Sector structure and compositional zoning of garnets from the Higo metamorphic rocks, west-central Kyushu, Japan

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Garnets with textural sector structures were found in garnet-biotite-cordierite gneisses from the Higo metamorphic belt, western-central Kyushu. The garnet contains dusty core and clear margin. The dusty core is hexagonal or octagonal in shape in thin section, and contains abundant very-fine inclusions ($<1\ \mu\text{m}$) of both fluid and solid phases. The fine inclusions are aligned nearly straight, being perpendicular to the outline of the dusty core. The sector structure is interpreted in terms of the rhombododecahedral model garnet that consists of twelve rhombohedral pyramids within which fine inclusions are aligned straight perpendicular to the basal surface $\{110\}$. The garnets show well-developed compositional zoning (Mn- and Ca-rich core; Mg- and Fe-rich rim). The compositional contour lines, obtained from two-dimensional compositional mapping using an electron probe microanalyzer, are nearly perpendicular to the fine-inclusion lineations within each sector. We consider that this orthogonal relationship between the inclusion-lineation and the compositional structures is an important primary feature determined during the crystal growth of garnet, and that the isochemical contour lines (or isochemical surfaces in three dimensions) are 'isochronal surfaces' parallel to crystal surfaces $\{110\}$ during the crystal growth. The possibility of the surface equilibrium during the crystal growth and the extent of the diffusion modification of the primary (i.e., growth) zoning are discussed.

Keywords: Sector structure, Garnet, Inclusion geometry, Compositional zoning, Higo metamorphic rocks, Surface equilibrium

I. Introduction

Garnet is an important mineral that occurs under a wide range of metamorphic conditions. It typically shows compositional zoning reflecting its history of crystal growth. Much work has been carried out to deduce metamorphic conditions (Tracy *et al.*, 1976; Thompson *et al.*, 1977; Banno *et al.*, 1986) and to deduce P - T paths of metamorphism by means of analyzing such zoned garnets (Spear and Selverstone, 1983; Spear 1989, 1993). At relatively higher grades, a primary zonal structure

that was formed during the crystal growth may be partially modified through homogenization by solid diffusion (Chakraborty and Gangluy, 1991). All the above works are based on the assumption that a local equilibrium was maintained during the growth of the garnets.

On the other hand, many metamorphic garnets have been reported as showing sector structures that are indicative of the rapid growth of crystals. Two kinds of sector structures are known for metamorphic garnets; (1) textural sector structure, in which each sector is distinguished by an inclusion geometry [Glen

Lyon in Scotland (Harker, 1950); Magerøy in northern Norway (Andersen, 1984); Abukuma metamorphic belt (Kishi and Hiroi, 1987; Hiroi and Kishi, 1987, pers. communication, Kano, 1993, pers. communication); and Cula Group in central Norwegian Caledonides (Rice and Mitchell, 1991)], and (2) compositional sector structure, in which each sector has a different composition [Sanbagawa metamorphic belt (Kitamura *et al.*, 1993)]. The textural sector garnets from northern Norway were ascribed to a rapid growth of crystals upon rapid heating (Andersen, 1984; Jamtveit and Andersen, 1992). A common feature among these occurrences is the presence of straight and semi-parallel alignment of inclusions. These inclusions are mostly quartz, and their shape is either (a) tubular or rod-like, or (b) spherical to elliptical. The inclusions from the Scottish and northern Norwegian garnets are tubular in shape, while those from Abukuma are spherical to elliptical, like those in Higo. The central Norwegian garnets (Rice and Mitchell, 1991) contain both types. Kitamura *et al.* (1993) argued that textural sector-zoned garnet may have been formed under conditions even more remote from the equilibrium than those showing compositional sector structures. The sector structure is thus regarded as representing a kind of disequilibrium feature produced in rapid crystal growths under highly supersaturated conditions. Care must be taken, therefore, in any attempt to deduce metamorphic conditions from analyzing such zoned garnets.

We found textural sector garnets from the Higo metamorphic belt — a low-P, high-T metamorphic belt in Southwest Japan. The garnets show a distinct compositional zoning. The purpose of the present paper is to report such an occurrence of garnet and to examine the problem of equilibrium as stated above. Special attention is paid to the relationship between the compositional zoning and the sec-

tor structure that is defined by the inclusion geometry.

II. Geological setting and petrography

The Higo metamorphic belt, located in the western part of central Kyushu, forms an east-west trending narrow belt of 25 km length and of up to 7 km width. It is intruded by granitic plutons in the south (Yamamoto, 1962) and is unconformably overlain to the north by the Mifune-Formation of the Upper Cretaceous period in age. The metamorphic grade monotonically increases from north to south toward the granite intrusions and the metamorphic belt has been mapped into five zones of different grades, A, B, C, D and E, in the order of increasing grade, on the basis of mineral assemblages of pelitic and psammitic rocks (Nagakawa *et al.*, 1991). Zone A is characterized by the presence of chlorite and muscovite; zone B by the appearance of biotite and the stability of andalusite; zone C by the appearance of K-feldspar and the stability of sillimanite; zone D by the stability of the garnet-cordierite assemblage; and zone E by the appearance of hypersthene in the absence of sillimanite and cordierite. From the occurrence of migmatites in zones D and E, we interpreted that partial melting had started to occur in zone D and culminated in zone E (Obata *et al.*, 1994).

Garnet porphyroblasts with sectoral structure occur in garnet-biotite-cordierite gneisses from zone D. The rocks have a distinct gneissose structure; the leucocratic part comprises quartz, plagioclase and K-feldspar and the melanocratic part, biotite, garnet, and cordierite. Common accessory phases are apatite, ilmenite, pyrite and graphite. Sillimanite is mostly fibrolite and occurs as inclusions in the cordierite. The garnet occurs in the melanocratic part associated with biotite. The garnet porphyroblasts are euhedral to subhedral and

Fig. 1. Photomicrographs of typical sector structural garnets from Higo garnet-cordierite-biotite gneisses. The core is dusty because of the presence of abundant fine inclusions. The boundaries between the dusty core and inclusion-free margin are sharp and straight.

(a) The dusty core outline is octagonal in shape; eight sectors are recognized. Scale bar is 1 mm. (b) The dusty core outline is hexagonal in shape; six sectors are recognized. Scale bar 1 mm. (c) Fine inclusions forming linear trails in the dusty core region. The inclusions are very small ($<1\ \mu\text{m}$), either fluid or solid, including quartz and unidentified minerals. Scale bar $40\ \mu\text{m}$.

vary from 2 mm to 5 mm in diameter. These garnet crystals commonly contain dusty cores and clear, inclusion-free margins. The dusty core is hexagonal or octagonal in shape, the outlines of which are sharp and straight (Figs. 1 and 2). The dusty appearance in the core is due to the presence of abundant tiny inclusions. Most inclusions are very small ($<1\ \mu\text{m}$); they are either fluid, quartz or other unidentified minerals. These inclusions are spherical or elliptical in shape (Fig. 1c) and they form linear arrays like 'brush trails' resulting a radial corona-like patterns. By the orientation of these trails, the dusty core region is subdivided

into several domains or sectors. Within each sector, inclusions are aligned semi-parallel to each other keeping inter-trail distances more or less constant and the inclusion lineations are oriented nearly perpendicular to the dusty core outlines. These fine inclusions tend to get coarser along the sector boundaries ($2\sim10\ \mu\text{m}$ in size) giving rise to even-more dusty appearances in these regions. These coarser inclusions are mostly quartz, K-feldspar, plagioclase and opaque minerals. The crystal outline of the garnet porphyroblast tend to be concaved outward forming cusps near the sector boundary positions (Figs. 1 and 2).

Fig. 2. Sketches of sectoral garnets, drawn from the photomicrographs in Figs. 1a and 1b, respectively. Note that fine inclusions are aligned straight, semiparallel each other within each sector and that the alignments are normal to the dusty core outline. Marked A and B in (a) indicate the location for the line profile in Fig. 4.

Rice and Mitchell (1991) noted a common association of graphite with such sector garnets from Norwegian Caledonides either as inclusions within garnets or in the matrix of the garnet, and they emphasized the role of graphite in the formation of the fine inclusions. In the Higo samples, however, graphite inclusion is much less abundant and less conspicuous.

Besides these fine inclusions, large inclusions (20~400 μm in size) of minerals such as quartz, K-feldspar, plagioclase, muscovite, biotite, apatite, ilmenite, pyrite and zircon occur in the garnet. The K-feldspar, plagioclase and biotite have mostly suffered from secondary alteration. Some of these inclusions, particularly those of quartz, K-feldspar and plagioclase, are euhedral; some show hexagonal or octagonal crystal outlines. These large inclusions are abundant in the dusty core (Fig. 2), and tend to be concentrated along sector boundaries. Muscovite inclusions exclusively occur in the core, while biotite inclusions

occur in more outer part of garnet crystals either within the rim of the dusty core or in the clear rim. Apatite inclusions are scattered throughout the garnet grain; large apatite inclusions (100~200 μm) occur only in the clear rim. The plagioclase inclusions vary considerably in composition (from An 96 to An 46) even within a single grain of garnet, with a tendency towards more calcic ones occurring on the inner side of the crystal, but they are systematically more calcic than those in the matrix (An 26-33).

The garnet occurs in the zones B, C, D, and E in the Higo metamorphic belt. Garnets from zones B and C contain abundant mineral inclusions, but do not have the sector structure as observed in the zone D. The garnets from the zone E are compositionally relatively homogeneous. They contain inclusions of biotite and sillimanite (fibrolite) but are free from the fine inclusions. More comprehensive description on the zoned garnets from the Higo metamor-

Fig. 3. Two-dimensional compositional maps of a sector structural garnet showing eight sectors (Fig. 1a, Fig. 2a), obtained by means of a fully-automated WDS electron probe microanalyzer (analyst: Y. Kondo). Compositions are shown in oxide weight percent. The color sequence of increasing concentration is: black-blue-green-yellow-red-pink-white for each element. Width of view is 3.6 mm for each image.

Fig. 4. A compositional line profile for the sector structural garnet (Fig. 1a, 2a), obtained by means of EDS electron probe microanalyzer. Arrows indicate the inflections (see text).

phic belt is given in Yoshimura (1995).

III. Compositional zoning of garnet and its relationship to the sector structure

The chemical structure of the above garnet porphyroblasts were examined in detail by means of an electron microprobe analyzer. Figure 3 shows an example of the two-dimensional compositional map, obtained by means of a wave-length dispersive electron probe microanalyzer (WDS) with automated stage

Table 1. Representative (EDS) microprobe analyses of sector structural garnet

	1	2	3
SiO ₂	37.56	37.93	37.45
TiO ₂	0.14	n.d.	n.d.
Al ₂ O ₃	21.34	21.59	21.29
FeO*	15.05	30.70	32.03
MnO	16.77	4.81	6.34
MgO	0.12	4.42	2.57
CaO	9.83	1.49	1.07
Total	100.81	100.94	100.75
Si	2.994	2.995	3.003
Ti	0.008	—	—
Al	2.005	2.009	2.012
Fe ⁽²⁺⁾	1.003	2.027	2.148
Mn	1.132	0.322	0.431
Mg	0.014	0.520	0.307
Ca	0.839	0.126	0.092
Total	7.996	8.000	7.992
Mg/(Mg+Fe)	0.014	0.204	0.125
Pyp	0.5	17.4	10.3
Alm	33.6	67.7	72.1
Sps	37.9	10.7	14.5
Grs	28.1	4.2	3.1

O=12; * = Total Fe as FeO

n.d., not detected

1, core; 2, most magnesian mantle; 3, rim
Pyp, Pyrope; Alm, Almandine; Sps, Spessartine; Grs, Grossular

(JEOL 8600, JEOL LTD.). Figure 4 shows line profiles for MgO, FeO, MnO and CaO across the same grain, which were obtained by means of an energy-dispersive electron probe microanalyzer (Hitachi S-650 scanning electron microscope equipped with Kevex Deltal system (EDS), Kumamoto University).

For the compositional mapping using the WDS, an accelerating voltage of 15 kV and a large probe current of 1 μ A were used. The sample stage was driven continuously along a transect with a computer-controlled pulse motor at a rate of 230 μ m per second and the X-ray counts were accumulated every 35 milliseconds (i.e. 8 μ m interval). The interval between the line transects was kept always 8 μ m. For the EDS analyses, an accelerating voltage of 20 kV and a probe current of 150 pA

Fig. 5. The relationship between the inclusion structure and the compositional zoning pattern. (a) Eight-sectored (Fig. 1a, 2a) type. (b) Six-sectored type. The compositional contour lines were taken from the two-dimensional compositional maps and were superimposed on the sketch of the inclusion structure of the sectoral garnet. Qz, quartz; Pl, plagioclase; Kf, K-feldspar; Il, ilmenite; Ap, apatite. Scale bar 1 mm.

were used. The X-ray spectral data were processed following the method of Mori and Kanehira (1984) and the ZAF correction method was used. Representative microprobe analyses obtained by the EDS are given in Table 1.

As is shown in these figures, the sector structural garnet shows a well-developed compositional zoning. The zoning pattern is nearly concentric and symmetric (Fig. 3). It is not quite spherical, however, but is somewhat sub-angular, being nearly in accordance with the outline of the dusty cores (compare with Fig. 2a). The MnO and CaO contents are highest in the core and gradually decrease approaching the rim. In more detail, there occurs a sudden increase in the rate of decrease of the CaO content in the middle of the grain, resulting in a pair of inflections in the CaO-line profile (Fig. 4). On the contrary, FeO and MgO contents are lowest in the core (MgO is nearly nil in the core) and they gradually increase

outward. Very near the edges of the grain (within $50\ \mu\text{m}$), there occurs a slight but sharp decrease of MgO and FeO contents and a sharp increase of MnO (Fig. 4). The average composition of the core region (inner $1000\ \mu\text{m}$ diameter) is $\text{Pyp}_{0.5}\text{Alm}_{34}\text{Sps}_{38}\text{Grs}_{28}$; the most magnesian rim ($\sim 200\ \mu\text{m}$ from the grain edge) is $\text{Pyp}_{17}\text{Alm}_{68}\text{Sps}_{11}\text{Grs}_4$; and the outermost rim (within $\sim 5\ \mu\text{m}$ from the edge) is $\text{Pyp}_{10}\text{Alm}_{72}\text{Sps}_{15}\text{Grs}_3$.

It is difficult to assess the effect of the fine inclusions on the microprobe analyses of the dusty cores. The inclusions are so small in size that they are hardly visible on a polished surface, even on the SEM image. The presence of fluid inclusions should not greatly affect the ratio of X-ray intensities of other elements in silicates. Contributions in X-ray intensities from other solid inclusion-phases such as quartz, if ever present, are expected to be negligible because of their extremely small

grain-size and the small volume-fraction. The actual microprobe analyses yield satisfactory stoichiometries or structural formula for garnets (Table 1). We, therefore, conclude that the analyses obtained by this method, both WDS and EDS analyses, represent those of the host garnet phase, at least with those major elements such as Mg, Fe, Mn and Ca.

As for the minor elements, TiO_2 content is highest (~ 0.2 wt%) in the dusty core and lowest in the clear rim, forming a good correlation pattern with the inclusion structure. In more detail, TiO_2 is not uniform in distribution within the dusty core, but its abundance appears to be correlated with the fine structures of the inclusion alignment (Fig. 3). On the contrary, P_2O_5 is more abundant in the clear rim (~ 0.1 wt%) than in the dusty core, and again shows a good correlation with the inclusion distribution.

In order to examine more closely the relationship between the inclusion structure and the compositional zoning pattern, compositional contour lines taken from the two-dimensional compositional maps are superimposed on the drawings of the inclusion structure of the garnet (Figs. 5a and 5b). It may be seen in these figures that the contour lines are mostly perpendicular to the lineation of the fine inclusions. This orthogonal relationship is particularly remarkable where the inclusion lineations are straight within each sector. In detail, however, where the lineations are significantly curved or where large inclusions occur, the orthogonal relationship does not hold. It may be noted that for the garnet sketched in Fig. 5b, there are some discordancy of contour lines among different elements. The outermost contour line of CaO (for 3.2 wt %) is concaved inward to the lower right, in accordance with the outline of the dusty core; while those of other elements, MgO, FeO and MnO, are rather straight, being discordant with the dusty-core

outline. Moreover, the curvature and distortions of the contour lines around the large inclusions (of quartz and feldspars) are the greatest for CaO compared with other elements. These discrepancies of zoning pattern among different elements may be explained in terms of relaxation processes by diffusion, as discussed below.

IV. Discussion

1. Interpretation of 3-D structure and the origin of the sector structure

The textural sector structure observed in the Higo garnets may be explained in terms of the rhombododecahedral model garnet, as proposed by Burton (1986). The garnet rhombododecahedron (Fig. 6a) is composed of twelve equidimensional rhombohedral pyramids (Fig. 6b), all meeting on their apices at the center of the crystal. Each pyramid is crystallographically equivalent and represents a growth unit; its base coincides with the crystal surface $\{110\}$. Within each pyramid, inclusions are assumed to be aligned normal to the basal face $\{110\}$ (Fig. 6b). If the $\{110\}$ face represents the crystal growth surface of garnet, then it follows that the lineation of the inclusions represents the growth direction of the crystal. Burton (1986) discussed several possible mechanisms whereby these small inclusions (quartz) are incorporated into a growing crystal of garnet, forming linear arrays of inclusions or tubes of quartz parallel to the garnet crystal-growth direction. The fine inclusions are newly formed phases, being associated with the growth of garnet, while the coarse inclusions are considered to be relicts of pre-existed minerals or unreacted (i.e., inert) phases for the garnet-forming reactions.

Several cross sections of such a model garnet crystal were drawn in Figs. 6c and 6d. The first section, normal to a trigonal axis, has hexagonal outline and six sectors with six-fold symmetry. Inclusion arrays are all parallel to

Fig. 6. (a) A garnet rhombododecahedron. X , Y and Z are the crystallographic (tetragonal) axes. Tri is a trigonal axis.

(b) A growth unit of the sectoral garnet (after Burton, 1986). The growth unit is a rhombohedral pyramid. Twelve such pyramids are assembled to form one rhombododecahedron shearing their apices at the center (Fig. 6a). The base of the pyramid coincides with the crystal face $\{110\}$. Fine inclusions are aligned straight, normal to $\{110\}$.

(c) (i) A projection of the rhombododecahedron (Fig. 6a) parallel to a trigonal axis (Tri). X' , Y' , and Z' are projections of crystallographic axes X , Y and Z , respectively. (ii) A side view of the rhombododecahedron. Tri is the trigonal axis. 'I' marks a projection of a cross section in Fig. 6c(iii). (iii) A cross section of the rhombododecahedron normal to the trigonal axis that goes through the center. There are six sectors (or sections of the growth unit pyramid (Fig. 6b)). Trends of fine inclusions are shown for each sector in solid lines; they are parallel to the cross section.

(d) (i) A projection of the rhombododecahedron parallel to a tetragonal axis (Tet) or crystallographic axis Z . (ii) A side view of the rhombododecahedron. I and II are projections of cross sections shown in Fig. 6d(iii) and 6d(iv), respectively. (iii) A cross section of the rhombododecahedron normal to the tetragonal axis that goes through the center. There are four sectors. The alignments of fine inclusions (shown in solid lines) are parallel to the cross section. (iv) Another cross section normal to the tetragonal axis but slightly off the center [plane II in Fig. 6d(ii)]. The outline is octagonal and eight sectors appear. The alignments of fine inclusions shown in solid lines are parallel to the section. The alignments of fine inclusions in four narrow rectangular sectors are oblique to the cross section and are indicated in "dashed" lines.

the section and normal to $\{110\}$. This model would simulate the observed pattern with six sectors (Fig. 2b). The second one, normal to a tetragonal axis, has the outline of a square with only four sectors with a four-fold symmetry. Inclusion arrays are also all parallel to the section. The third section is similar to the second; it is normal to a tetragonal axis but is

slightly off the center of the rhombododecahedron, therefore, it sees four additional sectors, giving rise to an octagonal outline for this section. We note that, for these new sectors, the inclusion arrays are oblique to the section. This last pattern may be correlated with the observed pattern in Fig. 2a. In this way, all variations of the garnet sector structures observ-

ed in the Higo garnets are interpreted in terms of this rhombododecahedron model. An important implication of this consideration is that this model provides a useful guide for orientating the garnet crystals and in deciding whether or not observed sections are those cutting through the center of the crystal; this will become an important information in interpreting chemical zoning, as discussed below.

2. Assessment of local equilibrium and its implications for P - T history estimation

As stated above, the sectoral structure has generally been interpreted as a product of rapid crystal growth under supersaturated conditions, the idea of which casts doubt on the attainment of chemical equilibrium, even locally (Kitamura *et al.*, 1993). The orthogonal relationship observed between the fine-inclusion lineations and the compositional zoning, however, favors a case of local equilibrium, as discussed below.

It was inferred that the inclusion lineation represents the growth direction of a garnet crystal, which is perpendicular to the crystal surfaces {110}. It was pointed out that the chemical contour lines are nearly straight within each sector and are perpendicular to the inclusion lineation. It follows, therefore, that these isochemical contour lines were always parallel to the instantaneous crystal surfaces {110} during the crystal growth and that the isochemical surfaces, in three dimensions, represent 'isochronal surfaces' of the garnet crystals. The coincidence between the isochronal surfaces and the isochemical surfaces indicates that there was no compositional gradient along crystal surfaces at any instance during the growth of garnet despite of the presence of the distinct compositional gradient *along the growth direction* as observed in the zoning. The growth zoning is interpreted as having resulted from instantaneous compositional changes at the crystal surfaces of the growing

garnet in response to conditional changes of the crystal environment (e.g. temperature, pressure, P_{H_2O}) during the crystal growth. An important inference here is that, although compositional variations occurred during the crystal growth and the thus-formed compositional zoning was preserved within the crystal due to the limited diffusion and homogenization, the chemical homogeneity *along crystal surfaces* appears to have been maintained always during the crystal growth. The surface homogeneity suggests the absence of any notable gradient of chemical potentials for respective components along crystal surfaces and in their immediate vicinity, which indicates that the size of the equilibrium domain was at least on the order of the grain size of the garnet. Of course, the above consideration cannot be a proof of local equilibrium but at least one can argue that there is no sound reason for discriminating the sector-zoned garnets from other ordinary zoned garnet (without sector structures) in deducing the P - T paths of metamorphism from the compositional zoning on the assumption of local equilibrium.

3. Effect of diffusion

Although the observed compositional zoning of the Higo garnet may be interpreted mostly to be a primary feature determined during the crystal growth, there appear to be some minor secondary modifications in the primary zoning due to solid diffusion. For example, the presence of narrow margins (~ 50 μm) of the steep compositional gradient (notably in Mg, Fe, and Mn) all around the edges of the garnet (Fig. 3) may be a manifestation of such effect, which may have been caused secondarily, probably during a cooling, by solid diffusion coupled with cation exchanges with surrounding ferromagnesian minerals such as biotite and cordierite. The discordance of zoning patterns among different elements may also be explained by the effect of diffusion.

The fact that CaO contour lines are in the best accordance with the outline of the dusty core as noted above (Fig. 5b) suggests that the primary chemical structure is best retained in the CaO distribution. Compositional patterns for other elements, i.e., MgO, FeO and MnO, were probably in a better accordance with that of CaO, matching in every details when first formed but those detailed structures were probably lost by diffusion homogenization. Detailed structures of shorter wave lengths such as small concaves and sharp inflections of compositional contours may be readily eliminated by smoothing-out by solid diffusion (Chakraborty and Ganguly, 1991). The presence of sharp inflections in the CaO contour lines, therefore, indicates sluggishness of CaO in the diffusion, which is also in accordance with the absence of a sharp gradient in the CaO content at the grain edges, in contrast to that of other elements. The experimental data on the diffusivity of Ca ions in garnet is still limited, but a small diffusivity of Ca relative to Mn^{2+} , Fe^{2+} and Mg has been suggested by some experimental data (Loomis *et al.*, 1985) and by observations of natural zoned garnets (Hiroi, 1993). As to the small compositional distortions around some of the large inclusions in garnet, it may be difficult to judge whether they are also due to secondary modification by diffusion, coupled with cation exchanges with the inclusion phases, or they are part of the primary features. The distortion of the CaO contours around the plagioclase inclusions could be explained by the diffusion modification coupled with a continuous reaction: grossular + sillimanite + quartz $\rightarrow$ anorthite (Ghent, 1976), but the distortions around the quartz inclusions, however, cannot be explained by this mechanism. The fact that the extent of the distortion is the greatest for supposedly-slowest diffusing species CaO and the presence of the CaO distortion around the quartz inclusions as well as the plagioclase

inclusions lead us to conclude that the latter is the case. It should be noted that the orthogonal relationship between the inclusion lineation and compositional zoning is not held there and thus the argument of local equilibrium made above may not be applicable for such anomalous portions, even though they are primary in origin.

As examined above, there certainly exist secondary modifications of primary zoning by diffusion, though relatively small for present samples. Even in the primary zoning, there occur some local anomalies around some large inclusions, in which chemical equilibrium is not likely to be maintained. Care must be taken to avoid such anomalies and to eliminate the effect of diffusion before any attempt of deducing P - T paths of the metamorphism is made. Other important implications of the above considerations are that, by correctly evaluating the extent of homogenization by solid diffusion, it should be possible, theoretically, to put some constraints on the time duration of the metamorphism (Chakraborty and Ganguly, 1991), provided that the diffusivity data are given as functions of temperature. More detailed discussions on the P - T evolution and the time estimates of the Higo metamorphism are beyond the scope of this paper and will be treated separately.

V. Summary and Conclusion

- (1) The sector garnets from the Higo metamorphic rocks are characterized by the presence of dusty cores, mantled with clear rims. Each sector is recognized within the dusty cores by the parallel arrangement of very fine inclusions of fluid and solid phases.
- (2) The sectoral structure and the inclusion geometry of the Higo garnet may be interpreted in terms of the rhombododecahedron model garnet as proposed by Burton (1986). The inclusion lineations are considered to represent

the growth direction of the garnet crystals.

(3) The garnets are compositionally zoned and the orthogonal relationships observed between the chemical contours and the inclusion lineations and the consistency between the zoning pattern and the outline of the 'dusty cores' in the garnet indicate that the isochemical surfaces are 'isochronal surfaces' and were nearly parallel to crystal surfaces {110} during the crystal growth. It follows that no compositional gradients were present along the crystal surfaces of garnet at any instance of crystal growth, which is consistent with the hypothesis of the surface equilibrium.

(4) The least-modified primary chemical feature may be seen in the CaO distribution, while the MnO-, MgO- and FeO-distributions have been somewhat modified through solid diffusion. A quantitative evaluation of the extent of the relaxation by diffusion homogenization for different elements would allow us to estimate the time duration of the metamorphism, provided the diffusivity data become available for those elements.

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肥後変成帯中に産するザクロ石のセクター構造と組成累帯構造

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組織的なセクター構造を有するザクロ石が、肥後変成岩類のザクロ石-黒雲母-キン青石片麻岩より見いだされた。このザクロ石は、dusty coreとclear marginを持つ。このdusty coreは、薄片上では六角形ないしは八角形を示し、流体と固相の微細(<1 μ m)な包有物を多数含んでいる。微細な包有物はほぼ直線的に配列しており、その方向はdusty coreの縁に対し垂直である。このセクター構造は、微細な包有物が{110}結晶面に対し垂直にそして直線的に配列している12個の菱形ピラミッドから成る斜方十二面体モデルによって説明される。また、このザクロ石は、コアでMnやCaに富み、リムでMgやFeに富む組成累帯構造がみられる。このザクロ石の2次元組成マップから得られた等組成線は、各セクター内での微細な包有物の配列方向に対し垂直な関係にある。この包有物の配列構造と組成累帯構造の直交性は、ザクロ石の結晶成長時の重要な初生的性質であると思われる。等組成線(3次元では等組成面)は、結晶成長時の{110}結晶面に平行な等時面であると考えられる。さらに結晶成長時の表面平衡の可能性、および初生的な(成長)組成累帯構造の拡散による改変の効果について議論した。