RESORPTION-OVERGROWTH OF GARNET FROM THE SAMBAGAWA PELITIC SCHISTS IN THE CONTACT AUREOLE OF THE SEBADANI METAGABBRO MASS, SHIKOKU, JAPAN

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Abstract Garnet in the Sambagawa metamorphic belt commonly shows a chemical zoning of bell-shaped MnO profile. However, in the contact aureole by the Sebadani high-temperature eclogite mass, garnets in the pelitic schists show a composite zoning. The garnet consists of two internal zones, the core and the mantle with a discontinuity between them. Inclusions in the core are arranged gently in sigmoidal shape, but those in the mantle are arranged parallel to the matrix schistosity. The internal fabric in the core is truncated by the mantle. The core as well as the mantle of the composite-zoned garnet shows normal zoning with outward decrease of MnO and increase of MgO.

The dual normal zonings with a discontinuity reflect two-fold events of the prograde metamorphism and a resorption stage between them. The former prograde metamorphism corresponds to the prograde portion of the Sambagawa metamorphism, and the latter to the contact metamorphism by the Sebadani mass. The temporary resorption of the garnet to be decomposed into chlorite was caused by decrease of temperature and increase of water pressure in the pelitic schists during the formation of the tectonic mélange zone in the high grade zone of the Sambagawa metamorphic belt.

Introduction

Chemical zoning of garnet in low- to medium-grade metamorphic rocks has been discussed in detail to reveal metamorphic history (*e.g.* BANNO, 1965; HOLLISTER, 1966; ATHERTON & EDMUNDS, 1966; KRETZ, 1973; TRACY *et al.*, 1976). The most commonly developed type of zoning, that is the normal zoning, is that of "bell-shaped" MnO profile with FeO and MgO behaving antipathetically (HOLLISTER, 1966). However, the other types of zoning are not uncommon (*e.g.* CHINNER, 1962; HOLLISTER, 1969; KANO & KURODA, 1973; PLIMER & MOAZEZ-LESCO, 1981). They include in terms of MnO from the core to rim, the profiles having the minimum of its content

in an intermediate part, and discontinuity between the core and the rim.

In the Sambagawa (Sanbagawa) metamorphic belt, the normal zoning of garnet is popular, but the other types of zoning are not rare. They are reverse zoning with Mn-rich rim (*e.g.* ITAYA, 1978; TAKASU, 1979; HARA *et al.*, 1983; SONODA, 1985), and composite-zoning formed by overgrowth on detrital garnet (HIGASHINO & TAKASU, 1982). The author has recently found another type of zoned garnet which suggests resorption-overgrowth history of the garnet. The mode of occurrence of such a composite-zoned garnet will be described and its implication in thermal history of metamorphic regime will be discussed.

Geologic setting

The Sambagawa metamorphic belt in Southwest Japan (Fig. 1) suffered a high pressure intermediate metamorphism (MIYASHIRO,

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Fig. 1. Location of the Besshi district in the Sambagawa metamorphic belt, Southwest Japan. M.T.L. : Median Tectonic Line, I.S.T.L. : Itoigawa-Shizuoka Tectonic Line.

1961) of the Cretaceous age. The composite-zoned garnets in question are found from the middle reaches of the Seba Valley in the Besshi district, central Shikoku, where the schists of the Upper Member of the Minawa Formation are widely exposed (HIDE *et al.*, 1956 ; TAKASU & MAKINO, 1980) (Fig. 2). The Sambagawa schists in the Besshi district are divided into the chlorite, garnet and biotite zones in ascending order of metamorphic grade with reference to the pelitic composition (BANNO, 1964 ; BANNO *et al.*, 1978 ; TAKASU, 1979 ; ENAMI, 1981). The composite-zoned garnet occurs in the biotite zone in the Sebadani area (Fig. 2).

In the Sebadani area there occurs the eclogite-bearing Sebadani metagabbro mass, a block in the tectonic mélange zone (TAKASU, 1984a, b ; KUNUGIZA, 1984), emplaced into a thin pelitic schist of the Upper Member of the Minawa Formation. According to TAKASU (1984a), the Sebadani mass was originally layered gabbro, which was once recrystallized in the eclogite facies before the emplacement into the Sambagawa schists as a solid body. Basic schists located close to the Sebadani mass (Fig. 3), which had first suffered the Sambagawa metamorphism of the albite epidote amphibolite facies, were then contact-metamorphosed at high pressure by the hot Sebadani mass. The contact aureole of the eclogite facies metamorphism surrounds the Sebadani mass within the distance of about 30 m from the border. The basic schists were dehydrated to form eclogitic basic schists, *i.e.*

garnet and omphacite porphyroblasts-bearing basic schists. The pelitic schists in the contact aureole contain the composite-zoned garnets as described below.

Petrography

The mineral assemblages of the pelitic and basic schists in the Sebadani area are listed in Table 1. The representative chemical compositions of the composite-zoned garnet are shown in Table 2.

Pelitic schists

Pelitic schists are composed mainly of quartz, phengite and garnet, with subordinate amounts of albite, clinozoisite, chlorite, rutile, sphene, apatite, ilmenite and graphite, and occasionally with some of biotite, hornblende, zoisite, paragonite, chloritoid, tourmaline, calcite, apatite, pyrite and ilmenite. They are highly schistose, and white micas and chlorite show a preferred orientation.

Garnet usually forms porphyroblast up to 5 mm in diameter, the size of which increases towards the Sebadani metagabbro mass. The composite-zoned garnet occurs in a narrow zone surrounding the Sebadani mass (Fig. 3). It includes quartz, phengite, paragonite, albite, rutile, clinozoisite, chlorite, chloritoid, pyrrhotite, ilmenite and graphite. Garnet is sometimes replaced by chlorite along the rim and crack. *Albite* has two modes of occurrence ; one is discrete grain, up to 1 mm in diameter, often including graphite, and the other is a constituent of symplectite together with albite, occurring in the neighbor of the

Fig. 2. Geologic and metamorphic zone map of the Besshi district, slightly modified from TAKASU (1984a). S: Sebadani metagabbro mass, T: Tonaru metagabbro mass, I: Iratsu mass, H: Higashiakaishi peridotite mass, Mt. H.: Mt. Higashiakaishi, M.T.L.: Median Tectonic Line.

Table 1. Mineral assemblages of the pelitic and basic schists in the Sebadani area.

		Qtz	Mus	Prg	Chl	Gar	Omp	Bit	Hbl	Czo	Zoi	Alb	Tur	Cal	Rut	Spn	Apt	Zrn	Ore	Gpt
PELITIC	818	+	+		+	+			+	+		+		+	+	+			+	+
	931	+	+		+	+		+				+	+		+	+	+		+	+
	1405-A	+	+	+	+	*		+	+	+		+		+	+	+	+	+	+	+
	1405-C	+	+	+	+	*		+	+	+	+	+		+	+	+			+	+
	1832	+	+		+	*				+		+	+		+	+	+	+	+	+
	1839	+	+		+	+		+				+				+	+		+	+
	1840	+	+	+	+	*		+	+	+		+			+	+			+	+
BASIC	1360	+	+		+	+			+	+		+		+	+		+		+	
	1402	+	+		+	+	+	+	+	+		+			+		+		+	

Qtz: quartz, Mus: muscovite, Prg: paragonite, Chl: chlorite, Gar: garnet, Omp: omphacite, Bit: biotite, Hbl: hornblende, Czo: clinozoisite, Zoi: zoisite, Alb: albite, Tur: tourmaline, Cal: calcite, Rut: rutile, Spn: sphene, Apt: apatite, Zrn: zircon, Ore: ore minerals, Gpt: graphite. The sample localities are shown in Fig. 3.

Fig. 3. Distribution of the composite-zoned garnet (c.z. garnet) and hornblende-albite symplectite (hb-ab symplectite). The latter is probably a pseudomorph after omphacite in the pelitic schists. Mineral assemblages of the pelitic and basic schists at the numbered localities are shown in Table 1.

Sebadani metagabbro mass (Fig. 3). X_{An} ($Ca/Ca+Na+K$) ranges from 0.01 to 0.04 with less than 0.01 of X_{Or} ($K/Ca+Na+K$). *Clinozoisite* is a euhedral to subhedral prism, 0.1–0.5 mm in length. *Hornblende* is pale green to pale bluish green ($Y=Z$) magnesio-hornblende, and has two modes of occurrence: one is subhedral prismatic, 0.3–1 mm in length, and the other forms symplectite. *Chloritoid*, bluish gray in color and 0.05–0.1 mm in size, rarely occurs included in the core of the garnet porphyroblast (TAKASU, in prep.).

Basic and eclogitic basic schists

Basic and eclogitic basic schists have been already described (TAKASU, 1984a). They are composed mainly of epidote, hornblende, garnet and phengite, with minor amounts of albite, quartz, chlorite, sphene, rutile and ore minerals. Omphacite ($X_{Jd}=0.25-0.40$) porphyroblast without preferred orientation occurs in the eclogitic basic schist in the aureole of the Sebadani mass (Fig. 3).

Texture and chemistry of the composite-zoned garnet in the pelitic schists

Most garnets in the pelitic schists in the aureole of the Sebadani mass have two internal textural zones, i.e., the core and the mantle. The inclusions in the core are arranged gently in sigmoidal pattern (Plate II-A) as are most garnets in the pelitic Sambagawa schists, but those in the mantle are nearly parallel to the matrix schistosity. In some garnets the inclusions especially graphite are concentrated at the core-mantle boundary (Plate I-B). The internal fabric of the core is truncated by the core-mantle boundary (Plate II-C). The Becke's line is observed there in some garnets.

Plates I-A and C and II-B and D show the backscattered electron images of the composite-zoned garnets. The core shows euhedral growth with concentric zoning, but is subrounded or rounded with irregular embayments. It is concordantly wrapped by the mantle, and the outer part of the mantle

Table 2. Chemical composition of the composite-zoned garnet (1405-A Ga-1).

	core				mantle			
	1	2	3	4	5	6	7	8
SiO ₂	36.99	37.02	37.29	36.92	37.62	37.25	38.01	38.04
TiO ₂	0.07	0.08	0.05	0.09	0.08	0.15	0.07	0.04
Al ₂ O ₃	21.13	21.58	21.52	21.43	21.30	21.71	21.08	21.73
FeO	26.47	29.46	29.96	29.70	25.75	28.63	26.61	25.87
MnO	6.32	2.26	0.61	0.56	4.11	1.32	0.28	0.30
MgO	0.80	1.13	1.35	1.62	1.50	1.93	2.93	3.41
CaO	8.01	8.84	9.36	9.49	10.22	9.54	10.29	10.11
Total	99.79	100.37	100.14	99.81	100.58	100.53	99.27	99.50
Si	2.985	2.961	2.977	2.958	2.985	2.955	3.015	2.996
Ti	0.004	0.005	0.003	0.005	0.005	0.009	0.004	0.002
Al	2.010	2.034	2.025	2.024	1.992	2.030	1.971	2.017
Fe	1.786	1.971	2.000	1.990	1.709	1.899	1.765	1.704
Mn	0.432	0.153	0.041	0.038	0.276	0.089	0.019	0.020
Mg	0.096	0.135	0.161	0.194	0.177	0.228	0.347	0.400
Ca	0.693	0.758	0.801	0.815	0.869	0.811	0.875	0.853
Total	8.006	8.017	8.008	8.024	8.013	8.021	7.996	7.992

shows again euhedral concentration zoning.

The compositional trend of the garnet discontinuously changes at the textural core-mantle boundary, across which MnO and CaO increase and FeO and MgO decrease (Fig. 4). The core shows a normal zoning with decrease of MnO and increase of MgO from the center towards the core-mantle boundary, and in the mantle MnO also decreases towards the outermost rim (Figs. 4 and 5). In some garnets, MnO slightly increases at the outermost rim.

Fig. 6 shows a MnO contour map in a composite-zoned garnet. The contours of 4% and 6% of MnO are apparently cut by the core-mantle boundary.

Discussion

Formation process of composite-zoned garnet

Garnets in the Sambagawa pelitic schists essentially grew keeping a surface equilibrium with chlorite (*e.g.* SAKAI *et al.*, 1985 ; BANNO *et al.*, 1986). In the core as well as in the mantle of the composite-zoned garnet, MgO and Mg/Fe increase antipathetically with the decrease of MnO. If the surface equilibrium model is accepted also for the composite-zoned garnets, the core and mantle crystallizations can be explained by dual events of the prograde metamorphism.

Across the boundary between the core and the mantle, the internal schistosity and the contours of MnO content in the core are dis-

Fig. 4. Zoning profile of the composite-zoned garnet. (a) 1405-A Ga-1. A and B in the figure correspond to A and B in the photomicrograph of Plate II-A. (b) 1405-C Ga-1. A and B correspond to A and B in the backscattered electron image of Plate II-D.

Fig. 5. Chemical composition of the composite-zoned garnet (1405-A Ga-1) and the detrital garnets of the eclogite and granulite facies (HIGASHINO & TAKASU, 1982). The area surrounded by the broken line shows the compositional range of the garnets in the Sambagawa pelitic schists (BANNO *et al.*, 1986, and the author's unpublished data).

Fig. 6. MnO contour map of the composite-zoned garnet (1405-A Ga-2). See the backscattered electron image in Plate I-C.

continuous to those of the mantle (Plate I-C and Fig. 6). This suggests a resorption of the garnet having crystallized during the first prograde metamorphism.

The innermost part of the mantle has distinctly higher MnO content than the outermost part of the core (Figs. 4 and 5). In general, MnO contents of coexisting garnet and chlorite depreciate as the metamorphic temperature increases during prograde metamorphism (*e.g.* HIGASHINO, 1975; BANNO *et al.*, 1986). When the first prograde metamorphism was completed, both the garnet-rim and chlorite must have had low MnO contents. Then the resorption of the garnet supplied Mn to the chlorite to form Mn-rich chlorite. Thereafter, the MnO-rich garnet again grew at the expense of the secondary MnO-rich chlorite at the beginning of the second prograde metamorphism.

The resorption may have owed to decrease of temperature, decrease of pressure, increase of water pressure or their combinations. It is difficult to determine what the major factor of the resorption was. However, the fact that the associated basic schists were converted into eclogites after the resorption stage, as will be discussed later, suggests that the pressure never decreased much.

This study has revealed that a type of composite zoning was formed by dual events of the prograde crystallization with a stage of resorption between them. This is, namely, a resorption-overgrowth model to give rise to

reverse or composite-zoned garnet. The origin of the reverse and composite-zoned garnets has been discussed intensively. The models include i) polymetamorphism (HOLLISTER, 1969; EDMUNDS & ATHERTON, 1971; KANO & KURODA, 1973), ii) overgrowth on detrital garnet (HIGASHINO & TAKASU, 1982), iii) non-equilibrium crystallization (KRETZ, 1973), iv) resorption or retrograde metamorphism (GRANT & WEIBLEN, 1971; BÉTHUNE *et al.*, 1975; SIVAPRAKASH, 1981; TYLER & ASHWORTH, 1981; DIETVORST, 1982), and v) surface equilibrium crystallization with limited diffusion in garnet and chlorite (KRETZ, 1973; BANNO & CHIL, 1976, 1978). The garnet described above is an example of another mechanism to form the composite-zoned garnet. A similar formation mechanism of a composite-zoned garnet from southern Vermont has been suggested by KARABINOS (1984). It is considered that the Sambagawa garnet from eastern Kyushu reported by SONODA (1985) was also formed by the resorption-overgrowth mechanism.

Occasional increase of MnO content at the outermost rim of the composite-zoned garnet can be explained by inwards Mn-diffusion accompanied by a retrograde metamorphism (model iv) (BÉTHUNE *et al.*, 1975).

Geological implications

The pelitic schists bearing the composite-zoned garnet coexist with the eclogitic basic schists in the Sebadani contact aureole, and hence both of them certainly shared the same P-T history. The eclogitic basic schists have at least two stages of metamorphism, the Sambagawa prograde metamorphism and the contact metamorphism by the Sebadani mass (TAKASU, 1984a) (Fig. 7).

The chemistry and the zoning pattern of the core of the composite-zoned garnet in the pelitic schists adjacent to the Sebadani mass coincide with those of the Sambagawa garnet in the common pelitic schists of the biotite zone. Moreover, the rotation fabric in the core of the composite-zoned garnet is compatible with the development of the schistosity in the eclogitic basic schists accompanied by deformation flow. Hence the core of the composite-zoned garnet was formed at the

Fig. 7. Temperature-time paths of the Sebadani mass, and the composite-zoned garnet and the basic schist in the contact aureole of the mass. Garnet in pel. sch.: Garnet in pelitic schist.

stage of the Sambagawa prograde metamorphism.

The resorption of the garnet probably took place during the formation stage of the tectonic mélange zone (TAKASU, 1984a; KUNUGIZA *et al.*, 1986), accompanied by the uplift of the metamorphic regime. The formation of the mélange zone was followed by the decrease of the metamorphic temperature. Besides, the pelitic schists in this zone were strongly sheared, and water phase flowed more easily through there than before the formation of the tectonic mélange zone. Then, the garnets in the sheared pelitic schists were partly resorbed.

The composite-zoned garnet having resorption-overgrowth texture is confined to the contact aureole of the Sebadani mass defined by the occurrence of the eclogitic basic schists

(Fig. 3). Also from a viewpoint of the texture, the inclusions without rotation fabric in the mantle of the composite-zoned garnet correspond to the formation of omphacite porphyroblasts, which are randomly oriented in the matrix of the eclogitic basic schists (TAKASU, 1984a). This suggests that both omphacite and the mantle of the composite-zoned garnet in the pelitic schists simultaneously crystallized under static condition. On the other hand, the fact that the garnets in the eclogitic basic schists have no evidence of resorption is probably explained by poor shearing and limited supply of water phase in basic schists during the formation of the tectonic mélange zone.

The mantle of the composite-zoned garnets is also similar in chemistry to the ordinary Sambagawa garnets (Fig. 5). This indicates that the crystallization of the mantle underwent

Fig. 8. Schematic P-T evolution of the composite-zoned garnet and the Sebadani mass. P-T grids are slightly modified from TAKASU (1984a). ECL : eclogite facies. GRAN : granulite facies, AMP : amphibolite facies, GS : greenschist facies, PP : prehnite-pumpellyite facies, EA : epidote amphibolite facies, GL : glaucophane schist facies, SP : Sambagawa prograde metamorphism, R : resorption stage, C : contact metamorphism by the Sebadani high-temperature eclogite mass, SR : Sambagawa retrograde metamorphism, HTE : high-temperature eclogite.

the condition not so far from the Sambagawa prograde metamorphism. 630–650°C and 7–17 kb are the estimated condition of the contact metamorphism forming the eclogitic basic schist (TAKASU, 1984a), and this temperature is similar to or slightly higher than $610 \pm 25^\circ\text{C}$ as the maximum temperature of the Sambagawa metamorphism as proposed by ENAMI (1983) (Fig. 8). This fact suggests that the eclogite facies metamorphic rocks are regionally distributed a little below the present surface of the high grade portion of the Sambagawa metamorphic terrane. In fact, recent discovery of the tectonic blocks consisting of the prograde eclogites from the Besshi and Kotsu districts in Shikoku (TAKASU & KOHSAKA, 1985 ; TAKASU & KAJI, 1985), supports the presence of regional eclogite facies in the high grade part of the Sambagawa metamorphism.

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- ** : in Japanese

(要 旨)

TAKASU, A., 1986 : Resorption-overgrowth of garnet from the Sambagawa pelitic schists in the contact aureole of the Sebadani metagabbro mass, Shikoku, Japan. *Jour. Geol. Soc. Japan*, **92, 781-792.** (高須 晃, 1986 : 四国三波川変成帯, 瀬場谷変はんれい岩体の接触変成帯に形成された融食・再成長の組織を示すざくろ石. 地質雑, **92**, 781-792.)

表題地域の泥質片岩中より, 融食・再成長の組織をもち, 複雑な累帯構造を示すざくろ石が見いだされた。組織と化学組成より, このざくろ石は核部と外套部に区分できる。核部の包有物の配列は弱いS字形を示し, これは外套部の包有物の配列に切られる。核部, 外套部とも, 内側から外側へ向かって Mn 減少, Mg 増加の正累帯構造を示す。核部と外套部の境界では, 化学組成にも著しい不連続が認められ, これは, すでに形成されていた核部のざくろ石が一度融食されたことを示すものである。このざくろ石の核部は三波川累進変成作用で形成された。核部の融食は, 三波川変成帯高変成度部におけるテクトニック・メランジェ帯の形成にともなう変成温度の低下, あるいは, 水蒸気圧の上昇により生じた。その後, テクトニック・メランジェ帯を上昇してきた, 高温のエクロジャイト岩体である瀬場谷変はんれい岩体の接触変成作用により外套部のざくろ石が再成長した。

Explanation of Plates

Plate I.

- A. Backscattered electron image of the composite-zoned garnet (1840 Ga-7). The resorbed core is rounded. Graphite is concentrated at the core-mantle boundary. See Plate I -B.
- B. Photomicrograph of the composite-zoned garnet (1840 Ga-7).
- C. Backscattered electron image of the composite-zoned garnet (1405-A Ga-2). The euhedral growth traces are apparently cut by the mantle.

Plate II.

- A. Photomicrograph of the composite-zoned garnet (1405-C Ga-1). Inclusions, mainly graphite, show a sigmoidal pattern in the core. See the scanning profile from A to B in Fig. 4 (a).
- B. Backscattered electron image of the composite-zoned garnet (1405-C Ga-1). The scale is the same as Plate II-A.
- C. Photomicrograph showing the boundary between the core and the mantle. The inclusion trail in the core is cut by the core-mantle boundary.
- D. Backscattered electron image of the composite-zoned garnet (1405-A Ga-1). See the scanning profile from A to B in Fig. 4 (a).