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Compositional Zoning of Garnet in Pelitic Schist from Klein Letaba Mine, Sutherland Greenstone Belt, South Africa.

Toshiaki TSUNOGAE*

Abstract

The Sutherland Greenstone Belt, located near the northeastern edge of the Kaapvaal Craton in South Africa, is composed mainly of Archean metasedimentary and metavolcanic rocks of amphibolite grade. Sample of pelitic schist collected from Klein Letaba Mine contains mineral assemblage of quartz, plagioclase, garnet, biotite, anthophyllite, gedrite, kyanite, staurolite, and tourmaline. Compositional profile of euhedral garnet shows growth zoning pattern (Fe+Mg increases and Ca+Mn decreases continuously from core to rim) which was produced during prograde metamorphism. In contrast, edge of the garnet is characterized by reverse trend; Fe+Mg decreases and Ca+Mn increases from rim to edge. The garnet is considered to have suffered subsequent overgrowth or modification of composition near the edge of the crystal after peak metamorphism. The retrograde event may be associated with thrusting of the high-grade Limpopo Belt onto the low-grade Kaapvaal Craton.

Introduction

Compositional zoning in metamorphic minerals give us a wealth of information about pressure and temperature (P-T) history of the host rock. Garnet is the most commonly occurring zoned mineral in low- to high-grade metamorphic rocks with various bulk chemical compositions. Because diffusion of Fe, Mg, Ca, and Mn within garnet crystal is slow compared to the other ferromagnesian minerals in low- to medium-grade conditions ($T < 650℃$), original compositional zoning pattern is usually preserved in the mineral. Recent development of analytical technique of electron microprobe and data processing enabled us to determine compositional zoning pattern of minerals more quantitatively as an indicator of metamorphic P-T history. Numerous studies have been done concerning garnet zoning in conjunction with metamorphic evolution (*e.g.* Hollister, 1966; Harte and Henley, 1966; Tracy, 1982).

This paper presents an example of zoned garnet in pelitic schist from the Sutherland Greenstone Belt in the Kaapvaal Craton (Fig. 1). The belt is geologically important because it is situated along a terrane boundary between low-grade Kaapvaal Craton and high-grade Limpopo Belt. It can be deduced that metamorphic rocks from the Sutherland Greenstone Belt may preserve high-grade episode of the Limpopo orogeny as well as low-grade event of the Kaapvaal Craton. Detailed study of garnet zoning is, therefore, important to investigate complex metamorphic history of the Sutherland Greenstone Belt. Compositions and zoning profile of the garnet will be discussed below.

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* Department of Earth Science, Faculty of Education, Shimane University, Matsue 690.

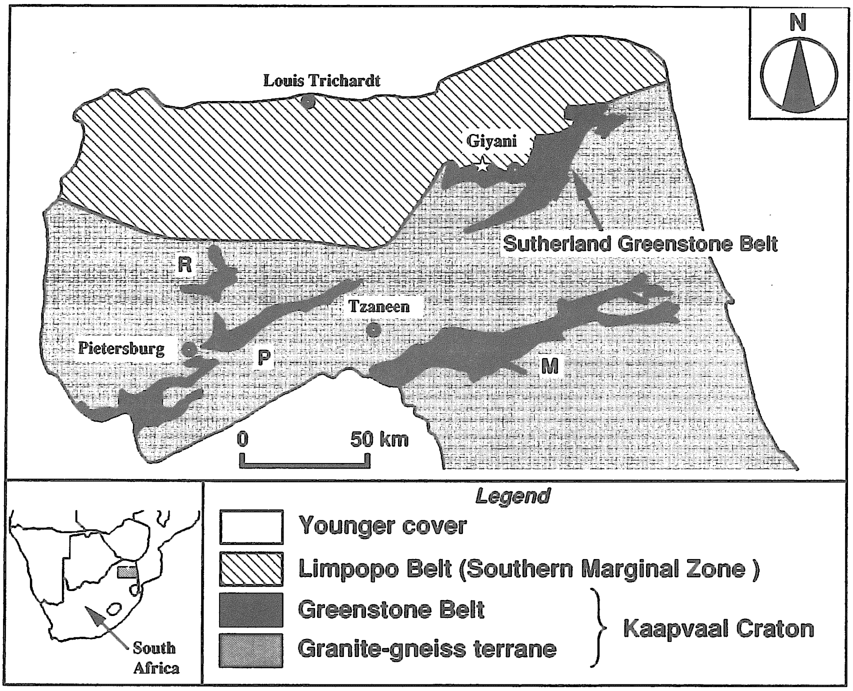

Fig.1 Simplified geological map of the Sutherland Greenstone Belt, South Africa, after van Reenen and Roering (1990). Circles and star indicate major towns and sample locality, respectively. P: Pietersburg Greenstone Belt, M: Murchison Greenstone Belt, R: Rhenosterkoppies Greenstone Belt.

General Geological Setting

The Sutherland (also known as Giyani) Greenstone Belt is located near the northeastern edge of the Archean Kaapvaal Craton in South Africa (Fig. 1). It crops out as a NE-SW trending belt of about 70 km long and 20 km wide. The belt is composed mainly of metasedimentary and metavolcanic rocks termed Giyani Group (SACS, 1980). Interlayered succession of ultramafic and mafic schists is a major lithology of the belt. Banded iron formation, often associated with quartzite and pelitic schist, occurs throughout the belt. Ferruginous dolomitic rock is present only as minor outcrops. Although metamorphic P-T conditions of the belt are not clearly understood, kyanite-staurolite assemblage in aluminous rocks and actinolite-tremolite assemblage in ultramafic schists indicate amphibolite facies environment (McCourt and van Reenen, 1992; de Wit *et al.*, 1992).

Syn- to post-tectonic granites in the vicinity of the Sutherland Greenstone Belt have yielded zircon U-Pb ages of 2.9 to 3.0 Ga (Barton, 1990) which are thought to be the timing of emplacement of the granites. The age of metasedimentary and metavolcanic rocks in the belt is unknown, but considered to be similar to that of the Barberton Greenstone Belt (up to 3.5 Ga; Armstrong *et al.*, 1990) which is situated about 300 km south of the Sutherland Greenstone Belt.

Petrography

Sample of pelitic schist was collected from Klein Letaba Mine which is located about 15 km west of Giyani township in northern Transvaal. The rock is dark brownish in color, medium-grained, and characterized by obvious schistosity. It is composed of quartz, plagioclase, garnet, biotite, anthophyllite, gedrite, kyanite, staurolite, tourmaline, and accessory amounts of rutile, zircon, apatite, and magnetite. The rock can be subdivided into two parts on the basis of mineral assemblages as follows;

garnet-biotite-anthophyllite-quartz-plagioclase (A)
gedrite-kyanite-staurolite-biotite-quartz-plagioclase (B)

Assemblage (A) constitutes a major part of the rock. Assemblage (B) is present as spots in assemblage (A). The compositions and mineral assemblages of ferromagnesian silicates are shown in AFM diagram (Fig. 2).

Porphyroblastic and medium grained (1 to 2 mm in diameter) garnet is abundant in assemblage (A) (more than 10 vol.%). It contains small inclusions of quartz and opaque minerals (mainly magnetite). Detailed compositional zoning pattern of garnet will be discussed later. Biotite, which is elongated along the schistosity of the rock, is the most abundant ferromagnesian mineral in the sample (about 20 vol.%). It is locally associated with garnet and anthophyllite. Anthophyllite forms a large prismatic grain (up to 2 mm) elongated along the schistosity.

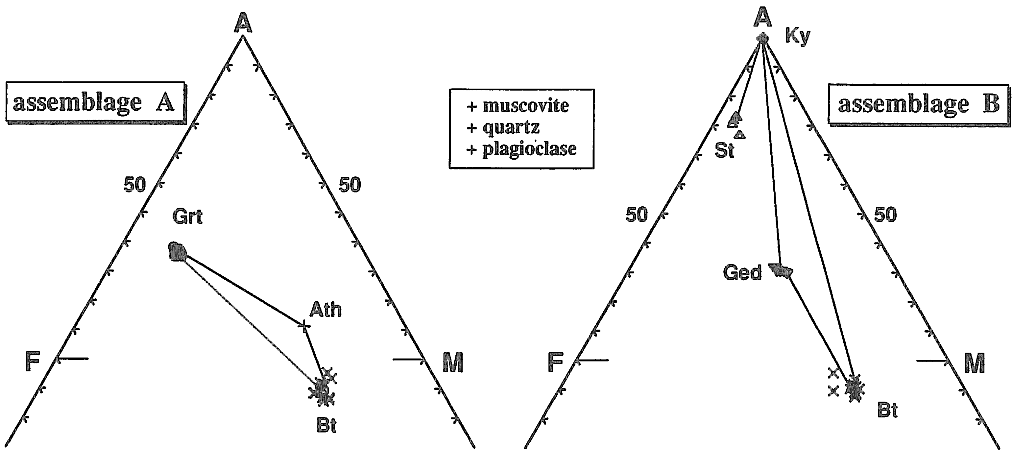

Fig.2 AFM diagrams (+ muscovite) showing mineral assemblages and compositions of pelitic schist from Klein Letaba Mine, Sutherland Greenstone Belt. See Table 1 for mineral abbreviation.

Table 1. Representative electron microprobe analyses of minerals in pelitic schist from the Sutherland Greenstone Belt. Grt: garnet, Bt: biotite, Ath: anthophyllite, Ged: gedrite, St: staurolite, Ms: muscovite, Ky: kyanite, Pl: plagioclase.

Mineral	Grt core	Grt rim	Grt edge	Bt contact	Bt isolated	Ath	Ged	St	Ms	Ky	Pl
Number of O*	12	12	12	22	22	23	23	23.5	22	5	8
SiO_2	35.22	36.12	36.42	35.91	37.34	56.30	42.40	27.52	45.86	36.41	58.27
Al_2O_3	22.33	21.89	21.73	18.46	18.92	0.75	17.43	52.51	40.28	62.06	25.46
TiO_2	0.05	0.05	0.07	1.37	1.65	0.01	0.19	0.61	0.03	0.00	0.00
Cr_2O_3	0.06	0.12	0.40	0.35	0.59	0.00	0.11	0.48	0.07	0.22	0.00
FeO**	31.25	33.20	31.50	12.21	11.59	16.24	20.45	10.65	0.21	0.12	0.10
MnO	3.17	0.74	0.78	0.04	0.00	0.35	0.16	0.81	0.00	0.02	0.00
NiO	0.00	0.00	0.00	0.00	0.06	0.00	0.08	0.04	0.04	0.00	0.00
MgO	4.87	5.96	5.73	16.10	15.98	23.64	13.72	1.52	0.06	0.00	0.00
CaO	1.98	2.02	2.59	0.02	0.00	0.35	0.33	0.00	0.49	0.01	7.42
Na_2O	0.08	0.06	0.04	0.50	0.75	0.07	1.76	0.03	7.27	0.00	8.34
K_2O	0.01	0.00	0.02	9.17	8.55	0.00	0.01	0.00	1.68	0.02	0.04
ZnO	0.00	0.05	0.00	0.00	0.00	0.03	0.06	1.16	0.00	0.06	0.00
Total	99.00	100.22	99.27	94.13	95.41	97.73	96.67	95.33	95.99	98.92	99.62
Si	2.850	2.877	2.910	5.355	5.440	7.920	6.258	3.990	5.866	0.995	2.624
Al	2.129	2.054	2.046	3.244	3.248	0.124	3.031	8.969	6.071	1.999	1.351
Ti	0.003	0.003	0.004	0.154	0.180	0.001	0.021	0.067	0.003	0.000	0.000
Cr	0.004	0.007	0.025	0.041	0.067	0.000	0.013	0.055	0.007	0.005	0.000
Fe	2.114	2.211	2.104	1.523	1.411	1.910	2.523	1.291	0.023	0.003	0.004
Mn	0.217	0.050	0.052	0.005	0.000	0.042	0.020	0.099	0.000	0.000	0.000
Ni	0.000	0.000	0.000	0.000	0.007	0.000	0.009	0.005	0.004	0.000	0.000
Mg	0.587	0.707	0.682	3.578	3.467	4.954	3.015	0.328	0.012	0.000	0.000
Ca	0.171	0.172	0.222	0.003	0.000	0.053	0.052	0.000	0.067	0.000	0.358
Na	0.012	0.009	0.006	0.145	0.211	0.019	0.503	0.007	1.802	0.000	0.728
K	0.001	0.000	0.002	1.744	1.588	0.000	0.001	0.000	0.273	0.001	0.002
Zn	0.000	0.003	0.000	0.000	0.000	0.003	0.006	0.124	0.000	0.001	0.000
Total	8.088	8.094	8.054	15.792	15.621	15.026	15.452	14.935	14.130	3.004	5.066

* Number of oxygen ** total Fe as FeO

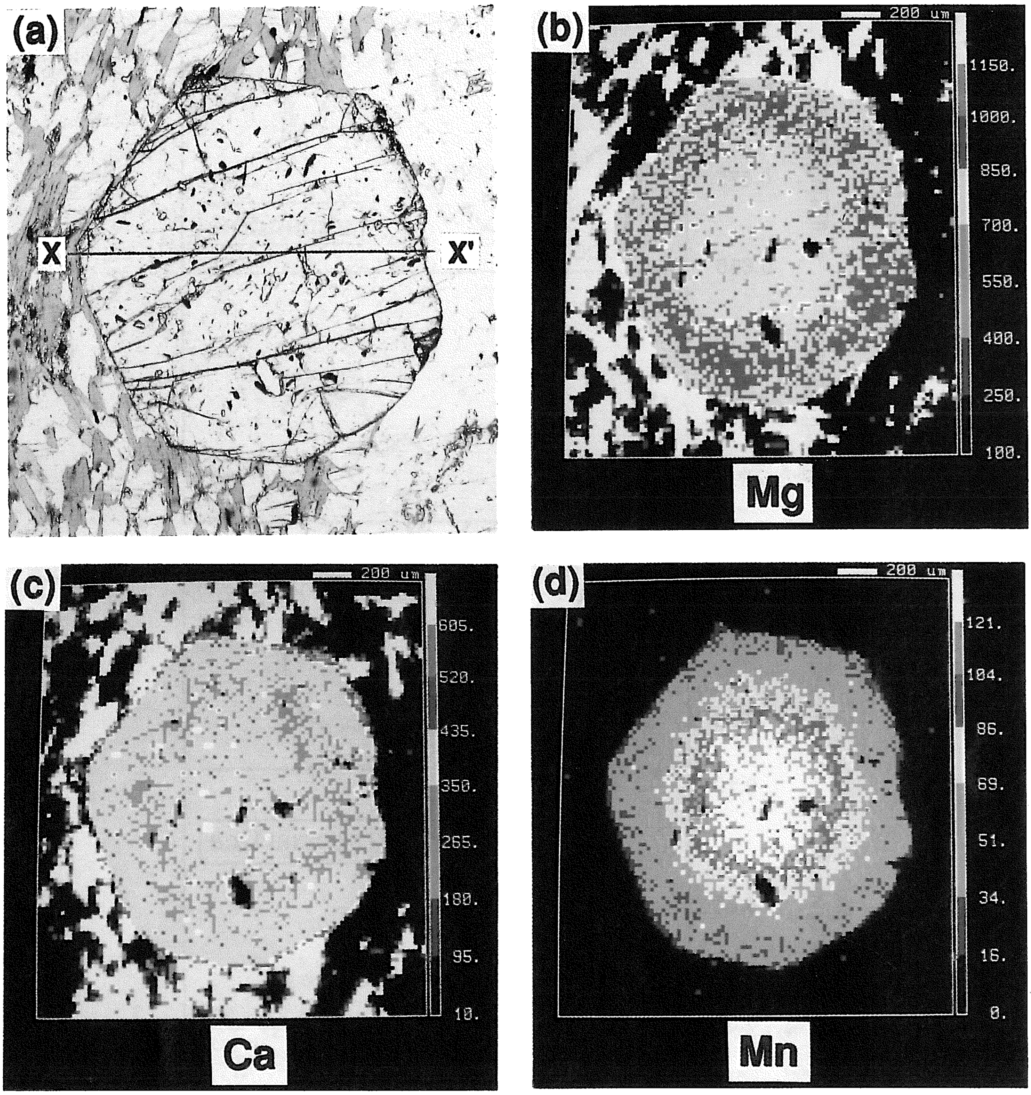

Fig.3. (a): Photomicrograph of garnet (1.5 mm in diameter) in pelitic schist from the Sutherland Greenstone Belt. X-X' indicates analytical line of compositional profiles shown in Fig. 4. Polarized light. (b), (c), and (d): Two-dimensional compositional mapping of Mg, Ca, and Mn in the garnet. Color bars indicate concentration of each element (counts per second).

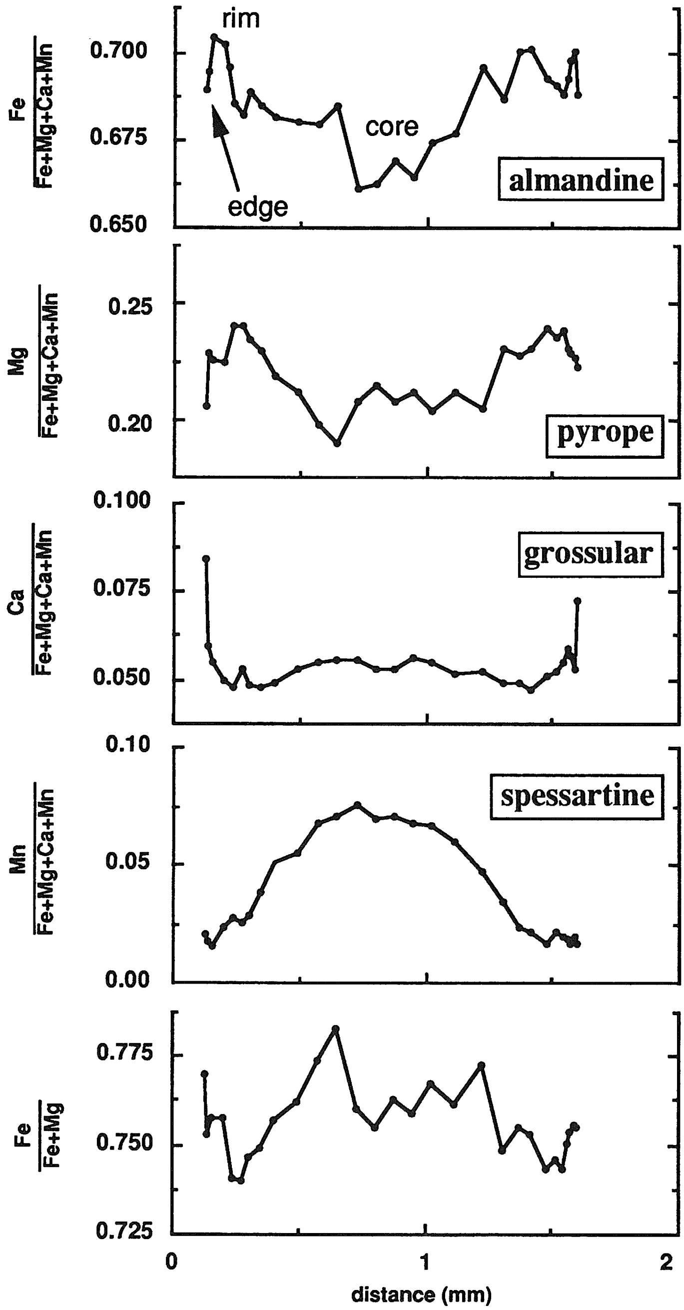

Fig.4 Compositional profiles of almandine (Fe／[Fe+Mg+Ca+Mn]), pyrope (Mg／[Fe+Mg+Ca+Mn]), grossular (Ca／[Fe+Mg+Ca+Mn]), and spessartine (Mn／[Fe+Mg+Ca+Mn]) molecules and Fe／[Fe+Mg] ratio across garnet in pelitic schist from the Sutherland Greenstone Belt. See Fig. 3(a) for analytical line.

In assemblage (B), gedrite is present as small (less than 0.1 mm) needle-like aggregates in conjunction with quartz and prismatic kyanite. The mineral assemblage can be explained by the following reaction (1), although cordierite is absent in the assemblage.

cordierite + water = gedrite + kyanite + quartz (1)

The reaction (1) is a hydration reaction which is associated with H_2O-bearing fluid activity. The evidence implies that the rock has suffered retrograde metamorphism during cooling. Both staurolite and tourmaline are small ($<$0.05 mm in diameter) and their modal abundances are less than 1 vol.%.

Garnet zoning

Chemical analyses of minerals were performed by electron microprobe (JEOL JXA-8621) at the Chemical Analysis Center of the University of Tsukuba. The data was obtained under conditions of 15 kV accelerating voltage and beam current of $1x10^{-8}$ A (spot analysis) and $1x10^{-7}$ A (map analysis), with data processing by oxide-ZAF model correction program supplied by JEOL. Representative electron microprobe analyses of rock forming minerals are listed in Table 1. Two-dimensional compositional mapping and line profiles of euhedral garnet are illustrated in Figs. 3 and 4, respectively.

The garnet suggests what has commonly been described as "normal or growth zoning" pattern; Fe+Mg increases and Ca+Mn decreases continuously from core to rim (see Figs. 3 and 4). The Mn decrease toward rim is interpreted as a result of continuous depletion of Mn in the matrix, because garnet is the only Mn-bearing mineral in the present mineral assemblage. Because no compositional gap can be observed from the zoning pattern (core to rim), the garnet should be formed during single metamorphic event.

An interesting feature of this garnet is the reversal in Mn and Ca near the edge of the crystal. Spessartine molecule (Mn/[Fe+Mg+Ca+Mn]) decreases continuously from 0.075 (core) to 0.015 (rim), and slightly increases up to 0.020 near edge. Grossular molecule (Ca/[Fe+Mg+Ca+Mn]) also decreases gradually from 0.055 (core) to 0.045 (rim), but sharply increases toward edge (0.085). Opposite trends can be observed from pyrope (Mg/[Fe+Mg+Ca+Mn]) and almandine (Fe/[Fe+Mg+Ca+Mn]) molecules in the garnet. Pyrope molecule increases continuously from 0.20 (core) to 0.24 (rim), but slightly decreases to 0.20 near edge. Almandine molecule also increases from 0.66 (core) to 0.70 (rim) and decreases to 0.69 near edge. There are two possible explanations for this behavior; (a) formation of garnet in a new reaction during prograde and/or retrograde metamorphism (breakdown reaction of Ca- and Mn-bearing minerals to form grossular- and spessartine-rich garnet); (b) retrograde modification of already present garnet rim (cation exchange reaction or volume diffusion with Ca-bearing, Mn-bearing, and other ferromagnesian minerals). Although the likelihood of the two processes is not clearly understood, formation of edge may be associated with changing metamorphic P-T conditions.

Fe/[Fe+Mg] ratio of garnet is an indicator whether the garnet was produced during increasing or decreasing temperature. Fe-Mg cation exchange reaction between garnet and adjacent ferromagnesian mineral "A" can be explained by the following reaction (2);

almandine + A (Mg end-member) = pyrope + A (Fe end-member) (2)

Biotite, anthophyllite, and gedrite are possible phases which are likely to have undergone Fe-Mg cation exchange with garnet in this sample. Because distribution coefficient (K_D) of the reaction (2) increases as increasing temperature, garnet will become enriched in Mg relative to Fe during prograde metamorphism. As shown in Fig. 4, the Fe/[Fe+Mg] ratio of garnet decreases slightly from core (0.76 to 0.78) to rim (0.74), but increases toward edge (up to 0.77). The evidence implies that increase of metamorphic temperature during garnet growth (core to rim) was followed by overgrowth or modification of already present rim (formation of edge) during retrograde metamorphism. It has to be noted, however, that the explanation is based on the assumption that the garnet was in equilibrium with the other ferromagnesian minerals during the growth.

The retrograde event which affected garnet can also be traced from Ca zoning pattern. Garnet showing grossular zoning appears to occur in conjunction with Ca-bearing mineral. Plagioclase (anorthite) is a possible Ca-bearing phase in this sample, and the compositions of these two minerals may be controlled by equilibria involving each phase. One such reaction applicable to this sample is;

$$\text{grossular} + \text{kyanite} + \text{quartz} = \text{anorthite} \qquad (3)$$

Because grossular is on the high-pressure or low-temperature side of the reaction (3), the pattern of increasing grossular content toward edge is consistent with overgrowth or reequilibrium of the garnet under condition of increasing pressure or decreasing temperature.

Metamorphic P-T conditions of the Sutherland Greenstone Belt

Compositional zoning pattern of garnet in pelitic schist from the Sutherland Greenstone Belt implies that the garnet was crystallized during prograde metamorphism. It has suffered slight modification of zoning at edge, but peak metamorphic temperature was not high enough to obliterate whole zoning pattern. Woodsworth (1977) reported homogenization of zoned garnet above 600℃, and Yardley (1977) estimated that volume diffusion begins to affect zoning profiles between 615 to 665℃. The radially symmetrical compositional profile shown in Fig. 3 implies that peak metamorphic temperature was lower than 650℃, which is enough for garnet to avoid volume diffusion.

Metamorphic temperature of the pelitic schist was estimated independently using garnet-biotite geothermometer of Ferry and Spear (1978), Hodges and Spear (1982), and Ganguly and Saxena (1984). Temperatures from rim of garnet and isolated biotite are 460-490℃, 480-510℃, and 390-420℃, respectively, at 4 kbar. The temperature ranges are consistent with the evidence that growth zoning is present in the garnet. Peak pressure of the metamorphism could not be estimated in this study, but it should be more than 4 kbar at stability field of kyanite (based on sillimanite-kyanite reaction curve of Helgeson *et al.* (1978)).

Estimated peak P-T condition from the Sutherland Greenstone Belt is lower than that of the Southern Marginal Zone of the Limpopo Belt (750℃ at 7.5 kbar; Tsunogae and Miyano, 1989) which is located about 30 km northwest of the greenstone belt. It is also supported by the evidence that the garnet zoning is preserved in this sample, while garnet in the Southern Marginal Zone is completely homogenized in composition during high-grade metamorphism (Tsunogae and Miyano, 1989). According to van Reenen and Roering (1990), boundary between the Limpopo Belt and the Kaapvaal Craton is defined by the Hout River shear zone, where high-grade lithologies of the Limpopo Belt have apparently thrusted onto the low-grade Kaapvaal Craton. Because the Sutherland Greenstone Belt is situated close to the contact with the granulite terrane of the Limpopo Belt, the retrograde metamorphism recorded in the garnet may be associated with the thrusting of the Limpopo Belt onto the Kaapvaal Craton. The thrusting and subsequent increase of pressure and temperature may have brought about Ca- and Mn-rich edge of the garnet. Although detailed mineralogical, petrological, and geochlonological studies are indispensable to compare metamorphic history of the two terranes, comparison of garnet zoning discussed above must be an important key to solve the problem.

Conclusion

Garnet in pelitic schist from the Archean Sutherland Greenstone Belt shows growth zoning pattern (Fe+Mg increases and Ca+Mn decreases continuously from core to rim) which was produced during prograde metamorphism. The garnet has suffered subsequent overgrowth or modification of composition near edge of the crystal during retrograde metamorphism. The retrograde event may be associated with thrusting of the high-grade Limpopo Belt onto the low-grade Kaapvaal Craton.

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