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Plutonic garnets from the Werner batholith, Lassiter Coast, Antarctic Peninsula

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Abstract

Electron microprobe analyses and physical and optical properties of six garnets from plutonic rocks of the composite concentrically-zoned Werner batholith show that the garnets are dominantly almandine (65–70 percent) with lesser amounts of spessartine (13–29 percent), pyrope (2–11 percent), and grossular (1–5.6 percent). Garnets from two contaminated facies (diorite and granodiorite) of the batholith are interpreted as xenocrysts derived from surrounding pelitic metasediments, while those from an aplite dike which intrudes the granodiorite are considered to be phenocrysts.

Introduction

Almandine-rich garnet phenocrysts have been recorded in calc-alkaline igneous rocks in many parts of the world. The host rocks are commonly granodiorite, rhyodacite, and dacite, but also include rhyolite, granite, andesite, quartz diorite, norite, and felsic pegmatite. Origins other than as phenocrysts have, however, been postulated for these crystals. Zeck (1970), Birch and Gleadow (1974), and Makarov and Suprychev (1964) have respectively concluded that garnets in Spanish, Australian, and Russian igneous rocks are xenocrysts or residuals derived from adjacent pelitic metamorphic rocks. Elliott (1965, 1966) attributed the origin of Antarctic igneous garnets to the assimilation of pelitic sediments, and Bartrum (1937) and Edwards (1936) postulated that New Zealand and Australian garnets crystallized from a magma after its contamination with pelitic material.

This paper provides electron microprobe analyses and physical and optical properties for four garnet xenocrysts collected from two contaminated facies (diorite and granodiorite) of a composite concentrically-zoned batholith in the southern Antarctic Peninsula and from two garnet phenocrysts collected from an aplite dike that intrudes the granodiorite. Physical and optical properties of three garnet separates from contact metamorphic rocks associated with the Werner batholith are reported, and a discussion of the origin of the igneous garnets is given.

Methods of study

Garnet concentrates were obtained with conventional heavy-liquid and magnetic separation techniques. Compositions were determined with an ARL-EMX microprobe[1] with the following operating conditions: excitation potential of 15 kV, specimen current of 0.025 microamperes and a beam diameter of <1 micron swept over a 10- by 10-micron area. An almandine garnet standard analyzed by wet-chemical methods was used for determination of major elements, and minor elements were determined with other appropriate mineral standards. Corrections were made for background, atomic-number effects, absorption, characteristic fluorescence, and instrumental drift (Beeson, 1967; Beaman and Isasi, 1970).

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[1] Use of brand names in this report is for descriptive purposes only and in no way constitutes endorsement by the U.S. Geological Survey.

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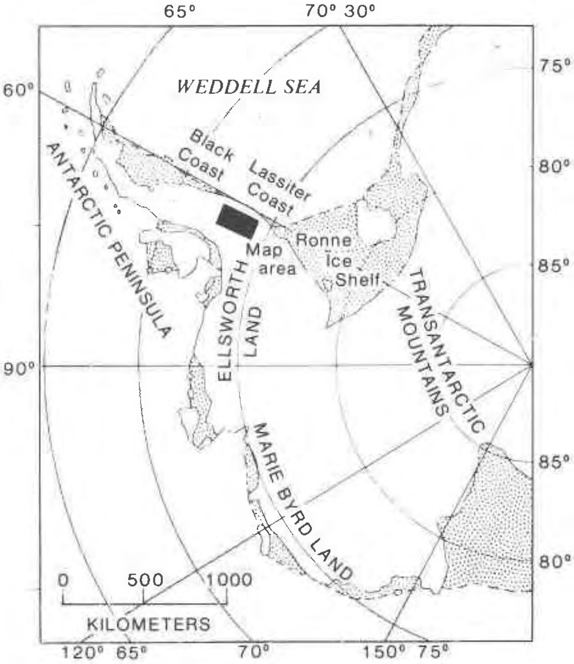

Fig. 1. Index map showing location of the Black and Lassiter Coasts, Antarctic Peninsula. Black rectangle outlines outcrop area of Werner batholith (Vennum, 1978).

Geologic setting

Williams *et al.* (1972), Williams and Rowley (1971), and Rowley (1973) summarized the geology of the entire Lassiter Coast and southern Black Coast (Fig. 1). The Upper Jurassic Latady Formation, a sequence of intensely-folded black and gray shale, siltstone, and minor sandstone, is the oldest and most widespread unit on the Lassiter Coast. It contains abundant volcaniclastic material (Williams and Rowley, 1972), and is overlain by and intertongued with silicic ash-flow tuff, andesitic to dacitic lava flows, and air-fall tuff (Williams *et al.*, 1972). These rocks are considered to be Upper Jurassic on the basis of apparent intertonguing with the Latady Formation and on the basis of age relations of similar volcanic rocks exposed elsewhere on the Antarctic Peninsula (Adie, 1972; Dalziel and Elliott, 1973).

The Latady Formation and overlying volcanic rocks were intruded and contact-metamorphosed to hornblende-hornfels facies (Plummer, 1974) by more than 50 stocks and batholiths that are largely quartz monzonite, granodiorite, and quartz diorite, but range in composition from gabbro to granite. Field relations, petrography, and chemistry (Rowley and Williams, 1974) indicate that the plutonic rocks are correlative with the Andean intrusive suite, a series of calc-alkaline plutonic rocks exposed extensively throughout the Antarctic Peninsula and Chilean and Patagonian Andes (Adie, 1955). K–Ar dates on 15 samples from eleven plutons yield Upper Cretaceous ages (Mehnert *et al.*, 1975; Rowley *et al.*, 1976).

The largest pluton in the Lassiter Coast is the Werner batholith, which is named for extensive exposures of this body in the Werner Mountains (Vennum, 1978). This batholith averages about 20 km in width and extends for nearly 150 km southward from the southern Black Coast to the central Lassiter Coast. Most of this concentrically-zoned batholith consists of quartz diorite and granodiorite which locally intrude a thin marginal facies (generally less than 2 km wide) of heterogeneous diorite and minor gabbro (Rowley, unpublished data, 1976). Five K–Ar dates that range from 98.2 to 114.4 m.y. have been obtained from the Werner batholith (Rowley *et al.*, 1976). The main felsic facies is about 100 m.y. old, and the mafic marginal facies is probably about 114 m.y. old.

Petrography, mineralogy, chemistry, and detailed field studies in the southwestern Dana Mountains of the northern Lassiter Coast (Vennum, 1978) indicate that both facies of the Werner batholith have been locally contaminated by assimilation of stoped blocks and inclusions of Latady Formation, and that composition of the granodiorite has been further modified by assimilation of stoped blocks and inclusions of diorite and gabbro. Contacts between the plutonic rocks and the Latady Formation are extremely irregular, and many of the abundant xenoliths and stoped blocks found in both facies of the batholith appear to be partially digested by the magma. Flat-lying pegmatite bodies and abundant inclusions, roof pendants, and septa of both metasedimentary rocks and gabbro–diorite suggest that the granodiorite lies near the roof of the batholith.

Chemical analyses of igneous rocks from the southwestern Dana Mountains which have identical silica percentages differ from each other chemically and mineralogically by as much as 6.7 percent Al_2O_3, 4.8 percent MgO, 13 percent modal plagioclase, 11 percent modal biotite, 15 percent modal hornblende, and 10 percent modal potassium feldspar.

In addition to the variation in chemistry and mineralogy, several textural features often reported in contaminated plutonic rocks have been noted in samples from the southwestern Dana Mountains. These include strongly poikilitic or sieve-textured mafic minerals, clots of mafic minerals, and plagioclase grains with moderately-zoned calcic cores sharply demarcated from a weakly-zoned or nonzoned albitic rim that is not in optical continuity with the core.

Megascopic (2 mm) red-brown garnets are irregularly distributed throughout both facies of the Werner batholith in the southwestern Dana Mountains, and sub-megascopic garnets appear in 15 percent of the thin sections examined from the same area. No significant textural or mineralogical differences exist between the garnet-bearing and garnet-free plutonic rocks. Garnets are apparently absent elsewhere within the batholith.

Garnets from the heterogeneous diorite facies are anhedral to subhedral, occasionally display weak birefringence (δ = 0.000–0.002), are pale chocolate-brown in plane-polarized light, or are irregularly zoned from pale chocolate-brown cores to colorless rims. Those from the granodiorite are anhedral, colorless, and weakly birefringent (δ = 0.001–0.002). Although none of the garnets in either facies displays good crystal form, none appears strongly resorbed or embayed, nor do they appear to have reacted with any of the primary igneous minerals. Euhedral isotropic pale-brown garnets as much as 4 mm long occur in the Latady Formation. X-ray data and additional optical and physical properties are listed in Table 1.

Composition

Significant chemical differences exist between the garnets collected from the diorite, granodiorite, and aplite (Table 2). All contain 65–70 percent of the almandine component. Those from the diorite contain 26–29 percent spessartine, 2 percent pyrope, and 1.5 percent grossular; those from the granodiorite 13–15 percent spessartine, 10–11 percent pyrope, and 5–6 percent grossular; and those from the aplite 17–22 percent spessartine, 9–11 percent pyrope, and 3–5 percent grossular. Measurement of the FeLα and

Table 1. X-ray powder data, optical, and physical properties of garnets from the Werner batholith and associated contact-metamorphic rocks, Lassiter Coast, Antarctica

	V36		V42		V77		Ro232e		Ro290c		Bo30b	
hkl	d(obs)	I[1]	d(obs)	I	d(obs)	I	d(obs)	I	d(obs)	I	d(obs)	I
211							4.728	1				
220							4.100	1				
321							3.086	1				
400	2.867	4	2.886	4	2.867	4	2.875	7	2.860	5	2.985	7
420	2.601	10	2.583	10	2.567	10	2.587	10	2.565	10	2.669	10
332	2.454	1					2.456	1			2.548	1
422	2.319	4	2.360	1	2.344	1	2.356	4	2.340	4	2.438	6
510	2.254	2			2.254	1	2.265	2	2.251	2	2.343	3
521	2.103	4	2.105	1	2.097	2	2.108	3	2.105	2	2.185	3
440							2.043	1				
611	1.867	4	1.876	1	1.867	3	1.875	5	1.867	2	1.890	2
444	1.663	4	1.668	1	1.662	2	1.667	4	1.658	2	1.726	3
640	1.598	7	1.600	3	1.598	4	1.603	6	1.596	4	1.658	5
642	1.542	9	1.539	2	1.540	6	1.545	7	1.539	6	1.598	9
800	1.442	2			1.442	1	1.445	2	1.442	1	1.495	3
840					1.290	1	1.293	2	1.287	1	1.337	3
842					1.258	2	1.262	3	1.259	1	1.305	4
664					1.229	1	1.233	1			1.276	3
a(Å)[2]	11.54		11.55		11.53		11.57		11.56		11.95	
n[3]	1.815±0.005		1.815±0.005		1.805±0.005		1.795±0.005		1.795±0.005		1.825±0.005	
G.[4]	4.20±0.05		4.20±0.05		4.15±0.05		4.10±0.05		4.10±0.05		3.70±0.05	

V36 Garnet-bearing biotite diorite, 63°10′ W., 73°24′ S.

V42 Garnet-bearing hornblende biotite granodiorite, 63°22′ W., 73°25′S.

V77 Muscovite garnet aplite, 63°12′ W., 73°20′ S.

Ro232e Garnet-bearing slate, Latady Formation, 62°54′ W., 73°31′ S.

Ro290c Garnet-bearing hornfels, Latady Formation, 63°03′ W., 73°07′ S.

Bo30b Garnet-epidote inclusion in granodiorite, 62°38′ W., 73°26′ S.

X-ray analyses were made with a 114.6 mm powder camera using Ni-filtered CuK$_\alpha$ radiation operated at 35 kv and 18 ma. LiF was used as an internal standard.

[1] Visual estimation.

[2] Determined by graphing $1/2\left(\frac{\cos^2\theta}{\sin\theta} + \frac{\cos^2\theta}{\theta}\right)$ vs a(A) for each reflection and projecting a least-square's fit to these data back to the a(A) axis (θ = 90°).

[3] Values determined with sodium light source.

[4] Determined by suspension in Clerici's solution.

Table 2. Electron microprobe analyses of garnets from the Werner batholith, Lassiter Coast, Antarctica

	V36 Grain 1		V36 Grain 2		V42 Grain 1		V42 Grain 2		V77 Grain 1		V77 Grain 2	
	Center	Edge	Center	Edge	Center	Edge	Center	Edge	Center	Edge	Center	Edge
SiO_2--------	36.3	35.9	36.5	36.1	37.2	37.2	37.0	36.7	37.3	37.1	37.6	36.8
FeO*--------	28.9	29.3	29.4	28.3	29.0	29.8	31.0	30.7	29.8	27.7	30.2	30.0
MgO---------	0.6	0.5	0.6	0.5	2.7	2.6	2.6	2.4	2.7	2.1	2.9	2.5
CaO---------	0.6	0.5	0.6	0.5	2.0	2.1	2.1	1.6	1.1	1.3	1.7	1.1
TiO_2--------	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0
Al_2O_3-------	20.7	20.4	20.6	20.5	21.1	21.1	20.8	20.7	21.1	21.3	21.1	21.0
MnO**-------	11.2	11.1	11.4	11.9	6.3	6.5	5.7	6.3	7.3	9.6	6.5	7.5
Cr_2O_3-------	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total-----	98.5	97.9	99.3	97.9	98.5	99.5	99.4	98.6	99.5	99.2	100.1	99.1
Fe/(Fe+Mg)--	.98	.98	.98	.99	.92	.92	.92	.93	.92	.92	.91	.92
* Total Fe	** Total Mn											
Atomic Reductions (for 24 oxygen)												
Si----------	6.03	6.01	6.03	6.03	6.05	6.01	6.00	6.01	6.03	6.02	6.04	6.00
Fe----------	4.02	4.10	4.06	3.96	3.94	4.03	4.21	4.21	4.03	3.76	4.06	4.09
Mg----------	0.14	0.13	0.14	0.11	0.64	0.63	0.64	0.59	0.65	0.51	0.69	0.61
Ca----------	0.10	0.09	0.10	0.10	0.35	0.36	0.36	0.28	0.19	0.23	0.29	0.20
Ti----------	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00
Al----------	4.05	4.03	4.01	4.04	4.04	4.02	3.98	4.00	4.02	4.08	3.99	4.03
Mn----------	1.58	1.58	1.60	1.68	0.87	0.89	0.78	0.87	1.00	1.32	0.88	1.04
Cr----------	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Total-----	15.94	15.96	15.96	15.93	15.91	15.96	15.99	15.98	15.94	15.93	15.96	15.98
Alm***------	69.0	69.5	69.0	67.6	68.0	68.2	70.2	70.6	68.6	64.7	68.6	68.9
Sp----------	27.0	26.7	27.0	28.8	14.9	15.0	13.2	14.7	17.2	22.7	14.8	17.4
Py----------	2.3	2.3	2.3	2.0	11.1	10.7	10.6	9.9	11.0	8.7	11.7	10.3
Gr----------	1.7	1.5	1.7	1.6	6.0	6.1	6.0	4.8	3.2	3.9	4.9	3.4

*** Calculation of end member molecules follows the procedure of Rickwood (1968).

FeLβ peaks (Albee and Chodos, 1970) indicates that <10 weight percent of the total iron is present as Fe_2O_3. This is consistent with the atomic reductions in Table 2. Yttrium, potassium, and sodium were looked for but were not detected in significant amounts (<0.01 percent) above background intensity.

Although notable compositional differences exist between the cores and rims of the six analyzed samples, no consistent trends are apparent. Both samples from the granodiorite (V42) have cores enriched in pyrope (0.4 and 0.7 percent) relative to their rims. Almandine and spessartine vary antithetically in samples from the diorite (V36). Garnets from the aplite (V77) have rims enriched in spessartine (2.6 and 5.5 percent) relative to the core, while the cores of the same crystals contain more pyrope (1.4 and 2.3 percent respectively) than the rims.

Origin

Experimental work with natural garnet-bearing rhyodacite (Green and Ringwood, 1968, 1972) has shown that almandine garnet containing subordinate pyrope (16–30 percent) and grossular (7–20 percent) and minor spessartine (0.5–2.5 percent) is a liquidus phase in calc-alkaline magmas at pressures typical of the lower crust or upper mantle (9–27 kbar). Garnet phenocrysts presumably would become unstable at lower pressures and would then begin to be resorbed and react with the melt to form different phases in equilibrium at lower pressure. This would account for the common presence of overgrowths of cordierite and hypersthene (Miyashiro, 1955; Green and Ringwood, 1968, 1972), biotite (Lyons *et al.*, 1973; Edwards, 1936), feldspar (Edwards, 1936; Oliver, 1956), or chlorite and magnetite (Fitton, 1972) on garnet phenocrysts. Neither overgrowths nor the graphic intergrowths of garnet–quartz and garnet–feldspar cited by Wood (1974) and Oliver (1956) respectively as evidence of igneous crystallization are associated with the garnets from the southwestern Dana Mountains.

Edwards (1936) and Bartrum (1937) both postulated crystallization of garnet from a magma after its contamination with pelitic material. In both cases garnets are concentrated along the rims of hornblende–biotite-rich inclusions which were partially assimilated by granodiorite and diorite magmas respectively, and away from the xenolith margins the garnets became unstable and redissolved in the magma. Similar relationships between garnets and xenoliths were not observed in plutonic rocks of the Werner batholith.

If the plutonic garnets are xenocrysts, only roof rocks containing one type of garnet were incorporated by the magmas. This conclusion is supported by the following lines of evidence:

(1) Outcrops of roof rocks of the Werner batholith in the southwestern Dana Mountains are uniformly pelitic.

(2) The close similarity of physical and optical properties of the plutonic garnets and two of the metamorphic garnets (Table 1) suggests these crystals have similar compositions.

(3) Limestone is a minor constituent of the Latady Formation in the southern Lassiter Coast (Williams *et al.*, 1972), but does not crop out in the southwestern Dana Mountains. Physical and optical properties of garnet collected from a garnet–epidote inclusion (presumably an inclusion of contact-metamorphosed Latady limestone) in granodiorite (Table 1) are considerably different from the above-mentioned samples.

Several additional lines of evidence suggest that the garnets from the diorite and granodiorite are xenocrysts derived from the surrounding pelitic metasediments of the Latady Formation:

(1) They occur only in rocks of the southwestern Dana Mountains and are absent in rocks of similar composition elsewhere within the concentrically-zoned Werner batholith.

(2) They are irregularly distributed within that part of the batholith in which they occur.

(3) Experimental data (Hensen and Green, 1973) suggest that garnet containing less than 2 percent CaO and occurring in calc-alkaline plutonic rocks represents relic or refractory phases from partial melting of minor admixed pelitic sediments.

(4) Garnets from the granodiorite contain five times as much of the pyrope molecule as do those from the diorite. This is the reverse of what would be expected if these crystals resulted from fractional crystallization in a differentiating magma.

(5) Their physical, optical, and petrographic characteristics (refractive indices, cell edge, specific gravity, color, lack of inclusions) are similar to garnets from the Latady Formation (Table 1).

(6) Elliott (1966) reported both garnet ("presumably of the almandine–spessartine series") and andalusite from a granite pluton that assimilated argillaceous sedimentary rocks of the Carboniferous Trinity Peninsula Series, a unit lithologically very similar to the Latady Formation. This pluton crops out on the northwestern Trinity Peninsula, 1100 km north of the southwestern Dana Mountains.

(7) Miyashiro (1955) concluded that garnet phenocrysts in calc-alkaline plutonic rocks (excluding pegmatites and aplites) are generally rich in almandine, contain some pyrope, and are poor in spessartine.

The following evidence indicates that the garnets in the aplite dike are phenocrysts:

(1) Garnet-bearing aplite, pegmatite, and composite aplite–pegmatite dikes occur throughout the Werner batholith.

(2) The garnets in the aplite dike are large (3–4 mm) and euhedral.

(3) The lower pyrope content of the rims of the crystals is consistent with igneous zonation.

(4) Miyashiro (1955) noted that garnet phenocrysts in pegmatite associated with calc-alkaline plutonic rocks are rich in almandine–spessartine and poor in pyrope.

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