Petrological and mineralogical contrasts of basic lithologies between eclogite and non-eclogite units along the Kokuryo River of the Sanbagawa belt, Central Shikoku, Japan

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The Tonaru epidote-amphibolite is one of the large metagabbro dominated bodies and occurs in schistose rocks of the Sanbagawa metamorphic belt, central Shikoku. This body locally retains mineral parageneses of eclogite facies equilibrium prior to the epidote-amphibolite facies stage. The lithologic boundary between the epidote-amphibolite and the surrounding schistose rocks was well observed along the Kokuryo River in the western part of the Besshi region in central Shikoku. Boundary zone of 1.5–2.5 m wide is developed between the epidote-amphibolite and pelitic schist. This zone is composed of a basic layer and alternating layers consisting of thin amphibole-rich and mica-rich bands, which occupy the epidote-amphibolite and pelitic schist sides, respectively. The basic layer has a chondrite-normalized rare-earth element (REE) pattern with slight enrichment of light REEs, which corresponds to epidote-amphibolite. By contrast, the amphibole-rich band has a flat REE pattern similar to the basic schist of the Sanbagawa belt.

The basic layer in the boundary zone and epidote-amphibolite have composite-zoned garnet, showing a compositional discontinuity between the core and mantle parts, similar to that in the Sanbagawa eclogite unit. Garnet in the amphibole-rich and mica-rich bands of the alternating layers and pelitic schist shows simple normal zoning, which commonly occurs in the Sanbagawa non-eclogite unit. Sodic plagioclase occurs as inclusions in the mantle part of the composite-zoned garnet and normally zoned garnet as well as in a matrix phase. These lithologies belong to the oligoclase-biotite zone with equilibrium pressure/temperature conditions of 1.1–1.2 GPa/595–625 °C; discontinuity of metamorphic grade is not detected throughout the outcrop for the epidote-amphibolite facies stage.

These data suggest that (1) the basic layer is the fractured part of the epidote-amphibolite and (2) the tectonic boundary between the eclogite and non-eclogite units corresponds to the lithologic boundary between the basic layer and alternating layers of thin amphibole-rich and mica-rich bands in the boundary zone.

Keywords: Eclogite, Epidote-amphibolite, Garnet, Sanbagawa belt, Unit boundary

INTRODUCTION

The Sanbagawa belt, a part of the hot subduction zone that recorded a relatively high geothermal gradient (Aoya et al., 2003; Wallis and Okudaira, 2016), is composed of metamorphosed sedimentary and basic igneous lithologies of lower greenschist to epidote-amphibolite facies.
the regional thermal structure up to the epidote-amphibolite facies. There are two distinct interpretations on tectonic relationship between the eclogite-facies and lower-grade regions. Ota et al. (2004) supposed a single event of metamorphism suggesting that the Sanbagawa regional thermal structure up to the epidote-amphibolite facies essentially formed during an exhumation and hydration process and the Sanbagawa belt recorded a coherent and continuous tectonothermal structure from pumpellyite-actinolite, through the blueschist/greenschist transition and epidote-amphibolite, and up to eclogite-facies grades. On the other hand, Wallis and Aoya (2000) and Aoya (2002) proposed a nappage structure subdividing the higher-grade areas in the Besshi region into eclogite and non-eclogite units; the former is the highest structural level of the Sanbagawa belt. This model postulated the contingency of the two units forming nappage structure before the formation of the regional thermal structure up to the epidote-amphibolite facies grade of the Besshi region. The lithologies of the eclogite unit are considered to have been extensively recrystallized along with those of the non-eclogite unit during the subsequent prograde epidote-amphibolite facies stage after contingency of these two units (Aoya, 2001; Zaw Win Ko et al., 2005; Kabir and Takasu, 2010a; Kouketsu et al., 2014).

Kouketsu et al. (2014) proposed regional distribution of the unit boundary between the eclogite and non-eclogite units in the Besshi region based on combination of (i) compositional zoning of garnet, (ii) sodic phase inclusions in garnet, and (iii) residual pressures preserved in quartz inclusions in garnet. Taguchi and Enami (2014a) and Taguchi et al. (2019) reported jadeite-bearing metapelites from the Asemi-gawa region, which is approximately 20 km ESE of the Besshi region, and proposed a possibility that the eclogite unit in the Besshi region might extend eastward to the Asemi-gawa region. Mouri and Enami (2008) and Sakurai and Takasu (2009) suggested approximate positions of outcrops including a boundary between the eclogite and non-eclogite units along the Seki-gawa (Seki River) and Urayama-kawa (Urayama River) routes in the Besshi region, respectively. However, the strong recrystallization under prograde epidote-amphibolite facies condition after the formation of the nappage structure made it difficult to confirm the exact position of the direct contact of these two units at an outcrop scale, and their field relationship has not been well understood.

The Kokuryo-gawa (Kokuryo River) route is situated along the western side of the Besshi region, and passes transversely across the boundary between the Tonaru epidote-amphibolite body, which underwent eclogite facies recrystallization (Miyagi and Takasu, 2005), and the surrounding pelitic and basic schists. Therefore, a possible westward extension of the boundary between the eclogite and non-eclogite units is expected to occur along this route (Aoya et al., 2017). In this study, we discuss the petrological and mineralogical similarities and differences of the lithologies at an outcrop including the probable boundary between these two units and define its exact position on the outcrop scale. This result suggests a tectonic contingency of the exhumed eclogite unit and the subducted non-eclogite unit before the prograde epidote-amphibolite facies stage, and supports the eclogite nappage model. The pressure (P)-temperature (T) conditions of the epidote-amphibolite facies stage were reviewed employing suitable and conventional geothermobarometers and pseudosection method.

GEological BACKGROUND

The Sanbagawa metamorphic belt, a Cretaceous subduction metamorphic belt, extends more than 800 km from the Kanto Mountains in the east to eastern Kyushu in the west. To the north, the Sanbagawa belt is separated from the Cretaceous Ryoke high-temperature belt by the Median Tectonic Line, which is the major strike-slip fault dividing southwestern Japan into the Inner and Outer zones (Fig. 1a). The Sanbagawa metamorphic belt has a maximum width of approximately 30 km in central Shikoku and is well exposed in the Besshi region. Regional thermal structures of the Besshi and neighboring regions are typically described in terms of four mineral zones based on the matrix assemblages of the pelitic schist: the chloritite, garnet, albite-biotite, and oligoclase-biotite zones in ascending order of metamorphic grade (Fig. 1b: e.g., Enami, 1982, 1983; Higashino, 1990a, 1990b). Equilibrium conditions of the albite-biotite and oligoclase-biotite zones are approximately equivalent to the epidote-amphibolite facies (e.g., Enami, 1983; Higashino, 1990b; Otsuki and Banno, 1990). Coarse-grained, massive mafic (Iratsu, Tonaru, and Seba)-ultramafic (Higashiakaishi) bodies of various sizes are sporadically distributed in the higher-grade zone such as the albite- and oligoclase-biotite zones of the Besshi region. Most of these massive basic bodies are composed of metamorphosed gabbro and lesser amounts of basaltic and sedimentary lithologies.

Lines of evidence for higher-pressure recrystallization before the epidote-amphibolite facies stage are found in the metaperidotite (Higashiakaishi body), metagabbro (Iratsu, Tonaru, and Seba bodies), and associated lithologies (Banno et al., 1976; Kunugiza et al., 1986; Takasu, 1989; Enami et al., 2004; Ota et al., 2004). The ultramafic body records an equilibrium under a garnet lherzolite facies of 2.3–3.8 GPa/700–810 °C (Enami et al., 2004;
Mizukami and Wallis, 2005). The mafic bodies and associated lithologies share a similar P–T history, which records two stages of prograde metamorphism of the prograde eclogite facies stage → exhumation and hydration stage → prograde epidote–amphibolite facies stage (e.g., Aoya, 2001; Zaw Win Ko et al., 2005; Sakurai and Takasu, 2009; Kabir and Takasu, 2010a; Kouketsu and Enami, 2010; Kouketsu et al., 2010, 2014; Enami et al., 2017), and a wide distribution of the eclogite unit has been supposed for the Besshi region (Aoya et al., 2013; Kouketsu et al., 2014) (Fig. 1b). These eclogite facies lithologies might be grouped into kyanite–eclogite, common mafic eclogite, and associated schistose rocks of basic and pelitic lithologies. The kyanite–eclogite, in which protoliths might be mixtures of pelitic and basic volcanoclastic rocks (Takasu, 1989; Takasu et al., 1994; Utsunomiya et al., 2011; Enami et al., 2019), records P/T conditions of 2.3–2.5 GPa/570–740 °C for the eclogite facies stage (Miyamoto et al., 2007; Endo and Tsuibo, 2013). However, common mafic eclogite retains a slightly lower P/T equilibrium of 1.8–2.1 GPa/520–590 °C (e.g., Endo, 2010; Kabir and Takasu, 2010b). Schistose metapelitic of the eclogite unit shows similar P/T conditions to those of common mafic eclogite for the eclogite stage (1.8–1.9 GPa/495–550 °C: Zaw Win Ko et al., 2005; Kouketsu et al., 2010).

The Tonaru body is situated at western part of the possible eclogite unit. Although the P–T history of the Tonaru body has not been clarified compared to other eclogitic lithologies, its equilibrium conditions in the eclogite stage are reported to be approximately >1.5 GPa/700–730 °C (Miyagi and Takasu, 2005). Protoliths of the Tonaru body are grouped into sedimentary mixtures of basic and pelitic lithologies in the southern part and a layered gabbro sequence in the central and northern parts along the Kokuryo River (Banno et al., 2001; Huang et al., 2018). These lithologies were strongly recrystallized under the prograde epidote–amphibolite facies conditions and were conventionally named as epidote–amphibolite. The epidote–amphibolite and the surrounding basic and pelitic schists were well exposed along the Kokuryo River (Yoshida, 1981; Banno et al., 2001). The outcrop discussed in this study was observed along this route (Fig. 1b).

**PETROGRAPHY**

Figure 1c shows a simple lithologic map around the boundary between the Tonaru epidote–amphibolite and schistose rocks on its NE side, and the sample localities studied. A close-up photograph of the outcrop at the boundary is shown in Figure 2. Two lithologic types of alternating and basic layers developed between the epidote–amphibolite and pelitic schist. The alternating and basic layers occur on the NE pelitic schist side and on the SW epidote–amphibolite side, respectively. The alternating layers mainly consist of thin greenish amphibole–rich and brownish mica–rich bands (0.3–3 cm thickness). Bands enriched in both amphibole and biotite are rarely found in the alternating layers. Relatively larger amphibole–rich or mica–rich domains (several cm in width) occur as lenses or rounded block in the alternating layers and are elongated parallel to the thin banding structure. The domain parts are distinguished from amphibole– and mica–rich bands in the alternating layers and are simply denoted as lenses hereafter. Quartz veins and lenses also de-
veloped in the alternating layers. Samples collected from the alternating and basic layers, pelitic schist, and epidote-amphibolite body were studied in detail (Figs. 1c and 2).

### Alternating layers

The alternating layers (TO18O01 and TO18O02) sometimes intercalates quartz-rich bands (0.3–0.7 cm in width) parallel to the main layer structure. This thin banding structure is similar to that of the sector-zoned garnet-bearing samples collected from a meter away from the northern boundaries of the Tonaru epidote-amphibolite by Shirahata and Hirajima (1995). Figures 3a and 3b show photomicrographs of the amphibole-rich and mica-rich bands of the alternating layers, respectively. The amphibole-rich and mica-rich thin bands both contain amphibole, garnet, epidote, biotite, muscovite, plagioclase, and quartz in common, although the modal amounts of the amphibole, biotite, and felsic phases are different between these bands. Biotite is a major phase in the mica-rich band and rarely occurs in the amphibole-rich band. Garnet grains in the amphibole-rich and mica-rich band are euhedral to subhedral and show bimodal grain sizes: approximately 1–1.5 mm and 0.2–0.5 mm in diameter in the amphibole-rich band and 0.5–1.0 mm and 0.04–0.3 mm in diameter in the mica-rich band. Sodic plagioclase occurs as a matrix phase and inclusions in garnet grains of both the amphibole-rich and mica-rich bands (Fig. 4a).

An amphibole-rich lens in the alternating layers (TOCV) shows banding structure consisting of amphibole- and plagioclase-rich fine layers 2–3 mm thickness.

Figure 2. Photograph of an outcrop at the boundary between the Tonaru epidote-amphibolite and pelitic schist [modified Fig. 1d of Huang et al. (2018)], showing distribution of the zoning pattern of the garnet and the Na-phases in garnet. Color version is available online from https://doi.org/10.2465/jmps.181107a.

Figure 3. Photomicrographs (plane polarized light) of (a) amphibole-rich and (b) mica-rich bands in the alternating layers (TO18O02) and (c) basic layer (TOCA01) of the boundary zone, and the (d) Tonaru epidote-amphibolite (TO13). Color version is available online from https://doi.org/10.2465/jmps.181107a.

Figure 4. MnKα X-ray images of garnet grains in the (a) amphibole-rich band (TO18O02), (b) amphibole-rich lens (TOCV), and (c) basic layer (TOCA01) of the boundary zone and in the (d) Sanbagawa pelitic schist (TN0906) collected ~50 m northeast from the boundary zone (cf. Figs. 1c and 2). The number in parentheses indicates the anorthite content of plagioclase included in garnet. Lines A-A’ and B-B’ indicate the positions of step-scan analyses as shown in Figures 8a and 8b, respectively. Color version is available online from https://doi.org/10.2465/jmps.181107a.

This lens is mainly composed of amphibole, garnet, biotite, muscovite, epidote, plagioclase, and quartz. Garnet grains are euhedral to subhedral, and their grain sizes are 30–800 µm in diameter. Sodic plagioclase usually forms fine porphyroblastic domains 0.5–1.3 mm in length.
along the long axis. Paragonite occurs as inclusion in garnet. The mica-rich lens (TOCP01) is pale grayish in color and contains less abundant graphite than the common Sanbagawa pelitic schists that are generally gray or dark in color. This sample is mainly composed of garnet, muscovite, amphibole, epidote/zoisite, plagioclase, and quartz with minor biotite (Fig. 4b of Huang et al., 2018). Paragonite occurs as inclusion in garnet.

Basic layer

The basic layer (TOCA01 and TOCA02), which shares a border with the epidote-amphibolite, is mainly composed of garnet, amphibole, epidote, muscovite, and plagioclase. Garnet grains are subhedral–anhedral and partly fractured (Figs. 3c, 4c, 5a, and 5b: also cf. Fig. 4a of Huang et al., 2018). Sodic plagioclase occurs as inclusions in garnet mantles (Fig. 4d). Most pelitic schist samples contain paragonite as a garnet inclusion. Paragonite occurs also as a major matrix phase in TN0906 (Fig. 5d). In this sample, paragonite and plagioclase show an intergrowth texture suggesting these two phases were in equilibrium. However, muscovite rarely occurs as an interstitial phase in paragonite and/or biotite aggregate and was not observed as an isolated phase in TN0906.

Epidote-amphibolite

Garnet-bearing epidote amphibolites (TO12 and TO13) of the Tonaru body show a layered structure consisting of mafic and felsic bands, which might correspond to those that are pyroxene-rich and plagioclase-rich in the layered gabbro of the protolith. These samples are composed of amphibole, garnet, epidote, muscovite, and plagioclase with minor quartz, similar to basic layer in the boundary zone (Fig. 3d). The garnet shows a rounded, anhedral form (Figs. 3d and 5e).

Pelitic schist

Pelitic schists (TN01, TN2401b, TN0906, and TN02), which occur along the NE side of the boundary zone, have a mineral assemblage of biotite, garnet, muscovite, amphibole, plagioclase, and quartz (cf. Fig. 4c of Huang et al., 2018). Sodic plagioclase occurs as a matrix phase and inclusions in garnet (Fig. 4d). Most pelitic schist samples contain paragonite as a garnet inclusion. Paragonite occurs also as a major matrix phase in TN0906 (Fig. 5d). In this sample, paragonite and plagioclase show an intergrowth texture suggesting these two phases were in equilibrium. However, muscovite rarely occurs as an interstitial phase in paragonite and/or biotite aggregate and was not observed as an isolated phase in TN0906.

ANALYTICAL PROCEDURES

Whole-rock–major and trace element analyses were conducted using an X-ray fluorescence analyzer (XRF), the Shimadzu SXF-1200, at Nagoya University. Rare earth element (REE) compositions were measured using an Agilent 7500 inductively coupled plasma mass spectrometer at Kwansei Gakuin University. The analytical procedures were identical to those of Huang et al. (2018).

Quantitative and X-ray mapping analyses of the major phases were conducted using a JEOL JXA-8900R (WDS + EDS) electron probe micro-analyzer (EPMA) at Nagoya University. The acceleration voltage and specimen current for quantitative analyses were maintained at 15 kV and 12 nA on the Faraday cup, respectively. A beam diameter of 5 µm was used for mica and plagioclase analyses, and a diameter of 2–3 µm was used for analyzing all other phases. Well-characterized natural and synthetic phases, including synthetic F-phlogopite (F = 8.7 wt%) for F and natural Cl-rich hastingsite (Cl = 3.27 wt%; Suwa et al., 1987) for Cl, were employed as standards. Matrix corrections were performed using the α-factor table from Kato (2005). The Fe³⁺/Fe²⁺ values for amphibole were estimated as an average of the maximum and minimum values proposed by Schumacher (1997), while the total iron was assumed to be Fe₂O₃ for epidote/zoisite and FeO for the other phases.

The crystallinity of graphite was measured by Nicolet Almaga XR laser Raman spectroscope (Thermo Fisher Scientific) at Nagoya University with a green laser (532 nm, Nd-YAG laser) passed through an optical micro-

Figure 5. Back-scattered electron (BSE) images of (a) TOCA01 and (b) TOCA02 of the basic layer in the boundary zone, (c) the MnKα X-ray map of garnet in an epidote-amphibolite (TO13), and (d) the combination of NaKα (matrix part) and MnKα (garnet grain) X-ray maps of the pelitic schist (TN0906). Color version is available online from https://doi.org/10.2465/jmps.181107a.
scope (Olympus, BX51). Raman spectra were decomposed using PeakFit 4.12 software (SeaSolve Software) with a Voigt area function by subtracting a linear baseline in the spectral range of 1100–1800 cm\(^{-1}\). Measurement conditions and method of spectrum treatment followed Kouketsu et al. (2019). Abbreviations for minerals and end-members follow those of Whitney and Evans (2010).

**WHOLE-ROCK COMPOSITION**

Whole-rock compositions of most samples from the Kokuryo River route discussed in this study were reported by Huang et al. (2018). The major, trace, and REE compositions of the amphibole-rich bands in the alternating layers (TO18001 and TO18002) and the REE compositions of the basic layer (TOCA01 and TOCA02) were newly analyzed in this study. The major and trace compositions and REE compositions are listed in Tables 1 and 2 (available online from https://doi.org/10.2465/jmps.181107a), respectively.

**Chemical comparison of basic lithologies**

A Ti/100–Zr–Sr/2 discrimination diagram (Pearce and Cann, 1973) was employed for comparing the chemical characteristics of the basic lithologies (Fig. 6). This diagram is also useful to chemically compare the protoliths of metamorphosed basalt and gabbro in the Sanbagawa belt as proposed by Huang et al. (2018). The amphibole-rich band of the alternating layers has a low Sr/2 proportion relative to the Ti/100 + Zr component similar to those of the Sanbagawa basic schists, whose protoliths were considered to be mid-oceanic ridge basalt (Okamoto et al., 2000; Nozaki et al., 2006; Utsunomiya et al., 2011; Uno et al., 2014). An amphibole-rich lens (TOCV) also has a whole-rock chemistry similar to the amphibole-rich band and the basic schist. The basic layer (TOCA01 and TOCA02) of the boundary zone, however, has a distinctly higher Sr/2 proportion and shows similar trace element compositions to the epidote-amphibolites of the Tonaru body (TO series of Huang et al., 2018) and Iratsu and Seba bodies reported in the literature (Fig. 6).

The amphibole-rich band and lens in the alternating layers show flat chondrite-normalized REE patterns similar to those of the common Sanbagawa basic schists (Fig. 7a). They characteristically show a negative Eu anomaly. Although some basic schists are characterized by a slight enrichment in La and Pr together with a conspicuous negative Ce anomaly (Nozaki et al., 2006), the amphibole-rich bands and lens do not show any Ce anomaly.

The basic layer (TOCA01 and TOCA02) has slightly light-REE-enriched patterns similar to those of the Tonaru epidote-amphibolites and the LREE-enriched-type of the Iratsu epidote-amphibolites (Utsunomiya et al., 2011), although the REE concentrations of the Tonaru samples are one digit lower than those of the LREE-enriched-type Iratsu samples (Fig. 7b). The basic layer and Tonaru epidote-amphibolite characteristically show a positive Eu anomaly, in contrast to the amphibole-rich band and lens showing a negative Eu anomaly.

**MINERALOGY**

Representative chemical compositions of the major phases of the basic lithologies and pelitic schist are listed in Tables 3 and 4 (available online from https://doi.org/10.2465/jmps.181107a), respectively.

**Garnet**

Zoning patterns of the porphyroblastic garnet are grouped into simple and normal (Figs. 4a, 4b, 4d, and 5d) and composite (Figs. 4c, 5a, 5b, and 5c) types, which have been reported from the non-eclogite and eclogite units, respectively (Kouketsu et al., 2014; Taguchi and Enami,
The simple zoned garnet usually shows a monotonous pyrope increase and spessartine decrease from crystal core to rim, and a maximum grossular content at an intermediate position (Fig. 8a), which is a common zonal structure in the Sanbagawa schists (e.g., Banno and Kurata, 1972; Sakai et al., 1985; Banno et al., 1986). The composite zoned garnet consists of core and mantle parts, indicating compositional discontinuity during the growth stage (Fig. 8b). This type of zoning usually shows a concentration of spessartine at the beginning of mantle growth. The simple zoned garnet occurs in the alternating layers and the amphibole-rich and mica-rich lenses of the boundary zone and the pelitic schist along the NE side (Figs. 1c and 2). On the other hand, the composite-zoned garnet was only observed in the basic layer of the boundary zone and the Tonaru epidote-amphibolite. Relatively small-grained garnet, which coexists with a porphyroblastic grain in the alternating layers, usually shows compositional sector zoning, as described by Shirahata and Hirajima (1995).

Porphyroblastic garnet grains in the basic layer (TOCA01 and TOCA02) show a distinct compositional contrast to those in the amphibole-rich band (TO18001 and TO18002) and lens (TOCV) of the alternating layers (Fig. 9). Garnet grains in the basic layer show a compositional range of Alm$_{51-66}$Sps$_{0-9}$Prp$_{6-27}$Grs$_{15-32}$ and X$_{Mg}$ (= Mg/(Mg + Fe$^{2+}$)) = 0.12–0.35, similar to those of the Tonaru and Iratsu epidote-amphibolites (Fig. 9). However, garnet grains in the amphibole-rich band and lens in the alternating layers show a wider and lower X$_{Mg}$ composition than those in the basic layer: Alm$_{53-70}$Sps$_{1-22}$Prp$_{3-16}$Grs$_{17-30}$ and X$_{Mg}$ = 0.05–0.20 for the amphibole-

Figure 7. Comparisons of REE patterns of (a) the amphibole-rich band (TO18001 and TO18002) and amphibole-rich lens (TOCV) for the Sanbagawa basic schist and (b) the basic layers (TOCA01 and TOCA02) for the Tonaru epidote-amphibolite (TO07 and TO10) and Iratsu epidote-amphibolite. The CI chondrite value is from Sun and McDonough (1989). Data for the Sanbagawa basic schist are from O00 (Okamoto et al., 2000), N06 (Nozaki et al., 2006), U11 (Utsunomiya et al., 2011), and U14 (Uno et al., 2014), and those of the Iratsu and Tonaru epidote-amphibolite are from U11 (Utsunomiya et al., 2011) and H18 (Huang et al., 2018). Data for TO18001, TO18002, TOCA01, and TOCA02 were newly analyzed in this study.

Figure 8. Step-scan analyses of the garnet grains in the (a) amphibole-rich band (TOCV) and (b) basic layer (TOCA01) of the boundary zone. Analytical positions are shown in Fig. 4. Two Prp-rich and Sps-poor positions in mantle part of TOCA01 indicated by an arrow correspond to a separated core part (also cf. Fig. 4c).
rich band and \( \text{Alm}_{37-69}\text{Sp}_{2-19}\text{Pr}_{12-32} \) and \( X_{\text{Mg}} = 0.04-0.16 \) for the amphibole-rich lens, which are similar to those of the Sanbagawa basic schists (Fig. 9).

Porphyroblast garnet grains in the pelitic lithologies have similar compositional ranges to each other, although the garnet grains in the mica-rich lens (TOCP01) lack Sps-rich compositions that correspond to those of the core part of the other garnet grains: \( \text{Alm}_{54-69}\text{Sp}_{13-14}\text{Pr}_{12-15}\text{Grs}_{15-32} \) and \( X_{\text{Mg}} = 0.11-0.21 \) for the mica-rich lens; \( \text{Alm}_{56-68}\text{Sp}_{13-15}\text{Pr}_{13-15}\text{Grs}_{13-31} \) and \( X_{\text{Mg}} = 0.04-0.19 \) for the mica-rich band; and \( \text{Alm}_{56-69}\text{Sp}_{14-15}\text{Pr}_{12-15}\text{Grs}_{12-31} \) and \( X_{\text{Mg}} = 0.03-0.21 \) for the pelitic schist (TN01 and TN0906).

Mica group minerals

Biotite grains in the alternating layers have narrow and similar compositional ranges to each other: \( \text{Si} = 2.76-2.82 \) (atoms per formula unit: apfu for \( O = 11 \)), \( X_{\text{Mg}} = 0.62-0.63 \), and \( \text{TiO}_2 = 1.7-2.0 \) wt\% for the amphibole-rich band; \( \text{Si} = 2.76-2.86 \) apfu, \( X_{\text{Mg}} = 0.58-0.64 \), and \( \text{TiO}_2 = 1.4-2.0 \) wt\% for the mica-rich band; and \( \text{Si} = 2.77-2.89 \) apfu, \( X_{\text{Mg}} = 0.56-0.60 \), and \( \text{TiO}_2 = 1.5-2.1 \) wt\% for the amphibole-rich lens. The pelitic schists contain a slightly higher \( X_{\text{Mg}} \) of biotite grains than the mica-rich band of the alternating layers: \( \text{Si} = 2.80-2.86 \) apfu, \( X_{\text{Mg}} = 0.64-0.69 \), and \( \text{TiO}_2 = 1.2-1.8 \) wt\%.

Matrix muscovite in the amphibole-rich and mica-rich bands, amphibole-rich lens, and basic layer show similar \( \text{Si} \) ranges of 3.13-3.15, 3.08-3.22, 3.13-3.20, and 3.14-3.19 apfu, respectively. In contrast, the matrix muscovite in the mica-rich lens and pelitic schists shows slightly \( \text{Si} \)-rich compositions of 3.14-3.29 and 3.15-3.25 apfu, respectively. The \( X_{\text{Na}} = [\text{Na}/(\text{Na} + \text{K} + \text{Ba} + \text{Ca})] \) values are 0.10-0.19 and are fairly constant. Muscovite included in the garnet of the basic layer is characterized by Si-poor (3.02 and 3.03 apfu) and has a lower \( X_{\text{Na}} \) value (0.02) than that of the matrix muscovite. Paragonite included in the garnet has a near end-member composition of \( \text{Si} = 2.95-3.01 \) apfu and \( X_{\text{Na}} = 0.89-0.96 \). In contrast, paragonite coexisting with muscovite in the matrix tends to have a lower \( X_{\text{Na}} \) value ranging from 0.78 to 0.94.

Amphibole and other phases

Amphibole grains in all lithologies show similar compositions to each other and mostly belong to the tschermakite-pargasite series of Leake et al. (1997) (Tables 3 and 4; https://doi.org/10.2465/jmps.181107a): \( \text{Si} = 6.15-6.58 \) apfu (for \( O = 23 \)), \([A](\text{Na} + K) = 0.41-0.64 \) apfu, and \( X_{\text{Mg}} = 0.56-0.66 \) for the amphibole-rich band; \( \text{Si} = 6.22-6.65 \) apfu, \([A](\text{Na} + K) = 0.41-0.64 \), and \( X_{\text{Mg}} = 0.58-0.64 \) for the mica-rich band; \( \text{Si} = 6.28-6.54 \) apfu, \([A](\text{Na} + K) = 0.47-0.60 \), and \( X_{\text{Mg}} = 0.51-0.57 \) for the amphibole-rich lens; and \( \text{Si} = 6.23-6.65 \) apfu, \([A](\text{Na} + K) = 0.37-0.60 \), and \( X_{\text{Mg}} = 0.60-0.64 \) for the mica-rich lens of the alternating layers; \( \text{Si} = 6.20-6.66 \) apfu, \([A](\text{Na} + K) = 0.41-0.60 \), and \( X_{\text{Mg}} = 0.57-0.68 \) for the basic layer and \( \text{Si} = 6.10-6.75 \) apfu, \([A](\text{Na} + K) = 0.36-0.54 \), and \( X_{\text{Mg}} = 0.64-0.71 \) for the pelitic schist, where \([A] \) indicates the largest 12-coordinated site. They show retrograde zoning with a slight decrease in the combination of tschermakite and edenite components towards the rim. The fluorine content reaches 0.11 wt\% and the CI content is less than the detection limit (2σ level) of 0.01 wt\%.

Plagioclase with \( \text{An}_{12-28} \) occurs in all of the samples studied (cf. Figs. 1c and 4 and Tables 3 and 4; https://doi.org/10.2465/jmps.181107a). The matrix plagioclase typically shows a zoning pattern consisting of a core with high \( \text{Ca} (\text{An}_{12-28}) \) and less calcic rim (\( \text{An}_{0-8} \)). Plagioclase included in the garnet has a variable composition of \( \text{An}_{12-22} \). Some epidote grains in the pelitic lithology have a REE-rich core (Sakai et al., 1984). \( X_{\text{Fe}} = [\text{Fe}^3+/\text{Fe}^{2+} + \text{Al}] \) values of the REE-poor portion of the epidote are 0.10–
0.17 and 0.11–0.20 in the pelitic and basic lithologies, respectively. $X_{Fe}$ values of zoisite are 0.03–0.05.

**METAMORPHIC P/T CONDITIONS**

**Conventional geothermobarometers**

The pelitic lithologies usually contain the common mineral assemblage of garnet–biotite–muscovite-plagioclase-quartz, whose equilibrium conditions were estimated using a conventional garnet–biotite Mg–Fe exchange geothermometer and the net-transfer reactions of the garnet–biotite–plagioclase–quartz (GBPQ), garnet–muscovite–plagioclase–quartz (GMPQ), and garnet–biotite–muscovite–plagioclase system (GBMP) calibrated by Wu et al. (2004), Wu and Zhao (2006), and Wu (2015), respectively. Although many calibrations have been published for the garnet–biotite geothermometer, two proposed by Bhattacharya et al. (1992) and Holdaway (2000), considering the influence of Al and Ti substitutions in biotite on the temperature estimation, were employed in the present study (Fig. 10).

Pressure–temperature conditions were estimated as 1.06–1.15 GPa/615–625 °C and 1.07–1.16 GPa/595–600 °C for the selected two pelitic schists of TN01 and TN0906, respectively, using the sets of rim composition of normal-zoned garnet, average compositions of the isolated matrix biotite and muscovite, and the An-rich plagioclase core listed in Table 4 (https://doi.org/10.2465/jmps.181107a). These P/T conditions are consistent with the reported values of 0.9–1.1 GPa/585–635 °C for oligoclase–biotite zone pelitic schists from the Besshi region (Enami, 1983).

**Raman graphite geothermometer**

Figure 11 shows temperature conditions of a mica-rich lens (TOCP01) estimated using Raman graphite geothermometer calibrated for regional metamorphic rocks by Aoya et al. (2010). To avoid the effects of mechanical polishing and deformation on the Raman spectrum (e.g., Beyssac et al. 2003; Kouketsu et al., 2019), graphite grains that are completely sealed within garnet porphyroblast were selected for temperature estimates. Although, the estimated temperatures show relatively a wide range, most graphite grains have high crystallinities suggesting equilibrium temperatures >500 °C, and some of them record >600 °C. These temperature conditions were estimated by analyzing graphite grains sealed in various positions of garnet, and thus, the wide temperature range might be due to that the graphite grains were included by garnet at various times and recorded equilibria at different stages of prograde metamorphism.

**Pressure–Temperature pseudosection**

A P/T pseudosection was computed for a paragonite-
was considered to be an excess phase. The whole rock composition of sample TN0906 is as follows (in wt%): SiO₂ (67.11), TiO₂ (0.59), Al₂O₃ (14.17), total iron as FeO (4.69), MnO (0.14), MgO (4.07), CaO (2.27), Na₂O (3.20), K₂O (1.49), and P₂O₅ (0.11) (Huang et al., 2018). The sample contains apatite [Ca₁₀(PO₄)₆(OH, F, Cl)] as an accessory phase, and thus, we assumed that a combination of P₂O₅ of 0.11 wt% and CaO of 0.14 wt% was sequestered in the apatite. Therefore, the whole rock composition, corrected for the appropriate amount of CaO as 2.13 wt%, was employed for calculation of the pseudosection diagram. Sources of the selected activity models for the relevant minerals in the pseudosection analysis are listed in the caption of Figure 10. The calculated result implies that the Sanbagawa pelitic schist (sample TN0906) (Fig. 10). The diagram was calculated by forward modeling using Perple_X_6.8.3 (Connolly, 1990), utilizing the internally consistent data set of Holland and Powell (1998). The chemical system for the general calculations of the pseudosection was K₂O–Na₂O–CaO–FeO–MnO–MgO–Al₂O₃–SiO₂–H₂O (KNCFMnMASH), and the H₂O fluid was considered to be an excess phase. The whole-rock composition of sample TN0906 is as follows (in wt%): SiO₂ (67.11), TiO₂ (0.59), Al₂O₃ (14.17), total iron as FeO (4.69), MnO (0.14), MgO (4.07), CaO (2.27), Na₂O (3.20), K₂O (1.49), and P₂O₅ (0.11) (Huang et al., 2018). The sample contains apatite [Ca₁₀(PO₄)₆(OH, F, Cl)] as an accessory phase, and thus, we assumed that a combination of P₂O₅ of 0.11 wt% and CaO of 0.14 wt% was sequestered in the apatite. Therefore, the whole-rock composition, corrected for the appropriate amount of CaO as 2.13 wt%, was employed for calculation of the KNCFMnMASH phase diagram. Sources of the selected activity models for the relevant minerals in the pseudosection analysis are listed in the caption of Figure 10.

The calculated result implies that the Sanbagawa pelitic schists have a wide P-T stability of coexisting sodic plagioclase with An₃₀ and paragonite (Fig. 10), which is consistent with the common occurrence of paragonite and sodic plagioclase aggregates as matrix phases in the studied pelitic schists (Fig. 5d). This sample has matrix assemblage of Grt + Bt + Amp + Pg + sodic Pl (An₂₄) + Qz with minor Ms, which might suggest an equilibrium condition around a lower pressure limit of muscovite-bearing assemblages in the pseudosection diagram (Ms) in Fig. 10. The P/T conditions of TN0906 and TN01 (1.1–1.2 GPa/595–625 °C) estimated using conventional geothermobarometries and temperature condition up to 650 °C (TOCP01) estimated using Raman graphite geothermometer are consistent with the inferred stability P-T conditions for the pelitic schist mineral assemblage.

**DISCUSSION**

**Boundary between the eclogite and non-eclogite units**

The Tonaru body belongs to the eclogite unit (Miyagi and Takasu, 2005), and thus, westward extension of the unit boundaries between the eclogite and non-eclogite units in the Besshi region should traverse the schist region on both the northern and southern sides of the Tonaru body or coincide with the lithologic boundaries between epidote-amphibolite and schist (Aoya et al., 2017). Garnet grains in the basic lithologies (basic layer, and amphibole-rich band and lens of the boundary zone) imply a critical contrast concerning their zoning patterns and compositional ranges. Garnet in the basic layer (TOCA01 and TOCA02) shows composite zoning with a discontinuous compositional change between the core and mantle (Figs. 4c, 5a, 5b, and 8b) corresponding to those of the Tonaru epidote–amphibolite (Fig. 5c). The compositional range of the garnet in the basic layer also has a resemblance to that in the Tonaru and Iatsu epidote-amphibolites, which record recrystallization under eclogite facies conditions (Fig. 9). The whole-rock trace-element compositions and REE patterns of the basic layer also resemble those of the epidote–amphibolite (Figs. 6 and 7). These data suggest that the basic layer is a fractured margin of the Tonaru body and belongs to the eclogite unit. Garnet in the amphibole-rich band (TO18001 and TO18002) and amphibole-rich lens (TOCV) in the boundary zone shows normal zoning and has a compositional range similar to that of the basic schist reported in literature (Fig. 9). These garnet grains sometimes contain sodic plagioclase as inclusion (Figs. 4a and 4b). The Raman analyses of quartz inclusions in the garnet (Enami et al., 2007) of the mica-rich band and pelitic schist in the Kokuryo River area, although limited, also show no evidence of equilibrium under the eclogite facies conditions. Therefore, the lithologies of the alternating layers and pelitic schist are considered to be a part of the non-eclogite unit, and the unit boundary between the eclogite and non-eclogite units probably corresponds to the lithologic boundary between the basic layer and the alternating layers in the boundary zone (cf. Fig. 2). The amphibole-rich band (TO18001 and TO18002) and lens (TOCV) in the alternating layers have whole-rock trace element compositions and REE patterns that resemble the basic schist (Figs. 6 and 7), implying a clear contrast in protoliths
between the basic layer and the set of amphibole-rich band and lens in the boundary zone. This fact supports the interpretation on the unit boundary mentioned above.

**Paragonite issue**

Paragonite occurs as an inclusion in the normal-zoned garnet grains of the amphibole-rich and mica-rich lenses and pelitic schist and as a matrix phase in the pelitic schist (TN0906). This phase also occurs as a matrix constituent of the Tonaru epidote-amphibolite (Miyagi and Takasu, 2005; Huang et al., 2018). Kouketsu et al. (2014) proposed the distribution of the eclogite unit in the Besshi region based on the combination of occurrences of the composite-zoned garnet, Raman quartz geobarometry (Enami et al., 2007), and occurrence of paragonite. Paragonite is a major phase in the pelitic schist instead of the sodic pyroxene under eclogite facies conditions as suggested based on the pseudosection analyses of the Sanbagawa pelitic schists by Kouketsu and Enami (2011). However, they also indicated that paragonite has a broad P-T stability field and could be stable to ~ 0.5 GPa depending on the $X_{\text{NA}}\left[=\frac{\text{Na(Al-2K+1.5Ca+N)}}{\text{whole-rock composition}}\right]$ molecular value of the whole-rock composition. The P-T pseudosection analysis of the sample TN0906 also indicates coexistence of paragonite and oligoclase is stable under the Sanbagawa epidote-amphibolite facies stage. Therefore, paragonite is not a critical phase indicating eclogite facies metamorphism, and its occurrence in the amphibole-rich and mica-rich lenses and pelitic schist in itself does not necessarily imply that these lithologies have undergone eclogite facies equilibria. Consequently, the paragonite occurrences in these lithologies do not conflict with the conclusion that these lithologies belong to the non-eclogite unit.

**Timing of unit contingence**

Pressure-temperature trajectories of the eclogite and non-eclogite units and their relationship have been discussed by many authors and are generally summarized as Supplementary Figure S1 of Huang et al. (2018). The exhumed Tonaru epidote-amphibolite body of the eclogite unit might have encountered the subducted schistose lithologies of the non-eclogite unit including the alternating layers in the boundary zone. In the basic layer (TOCA01 and TOCA02), the mantle part of the composite-zoned garnet contains sodic plagioclase with $\text{An}_{0.23}$, and the matrix phases show equilibrium under epidote-amphibolite facies conditions. Plagioclase grains with $\text{An}_{0.20}$ commonly occur as a matrix phase through the eclogite and non-eclogites units (Fig. 1c). These data indicate that there is no discontinuity in the metamorphic grade of the epidote-amphibolite stage throughout the study area and imply that the contingence of the eclogite and non-eclogite units occurred before the climax of the prograde epidote-amphibolite metamorphism at 1.1–1.2 GPa/595–625 °C. Shirahata and Hirajima (1995) discussed the origin of sector-zoned garnet in the samples collected from a meter away from the northern boundary of the Tonaru epidote-amphibolite. They considered that the formation of the sector-zoned garnet has progressed at the later stage of the (prograde) Sanbagawa metamorphism and was linked to the emplacement of the Tonaru body into the schist. The timing of contingence proposed in this paper is consistent with the interpretations suggested based on these mineralogical (Shirahata and Hirajima, 1995; Zaw Win Ko et al., 2005; Kouketsu et al., 2014) and geostuctural studies (Wallis and Aoya, 2000; Aoya, 2001).

The composite-zoned garnet grains in the basic layer belonging to the eclogite unit are extensively fractured, and the composite zoning pattern is broken (Figs. 5a and 5b). This suggests that the currently observed fracturing of the boundary layer probably formed following the peak metamorphic stage of the epidote-amphibolite facies and was not directly related to the joining of the eclogite and non-eclogite units. However, garnet grains in the alternating layers in contrast do not show a distinct crushed and cluster texture. This might have been the result of concentration of the shear stress into the mica-poor and massive epidote-amphibolite and/or buffering of the shear stress by the mica-rich band of the alternating layers.

**CONCLUSION**

1. The boundary between the eclogite and non-eclogite units at an outcrop scale was reported from the Kokuryo River route in the western part of the Besshi region. This outcrop consists of Tonaru epidote-amphibolite and pelitic schist and boundary zone between them. The boundary zone is composed of a basic layer on the epidote-amphibolite side and a fine alternation of amphibole-rich and mica-rich bands on the pelitic schist side.

2. Whole-rock and mineral compositions show a distinct contrast between the basic layer and the amphibole-rich band of the boundary zone, which are similar to those of the Tonaru epidote-amphibolite and basic schist, respectively. Garnet grains in the epidote-amphibolite of the Tonaru body and the basic layer show composite zoning consisting of core and mantle part, which represent two prograde stages of eclogite facies and the postulated epidote-amphibolite facies metamorphism, respectively. However, garnet grains in the amphibole-rich
and mica-rich lithologies in the alternation layers and pelitic schist show a simple bell-shape zoning similar to those of the non-eclogite unit. These facts indicate that the basic layer is a fractured lithology of the epidote-amphibolite, and the boundary between the eclogite and non-eclogite units coincides with the lithologic boundary between the basic layer and alternating layers of the boundary zone.

3. Plagioclase with An\textsubscript{10} extensively occurs in pelitic schists, alternating layers, basic layer, and epidote-amphibolite, suggesting that the juxtaposed eclogite and non-eclogite units recrystallized under prograde epidote-amphibolite facies conditions (1.1–1.2 GPa/595–625 °C).

4. The verification of the tectonic contact between the eclogite and non-eclogite units at an outcrop scale strongly supports an inferred nappe structure in the high-grade region of the Sanbagawa metamorphic belt.

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SUPPLEMENTARY MATERIAL

Tables 1–4 and color versions of Figures 2–5 are available online from https://doi.org/10.2465/ijms.181107a.

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