Finding of Vanadium-Bearing Garnet from the Sør Rondane Mountains, East Antarctica

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東南極，セールロンダーネ山地からバナジウム含有ザクロ石の発見

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要旨：東南極，セールロンダーネ山地中央部地域のメーニパ山塊において，バナジウムを含む緑色のガーネットが発見された．これらのガーネットは，グラニュライト相変成作用を受けた含グラファイト石灰質メタペライトの主要構成鉱物として出現し，次の3種類の産状をしめす．i) 大斑状変晶（タイプ-1），ii) タイプ-1 ガーネットを取り囲むケリファイト縁中の細粒結晶（タイプ-2），iii) 基質部の細粒斑状変晶（タイプ-3）．

これら3タイプの含バナジウムガーネットは，化学組成上異なる特徴をしめす．V^{3+}, Cr^{3+}, Fe^{3+} 含有量はタイプ-1, 2, 3 の順に増加し，これに伴いガーネットの緑色も強まる．しかし，Cr_2O_3/V_2O_3 と Fe_2O_3/V_2O_3 は一定である．従って，含バナジウムガーネット中の3価の陽イオンの置換関係は $4V^{3+}$, $(Cr^{3+}, Fe^{3+}) \rightleftharpoons 5Al^{3+}$ とみなせる．

本報告ではセールロンダーネ山地で発見された，含バナジウムガーネットの産状と化学組成の特徴をのべる．また，これらのガーネットの物理的特性についても検討する．

Abstract: Vanadium-bearing green garnets have been found in the Menipa mountain mass, central part of the Sør Rondane Mountains, East Antarctica. These garnets are the main constituent minerals of granulite-facies metamorphosed graphite-bearing calcareous metapelite. They show three types of mode of occurrence as follows; i) large porphyroblast (type-1), ii) fine crystal (type-2) in kelyphite rim around type-1 garnet, and iii) fine-grained porphyroblast (type-3) in matrix.

These three types of vanadium-bearing garnets exhibit distinct characters in chemical compositions. The V^{3+}, Cr^{3+} and Fe^{3+} contents in these garnets increase from type-1 to type-3 through type-2 with increasing consistency of green color, while the Cr_2O_3/V_2O_3 and Fe_2O_3/V_2O_3 ratios are constant. Therefore, the form of cation substitution in vanadium-bearing garnets is shown as $4V^{3+}$, $(Cr^{3+}, Fe^{3+}) \rightleftharpoons 5Al^{3+}$.

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Modes of occurrence and chemical characteristics of vanadium-bearing green garnets are described here, and physical properties of these garnets are also examined.

1. Introduction

During the geological field survey in 1990 as part of the 31st Japanese Antarctic Research Expedition (JARE-31), the gem-quality emerald-green vanadium-bearing grossular and goldmanite have been found in the Menipa mountain mass, central part of the Sør Rondane Mountains, East Antarctica.

The Sør Rondane Mountains, located at 22° to 28°E longitude and 71.5° to 72.5°S latitude, consists mainly of Proterozoic high- and medium-grade metamorphic rocks and various kinds of intrusive plutonic rocks. The vanadium-bearing grossular and goldmanite, which are extremely rich in V_2O_3 (up to 21 wt%), are found in granulite-facies metamorphosed calcareous metapelite from the Menipa mountain mass. The

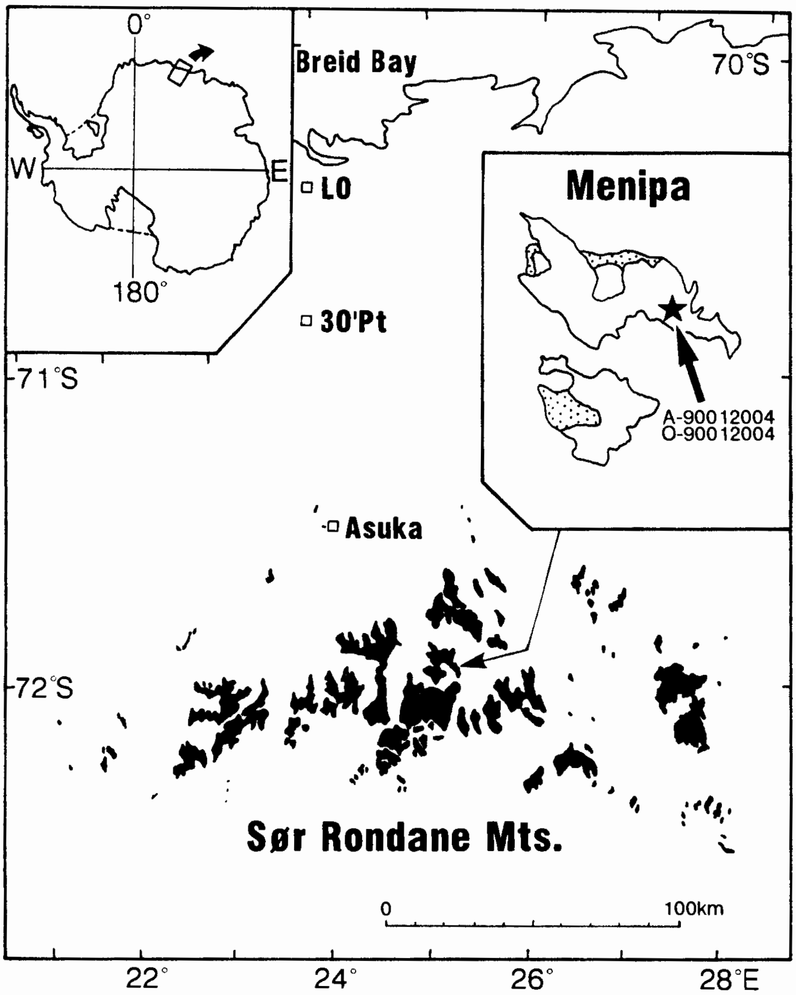

Fig. 1. Map indicates location of the Sør Rondane Mountains. Inset shows the locality of vanadium-bearing garnet (solid star) in the Menipa mountain mass. Dotted areas show the moraine field. General geology of the Menipa should be referred to ISHIZUKA *and* KOJIMA *(1987).*

outcrop of this metapelite is situated 60 km to the south of the Japanese 3rd station "Asuka" (Fig. 1).

This is the report of the first finding of vanadium-bearing garnets from Antarctica. We will describe the mode of occurrence and mineralogical characters of these garnets.

2. Geological Outline

The green garnet-bearing calcareous metapelite (A-90012004 and O-90012004) was found in the central area of the Menipa mountain mass, central part of the Sør Rondane Mountains (Fig. 1).

The metamorphic rocks in the Sør Rondane Mountains are divided into two groups, namely, the Teltet-Vengen group in the north trending WNW-ESE and the Nils Larsen-fjellet group in the south with E-W strike (VAN AUTENBOER, 1969; VAN AUTENBOER and LOY, 1972). The boundary between the two groups is an E-W trending large shear zone, named Main Shear Zone (MSZ: KOJIMA and SHIRAISHI, 1986). The Menipa mountain mass belongs to the southern end of the Teltet-Vengen group (ISHIZUKA and KOJIMA, 1987).

The Menipa mountain mass consists of garnet-biotite-hornblende gneiss, garnet-biotite-sillimanite gneiss and hornblende-biotite gneiss, with thin intercalations of marble, calc-silicate gneiss and calcareous metapelite. Partly, the metamorphic rocks, which have been extensively mylonitized in WNW-ESE trending with right-lateral strike-slip sense, are intruded by younger granite and pegmatite (SAKIYAMA *et al.*, 1988).

Vanadium-bearing green garnets are found only in the calcareous metapelites occurring as layers about 5–10 m thick, which are intercalated within garnet-hornblende-biotite gneiss and hornblende-biotite gneiss.

3. Petrography

The green garnet-bearing calcareous metapelite consists mainly of garnet, vanadian-clinopyroxene (Di: 54.0–75.0 mol%), plagioclase (An: 96.5–98.5 mol%) and quartz with subordinate amounts of vanadian-zoisite, vanadian-sphene and graphite. Minor mineral constituents are calcite, pyrrohtite, vanadian-magnetite and apatite. Clinopyroxene and plagioclase were replaced by secondary vanadian-actinolite and muscovite, respectively.

The garnets, which are completely isotropic, show three modes of occurrence as follows;

(i) large porphyroblast (type-1), (ii) fine crystal (type-2) in symplectic intergrowth with plagioclase, quartz and clinopyroxene in kelyphite rim around type-1 garnet porphyroblast, and (iii) fine-grained porphyroblast (type-3) occurring in the outer zone of kelyphite rim (matrix).

The large garnet porphyroblast (type-1) occurs as euhedral to subhedral single crystals, 0.5–20 cm in diameter, and shows color zoning from pale green (core) to deep green (rim) in hand specimen (Fig. 2) although colorless in thin section (Fig. 2). It has no inclusions and partly shows transparent gem-quality. The type-1 garnet porphyroblasts are usually surrounded by 1–10 mm thick kelyphite rim. The kelyphite rim consists of symplectic intergrowth of garnet (type-2), plagioclase, quartz, clino-

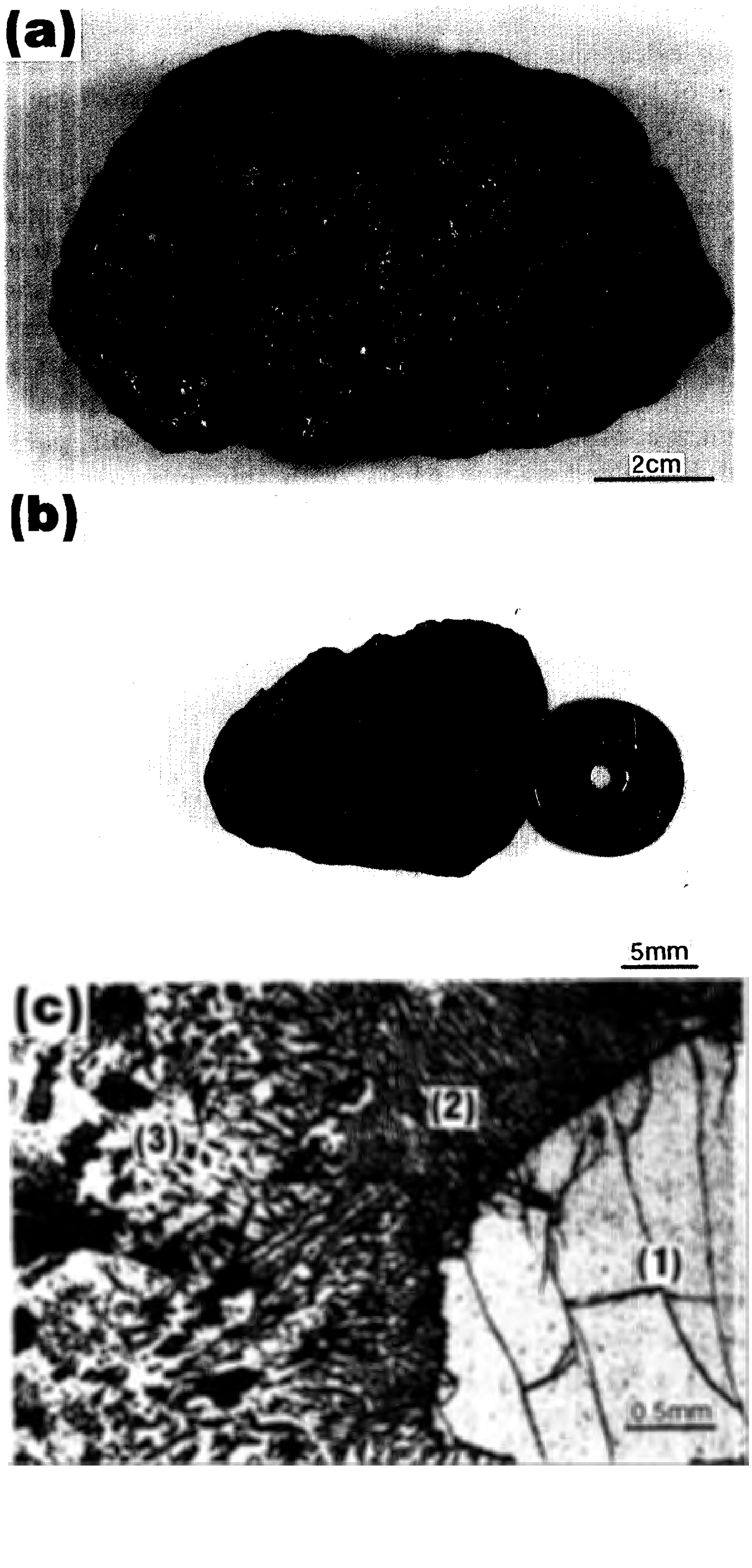

Fig. 2.
(*a*) *Large porphyroblast of type-1 garnet. Note the color zoning is observed from core to rim.*
(*b*) *Type-1 garnet porphyroblast is surrounded by kelyphite rim* (*brownish part*).
(*c*) *Modes of occurrence of type-1 porphyroblastic garnet* (*1*), *kelyphite rim* (*2*) *and outer zone of kelyphite rim* (*3*).

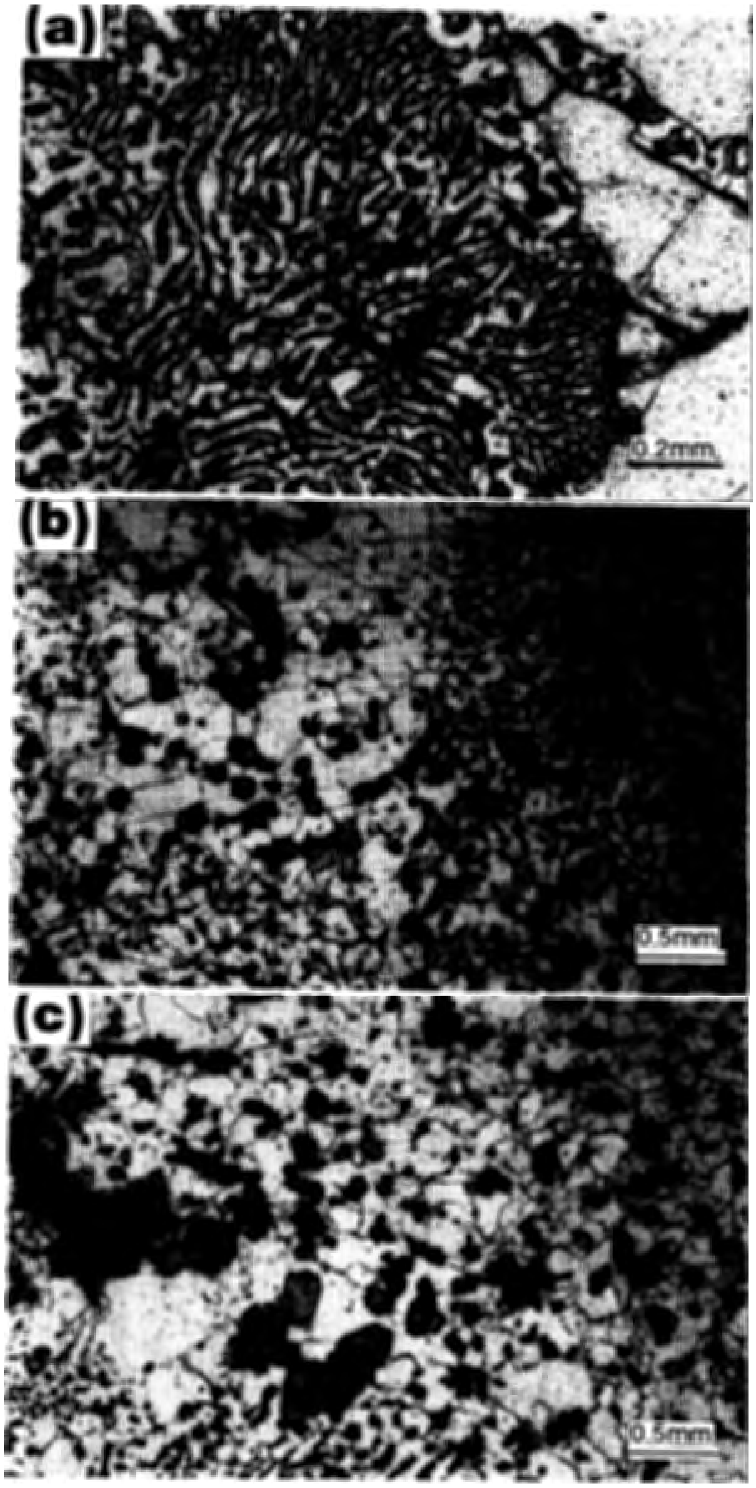

Fig. 3.
(*a*) *Type-1 garnet surrounded by symplectic intergrowth of type-2 garnet, plagioclase and clinopyroxene.*
(*b*) *Modes of occurrence of type-2 garnet* (*right side*) *and type-3 garnet* (*left side*).
(*c*) *Mode of occurrence of type-3 garnet, showing its intimate association with plagioclase, quartz and graphite. Small amounts of zoisite and clinopyroxene also are present.*

pyroxene and subordinate calcite (Figs. 3 and 4). In thin section, this type of garnet in kelyphite rim is colorless to pale green, 0.05–0.15 mm in size. Fine-grained garnet porphyroblast (type-3), coexisting with plagioclase, zoisite and quartz, occurs as subhedral to anhedral crystals (0.1–0.8 mm) in the outer zone of kelyphite rim (Fig. 3). This type of garnet characteristically shows a green color in thin section.

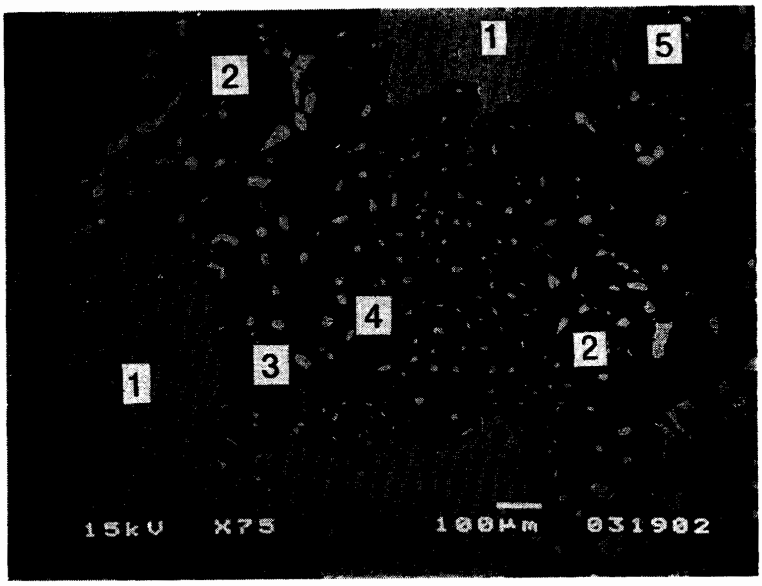

Fig. 4. Backscattered image of types-1 and -2 garnets. 1: type-1 garnet, 2: type-2 garnet, 3: plagioclase, 4: quartz, 5: V-clinopyroxene.

Table 1. Representative microprobe analyses of vanadium-bearing garnets from the Sør Rondane Mountains. Cation proportions are based on O=12.

Anal. No.	1–14	1–5	2–31	5–5	1–1	2–13	2–28	4–1	2–16
Type	1	1	1	2	2	2	3	3	3
SiO_2	39.20	38.86	41.75	37.64	37.63	37.89	36.15	35.85	34.96
TiO_2	0.27	0.15	0.26	0.69	0.07	0.06	—	0.09	—
Al_2O_3	21.02	21.31	22.07	12.46	13.00	9.01	5.46	4.68	3.51
Fe_2O_3	0.32	—	0.02	1.82	1.10	2.32	3.25	2.42	3.03
Cr_2O_3	0.09	0.04	—	1.09	1.01	1.38	1.82	2.00	1.93
MnO	0.31	0.08	0.24	1.58	1.01	1.16	1.81	1.62	1.41
MgO	0.26	0.14	0.21	0.17	0.26	—	0.22	0.07	—
CaO	37.53	38.07	34.62	34.59	34.04	33.73	32.27	33.14	33.97
V_2O_3	0.61	0.72	0.84	9.91	11.59	14.12	19.03	19.99	21.19
Total	99.61	99.19	100.09	99.95	99.71	99.67	100.01	99.86	100.00
Si	2.976	2.959	3.100	2.966	2.962	3.028	2.949	2.942	2.895
Ti	0.015	0.009	0.015	0.041	0.004	0.004	—	0.006	—
Al	1.882	1.913	1.933	1.158	1.206	0.849	0.525	0.453	0.343
Fe^{3+}	0.018	—	0.001	0.108	0.065	0.140	0.200	0.149	0.189
Cr	0.005	0.002	—	0.068	0.063	0.087	0.117	0.130	0.126
Mn	0.020	0.005	0.015	0.105	0.067	0.079	0.125	0.113	0.099
Mg	0.029	0.016	0.023	0.020	0.31	—	0.027	0.009	—
Ca	3.053	3.106	2.755	2.921	2.871	2.888	2.821	2.914	3.014
V	0.037	0.044	0.050	0.626	0.732	0.905	1.245	1.315	1.407

4. Chemical Character of Green Garnets

Table 1 lists the representative microprobe analyses of green garnets. The three types of green garnets exhibit distinct compositional ranges of V_2O_3, Fe_2O_3, Cr_2O_3 and Al_2O_3. These metal ions occupy the R^{3+}-site in common garnet formula of $R_3^{2+}R_2^{3+}R_3^{4+}O_{12}$.

The large porphyroblast type-1 garnet is low in V_2O_3, Cr_2O_3 and Fe_2O_3 and shows

Table 2. Calculated end-members mole percent of vanadium-bearing garnets.

	Type-1	Type-2	Type-3
Sps (spessartine)	0.16– 1.66	1.18– 3.78	0.57– 1.57
Pyr (pyrope)	0.33– 1.29	0.22– 1.37	0.00– 1.31
Gro (grossular)	92.58–96.84	30.16–80.92	15.98–39.76
Adr (andradite)	0.44– 2.09	3.35–19.08	4.83–10.77
Uvr (uvarovite)	0.00– 0.86	0.38– 4.75	5.63–18.69
Gld (goldmanite)	1.59– 3.07	9.90–46.81	37.06–65.59
Ymt (yamatoite)	0.01– 0.05	0.32– 3.95	1.23– 4.01

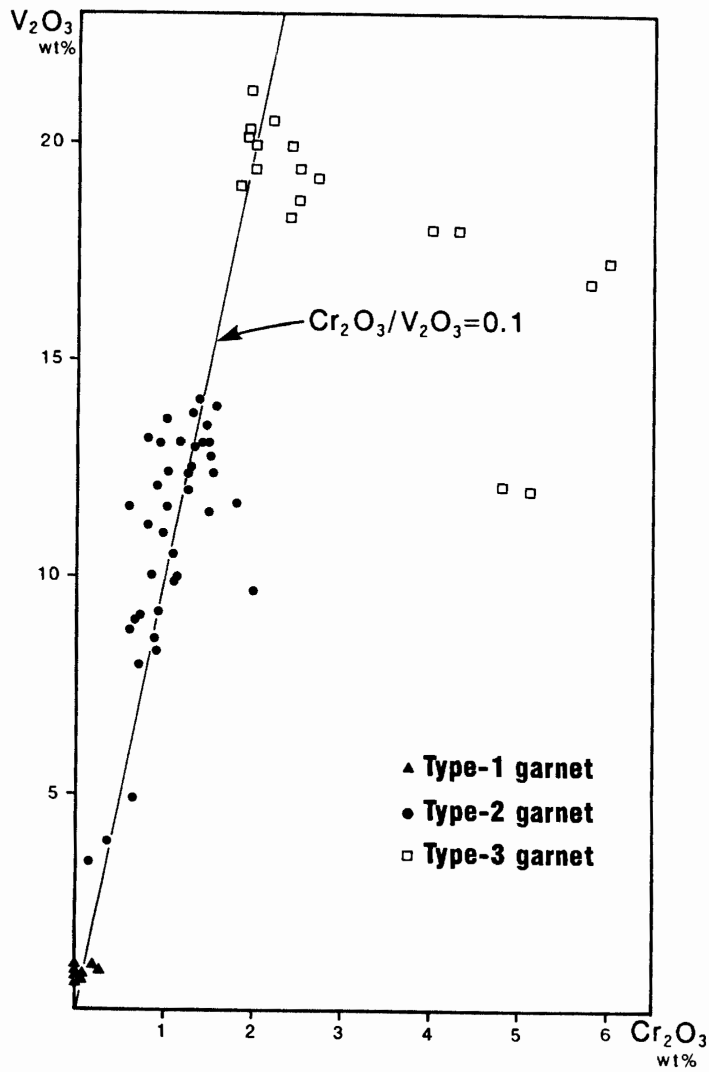

Fig. 5. V_2O_3 vs. Cr_2O_3 diagram for each type of garnet.

the compositional affinity to pure grossular ($Ca_3Al_2Si_3O_{12}$). On the contrary, the type-2 and type-3 garnets are relatively high in V_2O_3, Cr_2O_3 and Fe_2O_3.

The consistency of green color of garnet increases from type-1 (colorless in thin section) to type-3 (bright green) through type-2. This observation agrees with that of MANSON and STOCKTON (1982) who suggested that V_2O_3 and Cr_2O_3 contents are the important factors causing the green color of grossular garnet.

The calculated compositions of end-members for each type of garnet are shown in Table 2. Type-1 garnet is low in goldmanite component ($Ca_3V_2Si_3O_{12}$: MOENCH and MEYROWITZ, 1964) and very low in yamatoite component ($Mn_3V_2Si_3O_{12}$: MOMOI, 1964). On the contrary, type-3 green garnet is rich in goldmanite component (37.0–65.6 mol%). The type-2 garnet is intermediate in goldmanite component (10.0–46.8 mol%) between types-1 and -3, and a part of this type of garnet has slightly rich in yamatoite component.

The relationships of V_2O_3 *vs.* Cr_2O_3, and V_2O_3 *vs.* Fe_2O_3 for three types of garnet are indicated in Figs. 5 and 6. The V_2O_3-Cr_2O_3 relationship for all types of garnet is nearly located on the line of $Cr_2O_3/V_2O_3=0.1$. However, the vanadium-rich garnet

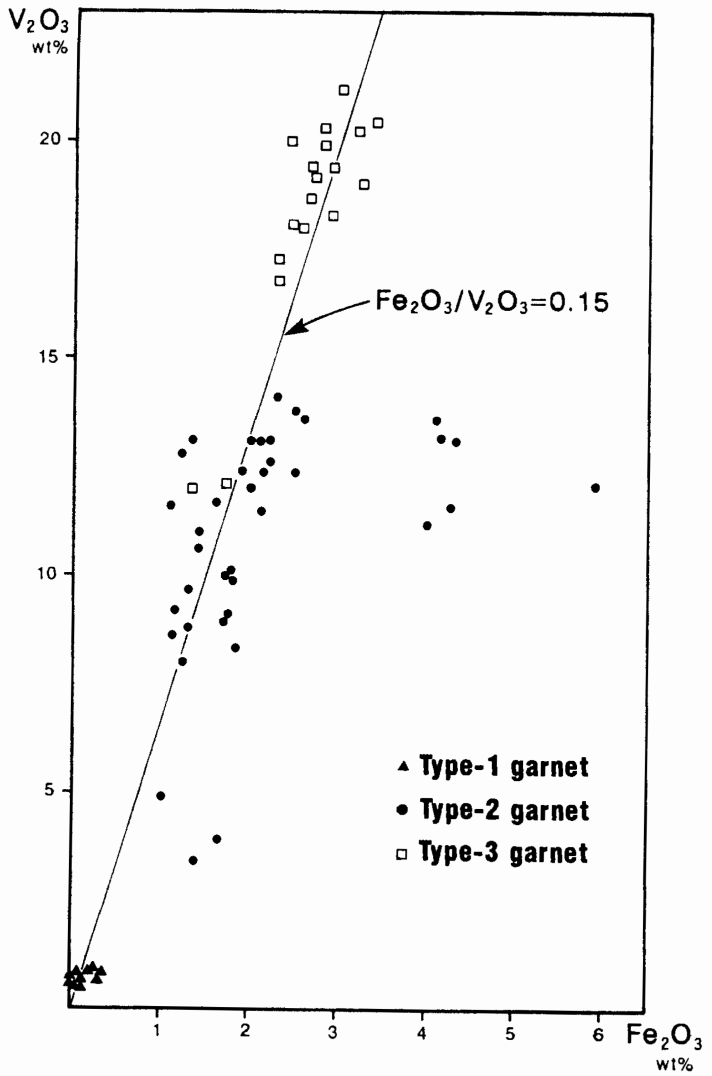

Fig. 6. V_2O_3 and Fe_2O_3 contents of vanadium-bearing garnet from the Sør Rondane Mountains.

(V_2O_3>12.0 wt%) of type-3 shows a tendency of enrichment in Cr_2O_3. SUWA *et al.* (1979) already suggested that the Cr_2O_3/V_2O_3 ratio in vanadium-bearing grossular is usually less than 0.1 for V_2O_3<5.5 wt% and more than 0.1 for V_2O_3>5.5 wt%. In Fig. 6, the Fe_2O_3/V_2O_3 ratio for almost all garnets shows 0.15 except type-2 garnet, which is rich in Fe_2O_3 and has less than 14.0 wt% V_2O_3 composition. The evidence indicates that the increase of V_2O_3 composition promotes the incorporation of Cr^{3+} and Fe^{3+} in R^{3+}-site.

Almost all garnets of three types show the substitutional relation of $4V^{3+}$, (Cr^{3+}, Fe^{3+})$\rightleftharpoons 5Al^{3+}$, which is shown in V^{3+}-Al^{3+}-($Cr^{3+}+Fe^{3+}$) diagram (Fig. 7). The chemical compositions of Cr-rich type-3 and Fe^{3+}-rich type-2 garnets are plotted toward the $Cr^{3+}+Fe^{3+}$-side and they show similar substitutional relation among V^{3+}, Cr^{3+}, Fe^{3+} and Al^{3+}.

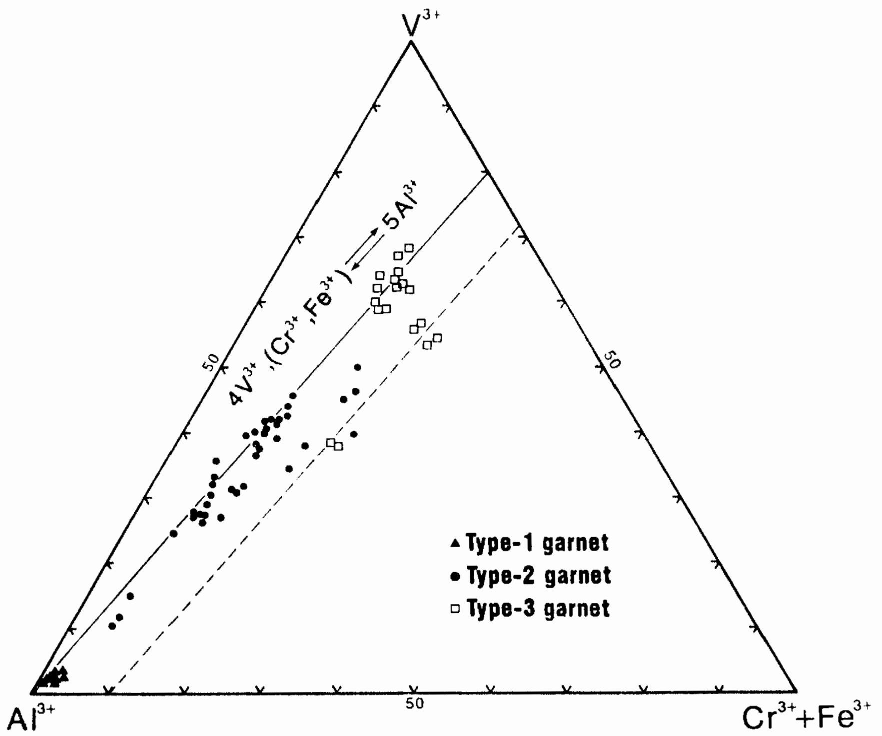

Fig. 7. A V^{3+}-Al^{3+}-$Cr^{3+}+Fe^{3+}$ ternary diagram showing the substitution trend among these elements in R^{3+}-site of vanadium-bearing garnets. Broken line shows the same substitution for Fe^{3+}- and Cr^{3+}-rich V-bearing garnet.

5. Physical Properties of Green Garnets

The X-ray powder diffraction data for types-1 and -2 garnets were obtained by the CuKa radiation under conditions of 30 kV and 20 mA. Table 3 shows the X-ray data for type-1 garnet in comparison with the standard grossular (JCPDS card No. 3–0826), and Table 4 shows type-2 garnet with the standard goldmanite (JCPDS card No. 16–714).

The unit cell parameters of type-1 garnet and type-2 garnet are a=11.854 Å and

Table 3. X-ray powder diffraction data for grossular and type-1 garnet.

1			2		
d(Å)	I/I_1	hkl	d_{obs}(Å)	d_{cal}(Å)	I/I_1
2.96	80	400	2.971	2.964	37
2.65	100	420	2.661	2.651	100
2.53	20	332	2.529	2.527	14
2.44	60	422	2.424	2.420	21
2.33	50	510	2.330	2.325	16
		431		2.325	
2.16	60	521	2.168	2.164	16
2.10	20	440	2.099	2.096	3
1.92	70	611	1.926	1.923	30
		532		1.923	
1.71	60	444	1.713	1.711	15
1.65	80	640	1.644	1.644	20
1.58	90	642	1.585	1.584	46
1.49	50	800	1.483	1.482	8
1.46	10	741	1.458	1.458	2
1.33	50	840	1.325	1.325	7
1.30	60	842	1.293	1.293	14
1.27	20	664	1.264	1.264	14
1.21	20	853	1.197	1.198	3
		941		1.198	
1.16	10	862	1.162	1.162	4
		10, 2, 0		1.162	
1.11	50	864	1.100	1.100	16
		10, 4, 0		1.100	
a_0=11.85 Å			a_0=11.854(2) Å		

1: grossular, JCPDS card No. 3–0826, 2: type-1 garnet from the Sør Rondane Mountains.

Table 4. X-ray powder diffraction data for goldmanite and type-2 garnet.

1			2		
d(Å)	I/I_1	hkl	d_{obs}(Å)	d_{cal}(Å)	I/I_1
4.26	12	220	4.22	4.21	15
3.01	65	400	2.980	2.980	69
2.688	100	420	2.671	2.666	100
2.565	10	332	2.541	2.542	12
2.453	40	422	2.439	2.433	45
2.357	16	510	2.340	2.338	10
2.194	16	521	2.179	2.176	8
1.951	20	611	1.940	1.934	14
1.901	8	620	1.885	1.885	2
1.735	8	444	1.720	1.721	2
1.667	18	640	1.653	1.653	4
1.607	50	642	1.595	1.593	20
1.502	10	800	1.489	1.490	3
1.345	10	840	1.331	1.333	3
a_0=12.011 Å			a_0=11.921(4) Å		

1: goldmanite, JCPDS card No. 16–714, 2: type-2 garnet from the Sør Rondane Mountains.

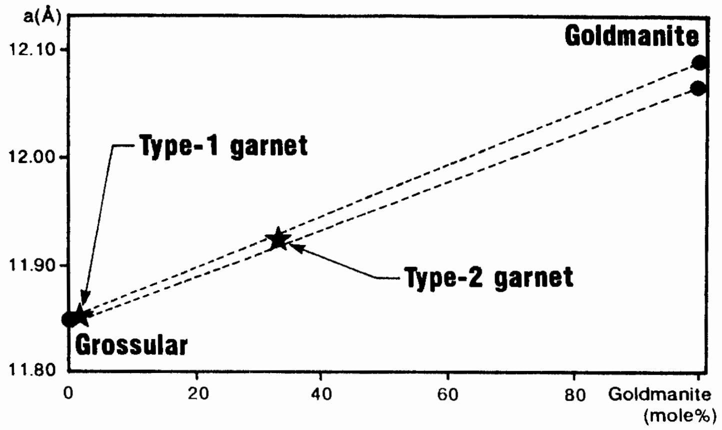

Fig. 8. Variation of vanadium-bearing garnets cell-dimension (Å) as a function of composition (goldmanite mole%). This diagram is modified from BENKERROU *and* FONTEILLES *(1989).*

a=11.921 Å, respectively. These cell parameters are plotted in the cell-dimension *vs.* chemical composition (grossular-goldmanite series) diagram (Fig. 8). For the plotting of type-2 garnet, the average chemical composition of 33.5 mol% of goldmanite is used. They are in agreement with their respective positions in the solid-solution series between grossular and goldmanite.

The refractive index and specific gravity for the type-1 garnet are 1.738 and 3.60, respectively (H. TAKANO, unpubl.). These results are in agreement with those of gem-quality grossular garnets (MANSON and STOCKTON, 1982), which are 1.731–1.754 for refractive index and 3.57–3.67 for specific gravity. Hardness is 6.5–7.0 on Mohs' scale.

6. Discussion and Summary

This paper describes the first occurrence of vanadium-bearing garnets from the Menipa mountain mass, central part of the Sør Rondane Mountains, East Antarctica and their mineralogical properties. These garnets were found only in the granulite-facies metamorphosed graphite-bearing calcareous metapelites and show the following three modes of occurrences;

i) Type-1: large porphyroblast,
ii) Type-2: fine crystal in symplectic intergrowth with plagioclase, quartz and clinopyroxene in kelyphite rim around type-1 garnet,
iii) Type-3: fine-grained porphyroblast in the outer zone (matrix) of the kelyphite rim.

These three types of vanadium-bearing garnets exhibit distinct characters in chemical compositions. MANSON and STOCKTON (1982) suggested that Fe_2O_3 causes the grossular to turn yellow to orange and V_2O_3 and/or Cr_2O_3 cause green grossular. The V^{3+}, Cr^{3+} and Fe^{3+} contents in these garnets increase from type-1 (V_2O_3 0.5–1.0%, Cr_2O_3 0–0.3%, Fe_2O_3 0–0.4%) to type-3 (V_2O_3 13.0–21.2%, Cr_2O_3 1.8–6.0%, Fe_2O_3 1.3–3.4%) through type-2 (V_2O_3 3.4–14.4%, Cr_2O_3 0.1–2.0%, Fe_2O_3 1.0–5.9%) with increasing the consistency of green color, while the Cr_2O_3/V_2O_3 and Fe_2O_3/V_2O_3

ratios are constantly 0.1 and 0.15, respectively. The form of cation substitution in R^{3+}-site of these garnets is shown as;

$$4V^{3+}, (Cr^{3+}, Fe^{3+}) \rightleftarrows 5Al^{3+} .$$

The calcareous metapelites including these vanadium-bearing green garnets were metamorphosed under the granulite-facies. These rocks also contain some kinds of vanadian silicates such as V-clinopyroxene, V-zoisite, V-sphene and V-actinolite. BENKERROU and FONTEILLES (1989) suggested that the goldmanite ($Ca_3V_2Si_3O_{12}$) content in grossular garnet is directly controlled by the V/Al ratio in the bulk chemical composition of rocks. The existence of vanadium and its concentration in graphite-bearing calcareous metapelites seem to be of biogenic and/or evaporitic origin (SUWA *et al.*, 1979).

The details of geological, petrological and mineralogical studies of these calcareous metapelites will be described and discussed in the nearest future.

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