Peak Metamorphic Conditions of Garnet Amphibolite from Luk Ulo Complex, Central Java, Indonesia: Implications for Medium-Pressure/High-Temperature Metamorphism in the Central Indonesian Accretionary Collision Complex

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Abstract - Garnet amphibolites, which suggest medium-pressure/high-temperature (MP/HT), are widely recognized in Luk Ulo Complex, Central Java. Their occurrences associated with high-pressure/low-temperature (HP/LT; eclogite, blueschist) metamorphic rocks in the Luk Ulo Complex will provide important constraint on the geodynamic model of Central Indonesian Accretionary Collision Complex (CIACC). This study aimed to estimates P-T metamorphic condition of garnet amphibolite from Luk Ulo Complex by using mineral parageneses, thermodynamic data, and NCKFMASHO pseudosection. Prograde stage assemblages represented by inclusions in the garnet, which are garnet core, zoisite, titanite, apatite, and quartz. Mineral coexistences at the peak P-T condition are garnet rim, magnesio-hornblende, zoisite, titanite, quartz, albite, and phengite. The retrograde stage represented by secondary minerals fill the crack in the garnet and other minerals, which are chlorite and quartz. P-T metamorphic condition of garnet amphibolite can only be interpreted from the peak metamorphic stage. The temperature of the garnet amphibolite is estimated using the garnet-amphibole and garnet-phengite geothermometers. Meanwhile, the pressure condition is estimated from phengite geobarometer. The results were compared to the stability and compositions of the phases in NCKFMASHO pseudosection in order to constrain the peak P-T metamorphic conditions. It is concluded that the peak P-T metamorphic condition for garnet amphibolite is 0.9 - 1.4 GPa and 558 - 606 ºC. The estimated peak P-T metamorphic temperature is higher compared to the previously published gradient geothermal of eclogite and tourmaline-eclogite in the Luk Ulo Complex. The MP/HT (amphibolite) and HP/LT (blueschist and eclogite) metamorphic rocks could have similar metamorphic ages if both footwall and hanging wall had initially very high thermal gradients and the rate of subduction was very slow (10 km/Ma or less).

Keywords: Luk Ulo Complex, Central Java, garnet amphibolite, medium-pressure/high-temperature, metamorphic condition

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INTRODUCTION

Background

High-pressure/low-temperature (HP/LT) metamorphic rocks (blueschist- and eclogite-facies) record subduction processes and provide geodynamic evolution of convergent plate boundaries. Those rocks are exposed in Central Indonesian Accretionary Collision Complex (CIACC; Kadarusman *et al*., 2007; Figure 1a) region, particularly in Luk-Ulo (Central Java), Bantimala (South Sulawesi), and Meratus (South Kalimantan) Complexes (Miyazaki *et al*., 1998; Parkinson *et al*., 1998; Kadarusman *et al*., 2007; Setiawan *et al*., 2015; Setiawan *et al*., 2016). Recent Rb-Sr geochronological studies of various metamorphic rocks from these areas yielded Early Cretaceous ages (130 - 120 Ma in South Sulawesi and 119 - 117 Ma in Central Java; Hoffman *et al*, 2019; Böhnke *et al*., 2019). Compared to Bantimala Complex, amphibolite-facies rocks (garnet amphibolite, epidote-albite amphibolite) are widely recognized in Luk Ulo Complex, Central Java (*e.g.* Setiawan *et al*., 2013; Hoffman *et al*., 2019). They are reported to have protolith of mafic rocks (Setiawan *et al*., 2013). Furthermore, based on the previous and recent studies, this type of rock was not reported yet in the Bantimala Complex, South Sulawesi. The amphibolite-facies rocks suggest medium-pressure/high-temperature (MP/HT) metamorphic processes that are stable over a wide *P-T*

range at the transition from amphibolite through granulite to the eclogite facies. They are reported to have formed at pressure as low as 0.5 GPa and as high as 2 GPa, where plagioclase decomposes (Graham and Powell, 1984). Their occurrences associated with HP/LT metamorphic rocks in the Luk Ulo Complex will provide important constraint on the geodynamic model of CIACC. The *P-T* estimation of MP/HT metamorphic rocks in Luk Ulo Complex has not been reported. In this study, new observational results of garnet amphibolite from Luk Ulo Complex, Central Java, are presented that preserve textural information of metamorphic processes and estimate their peak *P-T* condition. Such data are important to suggest the understanding of subduction processes in Luk Ulo Complex and to contrast with other metamorphic terranes in CIACC.

Geological Outline

Cretaceous accretionary complexes including subduction-related metamorphic rocks are sporadically exposed in the central Indonesian region through Java, Kalimantan, and Sulawesi Islands (*e.g.* Parkinson *et al*., 1998; Kadarusman *et al*., 2007; Figure 1a). Most of the metamorphic rocks are exposed in the limited areas as blocks and boulders along the rivers with other units including mélanges, dismembered ophiolites, cherts, and serpentinites (Parkinson *et al*., 1998; Setiawan *et al*., 2016). The metamorphic rocks exposed in Java were described in Karangsambung and Jiwo Hills,
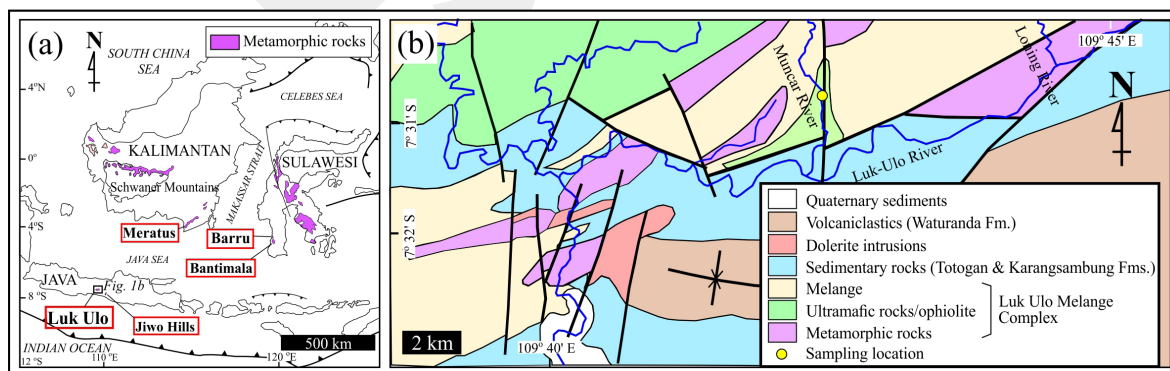

Figure 1. [a] Distribution of metamorphic rocks in Central Indonesian Accretionary Collision Complex, including Luk Ulo Complex located in Central Java. [b] Simplified geological map of Luk Ulo Complex (modified after Asikin *et al*., 2007).

Central Java, and Ciletuh, West Java (Figure 1a). In Central Java, the most significant metamorphic rocks are exposed on the Luk Ulo Complex in Karangsambung area (Figure 1b). Detailed geology of this area was described by Wakita *et al.* (1994), Miyazaki *et al.* (1998), Asikin *et al.* (2007), and Kadarusman *et al.* (2007). The Luk Ulo Complex consists of shale, sandstone, chert, basic to ultrabasic rocks, limestone, conglomerate, and metamorphic rocks. Dismembered ophiolites are well recognized in the central part of the complex (Suparka, 1988). Tectonic slices of the complex have a trend of ENE–WSW (Asikin *et al.*, 2007). Most of the metamorphic rocks in the Luk Ulo Complex are muscovite schist in which albite, quartz, and muscovite are abundant (Miyazaki *et al.*, 1998). The epidote amphibolite in which barroisite, garnet, epidote, albite, biotite, and phengite are present, intercalated with garnet-bearing pelitic schists (Miyazaki *et al.*, 1998). Small amounts of garnet amphibolite, eclogite, glaucophane rock, and jadeite-quartz-glaucophane rock occur as tectonic blocks embedded in sheared serpentinite (Miyazaki *et al.*, 1998).

High-Pressure Metamorphic Rocks in Luk Ulo Complex

The *P-T* conditions of the metamorphic rocks have been reported by Miyazaki *et al.* (1998) and Kadarusman *et al.* (2007). Miyazaki *et al.* (1998) estimated the peak *P-T* condition of jadeite-quartz-glaucophane rock at 2.2 ± 0.2 GPa and 530 ± 40 ºC. Meanwhile, Kadarusman *et al.* (2007) estimated eclogites metamorphosed at low temperature (2.0 - 2.3 GPa at 365 - 410 ºC) with low geothermal gradient (~6 ºC/km) and experienced both of counter-clockwise and clockwise *P-T* path for tourmaline eclogite and normal eclogite, respectively resulted by a subduction-channel environment. Rubidium-Sr dating of phengite, omphacite, glaucophane, and epidote from one eclogite and two epidote-glaucophane schists yielded 119 - 118 Ma ($\pm$ 0.6 - 0.8 Ma), whereas one epidote-amphibolite yielded 117 Ma $\pm$ 0.6 Ma (Hoffman *et al.*, 2019). These ages are in agreement with the previous reported K-Ar of quartz-mica schist that yielded 117.1 ± 1.1 Ma, 115 ± 6 Ma, and 110 ± 6 Ma (Ketner *et al.*, 1976; Miyazaki *et al.* 1998), whereas the dating of phengite from jadeite-glaucophane-quartz rock and eclogite yielded older ages of 119 ± 2 Ma and 124 ± 2 Ma (Parkinson *et al.*, 1998). Furthermore, the age data from radiolaria in the chert of this area indicate deposition age of Early to Late Cretaceous (Wakita *et al.*, 1994).

SAMPLING AND ANALYTICAL METHODS

Field Occurrences and Metamorphic Rock Samples

Most of the metamorphic rocks are found as river boulders in Muncar, Loning, and Luk Ulo Rivers (Figures 1b and 2a) as most of the outcrops have already experienced weathering due to the tropical condition. The HP/LT (eclogite and garnet-glaucophane rock) and MP/HT (garnet amphibolite, amphibolite) metamorphic rocks predominantly occur as boulders on the rivers in the western part of the complex (Muncar and Luk Ulo Rivers; Figure 1b and Figure 2a respectively). While in the eastern part of the complex (Loning River; Figure 1b) mostly medium- to low-grade metamorphic rocks could be found. The boundary of these rock types is between Muncar and Loning Rivers. The metamorphic rocks occurring in this complex includes HP metabasites (eclogite, garnet-glaucophane schist, and glaucophane schist), MP metabasites (amphibolite, garnet amphibolite), and pelitic schist (garnet-muscovite schist, muscovite schist). Other variations of low-grade schists found in this area are garnet-albite-actinolite schist, garnet-biotite-muscovite schist, apatite-quartz-muscovite schist, and chlorite-actinolite schist.

Totally fourteen samples of garnet amphibolite (twelve samples) and amphibolites (two samples) were collected from Muncar River during the fieldwork (Table 1; Figures 2a and 2b). All samples were prepared for thin section, then for microscopic studies using polarization microscope. Furthermore, most representative sample
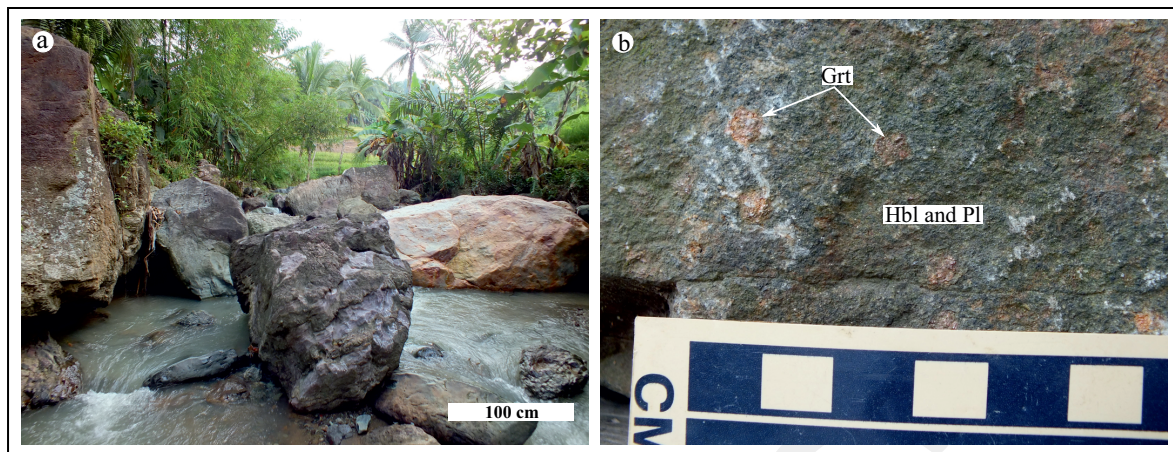
Figure 2. [a] Accretionary tectonic blocks as river boulders in the Muncar River. [b] Close up image of garnet amphibolite, consisting of major garnet mineral (Grt; red) and hornblende (Hbl; green), with or without plagioclase (Pl; white).

Table 1. Major and Minor Mineral Assemblages of Garnet Amphibolites and Amphibolites in Luk Ulo Complex

Sample No	Rock Name	Major Mineral						Minor Mineral		Secondary
		Grt	Ph	Qz	Hbl	Ep /Zo	Pl/ Ab	Rt	Ttn	
18T02G*	Grt amphibolite	⬤	▢	–	⊙	△	△	–	△	Chl
18T02H	Amphibolite	–	▢	–	⊙	⬤	△	±	▢	Chl
18T03A	Amphibolite	–	–	▢	⊙	⬤	⬤	–	△	Chl
18T03B	Amphibolite	–	▢	–	⊙	⬤	△	–	△	Chl
18T03C	Grt amphibolite	⬤	▢	△	⊙	△	△	–	△	Chl
18T03D	Grt amphibolite	⬤	±	△	⊙	△	⬤	±	△	Chl
18T03E	Grt amphibolite	▢	▢	–	⊙	△	△	±	▢	Chl
18T03K	Grt amphibolite	⬤	▢	–	⊙	⬤	△	–	△	Chl
19T01F	Grt amphibolite	⬤	▢	▢	⊙	⬤	△	–	△	Chl
19T01G	Grt amphibolite	▢	▢	△	⊙	△	⬤	±	▢	Chl
19T01H	Grt amphibolite	⬤	▢	△	⊙	△	△	±	▢	Chl
19T01J	Grt amphibolite	▢	▢	△	⊙	△	△	–	△	Chl
19T01K	Grt amphibolite	⬤	▢	△	⊙	△	⬤	–	△	Chl
KS01	Grt amphibolite	⬤	±	▢	⊙	△	△	–	△	Chl

⊙ Abundant, ⬤ rich, △ moderate, ▢ poor, – absent, ± occur only in some samples. Grt = garnet, Ph = phengite, Qz = quartz, Hbl = hornblende, Ep = epidote, Zo = zoisite, Pl = plagioclase, Ab = albite, Rt = rutile, Ttn = titanite, Chl = chlorite

*) XRF analysis for Pseudosection

with least hydration and alteration (18T02G) was selected for mineral chemistry analyses using EPMA and the whole rock chemical composition for pseudosection analysis using XRF.

Analytical Methods

Mineral chemistries of representative samples were analyzed with JEOL JXA-8530F hyperprobe EPMA and JEOL JED2140-JSM5301S scan-ning electron microscope with energy dispersive spectrometry system (SEM-EDS) in Kyushu University, Japan. The analytical conditions of EPMA were set on accelerating voltage of 15 kV, probe current of 0.4 nA for EDS and 12 nA, and 2 μm beam diameter for EPMA. Natural mineral samples (ASTIMEX-MINM-53) and synthesized oxide samples (P and H Block No. SP00076) were used as standards for the quantitative chemical

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analyses. The results were processed with ZAF correction method. The analytical conditions of X-ray mapping included 15 kV accelerating voltage and 50 nA probe current. Major, trace, and rare-earth element composition of representative samples (18T02G) were analyzed by X-ray fluorescence spectrometry (XRF) using Rigaku ZSX Primus II on a fused glass disk (sample: flux ratio, 1:2) to generate pseudosection.

Mineral chemistry analyses and formulae of garnet, phengite, amphibole, and epidote were calculated using algorithms suggested by Droop (1987), Rieder *et al*. (1998), Leake *et al*. (1997), and Armbruster *et al*. (2006), respectively. Furthermore, chemical analyses and formulae of titanite and chlorite were calculated following Deer *et al*. (1992). *P-T* condition of metamorphic rock was estimated by using mineral parageneses, thermodynamic data, and pseudosection. Mineral parageneses were provided by combining textural observation of metamorphic rocks using polarization microscope and mineral analyses obtained by EPMA. The geothermobarometry is based on data from laboratory experiments and thermodynamic calculations, which was facilitated by several reliable publications (*e.g.* phengite barometer by Massone and Schreyer, 1987; garnet-amphibole geothermometer by Graham and Powell, 1984; *etc*.). In order to constrain the peak *P-T* conditions, the mineral parageneses were compared to the stability and phases in pseudosection using Perple_X software (Connolly, 2005). All of mineral abbreviation in this paper follows Whitney and Evans (2010).

RESULTS AND ANALYSIS

Sample Descriptions

Petrographical observation reveals that garnet amphibolite has granoblastic texture and mainly consists of garnet, hornblende, zoisite, albite, phengite, titanite, with or without quartz (Figure 3a; Table 1). Sub-idioblastic coarse-grained garnet has porphyroblastic texture with size of 1–2 mm in diameter (Figures 3a, 3b, and 3c). Garnet core is

clouded by fluid and mineral inclusions (Figures 3b, 3c, and 3d). Whereas garnet rim has helicoidal inclusions of quartz, titanite, zoisite, and apatite (Figures 3e and 3f). Quartz, hornblende (0.1–1 mm), zoisite (0.1–0.5 mm), and titanite (<0.2 mm) are abundant in the matrix (Figures 3a, 3b, and 3f). Greenish colour hornblende has grano-nematoblastic texture with size of 0.1 - 1 mm in diameter (Figure 3a). Several zoisite grains (0.1 - 0.5 mm in diameter) in the matrix have allanite in the core portion. Phengite grains show direct contact with garnet (Figure 3f). Most of the phengite are replaced by chlorite (Figure 3f). Chlorite and albite fill the garnet cracks in replacing other minerals.

Mineral Chemistries
Garnet

Representative mineral chemistry analyses of garnet, phengite, epidote/zoisite, and other minerals are presented in Table 2. Fe^{3+} contents in garnet were calculated using algorithms suggested by Droop (1987). Garnet in the garnet amphibolite was analyzed for chemical mapping on the Si, Mn, Al, Mg, Fe, Na, and Ti elements (Figure 4). Subhedral garnet obviously has a strong chemical zoning of the Ca and Mn with slight zoning of the Fe and Mg elements (Figure 5a). The inclusions of zoisite, titanite, and apatite in the garnet are clearly identified particularly by Ca and Ti elements (Figure 5a). Based on the chemical zonation, core portion of garnet has higher spessartine and almandine, with lower grossular contents (Prp_{11-12}, Alm_{48-51}, Sps_{14-18}, Grs_{31-33}; Figure 5a) than mantle portion (Prp_{11-12}, Alm_{51-53}, Sps_{2-5}, Grs_{31-36}; Figure 5a). The rim portion of the garnet shows increasing of grossular but decreasing of almandine and spessartine contents (Prp_{10-11}, Alm_{49-51}, Sps_{1-3}, Grs_{36-39}; Figure 5a) compared to the mantle portion. Spessartine component is relatively constant from core to rim (Figure 5a).

Phengite

Phengite formulae have been calculated to eleven oxygen atoms with assuming all iron to be Fe^{2+} (Rieder *et al*., 1998). Phengite in the
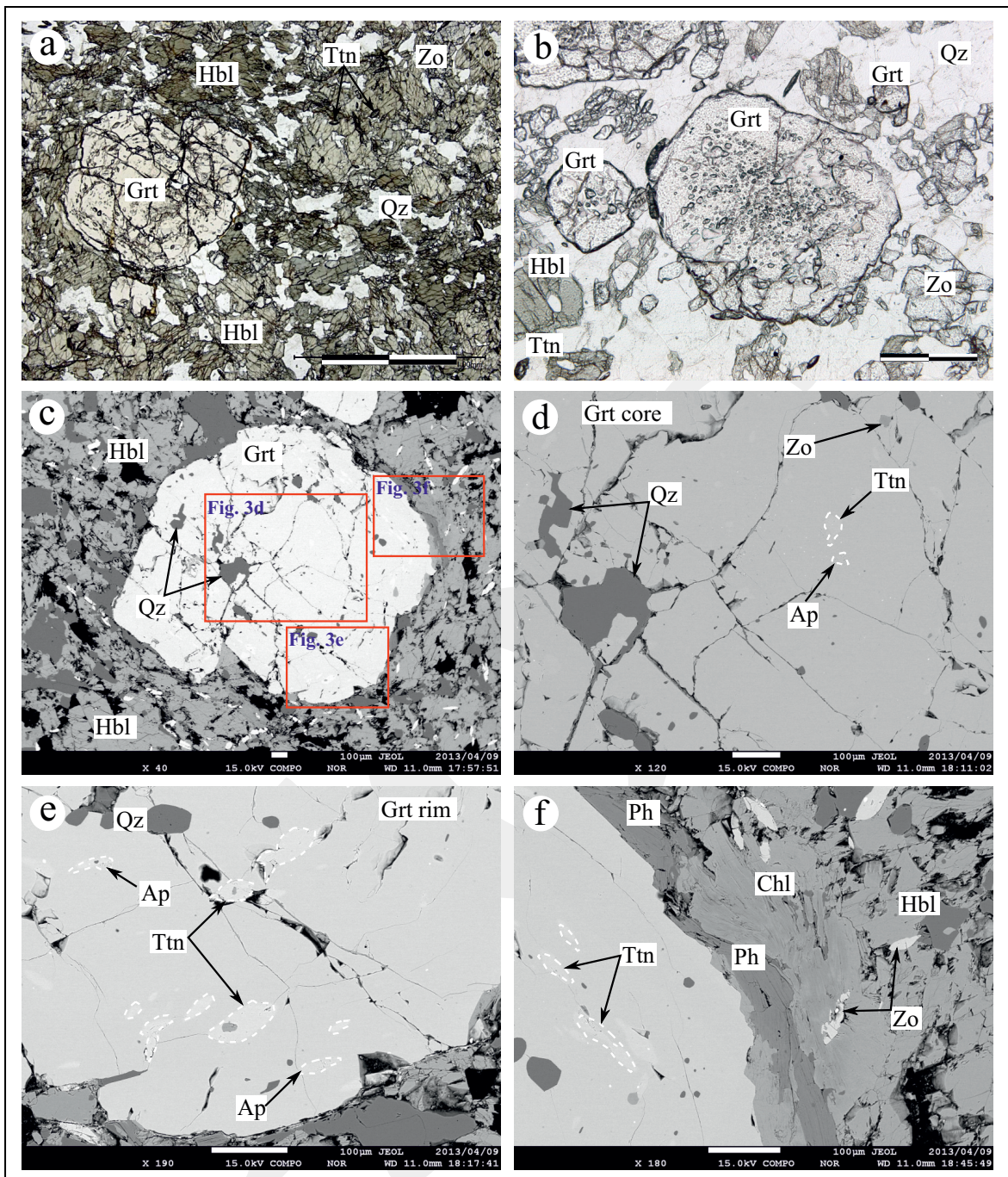
Figure 3. Photomicrographs and back-scattered electron images of garnet amphibolite. Scale bar correspond to 1 mm except for back-scattered images. [a] Garnet amphibolite mainly consists of garnet (Grt), hornblende (Hbl), zoisite (Zo), titanite (Ttn), and quartz (Qz). [b] Garnet core is crowded by mineral and fluid inclusions. [c, d, e] Mineral inclusions in garnet core and rim are titanite, apatite (Ap), zoisite, and quartz. [f] Garnet edge still preserves euhedral shape in contact with phengite (Ph) with chlorite (Chl) as secondary mineral.

garnet amphibolite only occurs in the matrix. It shows direct contact with garnet (Figure 3f). The phengite has X_{Si} values ranging from 0.578 to 0.585 (Figure 5b). Whereas X_{Mg} values range from 0.664–0.692 (Figure 5b).

Amphibole

Nomenclatures and calculated compositions of the amphiboles follow Leake *et al*. (1997). All of the amphiboles in the garnet amphibolite are magnesio-hornblende (X_{Mg} = 0.66 - 0.70 and Si =

Table 2. Representative Microprobe Analyses of Garnet, Phengite, Amphibole, Epidote, and Titanite in Garnet Amphibolite

Mineral Position	Garnet			Phengite		Amphibole		Epidote		Titanite	
	Core	Mantle	Rim‡	Matrix	Matrix‡	Matrix core‡	Matrix rim	Incl.	Matrix	Matrix	Matrix
SiO_2	38.03	38.14	38.34	47.29	47.97	45.66	45.39	38.37	38.53	30.05	29.93
TiO_2	0.14	0.12	0.05	0.24	0.14	0.42	0.35	0.26	0.09	38.54	37.89
Al_2O_3	21.09	21.56	21.30	28.49	28.74	12.96	13.21	28.50	31.12	1.16	1.49
Cr_2O_3	0.00	0.02	0.03	0.00	0.02	0.08	0.00	0.00	0.07	0.00	0.00
FeO	24.29	23.88	22.60	2.13	1.98	12.54	12.32	-	-	-	-
Fe_2O_3	-	-	-	-	-	-	-	5.35	2.14	0.83	0.76
MnO	2.69	1.72	0.77	0.06	0.00	0.06	0.01	0.10	0.01	0.05	0.01
MgO	2.92	2.97	2.61	2.36	2.50	11.42	11.48	0.07	0.04	0.01	0.03
CaO	10.84	11.79	14.20	0.03	0.11	9.77	9.82	23.31	24.12	28.02	28.39
Na_2O	0.00	0.03	0.00	0.81	0.84	2.93	2.90	0.01	0.00	0.01	0.04
K_2O	0.00	0.00	0.00	9.77	9.74	0.36	0.38	0.01	0.00	0.00	0.01
Total	61.97	62.09	61.56	91.19	92.05	96.19	95.86	95.97	96.11	98.68	98.54
O	12	12	12	11	11	23	23	12.5	12.5	5	5
Si	3.00	2.99	3.01	3.30	3.31	6.68	6.66	3.02	3.00	1.02	0.99
Ti	0.01	0.01	0.00	0.01	0.01	0.05	0.04	0.02	0.01	0.90	0.95
Al	1.96	1.99	1.97	2.34	2.34	2.23	2.28	2.65	2.85	0.09	0.06
Cr	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
Fe^{2+}	1.60	1.56	1.48	0.12	0.11	1.19	1.17	0.00	0.00	0.00	0.00
Fe^{3+}	0.00	0.00	0.00	0.00	0.00	0.34	0.34	0.32	0.13	0.06	0.02
Mn	0.18	0.11	0.05	0.00	0.00	0.01	0.00	0.01	0.00	0.01	0.00
Mg	0.34	0.35	0.30	0.25	0.26	2.49	2.51	0.01	0.00	0.00	0.00
Ca	0.92	0.99	1.19	0.00	0.01	1.53	1.54	1.97	2.01	0.96	1.01
Na	0.00	0.00	0.00	0.11	0.11	0.83	0.82	0.00	0.00	0.00	0.00
K	0.00	0.00	0.00	0.87	0.86	0.07	0.07	0.00	0.00	0.00	0.00
Total cation	5.01	5.02	5.00	7.01	6.99	15.43	15.44	7.98	8.00	3.04	3.03
Prp (%)	11.28	11.50	10.06	-	-	-	-	-	-	-	-
Alm (%)	52.68	51.88	48.89	-	-	-	-	-	-	-	-
Sps (%)	5.91	3.79	1.69	-	-	-	-	-	-	-	-
Grs (%)	30.13	32.83	39.36	-	-	-	-	-	-	-	-
Si/(Si + Al)	-	-	-	0.58	0.59	-	-	-	-	-	-
Na/(Na + Ca)	-	-	-	-	-	0.35	0.35	-	-	-	-
Mg/(Mg + Fe^{2+})	0.18	0.18	0.17	-	-	0.68	0.68	-	-	-	-
Fe^{3+}/(Fe^{3+} + Al)	-	-	-	-	-	-	-	0.11	0.04	-	-

‡ Data used for calculation peak P-T condition

6.53 - 6.64; Figure 5c). There is no chemical zoning identified on the amphiboles.

Epidote/Zoisite

Cation formulae of epidote have been calculated assuming all iron to be Fe^{3+} (Armbruster *et al.*, 2006). Zoisite in the garnet amphibolite shows low pistacite values in the matrix (X_{Fe}^{3+}

= 0.03 - 0.07) compared to the inclusion in the garnet (X_{Fe}^{3+} = 0.11 - 0.13).

Other Minerals

Titanite in this rock also occurs as inclusions in the garnet rim and in the matrix, which have similar ranges of X_{Al} = 0.04 - 0.07. Chlorite occurs along cracks of garnet and replacing other miner-
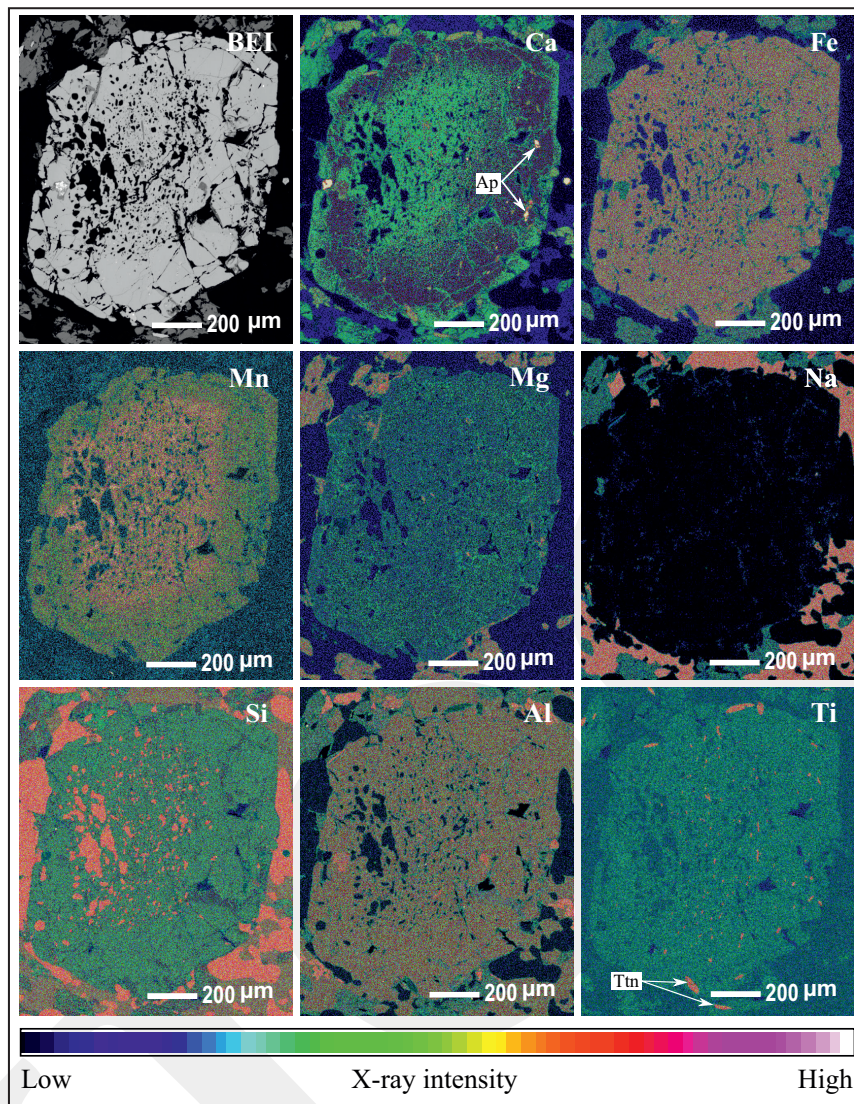
Figure 4. Backscattered image and X-ray maps of Ca, Fe, Mn, Mg, Na, Si, Al, and Ti. The chemical zonation of core and rim clearly defined by the Ca and Mn with slight zoning of the Fe and Mg elements. Ap = apatite, Ttn = titanite.

als, which range of X_{Fe} = 0.42 - 0.49. The mineral chemistry algorithm of titanite and chlorite is following Deer *et al*. (1992).

Pressure-Temperature Conditions for the Garnet Amphibolite

Based on the textural and mineral chemistry results, the metamorphic evolution of the garnet amphibolite is divided into three stages: prograde, peak, and retrograde ones (Table 3). Prograde stage assemblages represented by the inclusions in the garnet are garnet (core), zoisite, titanite, apatite, and quartz. Mineral coexistences at the peak *P-T* condition are garnet rim, magnesio-

hornblende, zoisite, titanite, quartz, albite, and phengite. While retrograde stage represented by the secondary minerals fill the crack in the garnet and other minerals, which are chlorite and quartz.

Due to the limiting of mineral parageneses in each stage (Table 3), *P-T* condition can only be interpreted from the peak metamorphic stage. The temperature condition of the garnet amphibolite is estimated using the garnet-amphibole geothermometer formulated by Graham and Powell (1984) and garnet-phengite geothermometer formulated by Green and Hellman (1982). The results give temperature ranging from 558 - 606 °C assuming pressure of 0.9 GPa (Figure 6a). The
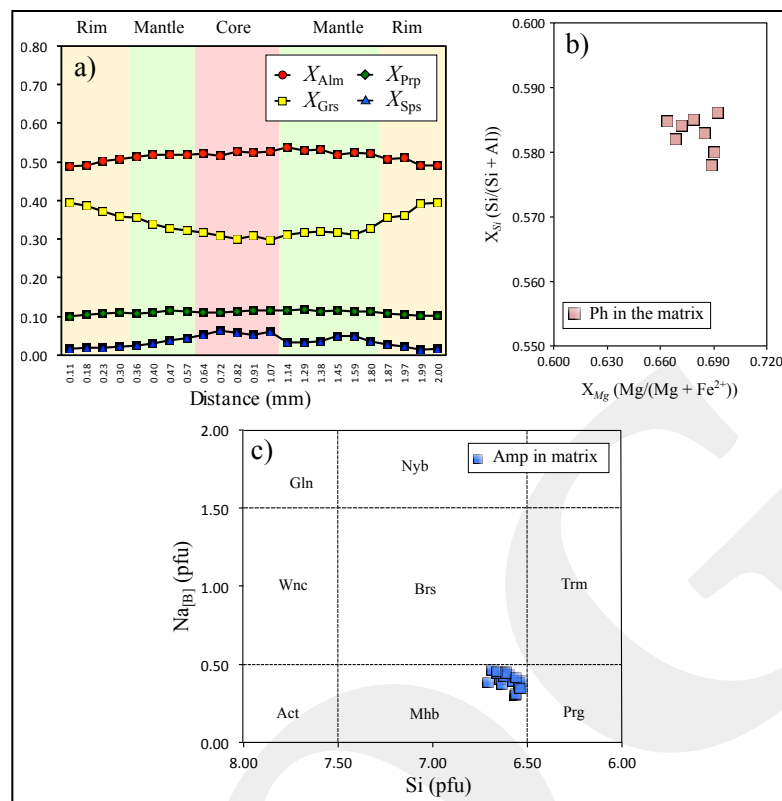
Figure 5. Garnet, phengite, and amphibole chemical characteristics. [a] Garnet core has higher spessartine and almandine, with lower grossular contents than mantle portion The rim portion shows increasing of grossular but decreasing of almandine and spessartine contents compared to the core and mantle portions. Spessartine component is relatively constant from core to rim. [b] The phengite has X_{Si} values ranging from 0.578 to 0.585 whereas X_{Mg} values ranging from 0.664 - 0.692. [c] All of the amphibole grains in the matrix are plotted on the magnesio-hornblende field.

Table 3. Mineral Parageneses of the Garnet Amphibolite at Each Stage

Rock Types	Metamorphic stage	Metamorphic facies	Mineral parageneses
Gtr amphibolite	Inc. in Grt	-	Gtr (core) + Zo + Ttn + Ap +Qz
	Peak *P-T*	Ep Amphibolite	Gtr (rim) + Mhb + Ph + Zo + Ab + Ttn +Qz
	Retrograde	Greenschist	Chl + Qz

Grt = garnet, Ph = phengite, Qz = quartz, Mhb = magnesio-hornblende, Zo = zoisite, Ab = albite, Ttn = titanite, Chl = chlorite, Ap = apatite

pressure is estimated using experimental phengite geobarometer formulated by Massone and Schreyer (1987). Since this phengite geobarometer originally proposed on the limiting assemblage with K-feldspar and phlogophite, which are not observed in this rock, the estimated pressure is considered as a minimum pressure of this rock. The result gives range of minimum pressure at 0.9 GPa (Figure 6a). Petrogenetic grid of Oh and Liou (1998) suggests this *P-T* conditions are plotted on the epidote amphibolite- and amphibolite-facies. Chlorite presents as secondary minerals filling in

the cracks of garnet and other minerals. Therefore, this rock should experience retrogression in the greenschist-facies.

In order to constrain the peak *P-T* conditions, the observed mineral assemblages, mineral composition, and the textural relationship were compared with the stability and compositions of the phases in pseudosection. The pseudosection modeling was computed using free-energy minimization of Perple_X software (Connolly, 2005) and end-member thermodynamic data from Holland and Powell (1998) in the system
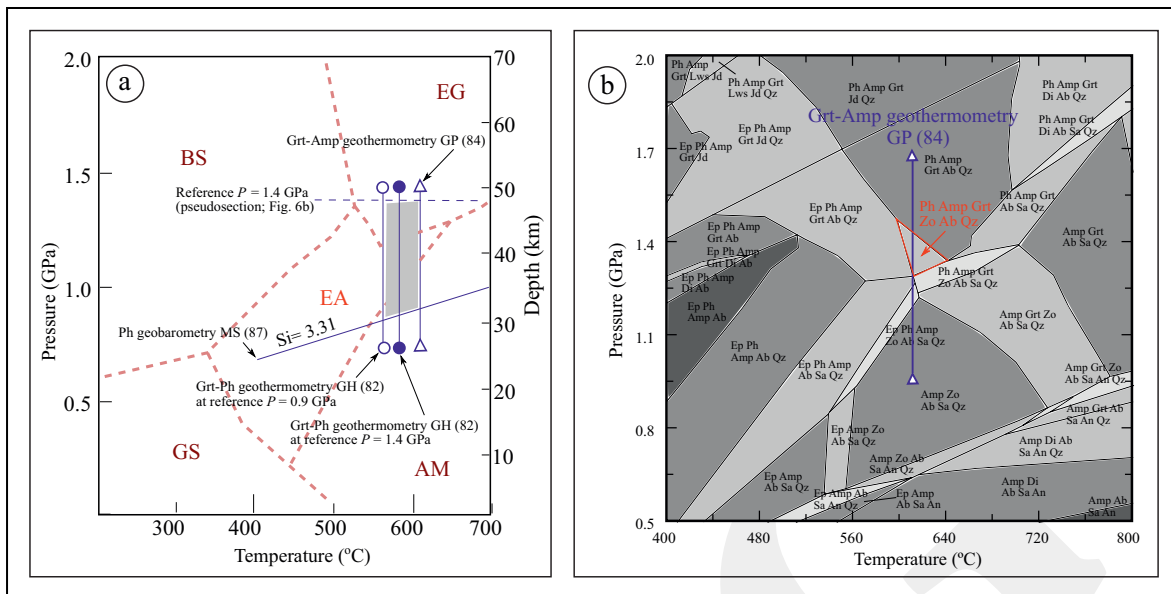
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Figure 6. [a] P-T diagram of garnet amphibolite from Luk Ulo Complex. [b] NCKFMASHO pseudosection with excess of H₂O content calculates as saturated component. The petrogenetic grids are from Oh and Liou (1998), the abbreviations as follows; BS = blueschist, EG = eclogite, EA = epidote amphibolite, AM = amphibolite, GS = greenschist facies. Garnet-amphibole geothermometry open triangle from Graham and Powell (1984) and garnet-phengite geothermometry open circle from Green and Hellman (1982). Geobarometry of phengite from Massone and Schreyer (1987).

Na_2O–CaO–K_2O–FeO–MgO–Al_2O_3–SiO_2–H_2O–Fe_2O_3 (NCKFMASHO) with excess of H_2O content calculated as saturated component. The end-member thermodynamic data and solution models are summarized in Table 4. The whole rock chemical composition of garnet amphibolite with sample number 18T02G (Table 5) is used in this calculation. The Fe_2O_3 concentration is assumed and ferric-ferrous ratio [$Fe^{2+}/(Fe^{2+} + Fe^{3+})$] of 0.86 is used as proposed by Presnall *et al.* (1979) for basaltic MORB. Therefore, analyses using whole rock chemistry with assumed ferric-ferrous should be semiquantitative.

The peak assemblage of the garnet amphibolite is garnet, magnesio-hornblende, phengite,

zoisite, albite, titanite, and quartz. The titanite is not shown in the NCKFMASHO pseudosection, therefore the assemblage yields *P-T* conditions from 1.3 - 1.5 GPa and 600 - 640 ºC (Figure 6b). The garnet-amphibole thermometer (Green and Powell, 1984) yields 606 ºC (P = constant). Based on the NCKFMASHO pseudosection, the garnet + zoisite + phengite + amphibole + albite + phengite + quartz appear around 1.3 - 1.4 GPa at 606 ºC (Figure 6b). The *P-T* conditions are speculative because the pressure for this stage cannot be estimated. The estimated *P-T* conditions by pseudosection (1.3 - 1.4 GPa and 606 ºC) are higher-pressure condition than estimated by normal *P-T* diagram (~0.9 GPa and 558 - 606 ºC).

Table 4. Thermodynamic Data Solution. Sources: (1) Diener *et al*. (2007); (2) Holland *et al*. (1998); (3) Holland and Powell (1998). Abbreviation see Table 1.

Symbol	Solution	Formulae	Source
Amp	Amphibole	$Ca_{2(y+u+v)}Na_{u+2(w+z)}[Mg_xFe_{1-x}]_{7-3u-2v-4(w+z)}Fe^{3+}_{2z}Al_{4y+3v+2w}Si_{8-(y+v)}O_{22}(OH)_2$, $u+V+w+y+z\leq1$	(1)
Ep	Epidote	$Ca_2Al_{3-2x}Fe_{2x}Si_3O_{12}OH$	(2), (3)
Grt	Garnet	$Fe_{3x}Ca_{3y}Mg_{3z}Mn_{3(1-x-y-z)}Al_2Si_3O_{12}$, $x+y+z\leq1$	(3)
Ph	Mica	$K_xNa_{1-x}Mg_yFe_zAl_{3-2(y+z)}Si_{3+y+z}O_{10}(OH)_2$	(2), (3)

Unless otherwise noted, the compositional variables of x, y, and z may varybetween zero and unity and are determined as a function of the computational variables by free-energy minimization.

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Table 5. Whole Rock Chemistry of Garnet Amphibolite with Sample Number 18T02G

Sample No Rock Type Unit	18T02G Grt-amphibolite (wt%)
SiO_2	50.49
TiO_2	1.62
Al_2O_3	13.86
Fe_2O_3*	12.67
MnO	0.17
MgO	6.90
CaO	10.76
Na_2O	2.75
K_2O	0.09
P_2O_5	0.14
LOI	0.85
TOTAL	100.31

Fe_2O_3*, total Fe as Fe_2O_3, LOI means loss-on-ignition

However, both of the results are still in agreement since the estimated pressure of 0.9 GPa by phengite barometer from Massone and Shreyer (1987) is considered as a minimum pressure condition in this rock. Therefore, it might be concluded that the estimated peak *P-T* condition for garnet amphibolite is 0.9 - 1.4 GPa and 558 - 606 ºC (Figure 6a).

DISCUSSION

Estimated peak P-T metamorphic condition for garnet amphibolite in Luk Ulo is at 0.9 - 1.4 GPa and 558 - 606 ºC. The estimated peak *P-T* temperature is higher compared to the estimated gradient geothermal of eclogite and tourmaline-eclogite (Figure 7; Kadarusman *et al.*, 2007). It could be in agreement with peak P-T condition of Jd-Qz-Gln rock (Figure 7; Miyazaki *et al.*, 1998) assuming that the exhumation is clockwise *P-T* path. However in this study, any relict of HP metamorphic mineral coexist could not be found in the inclusion or early stage on garnet amphibolite. As the result, only peak P-T condition, both trajectory of clockwise and counterclockwise P-T paths are still possible in Luk Ulo Complex.

The occurence of amphibolite and granulite facies (HT metamorphic rocks) in the subduc-

tion zone metamorphism is mostly considered as subduction "sole". Subduction sole occurs when the subduction slab beneath a hot hanging-wall during the initiation of subduction commences, conduction of heat downward from the hanging-wall warms up the subducting slab and creating an inverted thermal gradient (Peacock, 1987). It occurs during the initiation of the subduction zone, which mean it has the oldest ages in the HP metamorphic terrane (Wakabayashi, 1990). Therefore, the ophiolites in this setting commonly have a sole of HT metamorphic rocks along their lower boundaries [*e.g.* Fransiscan Complex, California (Peacock, 1987; Wakabayashi, 1990; Anczkiewicz *et al.*, 2004), Semail Ophiolite, Oman (Gnos, 1998), and, Nagalan Ophiolite Complex, India (Bhowmik and Ao, 2016)]. How-
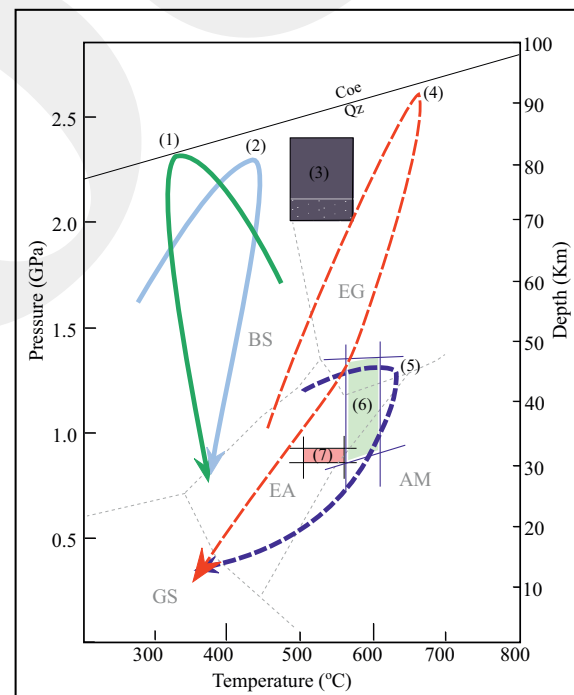

Figure 7. Compiled P-T conditions of metamorphic rocks from CIACC. Estimated P-T metamorphic condition of: (1) counter-clockwise tourmaline eclogite and (2) clockwise eclogite from Luk Ulo Complex (Kadarusman *et al.*, 2007); (3) jadeite-quartz-glaucophane rock from Luk Ulo Complex (Miyazaki *et al.*, 1998); (4) eclogite from Bantimala Complex (Setiawan *et al.*, 2016); (5) garnet bg. epidote-barroisite schist from Meratus Complex (Setiawan *et al.*, 2015); (6) garnet amphibolite from Luk Ulo Complex (this study); (7) garnet-biotite-muscovite schist from Barru Complex (Setiawan *et al.*, 2014). Explanations of petrogenetic grids see Figure 6a.

ever, based on the recent study, the amphibolite and HP metamorphic rocks (eclogite and blueschist) in Luk Ulo Complex have similar Rb-Sr ages (119 - 118 Ma for HP/LT metamorphic rocks and 117 Ma for epidote amphibolite; Hoffman *et al.*, 2019). The only condition under which temperatures corresponding to amphibolite and HP/LT metamorphic rocks could have similar metamorphic ages if both footwall and hanging wall had initially very high thermal gradients and the rate of subduction was very slow (10 km/ Ma or less; Anczkiewicz *et al.*, 2004). Hence, the present situation that amphibolite rocks sit directly to the blueschist and eclogite rocks might not derive from different tectonic blocks but mixing by tectonic processes accompanying exhumation.

Compared to other metamorphic terranes in CIACC (Figure 1a), the MP/HT metamorphic rocks were not reported yet in the Bantimala Complex, South Sulawesi. However, these types of rock are recognized in other metamorphic complexes in South Sulawesi namely as Barru (garnet-biotite-muscovite schist; Setiawan *et al.*, 2014) and Biru Complexes (epidote-garnet amphibolite; Jaya *et al.*, 2017). In the Meratus Complex, this type of rock is represented by garnet-bearing epidote-barroisite schist (Setiawan *et al.*, 2015).

The estimated peak *P-T* temperature of garnet amphibolite is higher compared to the estimated retrograde trajectory path of eclogites from the Bantimala Complex (Figure 7; Setiawan *et al.*, 2016). Rubidium-Sr white mica ages of HP/LT rocks in Bantimala Complex yielded 130 - 120 Ma (Böhnke *et al.*, 2019) which is older than Luk Ulo Complex (119 - 118 Ma; Hoffman *et al.*, 2019). The *P-T* path of HP/LT metamorphic rocks from Bantimala and Luk Ulo Complexes also differ from the others (Kadarusman *et al.*, 2017; Setiawan *et al.*, 2016). The result of garnet amphibolite peak metamorphic condition emphasizes the differences between these two complexes. Consequently, strike variations of metamorphic terranes with the specific P-T

stages and ages record differences in subduction zone geometry and subduction rates of a single converging system. The variations along strike subduction depend on many factors including subduction rates, obliquity along trenches, fluid flow, and subducting slab ages (Plunder *et al.*, 2018). However, these aspects need further attention in future studies.

Conclusion

This study aimed to estimate *P-T* condition of garnet amphibolite in the Luk Ulo Complex. Such data give significant information constraint to metamorphic evolution in the Luk Ulo Complex. Furthermore, the results are compared to other metamorphic terranes in CIACC. The main results are summarized as follows:

The P-T metamorphic condition of garnet amphibolite from Luk Ulo Complex is estimated by using mineral parageneses, thermodynamic data, and pseudosection. The estimated peak P-T condition is at 0.9 - 1.4 GPa and 558 - 606 ºC.

The estimated peak P-T metamorphic temperature of garnet amphibolite is higher compared to the estimated gradient geothermal of eclogite and tourmaline-eclogite in the Luk Ulo Complex.

The MP/HT (amphibolite) and HP/LT (eclogite and blueschist) metamorphic rocks in the Luk Ulo Complex would have similar Rb-Sr ages (119 - 118 Ma for HP/LT metamorphic rocks and 117 Ma for epidote amphibolite) if both footwall and hanging wall had initially very high thermal gradients and the rate of subduction was very slow (10 km/Ma or less).

The estimated peak P-T temperature of garnet amphibolite in the Luk Ulo Complex is higher compared to the estimated retrograde trajectory path of eclogites from the Bantimala Complex. Hence, strike variations of metamorphic terranes, with the specific P-T stages and ages, record differences in subduction zone geometry and subduction rates of a single converging system of CIACC.

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