Omphacite-bearing metapelite from the Besshi region, Sambagawa metamorphic belt, Japan: Prograde eclogite facies metamorphism recorded in metasediment

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Omphacite-bearing metapelite was found from the Seba area of the Besshi region, Sambagawa metamorphic belt, central Shikoku, Japan. Omphacite occurs as inclusions in garnet together with quartz, sodic amphibole, phengite, and paragonite. The major matrix phases are quartz, albite, phengite, chlorite, subcalcic amphibole, calcite, dolomite, and graphite. Garnet shows a prograde zoning and comprises three segments in order from the crystal center to the margin: the core, inner mantle, and outer mantle. The garnet core shows monotonic decrease of MnO content outward, and includes sodic phases: paragonite and glaucophane. The garnet mantle is substantially homogeneous in composition, and poorer in MnO and richer in MgO than the core. The inner mantle of garnet includes omphacite, paragonite and glaucophane. The outer mantle includes omphacite, but paragonite and glaucophane grains are absent. The jadeite content of omphacite inclusions ($X_{Jd}$) increases slightly from 0.55 in grains included in the inner mantle to 0.62 in the outer mantle of garnet.

The systematic distribution of sodic minerals in garnet documents a prograde evolution of metamorphism from the blueschist to eclogite facies conditions. The occurrence of omphacite-bearing metapelite in the Seba area of the Besshi region is direct evidence of: (1) at least some of the Sambagawa metapelites in the Besshi region certainly experienced eclogite facies metamorphism, and (2) eclogite facies metamorphism extends beyond the previously assumed eclogite facies area in the Sambagawa belt.

Keywords: Omphacite, Metapelites, Eclogite facies metamorphism, Sambagawa belt

INTRODUCTION

The Sambagawa metamorphic belt represents the deeper portion of a slab subducted along the eastern margin of the Eurasia plate in the late Cretaceous period. Eclogitic metagabbro and metabasite sporadically occurs in the higher-grade parts of the Sambagawa belt in the Besshi (e.g., Aoya, 2001; Miyagi and Takasu, 2005; Sakurai and Takasu, 2009) and Kotsu (Kugimiya and Takasu, 2002; Matsumoto et al., 2003) regions of central-eastern Shikoku. In contrast, few occurrences of eclogitic assemblages in the Sambagawa metasediments have been reported except in the Kotsu region (Matsumoto et al., 2003), and the Seba (Zaw Win Ko et al., 2005), Gongen (Miyamoto et al., 2007), Gazo (Sakurai and Takasu, 2009), and Togu (Kouketsu and Enami, 2010) areas of the Besshi region. These metasediments of eclogite facies are restricted in distribution, and occur as alternate layer with eclogitic metabasites except for the Togu metapelite. Determining the regional extent of the eclogite facies rocks is decisive in understanding the subduction and exhumation processes of the Sambagawa belt and probably for high-pressure metamorphic belts, in general. However, the relationship between eclogitic lithology and the surrounding non-eclogitic lithology has not yet been evidently examined in the Sambagawa belt. The major problems in defining the distributions of the eclogitic and non-eclogitic lithologies are that (1) the Sambagawa metamorphic rocks reequilibrated to various metamorphic degrees during exhumation, and (2) metasediments, which

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are the most dominant lithologies in the Sambagawa belt, are generally easier to recrystallize than the metagabbros and metabasites. Thus, the regional extent of the eclogite facies metamorphism in the belt cannot be precisely determined without careful assessment of the metapelitic lithologies.

Recently, Mouri and Enami (2008) applied the quartz-Raman barometry (Enami et al., 2007) on the Sambagawa metamorphic rocks and concluded that: (1) quartz inclusions in garnet in some metapelites and metabasites retain a high residual pressure comparable with that found in eclogite facies rocks, and (2) the eclogite facies area in the Besshi region has a far greater extent than the previously recognized. The quartz inclusions with high residual pressure reported by Mouri and Enami (2008), however, do not coexist with the typical eclogite facies assemblage of garnet-omphacite, and thus the areal extent indicated by the quartz-Raman barometry has not been confirmed by conventional petrological and mineralogical data.

Recently, we have found an omphacite-bearing metapelite in the Seba area in the Besshi region. In this paper, we describe the mineralogical characteristics of the metapelite and discuss its prograde metamorphism from the blueschist facies to the peak eclogite facies, based on geothermobarometry and change of the mineral assemblage. Abbreviations for minerals and end-members described in the text, figures, and table, except for Bar (barroisite) and Ams (amesite), follow Kretz (1983) and Miyashiro (1994).

**GEOLOGICAL OUTLINE**

The Sambagawa metamorphic belt stretches about 800 km throughout the Outer Zone of Southwest Japan. It is a Mesozoic accretionary prism that mainly consists of meta-
Omphacite-bearing Sambagawa metapelites

morphosed oceanic crust, seafloor sediments, and continental sediments of the late Cretaceous period (Isozaki and Itaya, 1990). The Sambagawa metamorphic belt in central Shikoku is mainly composed of metapelites, metabasite, and metachert, and has been divided into four mineral zones on the basis of the mineral assemblages of metapelites following an increasing metamorphic grade: chlorite, garnet, albite-biotite, and oligoclase-biotite zones, (Fig. 1a, Enami, 1983; Higashino, 1990). Metamorphic rocks of higher metamorphic grades are widely distributed in the Besshi region. Estimated peak P/T conditions are 0.8-0.95 GPa/520 ± 25 °C and 0.9-1.1 GPa/585-635 °C for the albite-biotite and oligoclase-biotite zones, respectively (Enami et al., 1994; Wallis et al., 2000). A large Alpine-type ultramafic complex (Higashihakaishi mass) occurs in the higher-grade area, and its equilibrium P/T conditions are estimated to be 2.9-3.8 GPa/700-810 °C (Enami et al., 2004). Omphacite + garnet + quartz assemblages sporadically occur in the area of the albite- and oligoclase-biotite zones around the ultramafic body (e.g., Takasu, 1989; Ota et al., 2004; Miyagi and Takasu, 2005). Wallis and Aoya (2000) and Aoya (2002) proposed that the eclogitic rocks form a single eclogite facies nappe, that comprises two major units of the Seba and Iratsu areas, at the highest structural level of the Sambagawa belt. This hypothesis was based on structural and petrological data implying that the eclogite units overlie the lower-grade non-eclogitic rocks, and occupy the hinge zone of a kilometer-scale synform. The peak P/T conditions of the eclogite facies stage in the Besshi region are estimated to be 2.3-2.4 GPa/675-740 °C for the Gongen samples (Miyamoto et al., 2007) and 1.8 GPa/520-550 °C (Zaw Win Ko et al., 2005) for the Seba samples.

In the Seba area, the eclogitic assemblage of garnet-omphacite is locally preserved either in the more common metabasite or in the less abundant metagabbro (Takasu, 1984; Aoya, 2001). Thus, the inferred areal extent of the eclogite unit overlie the lower-grade non-eclogitic rocks, and occupy the hinge zone of a kilometer-scale synform. The peak P/T conditions of the eclogite facies stage in the Besshi region are estimated to be 2.3-2.4 GPa/675-740 °C for the Gongen samples (Miyamoto et al., 2007) and 1.8 GPa/520-550 °C (Zaw Win Ko et al., 2005) for the Seba samples.

The major matrix phases of the omphacite-bearing metapelite (sample ZWK02) are garnet, phengite, chlorite, barroisite/taramite, albite, quartz, calcite, dolomite, and graphite. Accessory minerals include titanite, rutile, apatite, and zircon. Phengite and chlorite define the main schistosity. Minor biotite partly rims phengite. Barroisite/taramite occurs as deep bluish-green prismatic crystals of about 0.2-1.0 mm in length. Amphibole grains are ran-

**PETROGRAPHY**

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**Figure 2.** Photomicrographs of the omphacite-bearing metapelite from the Seba area (open nicols). Abbreviations for minerals: Grt, garnet; Omp, omphacite; Qtz, quartz; Ab, albite; Phe, phengite; Dol, dolomite; Chl, chlorite; Ap, apatite.
domly distributed. Albite porphyroblasts contain garnet, phengite, chlorite, barroisite, quartz, calcite, dolomite, epidote, titanite, apatite, and graphite as inclusions. Calcite and dolomite vein cut the schistosity and usually replace other matrix phases. The garnet porphyroblasts are 0.5–2 mm in size (Fig. 2a) and include quartz, epidote, titanite, rutile, apatite, calcite, dolomite, paragonite, phengite, interlayered chlorite–talc, omphacite, glaucophane/barroisite, and zircon. These inclusions are usually less than 50 µm in size. The fine-grained aggregates of quartz and apatite are characteristically concentrated in the intermediate zone between the core and rim of garnet (Fig. 2b). There is a systematic variation in the mineralogy of the inclusion phases from the core to the rim of garnet. The detailed distribution of mineral inclusions with respect to the chemical zoning in garnet are described below.

MINERAL CHEMISTRY

The chemical compositions of minerals were analyzed using a JEOL JXA-8800R (WDS + EDS) electron-probe microanalyzer (EPMA) at the Petrology Laboratory of Nagoya University. The accelerating voltage and specimen current for quantitative analyses were 15 kV and 12 nA on the Faraday cup, respectively. The beam diameter used for the analysis of mica was 5 µm and that for all the other phases was 2–3 µm. Representative analyses are listed in Table 1.

Garnet

All iron in garnet was assumed to be ferrous and the endmembers proportion ($X_i$) was calculated as $i/(Fe + Mn + Mg + Ca)$. Garnet belongs to the Ca-rich ($X_{Grs} = 0.21$–0.35) almandine–pyrope series ($X_{Alm} = 0.54$–0.65 and $X_{Prp} = 0.04$–0.08). They show prograde zoning with $X_{Prp}$ increasing from core to rim and higher $X_{Sps}$ (up to 0.14) at the core, except for the local increase in $X_{Sps}$ and decrease in $X_{Prp}$ at the outermost rim (Figs. 3 and 4). Garnet is divided into three parts of core, inner mantle, and outer mantle by the chemical compositions and inclusion assemblages as mentioned later. In the core, $X_{Alm}$ and $X_{Sps}$ values decrease from 0.65 to 0.56 and 0.14 to 0.05 towards outer portion, respectively, and $X_{Grs}$ increase from
0.21 to 0.33 towards the same direction. In the inner mantle, the chemical composition is substantially constant ($X_{\text{Alm}} = 0.54 - 0.60$, $X_{\text{Prp}} = 0.04 - 0.06$, $X_{\text{Grs}} = 0.29 - 0.35$, and $X_{\text{SpS}} = 0.05 - 0.07$). In the outer mantle, $X_{\text{Alm}}$ value increases from 0.57 to 0.62 and $X_{\text{Grs}}$ value decreases from 0.32 to 0.25 towards outermost rim. $X_{\text{SpS}}$ value ($X_{\text{SpS}} = 0.04 - 0.06$) is slightly lower than that of the inner mantle.

**Omphacite**

The $\text{Fe}^{3+}/\text{Fe}^{2+}$ value of omphacite was calculated as $\text{Fe}^{3+} = \text{Na} - \text{Al}$, and the end-members proportion was calculated as follows: $X_{\text{Id}} = \text{Na}$, $X_{\text{Aeg}} = \text{Fe}^{3+}$ and $X_{\text{Aug}} = 1 - (X_{\text{Id}} + X_{\text{Aeg}})$. Omphacite occurs in the Mn-poor mantle of garnet. The $X_{\text{Id}}$ value of the omphacite inclusions increases from 0.54 in the inner mantle to 0.62 in the outer mantle of garnet (Fig. 5), $X_{\text{Aeg}}$ value is less than 0.14.

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**Figure 3.** (a) MgKα, (b) FeKα, (c) CaKα and (d) MnKα X-ray mapping images of garnet in the omphacite-bearing metapelite from the Seba area.
Amphibole

Amphibole nomenclature follows Leake et al. (1997), and its Fe$^{3+}$/Fe$^{2+}$ value is calculated with total cations = 13 excluding Ca, Na, and K (O = 23). This is because the (Fe$^{2+}$ + Mn + Mg) contents in the octahedral B-sites of amphibole is usually low in high-P/low-T metamorphic rocks (Deer et al., 1997). The matrix amphiboles are subcalcic varieties of barroisite-taramite ($^{[B]}$Na = 0.75–0.90 per formula unit (pfu) and Si = 6.3–7.01 pfu for O = 23), where $^{[B]}$Na indicates the Na content of the B-sites (Fig. 6). Amphiboles included in the core and the inner part of garnet mantle are mostly glaucophane ($^{[B]}$Na = 1.63–1.89 pfu and Si = 7.67–8.00 pfu), while barroisite ($^{[B]}$Na = 0.56–0.78 pfu and Si = 6.81–6.89 pfu) rarely occurs in the inner part of mantle.

Micas and other minerals

White micas are phengite and paragonite. Matrix phengite shows weak zoning with its Si content decreasing from 3.35–3.39 pfu (O = 11) in the core to 3.26–3.30 pfu at the rim (Fig. 7a). The phengite inclusions in garnet have a slightly lower Si content (3.24–3.36 pfu) than the Si-rich core of the matrix phengite (Fig. 7b). $X_{Na} = [Na/(Na + K + Ca + Ba)]$ value is substantially constant between 0.08–0.13 in both the matrix and inclusion phases. The occurrence of paragonite is restricted to inclusions in garnet, which have a Si content of 2.97–3.02 pfu and $X_{Na}$ value of 0.93–0.95.

The matrix chlorite has a homogeneous composition with Si = 2.73–2.80 pfu and Mg$^#$ [= Mg/(Mg + Fe)] = 0.55–0.60. The pale-greenish sheet silicates included in
Omphacite-bearing Sambagawa metapelite

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Figure 8. Compositional range of chlorite in the matrix and possible finely interlayered chlorite-talc phase included in garnet of the omphacite-bearing metapelite from the Seba area.

Figure 7. (a) Zonal structure of phengite in the matrix. (b) Compositional range of phengite occurring as inclusion in the garnet and in the matrix of the omphacite-bearing metapelite from the Seba area.

INCLUSION SYSTEMATICS IN GARNET

Prograde change in inclusion assemblages in garnet

Assemblages of inclusions in garnet systematically change from the core, through the inner mantle, to the outer mantle of garnet. Figure 9 shows the relationship between the compositional zoning of garnet and distribution of sodic phase inclusions of a garnet grain. Paragonite, which is not shown in Figure 9a, occurs extensively from the core through the inner mantle to the outer mantle. Two other garnet grains also show similar compositional zoning and distributions of sodic phase inclusions to the garnet described in Figure 9. Assemblages included in various zones of garnet porphyroblasts document a systematic change during the prograde metamorphism. The inner part of the garnet core contains few inclusions, and glaucophane, paragonite, and quartz are found in the outer part of the garnet core (Fig. 9). The boundary between the core and inner mantle of garnet is defined by the first appearance of omphacite. The inner mantle of the garnet contains omphacite, glaucophane/barroisite, paragonite and phengite. Fine-grained quartz and apatite concentrate in this segment (Fig. 2b). The boundary between the inner mantle and outer mantle of garnet is marked by the disappearance of glaucophane and paragonite, implying that the omphacite-garnet assemblage was not in equilibrium with glaucophane and/or paragonite during the growth of outer mantle. Chemical composition of the boundary between the inner and outer mantles roughly corresponds to $X_{Prp} = 0.06$ and $X_{Sp} = 0.05$.

Raman analysis of quartz inclusions

The residual pressure retained by the quartz inclusions in garnet can be estimated as a function of the Raman shift ($\Delta\omega_1$), following the method described by Enami et al. (2007). The quartz inclusions common in the core of garnet, and their $\Delta\omega_1$ values are rather variable with bimodal frequencies of 4.6-6.5 cm$^{-1}$ and 7.6-11.8 cm$^{-1}$ (Fig. 10). The $\Delta\omega_1$ values of quartz inclusions are as high as those in the Sambagawa eclogitic rocks reported by Enami et al. (2007). In the core of garnet, the $\Delta\omega_1$ values of quartz inclusions are 4.6-11.8 cm$^{-1}$ and lower $\Delta\omega_1$ values are measured more frequently than the inner and outer mantle. In the inner mantle, there are lots of fine-grained quartz inclusions and their $\Delta\omega_1$ values are 2.3-11.8 cm$^{-1}$. The $\Delta\omega_1$ values of quartz inclusions in the outer mantle are 6.4-9.8 cm$^{-1}$, and tend to be slightly lower than those in the core and inner mantle of garnet. However, quartz inclusions are rare in the outer mantle of garnet, thus, it cannot be positively concluded that, statis-
tically, there is a difference in the $\Delta\omega_1$ values of the quartz inclusions among the core and inner/outer mantles of garnet, and the outer mantle formed under distinctly lower pressure conditions than the core and inner mantle.

**DISCUSSION**

**Stability of mineral inclusions in garnet**

Figure 11 is a simplified petrogenetic grid showing equilibria of metamorphic phases including sodic pyroxene, sodic amphibole, and paragonite in the NMASH model system calculated using THERMOCALC 3.25 and AX (Holland and Powell, 1998). The equilibrated set of sodic pyroxene, sodic amphibole and paragonite occurs only in the inner mantle of garnet. Thus, average compositions of the inner mantle of garnet and of its inclusions, excluding chlorite, were employed for the activity calculations of end-members. Prograde chlorite is inferred to occur as intimately interlayered with talc, and consequently it is difficult to determine its chemical composition using EPMA. Thus, the activities of chlorite end-members were estimated using a hypothetical composition (Si = 2.8 pfu for O = 14 and Mg# = 0.5) based on the composition of matrix chlorite.

The occurrence of different inclusions in garnet may be explained on the base of the following reaction:

$$\begin{align*}
\text{NaAl}_3\text{Si}_3\text{O}_{11}(\text{OH})_2 + \text{Na}_2\text{Mg}_3\text{Al}_2\text{Si}_2\text{O}_{23}(\text{OH})_2 \\
\text{paragonite} + \text{glaucophane}
= 3\text{NaAlSi}_2\text{O}_5 + \text{Mg}_3\text{Al}_2\text{Si}_2\text{O}_{12} + 2\text{SiO}_2 + 2\text{H}_2\text{O}.
\text{jadeite} + \text{pyrope} + \text{quartz}
\end{align*}$$

The different inclusions in garnet core and mantle suggest that the left-hand-side assemblage of the proposed reaction was not stable during the formation of the outer mantle of garnet. Glaucophane and paragonite reacted to form omphacite during prograde metamorphism from the blueschist facies stage to the peak eclogite facies stage.

**Geothermobarometry**

The thermobarometer calibrated by Krogh Ravna and
Terry (2004) was used on the garnet-clinopyroxene-phengite assemblage that occurs in the inner and outer mantles of garnet. The garnet and omphacite compositions are substantially constant in the inner and outer mantles, respectively, and compositional sets of the omphacite inclusion and the surrounding host garnet were adopted for the $P$-$T$ estimation. The phengite inclusions in garnet, however, are more heterogeneous in composition than other phases, and their Si content varies from 3.24 to 3.36 pfu in the inner mantle and 3.27 to 3.35 pfu in the outer mantle. Thus, pressure conditions were calculated for each case by employing the phengite compositions with maximum, minimum, and average Si contents (cf., Table 1 and Fig. 7b). The variations in phengite composition contribute to variations in pressure of 0.3 GPa. The average $P$-$T$ conditions calculated are 1.7–1.9 GPa/470–500 °C and 1.8–1.9 GPa/495–530 °C for the inner and outer mantle, respectively, implying nearly isobaric heating just before the prograde metamorphic peak (Fig. 12). The estimated isobaric $P$-$T$ trend well explains the prograde change in mineral parageneses documented by sedimentary lithologies in Figure 11. The temperature conditions of the outer mantle are defined as 510–530 °C in minimum at $P = 1.8–1.9$ GPa, and are consistent with those estimated by the conventional geothermometry.

The omphacite-bearing metapelite studied in this paper documents clear evidence of eclogite facies metamorphism recorded by sedimentary lithologies in this sector of the Sambagawa belt. The $P$-$T$ conditions estimated from inclusion in the outer mantle of garnets are similar to those of the chloritoid-bearing metapelites (1.8 GPa/520–550 °C) in the Seba eclogite unit (Zaw Win Ko et al., 2005). On the other hand, the temperature conditions of the Seba eclogitic metabasites reported by Aoya (2001) are 50–90 °C higher than our temperature estimations. Aoya (2001) employed the garnet-clinopyroxene geothermometry by Ellis and Green (1979) for the temperature estimations. This calibration generally give higher temperature conditions than that of Krogh Ravna (2000) which we employed in this paper (for a detail discussion see Nakamura and Hirajima, 2005): The Krogh Ravna’s (2000) calibration gives about 60 °C lower temperature estimations than the Ellis and Green’s (1979) calibration for the compositional dataset of garnet and omphacite reported by Aoya (2001). Thus, we assume that there is probably no considerable difference of metamorphic temperature conditions between Aoya (2001) and our study. The sample locality of the omphacite-bearing metapelites reported in Figure 1 is very close to the Seba eclogite unit proposed by Wallis and Aoya (2000). Therefore, it is likely that they belong to the same unit and probably share the same $P$-$T$ history with the lithologies in the Seba eclogite unit.
Evaluation of quartz-Raman barometry

The estimated Raman shift ($\Delta\omega$) of quartz inclusions in garnet in the omphacite-bearing metapelite is up to 11.8 cm$^{-1}$. We cannot clearly explain why the maximum $\Delta\omega$ value of quartz inclusions in the outer mantle of garnet is lower than that in the core and inner mantle. The obtained $\Delta\omega$ values, taken as a whole, clearly expand towards higher–side than that of the epidote–amphibolite facies rocks reported by Enami et al. (2007). The Raman shift from the omphacite–bearing metapelite implies that the quartz inclusions in garnet retain a residual pressure of 0.6–0.7 GPa based on the pressure–Raman shift relationship calibrated by Schmidt and Ziemann (2000). The estimated residual pressure suggests a metamorphic peak-pressure of 1.7–2.1 GPa at $T = 500$–700 °C employing the simple elastic model of Van der Molen (1981) and elastic and thermal expansion parameters listed in Enami et al. (2007). The peak–pressure conditions of metamorphism estimated from the residual pressure are in good agreement with those calculated by means of conventional thermobarometry (1.8–1.9 GPa). This good agreement between the pressure estimations by two independent methods validates the results of the quartz–Raman barometry. Thus, the quartz–Raman barometry is probably an efficient method to detect the evidence of eclogite facies metamorphism in the Sambagawa metapelitic rocks, even if the rocks have been strongly overprinted during exhumation.

High $\Delta\omega$ values of quartz inclusions in garnet are found in a number of metapelites and metabasites collected along the Seba stream that belongs to the formerly presumed non–eclogite unit (Fig. 1b: Wallis and Aoya, 2000). These data suggest that the eclogite facies metamorphism would extend beyond the previously recognized eclogite unit and include surrounding sedimentary lithologies.

SUPPLEMENTARY REMARKS

Kouketsu and Enami (2010, in press) cited in the “INTRODUCTION” of this manuscript describe the occurrence of an omphacite and aragonite–bearing metapelite from the Togu area of the Besshi region. Kouketsu and Enami (2010, in press) manuscript was submitted to “Island Arc” in 02 February 2009, and was accepted for publishing in 15 May 2009. It was initially written to document the occurrence of metamorphic aragonite in the Sambagawa metapelite. The occurrence of omphacite in the aragonite–bearing metapelite was confirmed during supplementary analyses of the sample considering reviewers’ comments after submitting the present paper to “Journal of Mineralogical and Petrological Sciences” in 17 February 2009. Thus the occurrences of omphacite in the Seba and Togu metapelites were separately reported in two papers of Kouketsu and Enami (2010, in press) and Kouketsu et al. (this paper).

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