Zeitschrift: Schweizerische mineralogische und petrographische Mitteilungen = Bulletin suisse de minéralogie et pétrographie

Band: 80 (2000)

Heft: 1

Artikel: Garnet in pelitic schists from a quartz-eclogite unit of the southern Dora-Maira massif, Western Alps

Autor: Matsumoto, Naoko / Hirajima, Takao

DOI: https://doi.org/10.5169/seals-60950

SCHWEIZ. MINERAL. PETROGR. MITT. 80, 53–62, 2000

Garnet in pelitic schists from a quartz-eclogite unit of the southern Dora-Maira massif, Western Alps

by *Naoko Matsumoto*[1] and *Takao Hirajima*[1]

Abstract

On the basis of grain size distribution, chemical zoning patterns and the nature of inclusions, two types of garnet are recognized in pelitic schists from a quartz-eclogite unit of the southern Dora-Maira massif, 1) an Alpine-stage garnet, and 2) a multi-stage (Alpine and pre-Alpine) garnet. Garnet, associated with chloritoid, paragonite, albite, phengite and quartz, occurs either as porphyroblasts with unimodal grain size distribution or as large and small grains with bimodal distribution. Porphyroblastic garnet commonly contains chloritoid inclusions throughout the grain, and has a concentric chemical zoning pattern with Mn decreasing and Ca increasing from core to rim. This suggests that the garnet grew during a single high-pressure metamorphic event, i.e., the high-pressure Alpine stage. The cores of the larger garnets show various zoning patterns. The rims of such garnets are Ca-rich and Mn-poor. Some grains have a clear chemical discontinuity between the core and rim. Chloritoid inclusions in such garnets are only found in the chemically distinct rims. The smaller garnets contain chloritoid throughout the grain and the composition is similar to that of the rim of the larger garnets. This suggests that the chemically distinct rim overgrew a pre-Alpine garnet relict during the high-pressure Alpine stage: the larger garnet records a multi-stage growth history. This is direct evidence for polymetamorphism of the quartz-eclogite unit in the Dora-Maira massif.

Keywords: garnet zoning, Dora-Maira massif, Alpine metamorphism, pre-Alpine garnet.

1. Introduction

Chemical zonation of garnet provides useful information in understanding the metamorphic history of low- to medium-grade metamorphic rocks (e.g., KRETZ, 1973; TRACY, 1982; GHENT, 1986; SPEAR, 1993). Since the sixties, many authors have discussed the origin of zonations in metamorphic garnets (e.g., HOLLISTER, 1966; TRACY et al., 1976; YARDLEY, 1977), and numerous new data have been accumulated. Recent improvements on compositional imaging techniques allow the production of X-ray maps that show two-dimensional (2-D) element variation in zoned crystals. This technique has shown that 2-D zoning patterns are more complex than previously assumed from line-scan studies (TRACY, 1994).

The Dora-Maira massif, one of the Penninic internal crystalline massifs in the Western Alps (Fig. 1), is thought to have undergone Variscan or earlier regional metamorphism. This was overprinted by Alpine high-pressure (HP) metamorphism, which was followed by a later low-pressure (LP) metamorphism. Several workers have reported evidence of a polymetamorphic history in the Dora-Maira massif (BORGHI et al., 1985; SANDRONE and BORGHI, 1992; CHOPIN et al., 1991; COMPAGNONI et al., 1995). Most of them succeeded in distinguishing pre-Alpine garnet from Alpine garnet on the basis of chemical composition and inclusion assemblages of the garnets. However, they did not produce 2-D zoning patterns. We characterized garnets in metapelites from a tectonic unit of the southern Dora-Maira massif by microscopic observation and microprobe analysis. X-ray maps showing 2-D zoning patterns which, when combined with inclusion patterns, allowed us to identify the origin of garnet and to estimate the P-T conditions during garnet formation. In this contribution, we will provide microscopic and microchemical data aimed at identifying the origin of the garnet, and briefly discuss the petrological significance.

[1] Department of Geology and Mineralogy, graduate school of Earth Science, Kyoto University, Kyoto, 606-8502, Japan. <hirajima@pet.kueps.kyoto-u.ac.jp>

2. Geological setting

The southern Dora-Maira massif, well known for the first report of coesite-bearing ultra-high pressure (UHP) rock by CHOPIN (1984) (Fig. 1), consists of a pile of thrust sheets differing in metamorphic grade from the HP Alpine event (CHOPIN et al., 1991). The whole nappe pile shows a rather homogeneous structural imprint that developed under greenschist-facies conditions during and/or after tectonic juxtaposition of the sheets (CHOPIN et al., 1991; MICHARD et al., 1995). Evidence for UHP is found in one of the thrust sheets and in various lithologic units. The sheet of interest is 5 × 10 × 1 km in size, and was defined as the Brossasco-Isasca unit by COMPAGNONI et al. (1995). In this paper, we will refer to this unit as UHP unit for simplicity. The two units immediately overlying and underlying the UHP unit have neither coesite nor coesite pseudomorphs, but contain quartz-bearing eclogite (Fig. 1). The main overlying unit will be referred to as quartz-eclogite unit. The estimated peak metamorphic conditions of the quartz-eclogite unit are 550 °C and 15 kbar (CHOPIN et al., 1991). Hereafter, we use the term "HP Alpine metamorphism" as a prograde or a subduction stage of the Dora-Maira Massif and "LP Alpine metamorphism" as a thermal event, which took place at lower crustal depths after the exhumation of HP and UHP rocks. Therefore, HP Alpine corresponds to early- or eo-Alpine, and LP Alpine corresponds to late- or meso-Alpine

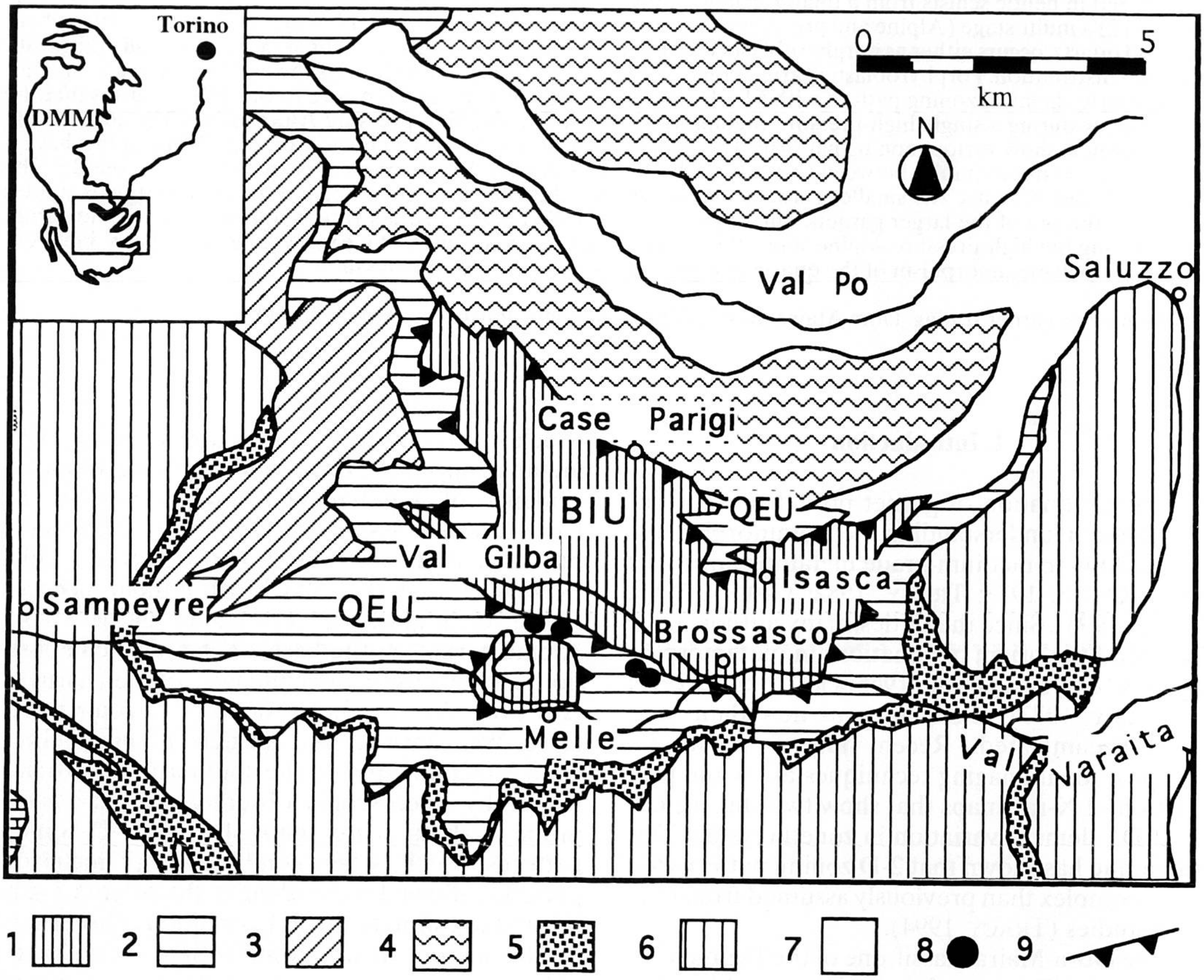

Fig. 1 Geological sketch map of the southern Dora-Maira massif (DMM) modified from COMPAGNONI et al. (1995) and MICHARD et al. (1995). 1: Brossasco-Isasca unit (BIU: pre-Alpine basement with middle-T eclogite facies overprint). 2: Quartz-eclogite unit (QEU: pre-Alpine basement with low-T eclogite facies overprint). 3: Pre-Alpine basement and Permo-Carboniferous + Permo-Triassic cover with low-T eclogite facies overprint. 4: Pinerolo unit (graphite-rich unit with epidote-blueschist facies overprint). 5: Oceanic sediments with blueschist facies overprint. 6: Upper Palaeozoic and Lower Triassic unit with blueschist facies overprint. 7: Post-orogenic sediments. 8: Sampling localities. 9: Tectonic contact of BIU (ornaments on the upper unit).

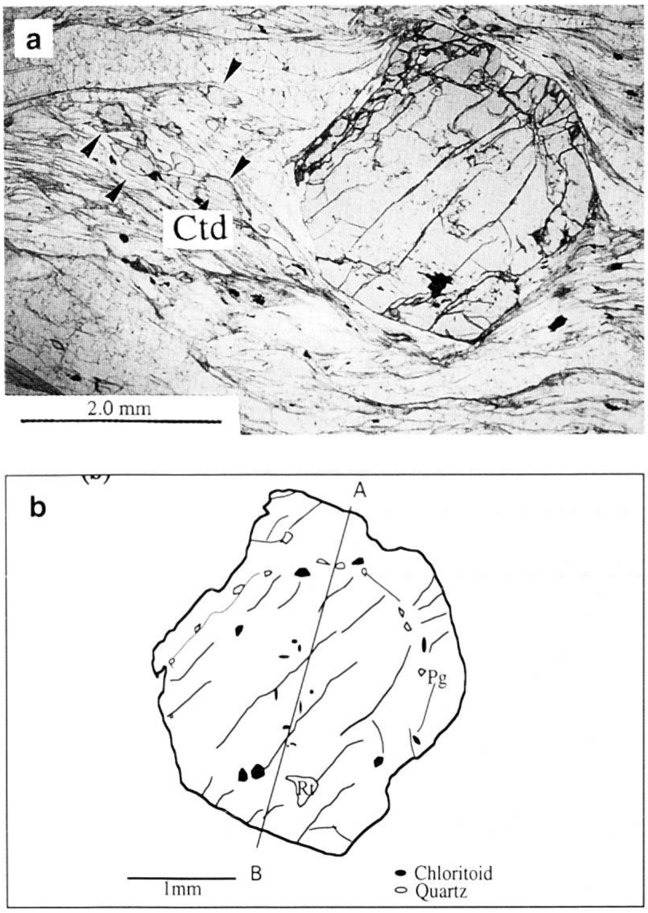

Fig. 2 (a) Unimodal garnet in a chloritoid-bearing metapelite (DM634). Ctd: chloritoid. X-ray maps for this grain are shown in figure 6a. (b) Sketch of unimodal garnet of figure 2a, showing the distribution of inclusions. Chloritoid is found in both the core and the rim. A–B: trace of zoning profile shown in figure 7a. Pg: paragonite, Rt: rutile.

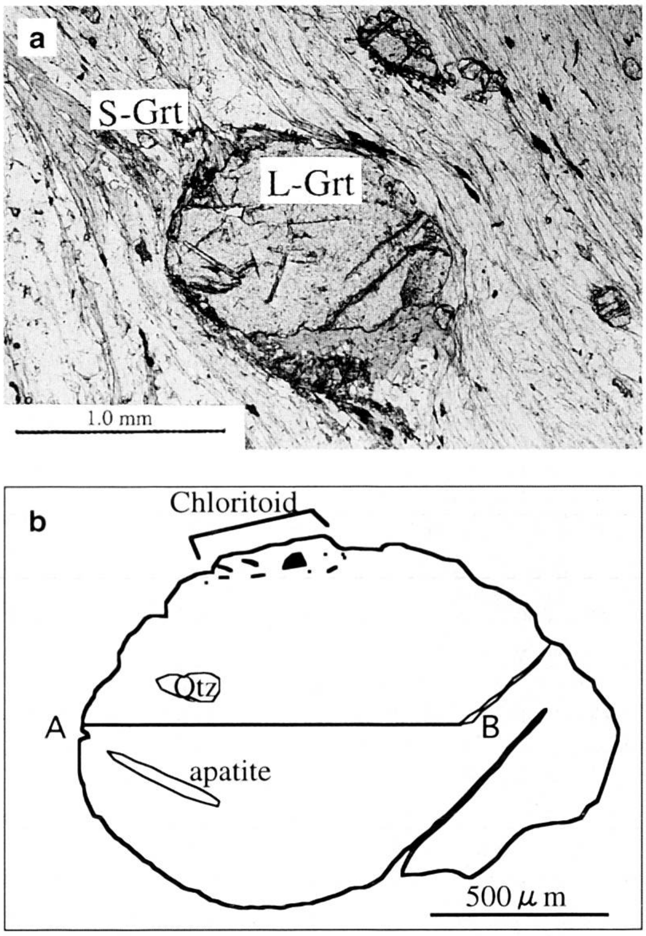

Fig. 3 (a) Large (L-Grt) and small (S-Grt) garnets in a chloritoid-bearing metapelite (DM636). Part of the large garnet is replaced by chlorite (lower part). X-ray maps for this grain are shown in figure 6b. (b) Sketch of the large garnet in figure 3a, showing the distribution of inclusions. Chloritoid inclusions occur in the outer part of the grain. A–B: trace of zoning profile shown in figure 7b.

metamorphism in this paper (see, e.g., SANDRONE and BORGHI, 1992). The exact timing of the HP Alpine metamorphism in the quartz-eclogite unit has not been determined yet. We, however, tentatively regard it almost coeval to that of the UHP unit and follow the geochronological framework of GEBAUER et al. (1997) in the southern Dora-Maira massif.

The metapelites analyzed in this study were collected from the quartz-eclogite unit overlying the UHP unit between Val Gilba and Val Varaita (Fig. 1). CHOPIN et al. (1991) recognized two lithological subunits, "the gneiss series" and "the varied formation", in the quartz-eclogite unit. The "gneiss series" consists mainly of augengneiss and medium- to fine-grained orthogneiss with minor magnesian schist. The "varied formation" consists of Fe-rich metapelites with eclogite and marble, and medium- to fine-grained phengite-rich gneiss. The metapelites in this study correspond to the Fe-rich metapelites of the "varied formation".

3. Petrography of metapelites

The metapelites consist mainly of garnet, phengite, paragonite and quartz, with chloritoid or albite. Chloritoid and albite have never been found occurring together in handspecimen. Accessory minerals are rutile, apatite, tourmaline, chlorite and epidote. Epidote contains a significant amount of rare-earth elements. Carbonate minerals have not been found. The main foliation is defined by the alignment of phengite and paragonite. Shear bands, which crosscut the main foliation, develop on various extent. Chlorite and biotite developed mainly at the edge of, or along the cracks in garnet, probably under greenschist-facies conditions. Some chlorite defining the main foliation, along with phengite and paragonite, should have equilibrated with other matrix phases. Chlorite and biotite also replace phengite at its

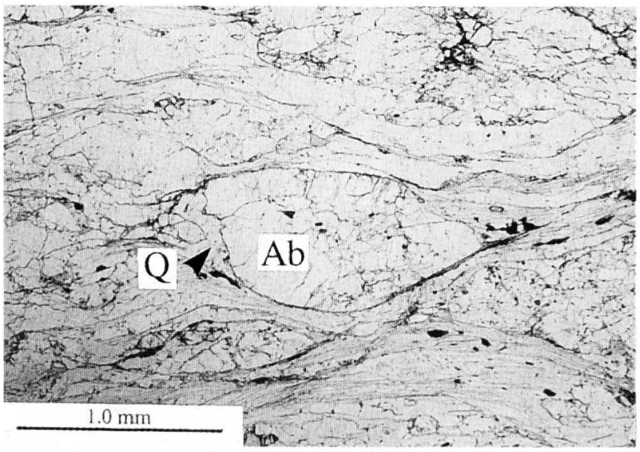

Fig. 4 Photomicrograph of porphyroblastic albite. Contact between quartz (Q) and albite (Ab) is sharp and no phase exists between them.

margins or occur in the shear bands, suggesting that the shear bands developed during the retrograde greenschist-facies stage. Rutile is commonly surrounded by ilmenite. These textures suggest that the stable assemblage at peak conditions was quartz-phengite-paragonite-garnet-rutile-chloritoid-chlorite. Porphyroblastic albite is difficult to relate to either the peak eclogite-facies stage, or to the retrograde greenschist-facies stage. Detailed microscopic information about garnet, chloritoid and albite is given below.

3.1. GARNET

We investigated 25 thin sections made from 13 hand specimens of metapelites. All the sections contain garnet. The grain size distribution of garnet is either: A – unimodal, with grain size from ca. 0.5 to 3 mm in diameter, or B – bimodal, composed of several large grains with 1–2 mm diameters and a few hundred small grains 0.2–0.3 mm in size.

Five hand specimens of the metapelites contain type A garnet, and the other eight type B. The grain size distribution of garnet is closely associated with its origin, and is discussed later. From here on, we refer to garnet A as unimodal garnet, and the large grains of type B as large garnet and smaller grains as small garnet. A similar grain size distribution was also recognized in metapelites (more than 10 hand specimens) collected from the quartz eclogite unit underlying the UHP unit (2 in Fig. 1) and upper Paleozoic and lower Triassic units (6 in Fig. 1).

The unimodal garnet is euhedral or subhedral in chloritoid-bearing metapelites (Fig. 2a), but has either rounded or euhedral shape in the albite-bearing metapelite. It commonly contains inclusions of quartz, muscovite, paragonite and rutile. Chloritoid inclusions are found throughout garnet grains in the chloritoid-bearing metapelite (Fig. 2b).

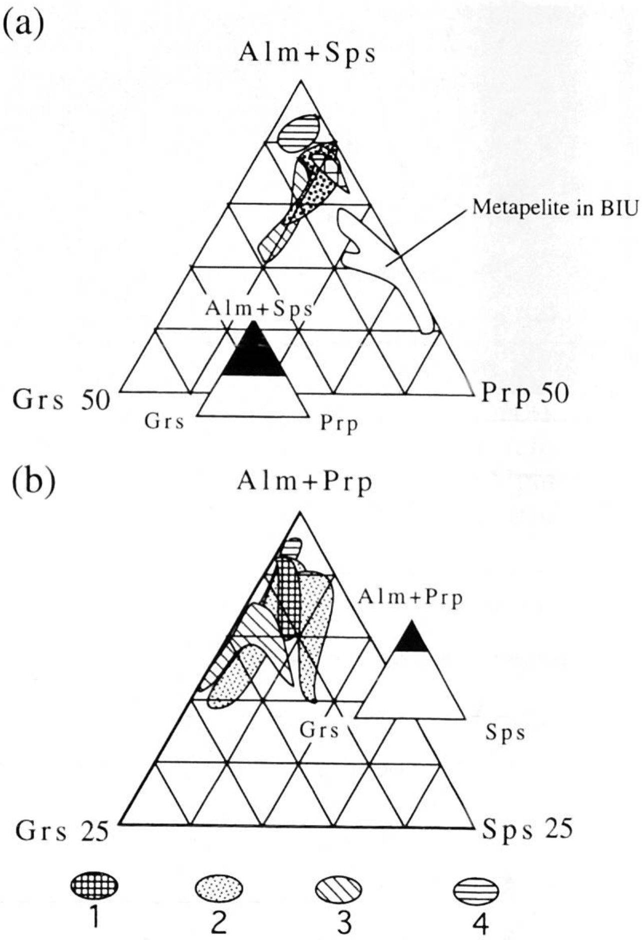

Fig. 5 Compositional variations of garnets in the metapelites from the quartz-eclogite unit and the Brossasco-Isasca unit (BIU: COMPAGNONI et al., 1995). Symbols: 1. Unimodal garnet in chloritoid-bearing samples. 2. Bimodal garnet in chloritoid-bearing samples. 3. Unimodal garnet in albite-bearing samples, 4. Bimodal garnet in albite-bearing samples. (a) (Fe + Mn)–Ca–Mg plot. (b) (Fe + Mg)–Ca–Mn plot.

The large garnet occurs as anhedral crystals, which are slightly elongated parallel to the main foliation (Fig. 3a). The small garnet is subhedral or euhedral. Most grains of the small garnet consist of both clear and dusty parts; the latter is crowded with tiny rutile inclusions. In places, the rutile grains are oriented at angles of 60/120° to each other, known as sagenite inclusion pattern. In addition, the large garnet and the small garnet contain inclusions of quartz, muscovite, rutile, ilmenite and minor paragonite. In the chloritoid-bearing metapelite, the small garnet contains chloritoid inclusions throughout the grain. Such inclusions are only found in the rim of the large garnet (Fig. 3b).

Tab. 1 Representative microprobe analyses of garnet. U: unimodal garnet. L: large garnet. S: small garnet. Ctd-bg: chloritoid-bearing. Ab-bg: albite-bearing.

Sample no.	DM634		DM636			DM909	
	Ctd-bg		Ctd-bg			Ab-bg	
type	U		L		S	U	
	core	rim	core	rim		core	rim
SiO_2	37.37	37.38	37.59	38.16	38.01	37.95	27.93
Al_2O_3	21.19	21.24	21.28	21.69	21.33	21.55	21.33
FeO	36.92	36.30	33.94	36.46	36.88	31.12	32.09
MnO	1.19	0.26	3.58	1.27	1.26	6.41	0.93
MgO	2.20	3.61	1.78	2.59	2.70	1.89	2.59
CaO	1.42	1.41	2.13	1.58	1.51	2.42	5.34
Total	100.29	100.20	100.30	101.75	101.69	101.34	100.21
O = 12							
Si	3.012	2.995	3.024	3.020	3.024	3.019	3.019
Al	2.013	2.006	2.018	2.021	2.002	2.020	2.001
Fe	2.489	2.432	2.284	2.411	2.525	2.070	2.136
Mn	0.081	0.018	0.244	0.085	0.047	0.432	0.063
Mg	0.264	0.431	0.213	0.305	0.319	0.224	0.307
Ca	0.123	0.121	0.184	0.134	0.057	0.206	0.455
Total	7.982	8.003	7.967	7.976	7.974	7.971	7.981
Mg/(Fe + Mg)	0.096	0.151	0.085	0.112	0.112	0.098	0.126
Alm	0.842	0.810	0.781	0.821	0.857	0.706	0.721
Sps	0.027	0.006	0.083	0.029	0.016	0.147	0.021
Prp	0.089	0.144	0.073	0.104	0.108	0.076	0.104
Grs	0.042	0.040	0.063	0.046	0.019	0.070	0.154

Tab. 2 Representative microprobe analyses of chloritoid, phengite and albite.

Mineral	Chloritoid			Phengite		Albite	
	matrix-core	matrix-rim	inclusion	core	rim	core	rim
SiO_2	25.00	24.81	25.44	51.87	46.63	69.28	67.30
TiO_2	–	–	–	0.19	0.46	–	
Al_2O_3	41.72	41.08	42.03	27.3	34.55	19.29	21.02
FeO	21.22	22.83	23.04	1.64	1.19	–	–
MnO	0.09	0.09	0.12	–	–	–	–
MgO	4.25	3.36	3.29	3.49	0.72	–	–
CaO	–	–	–	–	–	0.23	2.01
Na_2O	–	–	–	0.32	1.41	11.88	11.28
K_2O	–	–	–	10.45	9.25	0.03	0.05
Total	92.28	92.17	93.92	95.26	94.21	100.71	101.66
	O = 6			O = 11		O = 8	
Si	1.014	1.017	1.021	3.441	3.120	3.005	2.912
Ti	–	–	–	0.009	0.023	–	–
Al	1.995	1.984	1.989	2.134	2.726	0.986	1.072
Fe	0.720	0.782	0.774	0.091	0.067	–	–
Mn	0.003	0.003	0.004	–	–	–	–
Mg	0.257	0.205	0.197	0.345	0.072	–	–
Ca	–	–	–	–	–	0.011	0.093
Na	–	–	–	0.041	0.181	0.999	0.947
K	–	–	–	0.884	0.792	0.002	0.003
Total	3.989	3.991	3.984	6.946	6.981	5.003	5.027
	Mg/(Mg + Fe)					X_{Ab}	
	0.26	0.21	0.20			0.99	0.91

3.2. CHLORITOID

Chloritoid occurs both as a matrix phase and as inclusions in garnet. It shows a very weak pleochroism of X' = colourless and Z' = pale blue. Chloritoid in the matrix occurs parallel to the main foliation (Fig. 2a).

3.3. ALBITE

Albite occurs as porphyroblasts from 1 to 2 mm in diameter (Fig. 4). The porphyroblasts are in direct contact with quartz, and neither aegirine(acmite)-augite nor secondary amphibole coronas are found between albite and quartz. Albite porphyroblasts commonly contain quartz and phengite inclusions, but no garnet. Biotite is found rarely in albite porphyroblasts in pervasively retrograded samples.

4. Mineral chemistry and zoning patterns of garnet

Chemical analyses were performed with an electron microprobe (HITACHI S-550) with a Kevex energy dispersion system with Quantum detector at Kyoto University. The procedure follows that of MORI and KANEHIRA (1984) and HIRAJIMA and BANNO (1991). Tables 1 and 2 show representative microprobe analyses. X-ray element distribution maps were obtained by Kevex Advanced Image software with 128 × 256 pixels and dwell time between 1.0 and 1.5 s per point.

4.1. GARNET

All the analyzed garnets from metapelite are almandine-rich with small amounts of pyrope (< 15 mol%), grossular (< 20 mol%) and spessartine (< 8 mol%) components. Figure 5 shows the compositional variations of garnets. The garnet in the metapelite from the quartz-eclogite unit is poorer in Mg than that from the UHP unit. The chemical character of the three types of garnet, namely, unimodal garnet, large garnet and small garnet, can be summarized as follows in view of the 2-D zoning pattern and Mn-content profile (Tab. 3).

The unimodal garnet shows a concentric zoning with Mn decreasing and Mg increasing from

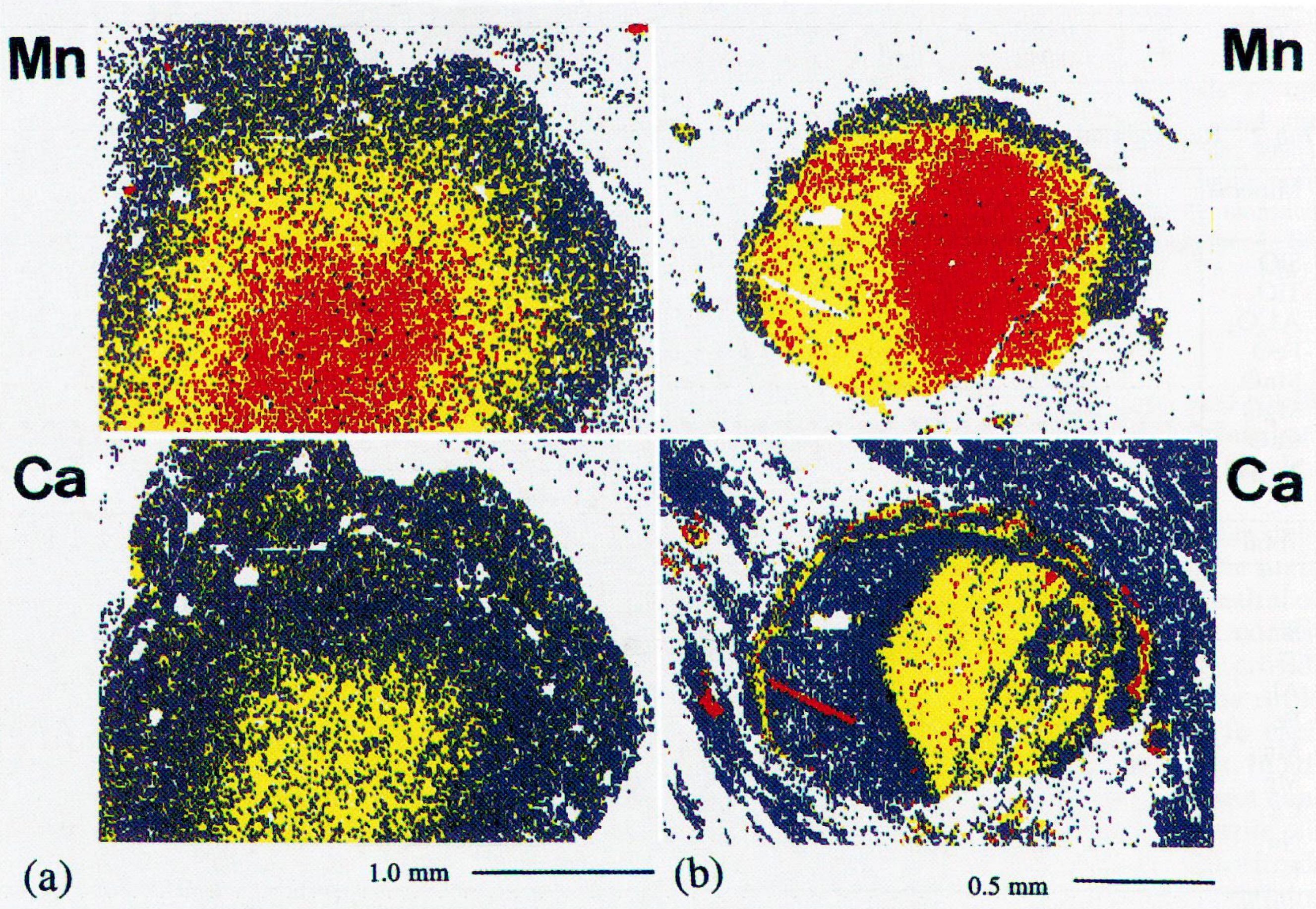

Fig. 6 A set of X-ray maps for Ca and Mn of (a) unimodal garnet in a chloritoid-bearing metapelite (DM634), and (b) large garnet in a chloritoid-bearing metapelite (DM636). The colour order, white-light blue-dark blue-green-yellow-red, shows relative content of each element from low to high.

Tab. 3 Relationship between zoning patterns and grain size distribution of garnet.

Types of garnet	Zoning	
	concentric	Mn bell-shape type
Unimodal	Yes	Yes
Large garnet	No	No
Small garnet	Yes	

core to rim (Figs 6a and 7a) both in chloritoid- and albite-bearing metapelites. Ca zoning is more varied, generally decreasing outward with a slight oscillatory change at the rim in the chloritoid-bearing samples (Figs 6a and 7a). In albite-bearing metapelites, the following types are recognized: 1) A band of maximum Ca contents occurs at an intermediate part of the grain; 2) Ca gradually increases from core to rim; 3) a Ca-poor euhedral core is surrounded by a Ca-rich rim. In all garnet types, the variation in the Ca content is correlated with the Fe content.

The zoning of the large garnet is not concentric. It can be chemically divided into two parts: a large core and a thin rim. The core shows various zoning patterns, while low Mn content systematically characterizes the rim. Some grains have a clear sharp chemical discontinuity between core and rim. Figure 6b shows Ca and Mn X-ray maps of one of them. The straight contour lines of Ca and Mn visible in the core suggest the original growth surface of euhedral crystals. The Mn-poor rim cuts them. A line traverse of this grain (between A and B in Fig. 3b) shows a compositional gap near A (arrow in Fig. 7b). The Mn content gradually decreases from the core to the core-rim interface and then drops substantially. Ca decreases outward up to the boundary, and then increases towards the margin. The chloritoid inclusions are confined to the chemically defined rim.

The small garnet is generally homogeneous in both Mg and Mn, but shows a slight antipathetic variation between Fe and Ca. Some grains have Ca-rich oscillatory bands parallel to the outline of the grains. Other grains have an irregular-shaped core with high Ca content. The small garnet is similar in the Mn content (Xsps = 0.03–0.05) to the rim of the large garnet (Fig. 8).

4.2. CHLORITOID

Chloritoid is slightly heterogeneous in each grain. The core is generally Mg-richer (X_{Mg} = Mg/(Fe + Mg) = 0.25–0.26) than the rim (X_{Mg} = 0.20–0.21) (Tab. 2). Fine-grained chloritoid was

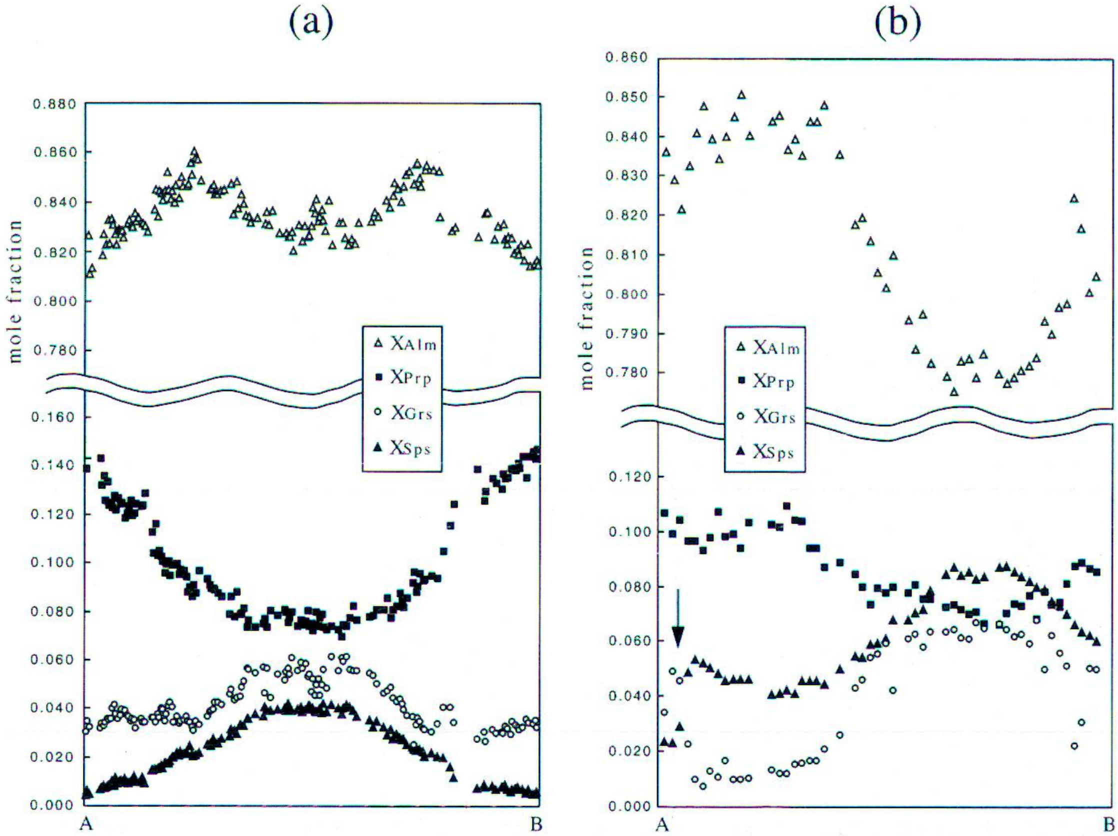

Fig. 7 (a) A set of compositional profiles along the line A–B in figure 2b for Fe, Mg, Ca and Mn of unimodal garnet. (b) Line profiles of large garnet along the line A–B shown in figure 3b. Arrow shows the position of chemical gap.

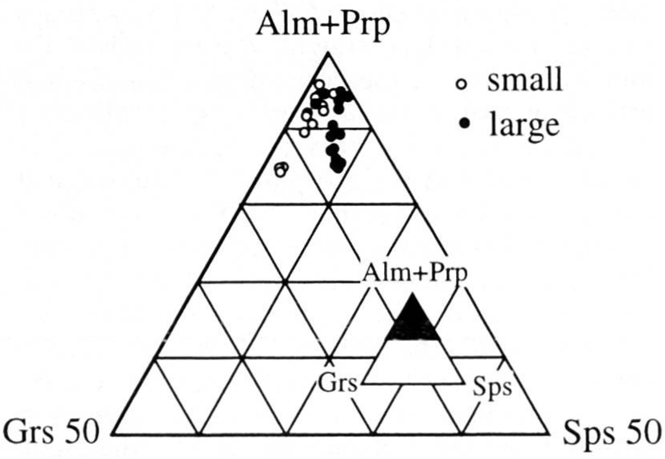

Fig. 8 Compositional variation of large garnet and small garnet in metapelite DM634. Rim of large garnet has the same low Mn content as small garnet.

identified as inclusions in garnet. It is too small to be analyzed quantitatively except for a few larger inclusions (X_{Mg} = 0.22).

4.3. ALBITE

Porphyroblastic albites are generally homogeneous with a small anorthite component (X_{An} = Ca/(Ca + Na) = 0.01–0.02), but some grains have a thin Ca-richer rim (X_{An} = 0.08–0.09) (Tab. 2). The backscattered electron image shows that the boundary between albite and quartz is sharp and no other phase exists at the boundary.

4.4. PHENGITE

Phengite is composed of a homogeneous core with high Si content and a thin rim with a lower Si content. The fish-shape phengite along shear bands is also Si-rich. In albite-bearing samples, the core composition ranges from Si = 3.3 to 3.4 calculated on the basis of 11 oxygens and the rim is Si = 3.1 on average (Tab. 2). In chloritoid-bearing samples, Si = 3.4–3.5 at the core and Si = 3.0–3.1 at the rim.

5. Discussion

5.1. TWO TYPES OF GARNET

The occurrence of multi-stage garnet has been documented in the other tectonometamorphic complexes of the Dora-Maira massif and neighbouring blueschist- and eclogite-facies units in the Western Alps (e.g., BORGHI et al., 1985; DESMONS, 1992; DESMONS and GHENT, 1977). BORGHI et al. (1985) and SANDRONE and BORGHI (1992) recognized three generations of garnet (interpreted as pre-Alpine, eo-Alpine and meso-Alpine) in metapelites of the northern Dora-Maira massif, mainly from grain size, coexisting minerals and chemical compositions.

In general, the 2-D zoning patterns obtained in this study support their observations. Our results also suggest that pre- and HP Alpine stage garnets occur in the metapelite of the quartz-eclogite unit, but we could not identify the LP Alpine garnet. In this section, we propose new criteria to distinguish the origin and/or growth stage of garnet based on grain size distribution, inclusion phases, and chemical-zoning patterns.

Chloritoid is a diagnostic mineral for Alpine HP metamorphism in the quartz-eclogite unit and other high-pressure nappes in the Dora-Maira massif (e.g., BORGHI et al., 1985). Previous works concluded that pre-Alpine metamorphism in the internal part of the Western Alps was mainly low- to medium-pressure type. The occurrence of pre-Alpine staurolite has been reported, but not of chloritoid (e.g., DESMONS et al., 1999). Therefore, we can use chloritoid inclusions as an indicator of Alpine stage metamorphism.

The unimodal garnet in the chloritoid-bearing metapelite shows a concentric bell-shape zoning of Mn (Figs 6a and 7a). Such a zoning pattern suggests that the garnet has grown during a gradual increase in temperature and maintained surface equilibrium (e.g., HOLLISTER, 1966; KRETZ, 1973). From the existence of the chloritoid inclusions, we attribute this single prograde event to the Alpine stage. Characteristics of the unimodal garnet in this study are consistent with the description of garnet in Fe-rich metapelite from this unit given by CHOPIN et al. (1991).

The chemical discontinuity observed in the large garnet from the chloritoid-bearing metapelites (Figs 6b and 7b) suggests a multi-stage growth. Chloritoid inclusion distribution indicates that only the rim developed during the HP Alpine stage. Chloritoid inclusions occur throughout the small garnet suggesting that these too, grew during the HP Alpine event. The similarity in Mn content between the small garnet and the rim of the large garnet (Fig. 8) supports the idea of their coeval growth, thus under quartz-eclogite-facies conditions during the HP Alpine stage. In one large garnet, the Ca content gradually decreases from the core towards the rim, but then sharply increases at the rim where chloritoid is present as inclusions (Fig. 6b). According to the interpretation of SANDRONE and BORGHI (1992), the Ca-rich rim could be meso-Alpine (i.e., LP Alpine stage) garnet. However, we interpret this rim as HP Alpine garnet, because of the occurrence of chloritoid.

Unfortunately, we have not found any evidence, which may help to determine the timing of the growth of the core of large garnet. There are at least two possibilities, a) during a pre-Alpine event or b) during the HP Alpine metamorphism. Following the latter option, the core of the large garnet would have grown under the blueschist- or eclogite-facies conditions of the HP Alpine stage, and then it should have been partly resorbed and grown again under the peak conditions of the quartz-eclogite unit. This idea, however, is unlikely, because the concentrically zoned unimodal garnet with chloritoid inclusions occurs in the same outcrop as the large garnet. Therefore, we favour the idea of a pre-Alpine growth for the core of large garnet.

The garnet in the albite-bearing metapelite also lacks a clear indication that it grew during the HP Alpine stage, such as the chloritoid inclusions. Only the grain size distribution and the chemical zoning are available for estimating the growth stage. A similar inference as in the chloritoid-bearing metapelite leads to the following interpretation: the unimodal garnet with Mn bell-shape zoning grew during the HP Alpine stage and the large garnet with complex zoning formed during several stages, including a possible pre-Alpine stage. The Mn-enriched rim partially developed around unimodal garnet may suggest a meso-Alpine growth as pointed out by BORGHI et al. (1985) and SANDRONE and BORGHI (1992).

In this paper, we do not adopt the variation of Ca as a criterion to distinguish the growth stages, mainly because the Ca-zoning pattern in our garnet is not systematic and some of the unimodal and the small garnets show an oscillatory pattern. The latter suggests that a disequilibrium situation was produced during the garnet growth.

Why is the multi-stage garnet so common in the Western Alps? The lower equilibrium temperature estimate at the peak of metamorphism (500–600 °C, CHOPIN et al., 1991) and the assumed short duration of the HP/UHP metamorphism (< 5 Ma, GEBAUER et al., 1997) may have prevented re-equilibration of pre-Alpine garnet. The other possible factors could be the nature of the protolith. The maximum metamorphic temperature of the Sanbagawa belt in Japan is almost identical (550–600 °C) (BANNO et al., 1986) with that of the quartz-eclogite unit. An overgrowth around a precursor garnet is also found in the metapelite from the Sanbagawa belt (HIGASHINO and TAKASU, 1982), but it is very rare. Most Sanbagawa garnet shows the Mn bell-shape zoning (BANNO et al., 1986) without evidence of an older core. This is due to the fact that the Sanbagawa schist is mainly derived from accretional sediments during Jurassic time, and most of the garnet should have grown from Mg–Fe–Mn hydrous phases, such as chlorite, during the prograde stage. On the other hand, the quartz-eclogite unit, as well as many other units from the Western Alps, is mainly derived from metamorphosed basement with garnet of Variscan or earlier age (Fig. 1).

5.2. PEAK METAMORPHIC CONDITIONS OF THE QUARTZ-ECLOGITE UNIT

CHOPIN et al. (1991) concluded that the quartz-eclogite unit recrystallized in the jadeite-quartz stability field from the Si content of phengite. However, no jadeite has been reported from the quartz-eclogite unit, and metapelite in this unit commonly contains albite porphyroblasts. In such a case, it is very difficult to determine whether the albite has been transformed from jadeite or not. There are some examples which suggest the transformation from jadeite to albite: 1) secondary coronitic aegirine (acmite) and/or amphibole developed along the grain boundary between albite and neighbouring quartz in granitic rocks (COMPAGNONI and MAFFEO, 1974; HIRAJIMA, 1983) and 2) a "felty aggregate" of albite + minor phengite + zoisite ± rare jadeite in the matrix of less deformed metapelite from the UHP unit of the Dora Maira massif (CHOPIN et al., 1991). Other possible reactions to form secondary albite are: Gln + H_2O = Ab + Chl + Act (BORGHI et al., 1985), or Pg = Ab + Ky + H_2O. However, we cannot find such textures in the metapelite (Fig. 4). Clear "porphyroblastic" albite is developed in well-foliated metapelite from the UHP unit (C. Chopin personal communication). Our observations in the quartz-eclogite unit are consistent with his observations for the UHP unit, but we did not find any trace of the transformation from jadeite to albite even in less deformed rocks (e.g., less deformed metagranitoid) of the quartz-eclogite unit.

The peak condition of the quartz-eclogite unit in the southern Dora-Maira is probably near the reaction curve, Jd + Qtz = Ab. In the northern Dora-Maira massif, the peak conditions of another quartz-eclogite unit are estimated at slightly lower pressure than the Jd + Qtz stability field (SANDRONE and BORGHI, 1992). Further mineralogical studies on less deformed lithologic units are necessary to define the maximum pressure conditions of the quartz-eclogite unit in the southern Dora-Maira massif.

6. Conclusions

Garnet in the metapelites of the quartz-eclogite unit in the southern Dora-Maira massif falls into one of two grain size distributions: unimodal or bimodal. The zoning pattern and the composition of garnets, and the inclusion distribution indicate that the unimodal garnet, the small garnet and the rim of the large garnet grew during HP Alpine stage and that the core of the large garnet is inherited from pre-Alpine metamorphic rocks. On the basis of these observations, we propose new criteria to distinguish the pre-Alpine garnet under the microscope, i.e., the unimodal garnet formed during HP Alpine stage and the bimodal garnet results from pre- and HP Alpine growth stages. Possibly a third garnet generation formed during the LP Alpine stage exists in the Dora-Maira massif, as pointed out by SANDRONE and BORGHI (1992). However, we have not found such examples during our study.

Acknowledgements

The authors are grateful to R. Compagnoni, K. Shirahata and A. Borghi for critical reading and discussions and to Callum Hetherington for polishing the English. We also express grateful thanks to C. Chopin and J. Desmons for their constructive reviewing. The results presented here are part of a collaborative project between Torino University and Kyoto University funded by the Japanese Society for the Promotion and the Ministry of Education of Japan (Grant-in-Aid Research, No. 0845454156).

References

BANNO, S., SAKAI, C. and HIGASHINO, T. (1986): Pressure-temperature trajectory of the Sanbagawa metamorphism deduced from garnet zoning. Lithos, 19, 51–63.

BORGHI, A., CADOPPI, P., PORRO, A. and Sacchi, R. (1985): Metamorphism in the north part of the Dora-Maira Massif (Cottian Alps). Boll. Mus. Reg. Sci. Nat. Torino, 3, 369–380.

CHOPIN, C. (1984): Coesite and pure pyrope in high-grade blueschists of the western Alps: A first record and some consequences. Contrib. Mineral. Petrol., 86, 107–118.

CHOPIN, C., HENRY, C. and MICHARD, A. (1991): Geology and petrology of the coesite-bearing terrain, Dora-Maira massif, Western Alps. Eur. J. Mineral., 3, 263–291.

COMPAGNONI, R. and MAFFEO, B. (1974): Jadeite-bearing metagranites and related rocks in the Monte Mucrone area (Sesia-Lanzo zone, Western Alps). Schweiz. Mineral. Petrogr. Mitt., 53, 355–378.

COMPAGNONI, R., HIRAJIMA, T. and CHOPIN, C. (1995): Ultra-High-Pressure Metamorphic Rocks in the Western Alps. In: COLEMAN, R.G. and WANG, X. (eds): Ultrahigh Pressure Metamorphism, 206–243, Cambridge Univ. Press.

DESMONS, J. (1992): The Briançon basement (Pennine Western Alps): Mineral composition and polymetamorphic evolution. Schweiz. Mineral. Petrogr. Mitt., 72, 37–55.

DESMONS, J. and GHENT, E.D. (1977): Chemistry, zonation and distribution coefficient of elements in eclogitic minerals for the eastern Sesia unit, Italian western Alps. Schweiz. Mineral. Petrogr. Mitt., 57, 397–411.

DESMONS, J., COMPAGNONI, R., CORTESOGNO, L., FREY, M. and GAGGERO, L. (1999): Pre-Alpine metamorphism of the internal zones of the Western Alps. Schweiz. Mineral. Petrogr. Mitt., 79, 23–39.

GEBAUER, D., SCHERTL, H.P., BRIX, M. and SCHREYER, W. (1997): 35 Ma old ultrahigh-pressure metamorphism in the Dora-Maira Massif, Western Alps. Lithos, 41, 5–24.

GHENT, E.D. (1986): A review of chemical zoning in eclogite garnets. Eclogite and eclogite-facies rocks. Amsterdam: Elsevier, 207–236.

HIGASHINO, T. and TAKASU, A. (1982): Notes on petrography and rock-forming mineralogy (13), Detrital garnets from pelitic Sanbagawa schists in the Bessi area, central Shikoku. J. Japan. Assoc. Min. Petr. Econ. Geol., 77, 362–367.

HIRAJIMA, T. (1983): Jadeite + quartz rock from the Kanto Mountains. J. Japan. Assoc. Min. Petr. Econ. Geol., 78, 77–83.

HIRAJIMA, T. and BANNO, S. (1991): Electron-microprobe analysis of rock forming minerals with Kevex-delta IV (Quantum detector). Hitachi Sci. Instr. News, 34, 1118–1134 (J).

HOLLISTER, L.S. (1966): Garnet zoning: an interpretation based on the Rayleigh-fractionation model. Science, 154, 1647–1651.

KRETZ, R. (1973): Kinetics of the crystallization of garnet at two localities near Yellowknife. Canad. Mineral., 12, 1–20.

MICHARD, A., HENRY, C. and CHOPIN, C. (1995): Structures in UHPM Rocks: A Case Study from the Alps. In: COLEMAN, R.G. and WANG, X. (eds): Ultrahigh Pressure Metamorphism, 132–158, Cambridge Univ. Press.

MORI, T. and KANEHIRA, K. (1984): X-ray energy spectrometry for electron-probe analysis. J. Geol. Soc. Japan, 90, 271–285.

SANDRONE, R. and BORGHI, A. (1992): Zoned garnet in the northern Dora-Maira Massif and the contribution to a reconstruction of the regional metamorphic evolution. Eur. J. Mineral., 4, 465–474.

SPEAR, F.S. (1993): Metamorphic Phase Equilibria and Pressure-Temperature-Time Paths. Mineral. Soc. Amer. Monograph, Washington, D.C.

TRACY, R.J. (1982): Compositional zoning and inclusions in metamorphic minerals. In: FERRY, J.M. (ed.): Characterization of metamorphism through mineral equilibria. Reviews in Mineralogy, 10, 355–397.

TRACY, R.J. (1994): Rocks and minerals; Metamorphic petrology. Geotimes, 39, 31–32.

TRACY, R.J., ROBINSON, P. and THOMPSON, A.B. (1976): Garnet composition and zoning in the determination of temperature and pressure of metamorphism, central Massachusetts. Amer. Mineralogist, 61, 762–775.

YARDLEY, B.W.D. (1977): An empirical study of diffusion in garnet. Amer. Mineralogist, 62, 793–800.

Manuscript received August 17, 1999; revision accepted January 15, 2000.