LETTER

High-Mg garnets from pelitic schists adjacent to the Sebadani eclogitic metagabbro mass, Sambagawa metamorphic belt, central Shikoku, Japan

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Pelitic schists adjacent to the Sebadani metagabbro mass in the Sambagawa metamorphic belt of central Shikoku, Japan consist mainly of garnet, phengite, albite and quartz, and small or scarce amounts of Na-Ca and Ca-amphiboles, epidote, omphacite, kyanite, rutile and carbonaceous matter. Garnets are zoned from pale reddish brown cores to pale yellowish-green or colorless rims. The cores of the garnets are Mg- and Ca-rich (MgO 3.50–11.30 wt%; CaO 7.27–12.98 wt%), and are overgrown by Fe-rich inner and outer rims. Kyanite occurs as inclusions in the high-Mg cores of the garnets. Inclusion assemblages of the high-Mg core of the garnets indicate relatively high-T conditions such as the kyanite eclogite facies (821 ± 32 °C and 19.4 ± 1.6 kbar). The cores of the garnets are anhedral with irregular embayments, and the outlines of the inner rims also show similar texture. The cores are also intensely fractured and filled by Fe-rich garnet with the same composition as the inner rims. The texture and chemical compositions of the high-Mg cores in the garnets are similar to those of garnets in the eclogites in the Sebadani metagabbro mass. The possible origin of the high-Mg cores are (i) in situ high-T regional metamorphism, (ii) detrital origin, and (iii) mechanical mixing of eclogites in the Sebadani metagabbro and surrounding pelitic schists. It is probable that high-Mg garnets were stripped from the Sebadani metagabbro mass and mechanically introduced into the pelitic schists when the Sebadani metagabbro mass was incorporated into the pelitic schists.

Keywords: High-Mg garnet, Kyanite, Omphacite, Eclogite, Sambagawa (Sanbagawa) belt

INTRODUCTION

Compositional zoning in garnet provides important information about the metamorphic evolution of regional metamorphic rocks. Garnets growing under low- and medium-temperature conditions generally show compositional zoning, and the most common of which is a bell-shaped Mn profile, with Fe and Mg behaving antipathetically. This type of zoning is widespread in the Sambagawa metamorphic belt (e.g., Banno et al., 1986), but other garnet types with reversed or composite zoning patterns are also found (e.g., Itaya, 1978; Inui, 2004). The Sebadani area in the Sambagawa metamorphic belt of central Shikoku consists of the eclogite-bearing Sebadani metagabbro mass and surrounding basic and pelitic schists (Takasu, 1984; Aoya, 2001; Fig. 1). Both the basic and pelitic schists sporadically contain eclogitic mineral assemblages. The Sebadani metagabbro mass is exposed over an area of about 300 m × 200 m (Fig. 1). The Sebadani metagabbro mass is considered to have undergone eclogite facies metamorphism at higher temperature conditions than the surrounding Sebadani eclogitic basic schists (Takasu, 1984).

The metagabbro body is surrounded by basic schists (eclogitic basic schists) with a thin layer of pelitic schists between them (Fig. 1). Nomizo (1992) reported three different types of garnets from the pelitic schists exposed adjacent to the Sebadani metagabbro mass. These are: Type 1: fine-grained garnet (~0.3 mm in diameter) with Mn generally decreasing from core to rim, and with resorption-overgrowth texture between core to rim. This type of garnet has been previously described as resorption-overgrowth garnet, from the same pelitic schists (Takasu, 1986; Takasu and Kondo, 1993). Type 2: medium-grained (~0.5 mm in diameter) garnets with high-Mg cores. The chemical composition and zoning pattern of the inner and outer rims of the garnet are the same as those of type 1 garnet. Higashino and Takasu (1982) described similar garnets, and regarded the high-Mg cores as being of detrital origin. Type 3: large (1–3 mm in diameter) poikiloblastic garnets with homogeneous composi-
tion that is correlated with the outermost rims of type 1 and type 2 garnets. Nomizo (1992) considered the variety of zoning pattern was due to differences in the timing of their nucleation, and that type 2 garnets recorded the complete metamorphic history of the pelitic schists.

In this paper we describe the high-Mg core-bearing garnets (Nomizo’s type 2) in the pelitic schists. These are the same as those described by Higashino and Takasu (1982) and Nomizo (1992), but for the first time we have found omphacite and kyanite as inclusions in the cores. The results provide important new constraints on the entire tectonometamorphic evolution of the Sambagawa belt. The mineral abbreviations used in the text, tables and figures follow Whitney and Evans (2010).

**PETROGRAPHY AND MINERAL CHEMISTRY**

Four pelitic schist samples were collected from an outcrop adjacent to the Sebadani metagabbro mass (Fig. 1). They consist mainly of garnet, phengite, albite and quartz. Small amounts of Na-Ca and Ca-amphiboles, epidote, chlorite, omphacite, kyanite, rutile, titanite, calcite, zircon, ilmenite, pyrite and carbonaceous matter are present. Modal proportion of amphibole in the pelitic schists is slightly greater than that in average Sambagawa pelitic schists (Nomizo, 1992), suggesting slight mixing of basic materials. Kyanite occurs as inclusions in garnet, and this is the first description of kyanite from the Sebadani area. A kyanite-bearing eclogitic mineral assemblage has been described from pelitic layers in the Quartz eclogite mass in the Besshi district (e.g., Miyamoto et al., 2007; Fig. 1). Omphacites (Jd 29–57 mol%) are present as inclusions in garnets and albite + amphibole (Mhb) symplectites after omphacite in the matrix. A schistosity is defined by preferred orientation of phengite and chlorite.

Garnets occur as euhedral to subhedral porphyroblasts up to 5 mm across. These are optically zoned from pale reddish-brown cores (high-Mg in composition) to pale yellowish-green or colorless rims (Figs. 2a–2c). Three zones (core, inner rim and outer rim) are identified by BSE image (Fig. 2c). The core is anhedral with irregular embayments, and the outline of the inner rim also shows similar texture (Fig. 2c). This texture and zoning are the same as those in Nomizo’s (1992) type 2 garnets. The cores of the garnets show a compositional zoning with core to rim compositional variations of Mg (0.72–1.13 cations per formula unit, pfu), and Fe (1.47–1.15 pfu), Ca (0.79–0.73 pfu), Mn (0.04–0.05 pfu) (Table 1, Figs. 3a, D1a and D3a: Figures D1, D2, D3, D4, and D5 and Tables 1, 2, 3, and 4 are available online from http://joi.jlc.jst.go.jp/JST.JSTAGE/jmps/110621d). An example of a high-Mg core in a garnet shows symmetric outward increase of Mg (0.41–0.85 pfu) and Ca (0.63–0.97 pfu), and decrease of Fe (1.82–1.39 pfu) and Mn (0.16–0.01 pfu) (Fig. D4). Elemental color maps show that the compositional core does not always lie at the morphological center (Fig. D3a), suggesting chemical resorption and/or mechanical erosion after the crystallization of the high-Mg garnets. Concentric zoning patterns of the garnets are not euhedral in shape (Fig. D4), probably because of subsequent elemental diffusion under high temperature conditions. The ranges of Mg contents in the cores differ from grain to grain, though the total range is from 0.41 to 1.27 pfu (MgO 3.50–11.30 wt%). The high-Mg cores vary widely in shape (rounded, subrounded, elliptical or elongate) and size (<4 mm) (Fig. 2a). The occurrences and distributions of high-Mg cores are variable. In some places most garnet grains contain high-Mg cores (Fig. 2a).
whereas in other places such garnets are scarce (Fig. 2b). This heterogeneous distribution of high-Mg cores and their variable in Mg-contents occur at both outcrop and thin section scale.

The inner rims of the garnets display prograde growth zoning, with symmetric outward decrease of Mn (0.22-0.06-0.10 pfu) and increase of Mg (0.34-0.21-0.33 pfu). The cores of the garnets are strongly fractured, and the fractures are filled by Fe-rich garnet with the same composition as the inner rim (Figs. 2c and D3a). The outer rims of the garnets also show a prograde growth zoning, and display symmetric outward decrease in Mn (0.11-0.01 pfu) and increase in Mg (0.33-0.83 pfu). According to the Mn-colors maps (Figs. D3 and D4), distinct Mn enrichment at both the core–inner rim and the inner rim–outer rim boundaries occurs.

The high-Mg cores of the garnets contain inclusions of kyanite (Fe2O3 <0.99 wt%; Cr2O3 <0.05 wt%), omphacite (Jd 32-56 mol.%), epidote (Ps 6-15), barroisite, paragonite, rutile and quartz (Figs. 2e-2f, D2a, and Tables 2-4). They also contain polyphase inclusions of barroisite + paragonite + chlorite and barroisite + rutile + ankerite. However, chlorites and paragonite inclusions are connected to the outside of the garnets by fractures (Fig. D2a). The inner rims of the garnets contain inclusions of omphacite (Jd 29-57 mol%; Aeg 0-21 mol%), epidote (Ps 3-26), Na-Ca/Ca-amphiboles, phengite (Si 6.53–7.27 pfu), paragonite, albite (An <3), quartz, titanite, ilmenite and carbonaceous matter (Table 2). They also contain polyphase inclusions of Ca-rich garnet (Ca 1.55–1.63 pfu).

Figure 2. Garnets in the pelitic schists adjacent to the Sebadani metagabbro mass. (a) Most of the garnets have high-Mg core (BEI). (b) Only a few garnets contain high-Mg cores (BEI). (c) Porphyroblastic garnet having a high-Mg core, overgrown by inner and outer rims (BEI). (d) Porphyroblastic garnet showing core and rim (BEI). (e) High-Mg core of a porphyroblastic garnet containing inclusions of kyanite, epidote and quartz (SEI). (f) Core of the garnet containing omphacite as inclusion (BEI).

Figure 3. Chemical compositions of zoned garnets in the pelitic schists (a) garnet with high-Mg core. (b) Garnet without high-Mg core.
High-Mg eclogitic garnets in the Sebadani pelitic schists

M. Numata

High-Mg cores of the garnets contain inclusions of kyanite, omphacite, barroisite, epidote, rutile, titanite, ilmenite, quartz and carbonaceous matter, and the outer rims also include symplectic aggregates of barroisite + albite and Mg-hornblende + albite (Figs. D2c and D2d). Abundant inclusions of carbonaceous matter are present in the inner and outer rim of garnets as described by Takasu (1986), but no carbonaceous matter is present in the high-Mg cores of the garnets.

Numerous of garnets lack high-Mg cores, and exhibit resorption between the core and the rim (Fig. 2d). These are the same as type 1 garnet of Nomizo (1992) and composite zoned garnet of Takasu (1986). Two zones (core and rim) were identified on the basis of texture and chemical composition (Table 1 and Figs. 2d, 3b, D1b, and D3b). The compositions of these cores and rims correspond to the inner and outer rims of the high-Mg core-bearing garnets. The cores of these garnets are rich in Mn and show prograde growth zoning with outward decrease in Mn (0.65-0.05 pfu) and increasing Mg (0.13-0.36) towards the core–rim boundary. The rims of the garnets also show a prograde growth zoning, and outward decrease in Mn (0.33-0.04 pfu) and increase in Mg (0.20-0.39 pfu). Initial Mn contents (0.65 pfu) in garnets without high-Mg cores are significantly greater than those in the inner rim (0.22 pfu) of garnets containing high-Mg cores.

Poikiloblastic garnets with homogeneous composition (type 3 garnet described by Nomizo, 1992) were not found in the pelitic schists in this study.

DISCUSSION

Metamorphic conditions deduced from the high-Mg cores of the garnets

Three generations of garnet are identified, based on microstructural relationships and chemical compositions. High-Mg cores of the garnets contain inclusions of kyanite, omphacites, barroisite, epidote, rutile and quartz. Aggregates of Mg-hornblende and quartz as well as barroisite and albite occur as inclusions in the inner rims of the garnets, suggesting that clinopyroxenes were present before crystallization of the inner rims. The mineral inclusions within the high-Mg garnets indicate relatively high-temperature metamorphic conditions such as the kyanite eclogite facies. THERMOCALC (v. 3.21) with an updated version of the internally consistent thermodynamic dataset (Holland and Powell, 1998) was applied for P-T estimations. The activities of the minerals used for the P-T estimations were obtained using the AX program (Holland and Powell, 1998). Assuming an equilibrium mineral assemblage of garnet-omphacite-kyanite-barroisite-epidote-quartz yields average P-T conditions of 821 ± 32 °C and 19.4 ± 1.6 kbar. The P-T conditions are estimated from different calibrations of garnet-clinopyroxene Fe2+-Mg exchange geothermometers (Kν = 5–7) and jadeite geobarometer (Jd 56 mol%; Holland, 1983) as the minimum pressures. The Ellis and Green (1979) geothermometer gives 795-845 °C and 19-20 kbar, and Nakamura (2009) yields 710-780 °C and 17-18 kbar (Fig. D5). The P-T conditions obtained from THERMOCALC and Ellis and Green (1979) have slightly higher metamorphic temperatures than those of the high-T eclogite conditions determined for the Sebadani metagabbro (720-750 °C, 12-24 kbar; Takasu, 1984), but the P-T conditions obtained from Nakamura (2009) are the same.

Kouketsu et al. (2010) reported omphacites as inclusions in complex zoned garnets in pelitic schists from the Sebadani area, and the chemical characteristics of the garnets and their inclusions are similar to those of the inner and outer rims of the high-Mg core-bearing garnets described in this paper. According to Kouketsu et al. (2010) the pelitic schists underwent eclogite facies metamorphism of 495-530 °C and 18-19 kbar.

Correlation of the garnets from the pelitic schists and the Sebadani metagabbro mass

Takasu (1984) reported that garnets within eclogites in the Sebadani metagabbro mass contain two zones, core and rim. The cores are richer in Mg and poorer in Fe and Mn than the rims. Mg and Ca contents in the cores range from 4.1-9.8 wt% (0.47-1.09 pfu) and 9.1-11.6 wt% (0.74-0.97 pfu), respectively (Table 1 and Fig. 3a). Plentiful of fractures are developed in the cores, and the fractures are filled by Fe-rich garnet with the same composition as the rims (Takasu, 1984). The cores of the garnets in the pelitic schists exposed adjacent to the Sebadani metagabbro mass are rich in Mg (MgO 3.5-11.3 wt%) and Ca (CaO 7.3-13.0 wt%), and poor in Fe and Mn. The cores of the garnets are also fractured, and these fractures are filled by Fe-rich garnet with the same composition as the inner rim. As Nomizo (1992) has already observed, the textures and the chemical compositions of the high-Mg cores of the garnets in the pelitic schists are identical to those of the garnets in the eclogites within the Sebadani metagabbro mass, suggesting a common metamorphic origin of both garnet types.

Implications of the high-Mg cores of garnets in the pelitic schists

Nomizo (1992) considered three possible origins for the
high-Mg cores of the garnets. They were (i) formed during regional high-T eclogite metamorphism, together with the garnets in the Sebadani metagabbro mass; (ii) mechanically introduced from the metagabbro and mixed into the pelitic schists; or (iii) of detrital origin, as previously suggested by Higashino and Takasu (1982). Nomizo (1992) favored an origin were a regional high-T eclogite metamorphism caused the crystallization of the high-Mg cores of the garnets. Aoya et al. (2006), Ota et al. (2004) and Wallis and Aoya (2000) also suggested that the Sebadani metagabbro and surrounding schists experienced a common eclogitic metamorphism. However, only one outcrop of pelitic schist adjacent to the Sebadani metagabbro mass contains high-Mg garnets, and such high-Mg garnets have not been reported from any other outcrops in the Sebadani area to date (Takasu, 1984, 1986; Aoya, 2001; Zaw Win Ko et al., 2005; Kouketsu et al., 2010; Kabir and Takasu, 2010a, 2010b). Moreover, the high-Mg garnets in the pelitic schists show considerable variation in size and chemical composition, and heterogeneous distribution, even at thin section scale (Figs. 2a and 2b). Furthermore, the inner and outer rims of the garnets contain abundant carbonaceous matter but this is lacking in the high-Mg cores. This suggests that the high-Mg cores grew in a different environment, i.e., carbonaceous matter was scarce during growth from the inner to outer rim. These observations are probably negative evidence for the model (i) of regional metamorphic origin for the high-Mg cores.

The occurrence of the high-Mg core-bearing garnets is, therefore, better explained by localized events in the vicinity of the Sebadani metagabbro mass. The limited occurrence of such garnets is favorable for models (ii) and (iii). Higashino and Takasu (1982) reported extensive distribution of high-Mg cores in garnets from the Besshi district, and considered that these garnets were detrital in origin. However, most of the high-Mg garnets are Ca-poor varieties probably derived from high-T (low-P) type metamorphic rocks, and they differ from the high-Mg garnets in the pelitic schists adjacent to the Sebadani metagabbro mass. Higashino and Takasu (1982) found only one grain garnet of high-Mg core and high-Ca content from the same outcrop that we describe in this paper. Consequently, Higashino and Takasu (1982) considered that the single garnet with a high-Mg core was a detrital grain that was accidentally mixed with the pelitic sediments. However, numerous high-Mg core-bearing garnets which are very similar to the Mg-rich garnets from the Sebadani metagabbro mass, have been found in the pelitic schists (Nomizo, 1992; this study). This suggests the high-Mg cores of the garnets were derived from the Sebadani metagabbro mass. In this case both the huge olistolith of the Sebadani metagabbro mass (300 m × 200 m) and the high-Mg garnet grains (<4 mm) are of detrital origin. However, if this is the case, it curious that cobble- and boulder-sized clasts of eclogitic metagabbro have seldom been found in the pelitic schists adjacent to the Sebadani metagabbro mass. This geological evidence suggests that model (iii) of detrital origin for the high-Mg garnets is less likely to consider.

A shear zone 3-10 m in width occurs along the margins of the Sebadani metagabbro mass. The metagabbros in the shear zone have a strong schistosity, and locally display tight to isoclinal folding, indicating high-strain deformation (Takasu, 1984; Aoya et al., 2006). In the marginal shear zone mafic-felsic layering up to 10 cm-scale is developed, and bulk rock compositions of the shear-zone rocks are intermediate between the Sebadani metagabbro and the surrounding pelitic schists (Aoya et al., 2006). These features strongly suggest mechanical mixing of the Sebadani metagabbro and the surrounding pelitic schists. The mixing probably occurred when the Sebadani metagabbro was incorporated into the pelitic schists as an eclogite body. The high-Mg garnets were stripped from the eclogites of the metagabbros and introduced into the pelitic schists. This juxtaposition occurred before or during crystallization of the inner rims of garnets containing high-Mg cores. This garnet grew during the eclogitic metamorphism defined by the surrounding eclogitic basic and pelitic schists (e.g., Aoya, 2001; Zaw Win Ko et al., 2005; Kabir and Takasu, 2010a, 2010b). The mechanical mixing model (ii) is thus more likely than the other models (i) and (iii), although it is still difficult to completely exclude these options. Further research is needed to reveal the significance of the high-Mg cores in the garnets within the pelitic schists adjacent to the Sebadani metagabbro mass.

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DEPOSITORY MATERIALS

Figures D1, D2, D3, D4, and D5 and Tables 1, 2, 3, and 4 are available online from http://joi.jlc.jst.go.jp/JST. JSTAGE/jmps/110621d.
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