure metamorphic rocks occur as tectonic blocks in sheared serpentinite.

The Jiwo Hills in Central Java has been previously considered to be composed of the very low-grade metamorphic rocks (Hamilton, 1979; Parkinson et al., 1998b). Setiawan et al. (2013b) confirms that very low-grade metamorphic rocks are abundant in this area. The most predominant rock types are phyllites. Most of the exposures are strongly weathered. Rarely blueschist-facies assemblage of epidote-glaucophane schist was found near the exposure of serpentinite in the western part of this complex with the foliation trend varies from 62–63 W dipping 55–70º to the South (Setiawan et al., 2013). While in the eastern part of this complex, the calc-silicate schist and phyllite are dominant. Recent investigation reveals that glaucophane-bearing marble crop out in the eastern part of this complex. It may give information that such rock experienced metamorphism under blueschist-facies condition. Several calc-silicate host rocks are converted to garnet-epidote-quartz skarn under the contact metamorphism caused by diabase intrusion. Other variations of low-grade schists found in this area, which are albite-muscovite schist, graphite phyllite/schist, and quartz phyllite.

**The Meratus Complex of South Kalimantan**

The metamorphic rocks in South Kalimantan occur in the Meratus Mountains. Those are particularly distributed in the southwestern part of the mountains called as Meratus Complex (Figure 4d). The Meratus Complex has also been previously considered to be composed of the high-pressure metamorphic rocks (Wakita et al., 1998; Parkinson et al., 1999b). Setiawan (2013) confirms that the dominant lithology is serpentinite and blueschist- to amphibolite-facies metamorphic rocks. The exposure of serpentinite could be found throughout in the complex. The blueschist- to amphibolite-facies rocks (e.g. epidote-barroisite schist) occurs in the Aranio River (Figure 4d). The schist consists of garnet- and quartz-rich layers, which has 80W trending foliation with dipping 66º to North (Setiawan, 2013). Other rock types are tremolite-talc schist, muscovite schist, epidote schist, and dacite porphyry. In the southern part of the complex, only serpentinized peridotites are found as metamorphic rocks and the others are ultramafic rocks and mafic rocks such as peridotite, olivine-gabbro, and hornblende-gabbro.

Petrographical observation reveals that several pelitic schists experienced metamorphism at blueschist-facies by the occurrences of glaucophane in the matrix (epidote-glaucophane schist) or as inclusion in the other minerals (garnet-bearing epidote-barroisite schist and epidote-barroisite schist; Setiawan, 2013).

**Whole Rock Chemistries**

Setiawan et al. (2014) suggests that the protoliths of the basic metamorphic rocks from the Bantimala Complex in South Sulawesi were derived from MORB, within-plate basalt, and arc with tholeite nature. Whereas from the Luk Ulo Complex in Central Java, basic metamorphic rocks were derived from MORB and within-plate basalt. Although previous studies reported that the protolith of the high-pressure metabasic rocks in these regions are of MORB-like affinity (Parkinson, 1996; Kadarusman et al, 2010), however Setiawan et al. (2014) suggests that within-plate basalt is widely distributed together with MORB and arc basalt in the Bantimala Complex of South Sulawesi. 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. Furthermore, proto island-arc, which could not be found in the Luk Ulo Complex, might subducted together with OIB and MORB in the South Sulawesi area.
In contrast, the eclogite and blueschist from the Luk Ulo Complex in Central Java mostly show within-plate basalt signatures, whereas protolith of amphibolites and garnet amphibolites are characterized by MORB (Table 1; Setiawan et al., 2014). Furthermore, Setiawan et al. (2014) suggest several possibilities: different component between upper and lower oceanic crusts; difference of the metamorphic age between high-P/T and low-P/T metamorphism; and change of the subduction angle between two metamorphic events. In order to examine these possibilities, detailed age determinations of both protoliths (MORB and within-plate basalt) and both metamorphisms (blueschist–eclogite and amphibolite) were performed. 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 (e.g. Hamilton, 1979; Parkinson et al., 1998b). In contrary, metamorphic rocks from South Kalimantan and Jiwo Hills of Central Java were show sedimentary protolith signature (Setiawan et al., 2013b). It is confirm by the metabasic rocks were never been found in Jiwo Hills area (Setiawan et al., 2013b). Summary of whole rock chemistries of metabasic rocks from South Sulawesi, Central Java, and South Kalimantan are presented in Table 2.

P-T Metamorphic Evolution

Metamorphic evolution of metamorphic rock from Bantimala Complex

Setiawan (2013) suggests that eclogite from Bantimala Complex shows clockwise P-T path (Figure 5). The prograde stage experienced M1 metamorphism at epidote blueschist-facies metamorphism on the stability field of epidote + titanite (0.9–1.5 GPa at 350–550 °C). The prograde stage path continued increasing pressure and temperature to the M2 metamorphism, which passed through the blueschist/eclogite-facies transition (1.6–1.9 GPa at 520–550 °C), until the peak condition of eclogite-facies metamorphism (M3 metamorphism) at 2.6–2.7 GPa and 615–678 °C that corresponds to the depth of 90–95 km (Figure 6-9). The estimated peak P-T condition is ~0.3 GPa higher-pressure and ~40 °C higher-temperature than previous calculated maximum peak P-T for eclogite in Bantimala Complex (Miyazaki et al., 1996). The prograde P-T path shows very low geothermal gradient of c. 5°C/km. The retrograde stage (M4 metamorphism) is presented by changing mineral compositions of amphiboles from the barroisite- to the actinolite-stability field (<0.5 GPa at <350 °C). The estimated P-T condition of retrograde stage is similar with previous eclogite calculated from this area (Miyazaki et al., 1996). Furthermore, Setiawan (2013) suggests that the eclogite was cooled during upward motion. The metamorphic evolutions of prograde to retrograde stages are clearly show a very narrow open clockwise P-T path or nearly retracing of the prograde trajectory with low geothermal gradient (c. 7.5 °C/km) (Figure 5).

Metamorphic evolution of metamorphic rock from Barru Complex

The pressure-temperature condition of garnet-biotite-muscovite schist from Barru Complex was estimated by Setiawan (2013) using mineral parageneses, reaction textures, mineral chemistries, and thermodynamic data. The P-T path of prograde stage passed the reaction of Ep + Ttn = Grt + Rt + Qz + H2O on 1.3 GPa at 400 °C to 0.6 GPa at 600 °C to the peak P-T condition of 501–562 °C and 0.89–0.97 GPa, which is on the stability field of garnet, biotite, muscovite, plagioclase, rutile, and quartz. Comparing with Bantimala Complex (30 km the south from Barru Compex), the estimated peak P-T condition of garnet-biotite-muscovite schist shows low-pressure and medium-grade conditions (Figure 5).
**Metamorphic evolution of metamorphic rocks from Luk Ulo Complex**

The pressure-temperature path of eclogite, garnet-glaucophane schist, and garnet amphibolite were estimated by Setiawan (2013) using mineral parageneses, reaction textures, and mineral chemistries. The obtained pressure-temperature path of the eclogite and garnet-glaucophane schist have clockwise path (Figure 5). The eclogite experienced prograde stage on the stability field of epidote + titanite and subsequent increasing pressure and temperature, which passed through the blueschist/eclogite-facies transition, until the peak $P$-$T$ condition at $550–625 \, ^\circ\text{C}$ and $2.15–2.25 \, \text{GPa}$. The retrograde stage is presented by changing mineral compositions of amphiboles from the barroisite- to the actinolite-stability field. By the presence of omphacite inclusion in the garnet and relict omphacite in the matrix, the garnet-glaucophane schist also experienced eclogite-facies at estimated peak $P$-$T$ condition $473–557 \, ^\circ\text{C}$ and $2.1–2.3 \, \text{GPa}$. The peak $P$-$T$ condition of garnet-glaucophane schist shows lower-temperature than the eclogite. The retrograde stage of garnet-glaucophane schist is also presented by changing mineral compositions of amphiboles from the barroisite- to the actinolite-stability field. Garnet amphibolite experienced peak $P$-$T$ condition at $434–443 \, ^\circ\text{C}$ and $0.7–0.8 \, \text{GPa}$ on the epidote-amphibolite facies. The results of $P$-$T$ condition of each metamorphic rock from Luk Ulo Complex show similar geothermal gradient (Figure 5).

**Metamorphic evolution of metamorphic rocks from Meratus Complex**

The pressure-temperature path of garnet-bearing epidote-barroisite schist and epidote-glaucophane schist were estimated by Setiawan (2013) using mineral parageneses, reaction textures, and mineral chemistries. The obtained pressure-temperature paths of the garnet-bearing epidote-barroisite schist have clockwise pattern (Figure 5). The rock experienced primary stage on the stability field of paragonite + glaucophane + epidote and subsequent increasing pressure and temperature to the stability field of barroisite, which was peak $P$-$T$ condition of this rock at $547–690 \, ^\circ\text{C}$ and $1.1–1.5 \, \text{GPa}$ on the albite epidote amphibolite-facies that correspond to the depth of 50–60 km. The retrograde stage is presented by changing mineral compositions of amphiboles from the Si-rich barroisite- to the actinolite-stability field through Si-poor barroisite / magnesio-hornblende / taramite / pargasite, which lies near $0.5 \, \text{GPa}$ at $350 \, ^\circ\text{C}$. In the other hand, epidote-glaucophane schist experienced wide-ranges of peak $P$-$T$ condition at $285–550 \, ^\circ\text{C}$ and $0.6–1.1 \, \text{GPa}$ on the epidote-blueschist facies, which correspond to the depth of 38–45 km. It might be concluded that metamorphic rocks from Meratus Complex experienced high-pressure condition on the blueschist-facies and high-pressure amphibolite facies (Figure 5).

**Age References of LA-ICP-MS U-Pb Zircon Age Dating of Pelitic Schists from Bantimala and Barru Complexes**

Age references using U-Pb zircon age dating of politic schists from Bantimala and Barru Complexes were performed by Setiawan (2013). Zircon grains in the garnet-glaucophane-quartz schist from Bantimala Complex are $10–50 \, \mu\text{m}$ in size, with elongated, anhedral, and broken shapes. The grains have broad oscillatory and sector zoning. All of the zircons are considered as detrital grains by its textures and also be confirmed that no metamorphic rims were observed under the CL images. Hence the zircons could only provide provenance ages of the metamorphosed sedimentary rocks. All data concentrate at $ca. 200–430 \, \text{Ma}$ (Figure 6) from 6 analyses of 6 grains. The oldest age is $431 \pm 12 \, \text{Ma}$, while the younger age is $199 \pm 6 \, \text{Ma}$ (Figure 6a).
Zircon grains in the garnet-biotite-muscovite schist from Barru Complex are 10–50 μm in size with elongated and subhedral shapes. It also has broad oscillatory zoning. Since no metamorphic rims were observed in the zircon grains, all of the zircon grains are considered as detrital grains. Hence the zircon grains can only provide provenance ages of the metamorphosed sedimentary rocks. The data concentrate at ca. 280–550 Ma, 1050 Ma, 1400–1600 Ma, 1730 Ma and 1930 Ma from 42 analyses of 42 grains (Figure 6b).

The K-Ar ages of metamorphic rocks from Bantimala and Barru Complexes are ranges from 106 to 137 Ma (Wakita et al., 1994, 1996; Parkinson et al., 1998b), which are relevant to Early to Late Cretaceous. LA-ICP-MS U-Pb detrital zircon age distribution of metamorphic rocks from Bantimala and Barru Complexes might give an information of provenance before metamorphism. Both of the complexes have similar age cluster at 280–430 Ma (Permian to Silurian; Figure 6). This indicates that the Bantimala and Barru Complexes have similar provenance of sedimentary rocks at that age (Setiawan, 2013).

The youngest ages of detrital zircon from Bantimala Complex shows 199 ± 6 Ma (Early Jurassic; Setiawan, 2013) (Figure 6). Therefore, the metamorphic age must be younger than ca. 200 Ma, and there is a possibility of metamorphism at Cretaceous and the subduction that generates the high-pressure metamorphic rocks occured during Jurassic.

**Tectonic Implication and Discussion**

The estimated P-T metamorphic evolutions of the high-pressure metamorphic rocks from central Indonesia by Setiawan (2013) are in agreement with the previous researcher. Miyazaki et al. (1996) suggested the eclogites from Bantimal Complex metamorphosed at 1.8–2.4 GPa and 580–640 ºC, which are ~38 ºC and 0.3 GPa lower temperature and pressure than estimated eclogite from Bantimala Complex in this study (Figure 5). In addition, Parkinson et al. (1998b) estimated peak P-T condition from jadeite-garnet-quart rock on ultrahigh pressure condition at >2.7 GPa and 720–760 ºC (Figure 5). However, there is no evidence of coesite grains or quartz-pseudomorph after coesite in the studied eclogites. SiO₂ inclusions in the garnet were identified by Raman spectrometry and they are quartz, not coesite. Miyazaki et al. (1998) estimated peak P-T condition of jadeite-quart-glaucophane rock from Luk Ulo Complex at 2.2 ± 0.2 GPa and 530 ± 40 ºC. The result is in range with the peak P-T condition of eclogite and garnet glaucophane schist in this study (2.1–2.3 GPa and 473–635 ºC) (Figure 5). The P-T metamorphic evolution of high-pressure metamorphic rocks from South Sulawesi and Central Java have similar low geothermal gradient (Figure 5). Peak pressure and temperature conditions of metamorphic rocks from Central Java are slightly lower than South Sulawesi (~50 °C and ~0.45 GPa). Whereas high-pressure metamorphic rocks from South Kalimantan (garnet-bearing epidote-barroisite schist), have lowest peak pressure but give higher temperature (547–690 °C) at pressure 1.1–1.5 GPa (Figure 5). The estimated peak pressure and temperature conditions of garnet amphibolite from Luk Ulo Complex, garnet-biotite-muscovite schist from Barru Complex, and garnet-bearing epidote-barroisite schist from Meratus Complex are on the retrograde trajectory part of high-pressure metamorphic rocks from Bantimala and Luk Ulo Complexes. These concluded that all of the high-pressure metamorphic rocks complexes in Central Indonesia have similar geothermal gradients.

Similar geothermal gradients of metamorphisms might be indicated that these metamorphic rocks were metamorphosed on the similar tectonic environments. The prograde P-T path of high-pressure metamorphic rocks from Bantimala and Luk Ulo Complexes show very low geothermal gradient of c. 5 °C/km (Figure 5), which can be attained only by the subduction of old and cold oceanic crust with its lithosphere and rate of shear-heating is low (Peacock, 1996; Tsujimori et al., 2006). The metamorphic
evolutions of prograde to retrograde stages are clearly show a narrow open clockwise $P-T$ path or nearly retracing of the prograde trajectory with low geothermal gradient ($c.$ 7.5 °C/km) (Figure 5). The nearly retracing of the prograde trajectory in the early retrograde stage might be explained by the exhumation processes migrated back-up of the thin slices high-pressure complex in the subduction zone and relatively parallel to the subducting plate in response to isostatic forces during a continued oceanic plate descent (Ernst, 1988; Maruyama et al., 1996; Ernst et al., 1997).

The geochemical characteristics suggest that 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 metabasic rocks from South Sulawesi and Central Java is considered as alkali basalt or sub-alkali andesite to basalt. Eclogites and blueschists from South Sulawesi contain E-MORB, N-MORB, within-plate basalt, and arc signatures that might indicate several ocean islands and proto-volcanic arc existed and subducted together with oceanic floor composed of MORB during Cretaceous. Eclogites and blueschists from Central Java mostly show within-plate basalt signatures whereas amphibolites and garnet amphibolites are characterized by MORB. The significant difference of protolith between South Sulawesi and Central Java is the occurrence of volcanic-arc protolith, which could only be found in South Sulawesi. Therefore, the proto-volcanic arc should be near the South Sulawesi area, in which the location is uncertain whether in the oceanic crust (island arc) or in the continental crust. This arc should be mixed with MORB and OIB and deeply subducted in the eclogite-facies $P-T$ condition. During the subduction, the trench-fill turbidites, volcaniclastics, and blocks of igneous rock from volcanic arc were involved into the margin of Sundaland and metamorphosed.

The exhumation mechanism is presented in Figure 7. The high-pressure metamorphic rocks in the Bantimala and Luk Ulo Complexes are enclosed in sheared serpentinite and intercalated with mélange units (Sukamto, 1982; Miyazaki et al., 1996). Whereas in the Meratus Complex, the garnet-bearing epidote-barroisite schist was not observed enclosed by serpentinite. However, the serpentinite outcrops in this area are the most abundant compared with the other terranes. The serpentinites possibly originate from the hydrated mantle wedge or from hydrothermalized slab mantle. Platt (1993) pointed out that buoyancy is the only effective force to exhume rocks from deeply subducted levels to the base of the crust. The serpentinites are extremely buoyant with respect to the oceanic crust that mainly consists of mafic rocks that have been transformed to eclogites during subduction and increasing their density, which are denser than average mantle rocks (Hermann et al., 2000). However, serpentine has a restricted $P-T$ limit in the subduction zone that about 650 °C at 2.7 GPa (Wunder and Schreyer, 1997; Agard et al., 2009), which is still in range of estimated peak $P-T$ result of eclogite (2.6–2.7 GPa at 615–678 °C). Thus, serpentinites might be counter-balancing the negative buoyancy, decouple and facilitate exhumation of the high-pressure rocks (Hermann et al., 2000; Ernst, 2010). Furthermore, the presence of mélange units intercalated with high-pressure metamorphic rocks and chaotic occurrence of different metamorphic facies (e.g., eclogite, blueschist, greenschist) (Sukamto, 1982) is typically formed in the subduction channel environment (Gerya et al., 2002; Federico et al., 2007). Based on Agard et al. (2009), the oceanic crust appears to be exhumed episodically that restricted on the specific time window. It is pointed out that the occurrence of lawsonite-bearing metamorphic rocks in Bantimala Complex (Setiawan et al., 2013a) and Luk Ulo Complex (Miyazaki et al., 1998) confirms the metamorphic condition is high-pressure and very low-temperature. The possibility exhumation condition is maintained the refrigerant condition of rock by migrated back-up of the thin slices high-pressure complex in the subduction zone and relatively parallel to the subducting plate (Figure 7).
The significantly different volume proportion of sedimentary protolith of metamorphic rocks from Jiwo Hills and Luk Ulo Complex (JH: ~100%; LU: 60%) suggest that these two metamorphic terranes, which separate 80 km, might have 1) segmented on the single subducted plate, 2) different subduction plate, 3) single subducted plate but different timing of exhumation, 4) Jiwo Hills might has possibility as subducted-microcontinent as proposed by several researchers (e.g. Clements and Hall, 2011; Hall and Sevastjanova, 2012; Satyana, 2014). In order to understand the detailed tectonic evolution of central Indonesia metamorphic terranes, the metamorphic ages and structural element on each metamorphic terranes are to be investigated in detail. However, the present results are definitely a step towards this direction.

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Table 1. Summary of metamorphic rock types in high-pressure metamorphic terranes in central Indonesia region (Setiawan, 2013).

<table>
<thead>
<tr>
<th>Complexes and metamorphic grades</th>
<th>Rock Types</th>
<th>Ultramafic rocks / Calc-silicate rock</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Polite/Felsic rocks</td>
<td>Mafic / Intermediate rocks</td>
</tr>
<tr>
<td>Bantimala Complex</td>
<td>Grt-Gln-Qz schist</td>
<td>Elogite</td>
</tr>
<tr>
<td>Eclogite, blueschist, greenschist, serpentinite</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barru Complex</td>
<td>Grt-Bt-Ms schist</td>
<td>Elogite</td>
</tr>
<tr>
<td>Amphibolite, greenschist</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Luk Ulo Complex</td>
<td>Ep-Gln-Qz schist</td>
<td>Elogite</td>
</tr>
<tr>
<td>Eclogite, blueschist, amphibolite, greenschist, serpentinite</td>
<td></td>
<td>Gt-Ms schist</td>
</tr>
<tr>
<td>Jiwo Hill</td>
<td>Phyllite</td>
<td>Ep-Gln schist</td>
</tr>
<tr>
<td>Bluenschist-greenschist, serpentinite</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meratus Complex</td>
<td>Grt-bg Ep-Brs schist</td>
<td>Ep-Brs schist</td>
</tr>
<tr>
<td>Bluenschist-amphibolite (high-P), greenschist, serpentinite</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Summary of whole rock chemistries of high-pressure metamorphic rocks from central Indonesia (Modified after Setiawan et al., 2014).

<table>
<thead>
<tr>
<th>Locality</th>
<th>Protolith</th>
<th>Metabasic rocks</th>
<th>Metasedimentary rocks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OIB</td>
<td>MORB</td>
<td>Arc</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bantimala Complex</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Barru Complex</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Luk Ulo Complex</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Jiwo Hills</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Meratus Complex</td>
<td></td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>
Figure 1. Global distribution and peak metamorphic ages of coesite- and diamond-bearing UHPM terranes and lawsonite eclogite localities. Updated and modified after Dobrzhinetskaya and Faryard (2011).
Figure 2. Tectonic setting of exhumation of high-pressure low-temperature metamorphic rocks in subduction zones. HMW: hydrated mantle wedge; HSM: hydrothermalized slab mantle (Agard et al., 2009).

Figure 3. Representative rock types and distribution of high-pressure metamorphic rocks in central Indonesia (Setiawan, 2013). Focus of the studies are in [1] Bantimala and Barru Complexes of South Sulawesi, [2] Luk Ulo Complex and Jiwo Hills of Central Java, and [3] Meratus Complex of South Kalimantan.
Figure 4. Simplified geological map with metamorphic rocks sampling points (Setiawan, 2013) of [a] Bantimala Complex (modified after Sukamto, 1982), [b] Barru Complex (modified after Sukamto, 1982), [c] Luk Ulo Complex (modified after Surono et al., 1992), and [d] Meratus Complex (modified after Sikumbang and Heryanto, 2009).
Figure 5. Compiled $P$-$T$ metamorphic evolution of high-pressure metamorphic rocks from central Indonesia (Setiawan, 2013). Petrogenetic grids from Oh and Liou (1998). The pressure-temperature paths of each metamorphic rock types were estimated using mineral parageneses, reaction textures, and mineral chemistries. Briefly explanation of $P$-$T$ path for each types of rocks are given in the text. The estimated $P$-$T$ metamorphic evolutions are in agreement with previous researcher (e.g. Miyazaki et al., 1996, 1998; Parkinson et al., 1998). The paths show relatively similar geothermal gradients that might be indicated metamorphosed on the similar tectonic environments. The nearly retracing of prograde trajectory in the early retrograde stage might be explained by exhumation processes migrated back-up the thin slices high-pressure complex in the subduction zone and relatively parallel to the subducting plate in response to isostatic forces during a continued oceanic plate descent.
Figure 6. Histograms of detrital zircon from Bantimala Complex (Setiawan, 2013) [a], Barru Complex [b], and age reference data from Malino Complex of Central Sulawesi [c]. Bantimala and Barru Complexes of South Sulawesi have similar clustering ages of 430–280 Ma. The detrital zircons from Malino Complex of Central Sulawesi (Leeuwen et al., 2006) also give similar clustering at that ages. Furthermore, it also has clustering age near 1550 Ma, which similar with Barru Complex.
Figure 7. Exhumation models of high-pressure metamorphic rocks from central Indonesia. The serpentinite, which originate from the hydrated mantle or hydrothermalized slabe mantle, might be counter-balancing the negative buoyancy, decouple and facilitate exhumation of the high-pressure metamorphic rocks. The possibility exhumation condition that maintain high-pressure low-temperature is refrigerator condition of rock by migrated back-up of the thin slices high-pressure complex in the subduction zone and relatively parallel to the subducting plate. The protolith of metamorphic rocks are various of metabasic rocks (MORB, OIB, Arc) and oceanic/continental sediment that subducted beneath Sundaland.