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A DETAILED STUDY OF MORPHOLOGY AND CHEMISTRY OF GARNET CRYSTALS WITH SUGGESTION OF NEW SUBDIVISIONS: DATA FROM PELITIC SCHISTS, HORNFELSES AND APLITES OF HAMEDAN REGION, IRAN*

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Abstract – The study area is a part of the Sanandaj-Sirjan metamorphic belt comprising low- to high-grade regional and contact metamorphic rocks that are intruded by various plutonic bodies. Garnet crystals are abundant in pelitic schists, amphibole schists, migmatites, hornfelses and aplites. They are mostly almandine-rich (X_{Alm}>60) pyralspite garnets and show dodecahedron, trapezohedron and mixed (dodecahedron-trapezohedron) forms. Garnets in pelitic schists have different forms, but in hornfelses and aplites they have a mostly trapezohedron form. Sometimes, in some layers adjacent to each other that have experienced equal pressure and temperature, observed crystal forms are various, which may be due to the changes in the chemical composition of the mineral and its host rock. Absolute temperature may not be so important for form variations but temperature gradients during crystal growth may have affected the crystal forms. In more rapid temperature gradients the trapezohedron form is more common, but in slow gradients the dodecahedron form is more common. Mn-rich/Ca-poor crystals have a pure trapezohedron form; Mn-poor/Ca-rich crystals have a dodecahedron form and others have mixed forms.

Keywords – Morphology, chemistry, garnet crystals, dodecahedron, trapezohedron

1. INTRODUCTION

Garnet crystallizes in the cubic system and mostly in dodecahedron (rhomb-dodecahedron) and trapezohedron (tetragon-trioctahedron) crystal forms. The general chemical formula of this mineral is: $R_3R'_2(SiO_4)_3$. Bivaliant cations (i.e., Mg^{2+}, Fe^{2+}, Mn^{2+}, Ca^{2+}) occur in the R site and trivaliant cations (i.e. Al^{3+}, Cr^{3+}, Fe^{3+}) in the R' site. Commonly, more than one cation lies in R and R' sites and therefore garnet crystals give rise to an isomorphous (solid solution) series of minerals. If Al^{3+} is located in the R' site, the pyralspite group $[(Fe^{2+}, Mg^{2+}, Mn^{2+})_3 Al_2(SiO_4)_3]$ with almandine $[(Fe^{2+})_3 Al_2 (SiO_4)_3]$, pyrope $[(Mg^{2+})_3Al_2 (SiO_4)_3]$ and spessartine $[(Mn^{2+})_3Al_2(SiO_4)_3]$ end members will form. If Ca^{2+} is located in the R site, the ugrandite group $[(Ca^{2+})_3(Al^{3+},Fe^{3+},Cr^{3+})_2(SiO_4)_3]$ with grossularite $[Ca_3Al_2(SiO_4)_3]$, andradite $[Ca_3(Fe^{3+})_2(SiO_4)_3]$ and uvarovite $[Ca_3(Cr^{3+})_2(SiO_4)_3]$ end members will form. Some other cations may also be emplaced in R and R' sites (according to [1 and 2]).

Kostov [3] has discovered that there is a relationship between the garnet chemistry, the ratio of the bivaliant/trivaliant cationic radii, and the size of unit cells. In this model pyralspite garnets show a trapezohedron form, grossularite has a dodecahedron form, and andradite appears in mixed form between these two forms. The R^{2+}/R^{3+} ratio is largest in grossular crystals; the unit cell size is largest in andradite crystals; and pyralspite garnets have the smallest R^{2+}/R^{3+} ratio and unit cell size. Kostov [3] shows that pyralspite garnets (i.e., almandine) may have dodecahedron and mixed form (dodecahedron-

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trapezohedron) as well as trapezohedron form.

The morphology of crystals depends on many factors such as crystal structure, chemical composition, temperature and pressure [4].

Vance and Holland [5] concluded that the P-T condition of a metamorphic enviroment is an essential factor for the determination of active cations and therefore changes in garnet crystal forms. However, in this study, it has been found that the effect of absolute amount of P-T may not be so important on crystal form variations.

Theory and observations about the morphology of synthetic and natural garnets have been studied by Cherepanova et al. [6]. Boutz and Woensdregt [7] and Van Haren and Woensdregt [8] have studied the theoretical growth of natural garnets and their form variations.

2. GEOLOGICAL SETTING

The study area is a part of the Sanandaj-Sirjan metamorphic belt which is composed of low- to high-grade regional (orogenic) and thermal (contact) metamorphic rocks that are intruded by felsic, intermediate and mafic plutonic bodies. The metamorphic sequence comprises pelitic, psammitic, mafic, calc-pelitic and calc-silicate rocks. Pelitic rocks are the most abundant lithologies. The pelitic sequence is mostly made up of slates, phillites, micaschists, garnet schists, garnet andalusite (± sillimanite, ± kyanite) schists, garnet staurolite schists, mica hornfelses, garnet hornfelses, garnet andalusite (± fibrolite) hornfelses, cordierite (± andalusite) hornfelses, cordierite K-feldspar hornfelses and sillimanite K-feldspar hornfelses. Major plutonic rocks of this area are granitoids, diorites and gabbroids, which are intruded by aplite-pegmatitic and silicic veins (Fig. 1). Both metamorphism and plutonism of the region have occurred in Cretaceous time [9-11].

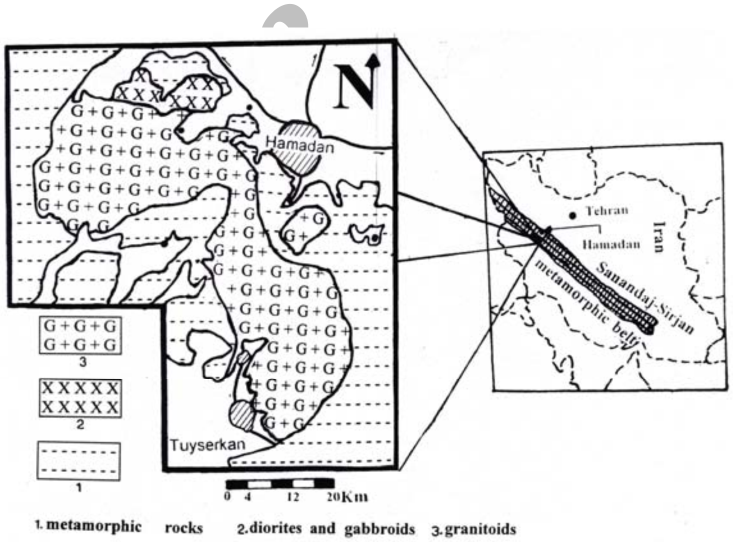

Fig. 1. The generalized geological map of the study area

3. METHOD OF STUDY AND ANALYTICAL PROCEDURES

The mineral chemistry of some garnets of the study area has been determined by other investigators [9, 10 and 12]. Reported analyses in these studies are mainly on mixed forms because these forms are widespread in pelitic schists and migmatites of the studied area. They are all from almandine-rich pyralspite garnets.

The dimensions of the studied garnet crystals range from a few millimeters to a few centimeters, and the garnets are easily separated from the host rock in the field and laboratory. Because of their idiomorphic (euhedral) shape, the number of crystal faces in single crystals and their crystal forms can easily be determined.

Some separated garnet crystals were analyzed the XRF method at the Kanpazhouh Geological and Mineralogical Company, Tehran, Iran. Other crystals were analyzed by microprobe at the University of Minnesota, USA, in order to determine the relationships between the crystal forms of the garnets and their chemical compositions.

4. COMMON GARNET-BEARING ROCK TYPES

In various metamorphic and igneous rocks in the studied area garnet occurs as major, minor or accessory minerals. The major garnet-bearing rocks are as follows:

-*Garnet mica schists:* These rocks are medium- to coarse-grained with a shiny black color. Their common texture is porphyrolepidoblastic with a usual crenulation cleavage. They are composed of quartz, biotite, garnet (up to 10 mm in diameter), muscovite, chlorite, with accessory plagioclase, graphite, tourmaline, apatite, calcite and iron oxides. Common porphyroblasts are garnet (almandine-rich, Fig. 2), muscovite and chlorite. Garnets have been locally chloritized, and have pressure shadows around some crystals. Garnet crystals have complex relationships to deformation; i.e., they are pre-, syn- and post-tectonic. Their common crystal forms are dodecahedron and mixed forms without any crystals having trapezohedron form.

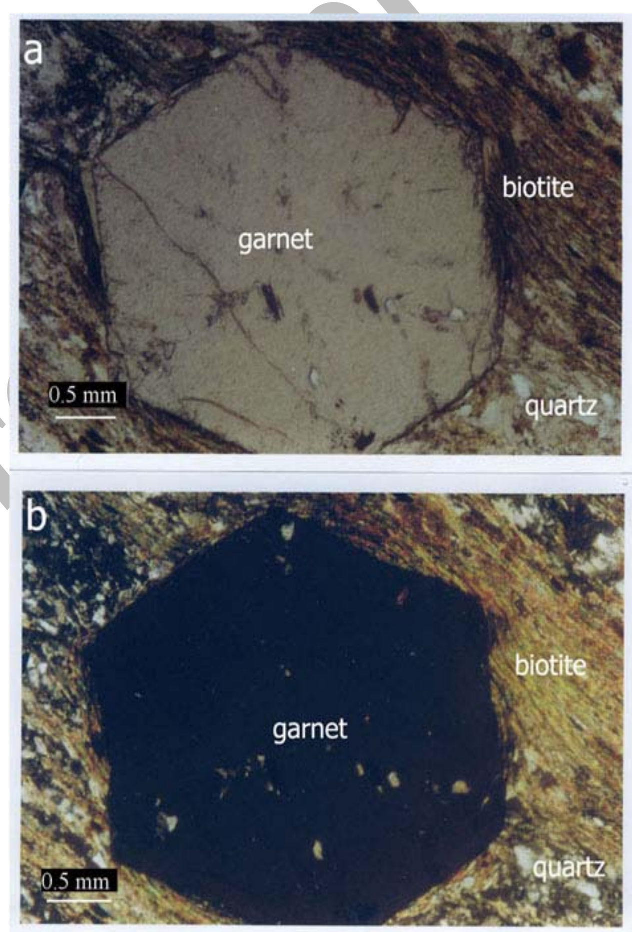

Fig. 2. Photomicrograph of an euhedral garnet crystal in a garnet micaschist sample

-*Garnet andalusite schists:* These rocks are medium- to coarsed-grained with a common lepidoporphyroblastic texture. Their common minerals are quartz, biotite, andalusite, garnet, muscovite and minor graphite, chlorite, plagioclase, tourmaline, apatite and iron oxides. Their usual porphyroblasts are pink to white andalusite (chiastolite) ranging up to 20 cm long, garnet and muscovite. Andalusite porphyroblasts are heavily sericitzed in some places (near faults and veins) and gradually change to sillimanite. Andalusite porphyroblasts are mostly pre-tectonic to syn-tectonic. Some staurolites occur in andalusite schists, especially near veins. Garnet crystals are fine grained (up to 5mm) with common mixed crystal forms.

-*Garnet staurolite schists:* These rocks are composed of quartz, staurolite, garnet, biotite, muscovite, chlorite, plagioclase, graphite and tourmaline. Their common texture is lepidoporphyroblastic with porphyroblasts of garnet, staurolite (up to 15 cm long), muscovite and chlorite. Staurolite porphyroblasts have been chloritized and sericitized near fault zones, veins and intrusive bodies, and many have euhedral garnet inclusions in both fresh and sericitized examples. Staurolite porphyroblasts are pre-, syn- to post-tectonic, but chlorite and muscovite porphyroblasts commonly are post-tectonic. Garnet crystals are fine grained (up to 5mm) and have mixed crystal forms.

-*Garnet sillimanite schists:* Sillimanite schists contain quartz, sillimanite (+/- andalusite, kyanite and staurolite), biotite, muscovite, garnet, plagioclase, potassium feldspar (perthitic orthoclase) and opaque minerals. Garnet crystals range up to 10 mm in these rocks and commonly have mixed forms. Sillimanite schists gradually change to migmatites with similar melanosome mineralogy.

-*Garnet amphibole schists*: These rocks contain quartz, amphibole (hornblende) and garnet, with minor amounts of clinozoisite and calcite. Garnet crystals range up to 5 mm and have pure dodecahedron forms. Garnet occurs both as porphyroblasts and as inclusions inside amphiboles (both with the same crystal forms).

-*Migmatites:* These rocks have interesting mineralogy, texture and structure. They are a sequence of metatexite-diatexite rocks with various structures such as stromatic, schollen, schlieric and massive. The melanosome mineralogy of most metatexites is very similar to high grade garnet sillimanite(+/- andalusite and kyanite) schists, but cordierite-bearing interlayers also occur. Both mesosome and leucosome layers have garnet crystals with mixed forms. The typical mineral assemblage of a melanosome is quartz, biotite, andalusite/sillimanite/kyanite (+/- cordierite), garnet, staurolite, spinel and graphite, and a leucosome is quartz, plagioclase (in some places orthoclase), mucovite and minor garnet and tourmaline.

-*Hornfelses:* Adjacent to plutonic bodies (<1000 m) different types of hornfelses (mostly pelitic but rarely mafic) occur. Three important types of hornfelses are:

Cordierite (+/- andalusite, and garnet) hornfelses with porphyrogranoblastic textures containing quartz, biotite, muscovite, cordierite (+/- andalusite), plagioclase, garnet, tourmaline and opaque minerals.

-Cordierite-feldspar (+/- garnet) hornfelses (in close contact with granitoids) containing minerals such as the previous hornfels type with perthitic orthoclase as a common mineral.

-Sillimanite-feldspar hornfelses (in close contact with gabbros) containing quartz, biotite, muscovite, sillimanite, plagioclase, orthoclase, garnet and opaque minerals. Garnet that occurs in hornfelses commonly has trapezohedron crystal forms, but some mixed forms also occur (without pure dodecahedron form).

-*Garnet-bearing aplites-pegmatites and granitic rocks:* In S-type granites and some aplitic-pegmatites garnet commonly occurs as a minor mineral. Garnets in aplitic-pegmatitic rocks commonly have pure trapezohedron form (Fig. 3), but garnets in granitic bodies have been mostly altered and pseudomorphed by chlorite and biotite, and only trapezohedron faces are visible in some crystals.

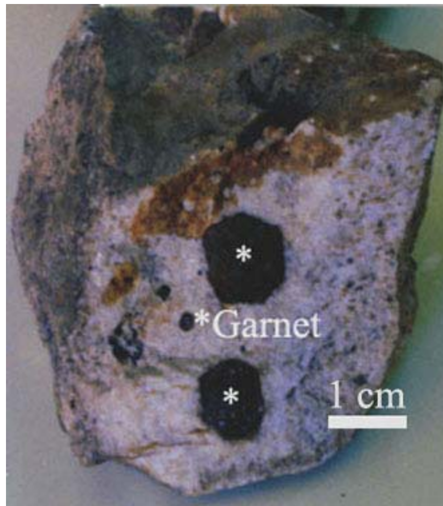

Fig. 3. Handspecimen photograph of a garnet-bearing aplite from the study area

In Table 1, common garnet-bearing rocks and the observed crystal forms of garnets in each rock type have been summarized.

Table 1. Common garnet-bearing rock types of the region and the observed forms in their garnet crystals. ddk=dodecahedron and tpz=trapezohedron

Common garnet-bearing rock types		**Observed garnet crystal forms**
Regional metamorphic rocks and migmatites	Garnet-mica-schist	Mostly ddk/some mixed
	Garnet-andalusite-schist	Mostly mixed
	Garnet-andalusite-sillimanite-schist	Mostly mixed
	Garnet-staurolite- schist	Mostly mixed
	Garnet-amphibole-schist	ddk
	Melanosome of migmatite	Mixed
	Leucosome of migmatite	Mixed
Contact metamorphic rocks	Garnet- cordierite- hornfels	Mostly tpz/some mixed
	Garnet-sillimanite- hornfels	Mostly tpz/somemixed
	Garnetite	tpz
Felsic plutonic rocks and dykes	Granites	Mixed
	Aplites	tpz
	Pegmatites	tpz/mixed

5. DISCUSSION

In hornfelses and aplites, the garnet crystals have only trapezohedron (icositetrahedron) form, but in pelitic schists they show both dodecahedron and mixed forms. In some crystals, rhombic faces are more clear than trapezohedron faces, but in some other crystals, trapezohedron faces are better developed than rhombic faces. On the other hand, some crystals have two types of faces that are nearly equally developed. In fact, variations between pure dodecahedron and trapezohedron forms are gradational, but for simplicity the garnet forms were divided into 3 types and one form into 3 subtypes:

1- Pure dodecahedron form with 12 rhombic faces

2- Pure trapezohedron (icositetrahedron) form with 24 trapezohedron faces

3- Mixed forms:

3-1- Mature mixed form with 12 rhombic and 24 trapezohedron faces (36 faces)

3-2- Impure dodecahedron with 12 rhombic and 1-23 trapezohedron faces (13-35 faces)

3-3- Impure trapezohedron with 24 trapezohedron and 1-11 rhombic faces (25-35 faces).

All garnet crystals belong to the pyralspite group of garnets, and are almandine rich (Tables 2, 3 and 4). Crystal forms of garnets in relation to their chemical compositions and the P-T conditions of the metamorphic host rocks were examined. With increasing CaO and decreasing MnO amounts in garnets, it was found that the garnet crystal-forms change toward pure dodecahedron form (Table 2/G-1), but with increasing MnO and decreasing CaO, garnet crystals having a pure trapezohedron form are common (Table 2/G-6, P-1, P-3, P-5, P-7, Gt1-5, Gap samples). Garnets with intermediate amounts of CaO and MnO have composite (mixed) crystal forms (Table 2/G-4 sample). The amount of MgO has little effect on the types of crystal forms in the garnets. Generally, the almandine crystals with decreasing amounts of Mn^{2+} or Mn/Ca and (Mn +Mg)/Ca) ratios, and with increasing Ca^{2+} and Ca/Mn or (Ca/(Mn+Mg)) ratios, have forms that change from trapezohedron to dodecahedron.

Although Kostov [3] emphasizes that pyralspite garnets (such as almandine-rich garnets) show trapezohedron form, several different forms in the almandine-rich garnets of the study area have been determined by the author.

However, the garnet crystal forms are partly related to their chemical compositions so that more calcic (grossular-rich) almandines such as the G-1 sample in Table 2, show dodecahedron form. These crystals have the greatest $X_{Grs}/ (X_{Alm}+X_{Sps})$ ratio; i.e., with decreasing of (Fe^{2+} + Mn^{2+}) and increasing Ca^{2+} cations in almandine, its form may change from trapezohedron to dodecahedron. The spessartine-rich and grossular-poor almandines, such as Gap in Table 2, have pure trapezohedron form. The amount of Mg^{2+} has little effect on the garnet crystal form so that garnets with chemical compositions between these two extereme cases have mixed dodecahedron-trapezohedron forms (Tables 2 , 3 and 4).

In zoned samples (Fig. 4) the compositions of cores for our interpretations were used because the crystal form depends on, and would be controlled by, its earlier nuclear shape rather than its later rim shape.

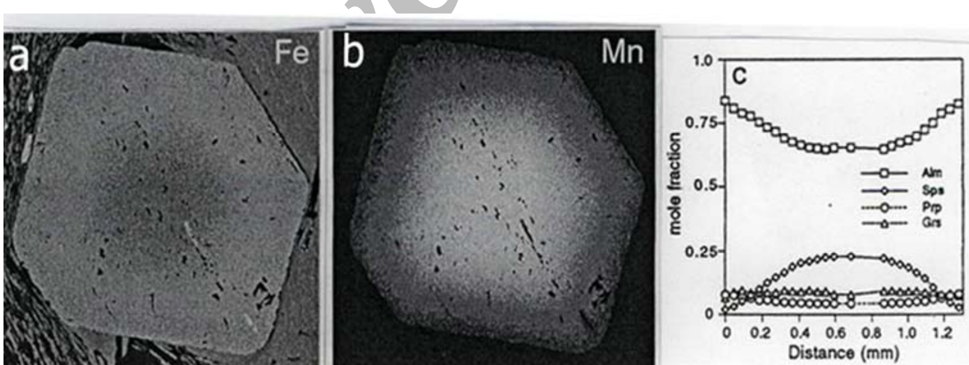

Fig. 4. Garnet X-ray maps showing intense zoning in a garnet crystal. a) X-ray map of Fe zoning b) X-ray map of Mn zoning c) Changes in mole fraction of garnet end members through a traverse from upper right to lower left of the grain [12]

The metamorphic reactions and thermobarometric studies of metamorphic rocks have shown that garnet mica schists are formed at 4.3 ± 0.5 Kbar and 568-586 °C and garnet hornfelses at 2.5 ± 0.1 Kbar and 539-569 °C [9], but these pelitic schists and hornfelses, in many places, have garnets with similar crystal forms (G-6, P-1, P-3, P-5, P-7, Gt1-2 in schists and Gt3-5 in hornfelses, Table 2). Thus, contrary to Vance and Holland [5], P-T changes have little effect on the form changes of the studied garnets. On the other hand, different forms of garnet crystals in adjacent layers of the metamorphic rocks have been seen. It is apparent that during metamorphism, the P-T conditions are approximately constant at very small scales, but chemical compositions of rocks, and therefore minerals, may be variable. Therefore, form changes are attributed to the chemical variations of the garnet crystals and their host rock. However, the trapezohedron form is more common in rocks that experienced more rapid temperature gradients, such as in hornfelses and aplites, and the dodecahedron form is more common in pelitic schists that experienced slower temperature gradients. So, despite the absolute degree of temperature, the temperature gradients may be important for variations in crystal forms.

Table 2. Chemical analyses (wt%) and garnet end members of some of the studied crystals

Samples/ Oxides	G-1#	G-4#	G-6#	P-1#	P-3#	P-5#	P-7#	Gt1*	Gt2*	Gt3*	Gt4*	Gt5*	Gap
SiO_2	36.42	36.56	37.69	37.91	37.72	39.16	38.80	36.82	41.82	51.49	55.22	40.22	35.87
Al_2O_3	20.99	20.82	20.54	20.65	20.73	20.10	20.34	20.01	18.89	19.00	19.68	19.03	20.63
Fe_2O_3	3.11	3.25	3.55	3.51	3.48	3.40	3.47	5.48	4.73	3.00	3.58	4.04	3.45
FeO	28.03	29.27	31.91	31.23	31.36	30.58	31.18	26.90	26.99	19.32	14.86	23.43	32.43
MnO	9.27	8.10	6.19	5.08	5.07	5.18	5.17	5.89	3.12	3.71	2.67	9.35	5.13
MgO	1.68	1.88	1.45	2.21	2.20	1.85	1.88	1.60	2.02	1.97	2.25	1.72	0.81
CaO	3.05	2.88	1.51	1.90	1.88	1.78	1.66	1.99	1.55	0.88	0.99	1.08	0.37
TiO_2	Nd	nd	nd	0.08	0.08	0.07	0.08	0.10	0.30	0.60	0.71	0.43	0.16
Total	102.55	102.56	102.84	102.57	102.52	102.75	102.58	98.79	99.42	99.97	99.96	99.30	98.86
weight percent of the garnet end members													
Almandine	63	66	75	73	73	74	74	73	77	70	65	65	84
Spessartine	21	18	14	12	12	13	13	14	8	14	12	23	12
Pyrope	7	8	6	9	9	8	8	7	9	13	17	7	3
Grossular	9	8	5	6	6	5	5	6	5	4	6	3	1
Crystal form	d	m	m	m	m	m	m	m	m	t	t	t	t
Host rock	gsch[1]	gsch	gasch[2]	gasch	gasch	gasch	gasch	gsch	gsch	hfs[3]	hfs	hfs	ap[4]

nd=not detected, d=pure dodecahedron, m=mixed dodecahedron and trapezohedron forms, t=trapezohedron, 1=garnet schist, 2=garnet andalusite schist, 3=garnet andalusite(± fibrolite) hornfels, 4= garnet aplite. # = data from [13], * = data from [14].

Table 3. Microprobe analyses of 3 garnet crystals with mixed forms (data from [9])

Samples/ Oxides (wt%)	2Gt-1		2Gt-2		2Gt-3
	Core	Rim	Core	Rim	
SiO_2	36.94	37.12	36.59	36.66	36.81
TiO_2	0.36	0.03	0.00	0.02	0.02
Al_2O_3	21.13	20.07	20.99	21.16	21.11
Cr_2O_3	0.04	0.07	0.00	0.00	0.00
Fe_2O3	0.00	0.00	0.00	0.16	0.00
FeO	30.76	32.49	28.96	36.12	36.66
MnO	7.14	5.53	9.39	1.59	2.26
MgO	2.11	2.14	1.23	6.19	2.53
CaO	1.82	1.80	2.22	2.26	0.62
Total	100.29	100.26	99.38	100.16	100.02
Garnet end members					
Uvarovite	0.12	0.23	0.02	0.00	0.00
Andradite	0.00	0.00	0.00	0.44	0.00
Pyrope	8.51	8.65	5.02	8.91	10.23
Spessartine	16.41	12.66	21.86	3.67	2.20
Grossular	5.19	4.98	6.53	6.12	1.81
Almandine	69.78	73.48	66.56	80.82	82.76

Table 4. electron microprobe analyses of some garnets with mixed forms in various host rocks of the study area [12]

Sample	G-gs		G-gas		G-gsts		G-gsis	
Oxides/ cations	core	rim	core	rim	core	rim	core	rim
SiO_2	37.23	37.25	37.38	37.36	37.36	37.30	37.33	37.43
TiO_2	0.06	0.03	--	0.01	0.04	0.02	0.01	--
Al_2O_3	21.04	21.07	20.89	21.19	21.24	21.21	20.95	21.12
FeO	27.93	36.18	21.29	34.36	31.61	34.31	31.10	34.66
MnO	9.56	1.12	5.44	4.39	7.38	4.65	6.15	2.79
MgO	1.00	1.95	2.38	1.80	2.22	2.33	2.76	2.68
CaO	2.81	2.42	1.38	1.01	0.82	0.64	1.74	1.88
Total	99.64	100.02	99.76	100.12	100.67	100.47	100.04	100.56
Number of cations on the basis of 12 Oxygens								
Si	3.02	3.01	3.02	3.02	3.00	3.01	3.01	3.00
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al	2.01	2.01	1.99	2.02	2.01	2.01	1.99	2.00
Fe	1.90	2.45	2.18	2.32	2.13	2.31	2.10	2.33
Mn	0.66	0.08	0.37	0.30	0.50	0.32	0.42	0.19
Mg	0.12	0.23	0.29	0.22	0.27	0.28	0.33	0.32
Ca	0.24	0.21	0.12	0.09	0.07	0.06	0.15	0.16
Amounts of garnet end members								
X_{Alm}	0.65	0.82	0.74	0.79	0.72	0.78	0.70	0.78
X_{Sps}	0.23	0.03	0.13	0.10	0.17	0.11	0.14	0.06
X_{Prp}	0.04	0.08	0.10	0.07	0.09	0.09	0.11	0.11
X_{Grs}	0.08	0.07	0.04	0.03	0.02	0.02	0.05	0.05

G-gs=garnet from garnet schist, G-gas=garnet from garnet andalusite schist, G-gsts=garnet from garnet staurolite schist, G-gsis=garnet from garnet sillimanite schist

6. CONCLUSIONS

The morphological and chemical studies on the garnet crystals of metamorphic rocks and aplites of the study area indicate that:

1. Pyralspite group garnets (such as almandine-rich garnets) may have various forms (i.e., dodecahedron, trapezohedron and dodecahedron-trapezohedron mixed forms with changing amounts of CaO and MnO). Almandine-rich garnets with small ratios of $X_{Grs}/(X_{Sps}+X_{Prp})$ have pure trapezohedron form; those with high $X_{Grs}/(X_{Sps}+X_{Prp})$ have pure dodecahedron form; and others with medium ratios of $X_{Grs}/(X_{Sps}+X_{Prp})$ have mixed dodecahedron-trapezohedron forms.
2. The crystal-form changes in the garnets are most probably due to variations in the chemical compositions of the crystals and their host rock, and the P-T conditions may have little effect on the crystal-form changes.
3. Despite the minimal effect of absolute temperature on the crystal morphology of studied garnets, the temperature gradient may be essential in relation to crystal morphologies so that most garnet crystals in hornfelses and aplites have trapezohedron form rather than dodecahedron form. The dodecahedron form may be produced under conditions that have slow temperature gradients (in schists and migmatites), but the trapezohedron is produced during rapid temperature gradients.

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