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METAMORPHIC EVOLUTION OF GARNET–BIOTITE–MUSCOVITE SCHIST FROM BARRU COMPLEX IN SOUTH SULAWESI, INDONESIA

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Abstract

This paper explains the first report in metamorphic evolution of pelitic schist from Barru Complex in South Sulawesi, Indonesia. Garnet-biotite-muscovite schist was examined petrologically to assess the metamorphic evolution history, which has implications on tectonic condition of this region. The rock mainly composed of garnet, biotite, muscovite, epidote, quartz, rutile, hematite, and plagioclase. Inclusions in the garnet preserve records of prograde stage of this rock, which are epidote, titanite, quartz, and apatite. Garnet, biotite, muscovite, quartz, rutile, and plagioclase are concluded as equilibrium assemblages at peak P-T condition of this rock, which estimated at 501–562 °C and 0.89–0.97 GPa. The result is still on the ranges of the estimated geothermal gradient P-T path of eclogite from Bantimala Complex. Similar geothermal gradients of metamorphisms might be indicated that these metamorphic rocks were metamorphosed on the similar tectonic environments.
Keywords: *Pelitic schist, Barru Complex, South Sulawesi, metamorphic evolution.*

1 Introduction

Accretionary units and regional metamorphic rocks crop out in South Sulawesi. Those are exposed in restricted area namely Bantimala and Barru Complexes. Bantimala Complex is well-known to be worldwide outcrop of high-pressure and ultra-high pressure metamorphic rocks (eclogite, blueschist; Sukamto, 1982; Wakita *et al.*, 1994a, 1996; Miyazaki *et al.*, 1996; Parkinson *et al.*, 1998; Setiawan, 2013). Whereas 30 km north of this complex, low- to medium-grade metamorphic rocks expose in more restricted area namely as Barru Complex. However, there were lacks of publications about metamorphic rocks from Barru Complex in particularly their metamorphic evolution.

This paper explains the occurrence of garnet-biotite-muscovite schist from Barru Complex. Detailed assessment of chemical zonation and inclusion texture of euhedral garnet and associated minerals are well correlated to the metamorphic evolution history. Furthermore, the manuscript attempts to interpret the tectonic implications of this metamorphic rock in comparison with other terranes in South Sulawesi. Mineral abbreviation in this paper follows Whitney and Evans (2010).

2 Geological outline

Cretaceous subduction complexes, which are represented by the occurrence of accretionary

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units such mélanges, pillow basalts, dismembered ophiolites, cherts, serpentinites, high-pressure metamorphic rocks, and occanionally granulites and garnet lherzolites are sporadically exposed in central Indonesia region through 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 1a. 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). In the South Sulawesi, the metamorphic rocks crop out in the restricted area namely as Bantimala and Barru Complexes (Figure 1b). The Bantimala Complex in South Sulawesi has significantly important meaning for one of the famous high-pressure metamorphic terranes in the world. Furthermore, Parkinson *et al.*, (1998) reported ultra-high pressure metamorphic rocks, which is garnet-jadeite-quartz rock that experienced peak metamorphism at >2.7 GPa on 720–760 °C from this complex.

The Barru Complex is located approximately 70 km northeast of the Makassar (Figure 1b). Metamorphic rocks in this area are bounded in the north with ultramafic rocks and in the south with Late Cretaceous sedimentary rocks (Figure 1c). The most common lithologies in this area are variably of garnetiferous quartz-mica schist and serpentinized peridotite. Most of the metamorphic rocks crop out along the Dengedenge River (Figure 1c). Reliable P-T condition of the metamorphic rocks in this area has not been reported previously. Wakita *et al.* (1994a) reported the phengite K-Ar age of the quartz-mica schist to be 106 ± 5 Ma, which interpreted as exhumation ages.

3 Occurrence and sample descriptions

The exposures of the metamorphic rocks in the Barru Complex are well preserved along the Dengedenge River (Figure 1c). The foliation of garnet-biotite-muscovite schist varies from N 80° E to N 30° E with dipping 30° to 60° to the east (Figure 2). Petrographical and mineral chemistry analyses were done on the garnet-biotite-muscovite schist with sample number 031202A. Mineral chemistries were analyzed with a JEOL JXA-8530F hyperprobe EPMA and a JEOL JED2140-JSM5301S scanning electron microscope with energy dispersive spectrometry system (SEM-EDS) in Kyushu University, Japan. The analytical conditios of EPMA was set an accelerating voltage of 15 kV, a probe current of 12 nA and a beam diameter of 2 μm. The analytical conditions of SEM-EDS JED2140-JSM5301S was set at an accelerating voltage of 15 kV, a probe current of ca. 0.35 nA, and a beam diameter of 1 μm. Natural mineral samples (ASTIMEX-MINM-53) and synthesized oxide samples (P and H Block No. SP00076) were used as standards for the quantitative chemical analyses. Fe^{3+} contents of garnet and plagioclase were calculated using algorithms proposed by Droop (1987). Micas formulae have been calculated to eleven oxygen atoms assuming all iron to be Fe^{2+}. Cation formulae of epidote and titanite have been calculated assuming all iron to be Fe^{3+}. Representative chemical compositions of the analyzed minerals are listed Table 1.

The garnet-biotite-muscovite schists are mainly composed of garnet, biotite, muscovite, epidote, quartz, rutile, hematite, and plagioclase. The schistosity is defined by alignments of muscovite and biotite (Figures 3a–b). Garnet porphyroblasts (~0.3 mm in diameter; Prp_{2-6}, Alm_{61-69}, Sps_{1-8}, Grs_{24-30}) have inclusions of quartz, titanite, apatite, and epidote [$X_{Fe^{3+}} = Fe^{3+}/(Fe^{3+} + Al) = 0.13–0.22$] (Figures 3c–d). Garnet has wide core and mantle of spessartine rich relative to almandine (Prp_{2-4}, Alm_{61-67}, Sps_{5-8}, Grs_{27-33}) (Figures 4a–b). Whereas the rim portion is characterized by slightly rich of pyrope and almandine, relative to spessartine (Prp_{4-7}, Alm_{63-69}, Sps_{0-3}, Grs_{24-33}) (Figure 4b). Grossular content is constant from core to rim (Figure 4b). The garnet forms augen shape surrounded by sheaf texture of biotite (0.1–0.5 mm; X_{Mg} = 0.47–0.55, X_{Si} = 0.59–0.63)

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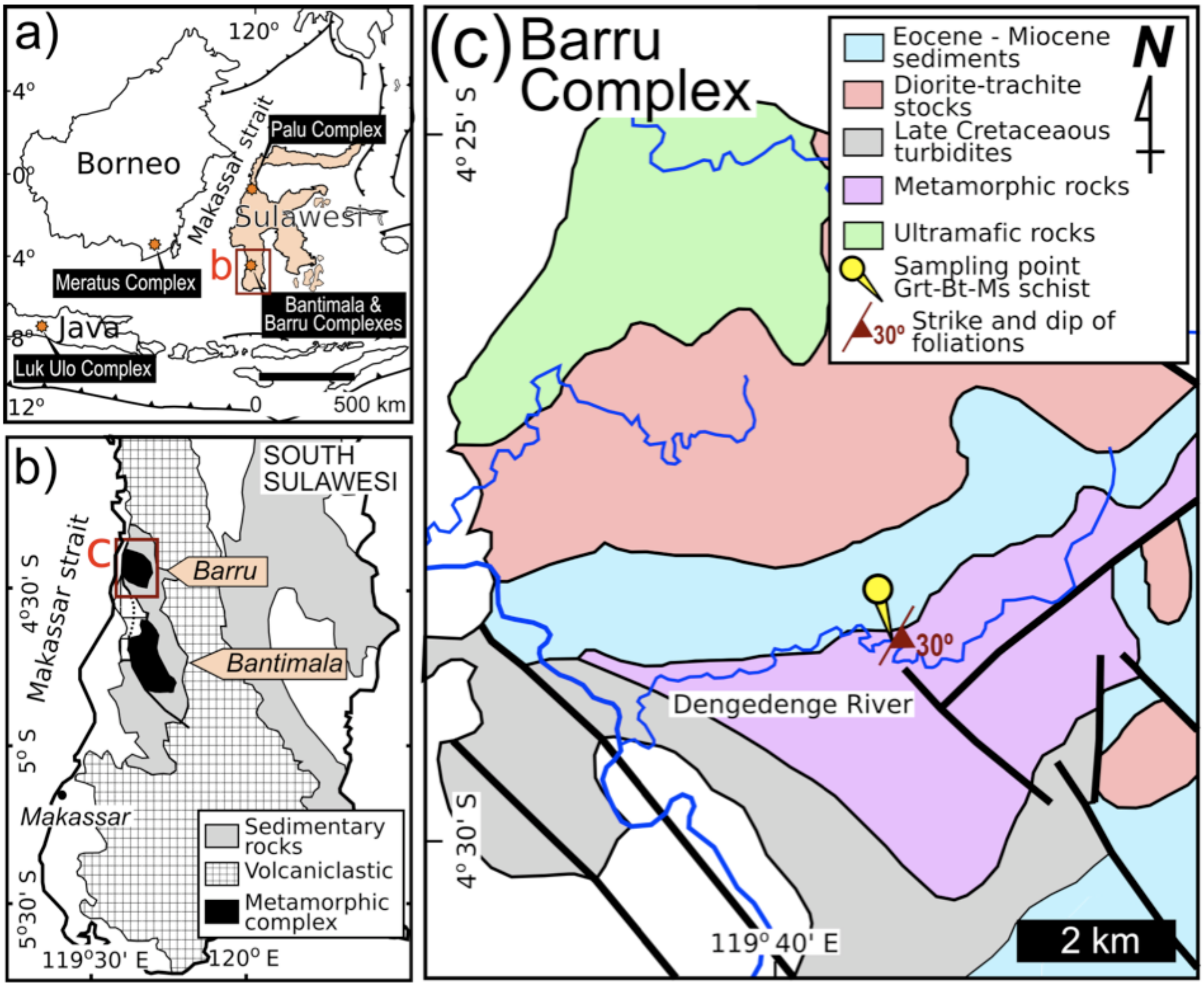

Figure 1: (a) Distribution of high-pressure metamorphic rocks related to the Cretaceous subduction complex in central Indonesia. (b) Location and (c) simplified geological map of the Barru Complex in South Sulawesi (modified after Sukamto, 1982) with sampling location.

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Table 1: Representative microprobe analyses of garnet, biotite, muscovite, and plagioclase in garnet–biotite–muscovite schist from Barru Complex.

Mineral	Grt			Bt		Ms		Pl	
	core	mantle	rim ‡	matrix‡	matrix	matrix‡	matrix	matrix‡	matrix
SiO_2	38.19	38.35	38.55	37.07	38.17	47.49	47.53	59.20	62.27
TiO_2	0.01	0.23	0.00	1.44	1.08	0.48	0.38	0.12	0.19
Al_2O_3	21.18	21.38	21.18	20.59	20.98	34.57	33.61	25.02	23.28
Cr_2O_3	0.00	0.00	0.00	0.00	0.19	0.02	0.00	0.02	0.00
FeO	27.17	27.06	27.36	17.25	16.19	0.80	1.80	0.00	0.00
Fe_2O_3	–	–	–	–	–	–	–	–	–
MnO	3.50	3.14	0.14	0.13	0.00	0.05	0.00	0.12	0.05
MgO	0.80	0.59	1.60	10.40	9.19	0.62	1.19	0.07	0.00
CaO	9.50	9.53	11.60	0.23	0.00	0.00	0.00	6.11	5.63
Na_2O	0.00	0.01	0.01	0.08	0.30	0.58	1.21	9.26	8.93
K_2O	0.00	0.00	0.13	7.21	9.03	10.19	9.33	0.25	0.01
Total	100.35	100.29	100.57	94.40	95.13	94.80	95.05	100.17	100.36
O	12	12	12	11	11	11	11	8	8
Si	3.04	3.04	3.03	2.76	2.83	3.16	3.16	2.65	2.76
Ti	0.00	0.01	0.00	0.08	0.06	0.02	0.02	0.00	0.01
Al	1.99	2.00	1.96	1.81	1.83	2.71	2.63	1.32	1.21
Cr	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00
Fe	1.81	1.80	1.80	1.07	1.00	0.04	0.10	0.00	0.00
Mn	0.24	0.21	0.01	0.01	0.00	0.00	0.00	0.00	0.00
Mg	0.09	0.07	0.19	1.15	1.01	0.06	0.12	0.00	0.00
Ca	0.81	0.81	0.98	0.02	0.00	0.00	0.00	0.29	0.27
Na	0.00	0.00	0.00	0.01	0.04	0.07	0.16	0.80	0.77
K	0.00	0.00	0.01	0.69	0.85	0.86	0.79	0.01	0.00
Total cation	7.97	7.94	7.99	7.60	7.64	6.94	6.98	5.09	5.01
Fe^{3+}	–	–	–	–	–	–	–	–	–
Fe^{2+}	1.81	1.80	1.80	1.07	1.00	0.04	0.10	0.00	0.00
Prp (%)	3.22	2.42	6.31	–	–	–	–	–	–
Alm (%)	61.32	62.20	60.51	–	–	–	–	–	–
Sps (%)	8.00	7.31	0.31	–	–	–	–	–	–
Grs (%)	27.47	28.07	32.87	–	–	–	–	–	–
An (%)	–	–	–	–	–	–	–	26.38	25.82
Ab (%)	–	–	–	–	–	–	–	72.34	74.12
Or (%)	–	–	–	–	–	–	–	1.28	0.05
$Fe^{2+}/(Fe^{2+} + Mg)$	0.95	0.96	0.91	–	–	–	–	–	–
Si/(Si + Al)	–	–	–	0.60	0.61	0.54	0.55	–	–
$Fe^{3+}/(Fe^{3+} + Al)$	–	–	–	–	–	–	–	–	–

Figure 2: Mode of occurences garnet–biotite–muscovite schist in Dengedenge River of Barru Complex, South Sulawesi.

and muscovite (0.1–0.5 mm; X_{Mg} = 0.52–0.67, X_{Si} = 0.53–0.61) (Figure 4c). Microcrystalline quartz occurs as pressure shadow adjacent to the garnet (Figure 3a). Plagioclase (0.2–0.7 mm in diameter; An_{14-26} Ab_{72-85}) forms abundant porphyroblasts in this schist (Figure 4d). Rutile (<0.1 mm), which present in the matrix, is commonly rimmed by titanite. Secondary chlorite [$Fe^{2+}/(Fe^{2+} + Mg)$ = 0.47–0.53] commonly replaces garnet porphyroblasts, micas, and other minerals (Figure 3b). Calcite and albite (X_{Ab} = 0.99–1.00; Figure 4d) occur as interstitial. The petrography and mineral chemistry analyses result of mineral assemblages in garnet-biotite-muscovite schist is summarized in Table 2.

4 Metamorphic evolution

The metamorphic evolution of garnet–biotite–muscovite schist from Barru Complex is estimated based on the mineral coexistence from the petrographical observation. Inclusions in the garnet preserve records of prograde stage of this rock, which are epidote, titanite, quartz and apatite. However, it is lack of mineral parageneses in the prograde stage to constraint the pressure-temperature condition. Hence, only peak metamorphic condition could be estimated from this rock. Garnet, biotite, muscovite, quartz, rutile, and plagioclase are concluded as equilibrium assemblages at peak *P-T* condition of this rock.

Metamorphic temperature is estimated using garnet-biotite geothermometer proposed by Holdaway (2000) based on the Fe^{2+}–Mg exchange between garnet and biotite. The pressure is estimated using garnet-biotite-plagioclase-quartz geobarometer from Wu *et al.* (2004) based on the reaction of pyrope + grossular + eastonite + quartz = anorthite + phlogophite and almandine + grossular + siderophyllite + quartz = anorthite + annite. High Ti content in biotite and high Ca content in garnet qualitatively indicate high temperature and pressure conditions (Holdaway, 2000). Rim of garnet with the highest grossular content and biotite with the highes TiO_2 composition are selected as a pair to this geothermometry which might give a maximum temperature and pressure at peak metamorphic condition. The combination of these thermo- and barometry gives *P-T* estimation at 562 ºC and 0.97 GPa (Figure 5). Garnet-muscovite geother-

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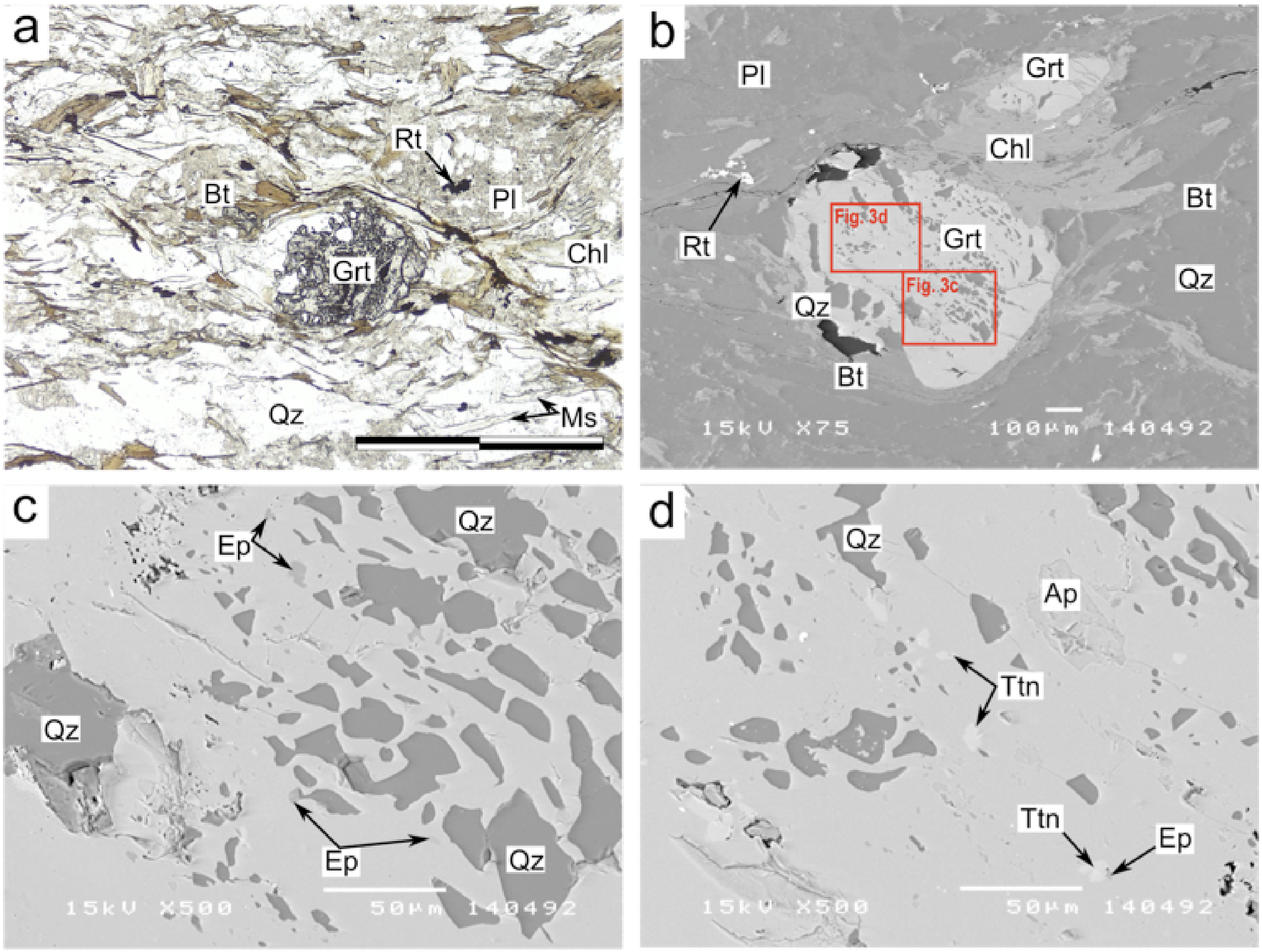

Figure 3: Photomicrograph and back-scattered electron images of garnet-biotite-muscovite schist from Barru Complex. The scale bar without expression in each of photomicrograph on this paper indicates 1 mm. (a) The schistosity defined by biotite and muscovite. Mainly consists of garnet, plagioclase, quartz, biotite, muscovite, and rutile. Secondary chlorite is also present in this picture. (b) Porphyroblastic garnet with abundant inclusions. (c) and (d) inclusions in the garnet consists of quartz, epidote, apatite, and titanite.

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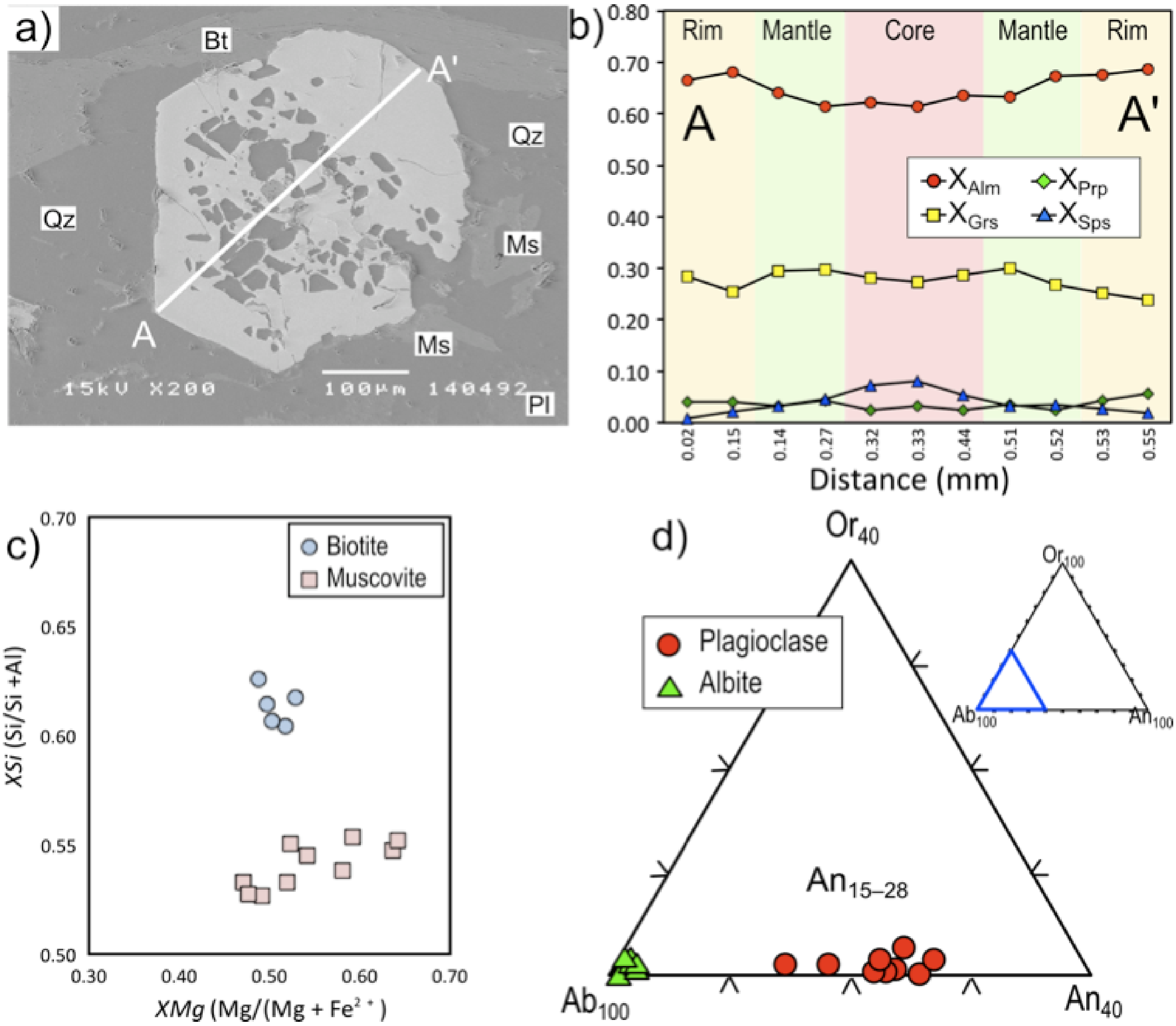

Figure 4: Representative chemical characteristic of garnet, micas, and plagioclase in garnet–biotite–muscovite schist. (a) and (b) Representative zoning profile of garnet. (c) Biotite and muscovite are distinct in X_{Si} component, which biotite has higher than muscovite. (d) Plagioclase in this rock has anorthite content ranges from 15 to 28. Others are albite as secondary minerals.

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Table 2: Summary of mineral assemblages with their stage of metamorphism.

***P-T* evolution**	**Prograde**	**Peak**	**Retrograde**
Apatite	—	—	—
Epidote	—	—	—
Chlorite	? —		—
Biotite		—	
Garnet	—	—	
Muscovite	? —	—	—
Plagioclase	? —	—	
Albite			—
Quartz	—	—	—
Rutile	—	—	
Titanite			—

mometer and garnet-muscovite-plagioclase-quartz geobarometer calibrated by Wu and Zhao (2006) have been used for comparison with the previous geothermobarometry. The Fe and Mg exchange between coexisting garnet and muscovite can be described as pyrope + Fe-celadonite = almandine + Mg-celadonite which is the basis of garnet-muscovite thermometer (Wu and Zhao, 2006). Whereas the equilibrium of pyrope + grossular + muscovite + quartz = anorthite + Mg-celadonite and almandine + grossular + muscovite + quartz = anorthite + Fe-celadonite are used for the basis of garnet-muscovite-plagioclase-quartz geobarometer (Wu and Zhao, 2006). The geothermobarometry gives *P-T* estimation at 501 °C and 0.89 GPa, which locate lower-pressure and -temperature conditions than estimation based on garnet-biotite-plagioclase-quartz equilibrium. It suggests that these conditions can be set as minimum pressure and temperature at peak metamorphic condition of this rock (Figure 5). Hence, the peak *P-T* conditions of the garnet-biotite-muscovite schist ranges at 501–562 °C and 0.89–0.97 GPa (Figure 5).

5 Discussion and Conclusion

The pressure-temperature condition of garnet-biotite-muscovite schist from Barru Complex was estimated by 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 + H_2O 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. The estimated peak *P-T* conditions of garnet-biotite-muscovite schist are plotted on the field of epidote amphibolite-facies petrogenetic grid proposed by Oh and Liou (1998; Figure 5). Comparing with Bantimala Complex (30 km to the south from Barru Complex; Setiawan, 2013), the estimated peak *P-T* condition of garnet-biotite-muscovite schist shows low-pressure and medium-grade conditions but still on the ranges of estimated geothermal gradient *P-T* path of eclogite from that complex (Figure 5). Similar geothermal gradients of metamorphisms might be indicated that these metamor-

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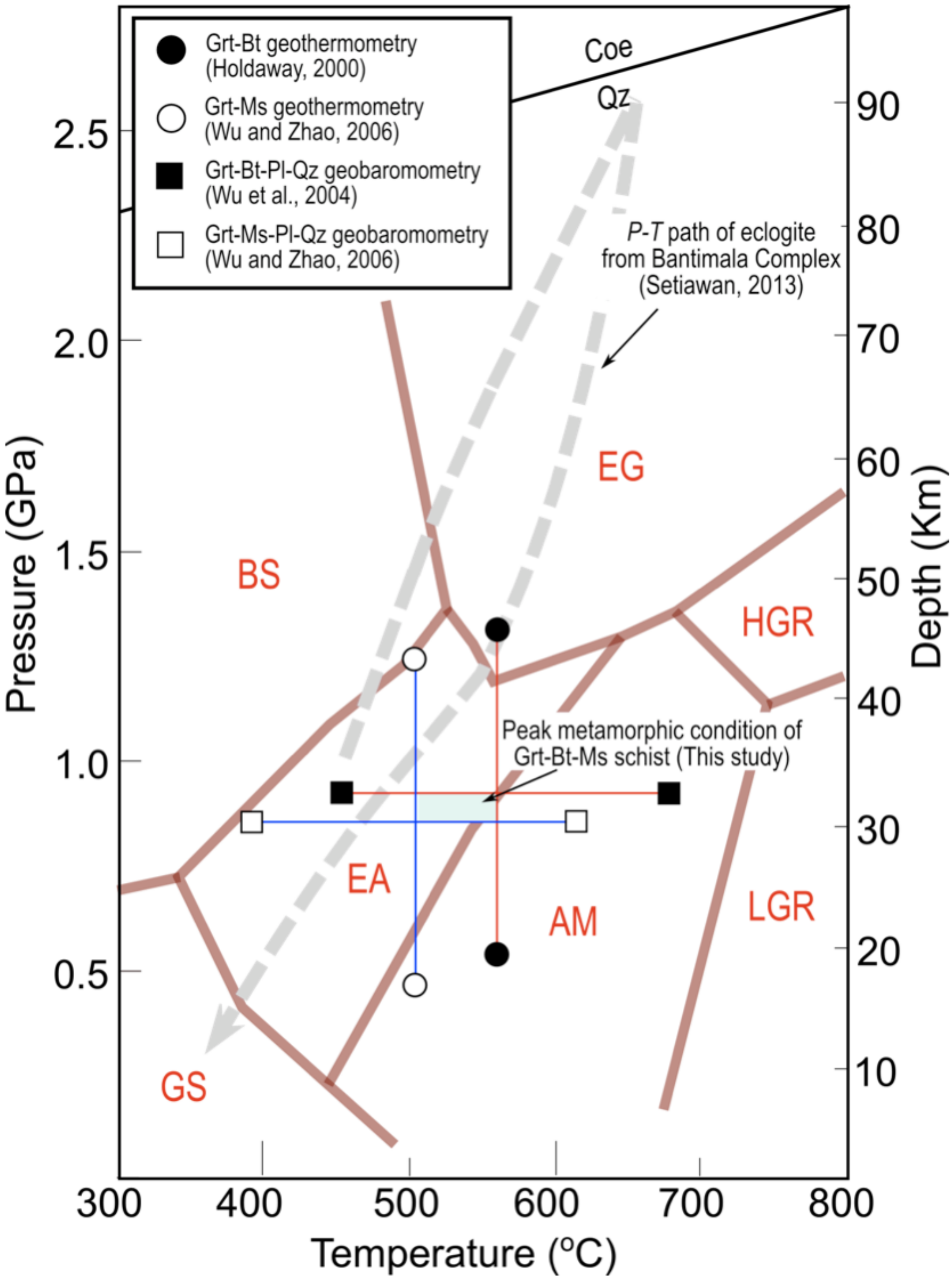

Figure 5: *P-T* estimation of garnet–biotite–muscovite schist from Barru Complex with background $P-T$ path of eclogite from Bantimala Complex (Setiawan, 2013). The petrogenetic grids from Oh and Liou (1998), the abbreviations as follows; BS: blueschist-facies, EG: eclogite-facies, EA: epidote amphibolite-facies, AM: amphibolite-facies, GS: greenschist-facies. Closed-circle is garnet-biotite geothermometry from Holdaway (2000). Open circle is garnet–muscovite geothermometry from Wu and Zhao (2006). Closed-square is garnet–biotite–plagioclase–quartz geobarometry from Wu *et al.* (2004). Open square is garnet–muscovite–plagioclase–quartz geobarometry from Wu and Zhao (2006).

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phic rocks were metamorphosed on the similar tectonic environments.

Up to now, high-pressure metabasic rocks were not reported from Barru Complex, which in contrast with Bantimala Complex (30 km to the south; Setiawan, 2014). Pelitic schists and serpentinites were only metamorphic rock types founded in this area. However, K-Ar age determination on metamorphic rocks from Bantimala and Barru Complexes show synchronology data (Bantimala Complex: 137–113 Ma, Wakita *et al.*, 1994a, 1996, Parkinson *et al.*, 1998; Barru Complex: 106 Ma, Wakita *et al.*, 1994a). Therefore, it is suggested during Cretaceous subduction of oceanic crust, the trench-fill turbidites, which is possibly protolith of the pelitic schist, involved into the margin of Sundaland and metamorphosed. Cenozoic tectonic activites made these main complexes separate 30 km in South Sulawesi and 500 to 1000 km with other Cretaceous accretionary complexes in Central Indonesia.

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