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CHEMICALLY SECTOR-ZONED GARNETS IN THE METAPELITIC ROCKS OF THE SILGARÁ FORMATION IN THE CENTRAL SANTANDER MASSIF, COLOMBIAN ANDES: OCCURRENCE AND GROWTH HISTORY

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ABSTRACT

Almandine-rich garnet in the Silgará Formation metapelitic rocks in the central Santander Massif usually shows concentric normal chemical zoning. However, different types of garnet zoning have been reported, including chemically sector-zoned garnet, which is described here. Recent studies reveal additional discoveries of this type of zoning in different localities. Textural sector-zoned garnets have been observed in the staurolite-kyanite metamorphic zone of the Silgará Formation. They are generally fine-grained (0.25-2.00 mm in diameter), and occur in quartz-rich bands with other textural types of garnet (skeletal and poikiloblastic). The study of the chemically sector-zoned garnet indicates that it has grown in the latest stage of the Silgará Formation metamorphism, during the emplacement of orthogneiss masses. Studies on garnet from the Silgará Formation pelitic rocks have shown the importance of this as a key piece for interpretation of the tectono-metamorphic history of this metamorphic unit.

Key words: Silgará Formation; Santander Massif; chemically sector-zoned; garnet; metamorphism.

RESUMEN

El granate tipo almandino en las rocas metapelíticas de la Formación Silgará en la región central del Macizo de Santander usualmente muestra zonación química concéntrica normal. Sin embargo, se han reportado diferentes tipos de zonación en el granate, incluyendo el granate químicamente sector-zonado, el cual es descrito aquí. Estudios recientes revelan descubrimientos adicionales de este tipo de zonación en diferentes localidades. Los granates que exhiben zonación sectorial textural han sido observados en la zona metamórfica de la estaurolita-cianita de la Formación Silgará. Estos son generalmente de grano fino (0.25-2.00 mm de diámetro), y ocurren en bandas ricas en cuarzo junto con otros tipos texturales de granate (esqueletal y poiquiloblástico). El estudio del granate químicamente sector-zonado indica que este creció en la etapa tardía de metamorfismo de la Formación Silgará, durante el emplazamiento de masas de ortoneis. Estudios sobre el granate en las rocas pelíticas de la Formación Silgará han mostrado su importancia como pieza clave en la interpretación de la historia tectono-metamórfica de esta unidad metamórfica.

Palabras clave: Formación Silgará; Macizo de Santander; granate químicamente sector-zonado; metamorfismo.

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INTRODUCTION

Metamorphic garnet in low- to medium-grade rocks often has distinct chemical zoning, and shows some of the greatest variability in terms of solid solution. Therefore, chemical zoning of garnet is of considerable value in the interpretation of the metamorphic P-T history.

Garnet in pelitic rocks of the Silgará Formation usually preserves chemical zoning, with decreasing X_{Mn} and increasing X_{Fe} and X_{Mg} from core to rim, suggesting that garnet grew during increasing temperature. X_{Ca} follows a radial trend, but in other cases it follows a patch trend. However, different types of garnet zoning have been reported by Castellanos (2001) from the Silgará Formation metapelitic rocks in the central Santander Massif: normal zoning, reverse zoning, and sector zoning. According to Kitamura et al. (1993), the sector-zoning in garnet can be interpreted as a result of compositional changes to reflect element distribution depending upon the curvature of growing garnet surfaces under disequilibrium conditions. Therefore, this type of garnet will generate two problems: the cause and extent of the disequilibrium conditions, and the stage at which the sector-zoned garnet grew in the history of the Silgará Formation metapelitic rocks. Recent detailed field work has been developed in the central Santander Massif, where Castellanos (2001) reported sector-zoned garnets in pelitic rocks of the Silgará Formation, in order to look for similar pelitic rocks and check the zoning structure of garnet. Similar optical zoning in garnet has been recognized in three localities in the study area.

In this paper, we reveal a remarkable discover, which corresponds to the occurrence of sector-zoned garnet, describing its mode of occurrence, its chemistry, as well as the relative time of its formation.

GEOLOGICAL SETTING

The Santander Massif is located in the northern portion of the Colombian Andes, where the Eastern Cordillera is branched into the northeast-trending Serranía de Perijá and the east-northeast-trending Mérida Andes of Venezuela.

The pre-Devonian metamorphic complex of the Santander Massif has been divided by Ward et al. (1973) into three formations in ascending order of tectono-stratigraphic level: Bucaramanga Gneiss Formation (BGF), Silgará Formation (SF), and Orthogneiss Formation (OF), which are cut by Paleozoic to Jurassic intrusive bodies (e.g., Boinet et al., 1985). However, smaller intrusive bodies have Cretaceous ages. The BGF consists mainly of pelitic gneiss, with minor amounts of amphibolite and orthogneiss. These rocks were metamorphosed to high temperatures as they are in part migmatitic. Goldsmith et al. (1971) reported a K-Ar hornblende age of 945±140 Ma and a Rb-Sr whole-rock isochron age of 680±14 Ma. The SF is a medium-grade metamorphic sequence, consisting of pelitic rocks with intercalations of mafic rocks intruded by granitoids and gabbros. Goldsmith et al. (1971) have reported K-Ar whole-rock ages of 221±8 Ma and 198±8 Ma from phyllites of this metamorphic unit, although these ages do not date the metamorphism but probably reflect a later thermal event. The OF generally show similar foliation and lineation with those of surrounding BGF and SF metamorphic rocks. K-Ar hornblende age of 413±30 Ma (metadiorite) and Rb-Sr whole-rock isochron age of 450±80 Ma (gneiss) suggest a magmatic event during the Late Ordovician or Early Silurian in the Santander Massif, and the metamorphism of the SF may have occurred at this time (Goldsmith et al., 1971).

The Silgará Formation that crops out in the central Santander Massif (FIGURE 1) generally strike N15-20^{o}E and dip 30-35^{o}SE. Here, the Silgará Formation metamorphic rocks consist on pelitic (feldspar-micaschist and micaschists), semipelitic (quartz-feldspar schists and mica-quartz schists, and feldspar quartzites, mica-feldspar quartzites, muscovite quartzites and feldspar quartzites), mafic (amphibole-bearing schists), and carbonate (marble) rocks. This metamorphic unit has been affected by a Barrovian type metamorphism, developing a sequence of metamorphic zones (biotite, garnet, staurolite-kyanite, and silimanite). Metamorphism has occurred under medium-pressure conditions. Castellanos (2001) has calculated temperatures and pressures in the study area, using the garnet-biotite geothermometer and the GASP geobarometers, respectively. Temperatures vary between 460-620 °C for sector-zoning garnet and 500-650 °C for poikiloblastic garnet, while pressures range from 4-7 kbars for sector-zoning garnet to 4-6 kbars for poikiloblastic garnet.

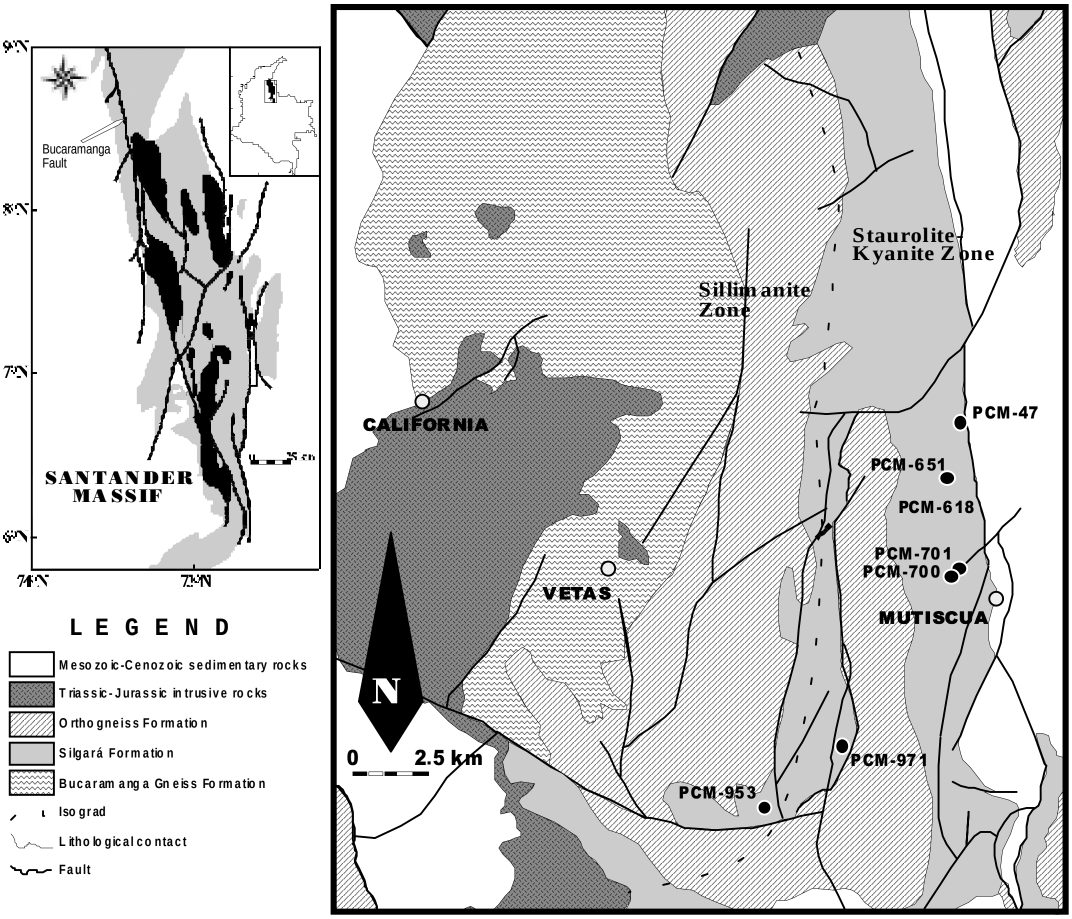

FIGURE 1. On the left side, generalized geological map of the Santander Massif rocks modified after Goldsmith et al. (1971), showing the distribution of metamorphic (gray colour), igneous (black colour) and sedimentary (white colour) rocks. On the right side, geological map of the central Santander Massif modified after Ward et al. (1973), showing sampling localities for garnet (open circles), including sector-zoned garnet (black stars).

PETROGRAPHY

The Silgará Formation metapelitic rocks in the central Santander Massif generally show a millimeter-scale compositional banding consisting of alternation of melanocratic and lepidoblastic bands (from 0.1 mm up to 10 mm thickness) of crystals of white mica-biotite-chlorite and coarse-fine grained (0.02 mm in diameter) leucocratic and granoblastic quartz-rich bands (with minor plagioclase, 2.5 mm in thickness, average). The schistosity is also due to the alignment of individual phylosilicate grains and the presence of aggregates of aluminosilicates, mainly sillimanite and kyanite, and also individual crystals of opaque minerals or graphite. The small scale folding of the schistosity plane has produced a crenulation cleavage, accompanied by segregation of quartz into horizontal layer. Schistosity is disturbed by the presence of porphyroblasts of garnet, staurolite, andalusite, kyanite, and plagioclase, concordant or discordant with the foliation of the rock. The matrix of these rocks is mainly composed of quartz, muscovite, biotite, plagioclase, and minor amounts of graphite and opaque minerals (ilmenite, Fe-oxides or rutile). Zircon, apatite and epidote are present as accessory phases.

These metapelitic rocks have been affected by multiple deformations giving rise to interference patterns. Petrographic and microstructural evidence indicates that they are multiply deformed with at least three deformational events (D_n, D_{n+1}, D_{n+2}), which progressively generated three schistosities (S_n, S_{n+1}, S_{n+2}), and extensive retrograde metamorphism during the last stage. According to Castellanos (2001), during deformation D_n (M_n phase), as a result of crustal shortening and thickening, the Silgará Formation metapelitic rocks were affected by a prograde metamorphism, through medium pressure conditions. Deformation D_{n+1} due to heating and thrusting occurred during a M_{n+1} phase. Deformation D_{n+2} due to slow uplift, presumably with erosional or tectonic thinning, which caused a decrease in pressure with an increase in temperature during a M_{n+2} phase. A cooling accompanied by an extensive retrograde metamorphism, occurred during a late retrograde event.

A polymetamorphism is suggested by the presence of multiple foliations and by garnet or staurolite porphyroblasts that have complex time relations and can be pre-tectonic or post-tectonic to a foliation, or by a mineral phase, which has different forms or time relations in different crystals. A S_n (formed during the first deformation, D_n) is defined by chlorite, muscovite and graphite. However, the most obvious structure in these rocks is a dominant schistosity S_{n+1} (formed during D_{n+1}), which is parallel to axial planes of isoclinal folds in intercalated quartz-feldspar-rich and phyllosilicate-graphite rich layers, and represents the main foliation recognized through all metamorphic zones. Later structures such as flat-lying crenulations, small chevron folds and kink bands overprint the main foliation, representing S_{n+2} (formed during D_{n+2}).

The relative chronology of porphyroblast growth and penetrative deformation is observed using inclusion trails and matrix foliation relationships mainly in garnet and staurolite porphyroblasts. Numerous porphyroblasts of garnet, staurolite, biotite and/or muscovite are present in most outcrops, and can be shown to have grown post-tectonically to D_n or D_{n+1}. Garnet porphyroblasts usually contain inclusions of quartz + ilmenite ± rutile that commonly define an internal schistosity (S_n), which is discordant to S_{n+1} and deformed during D_{n+1}, indicative of early garnet post-kinematic growth. A few micas of S_{n+1} wrap around garnet porphyroblasts (with pressure shadows), which are thus pre-tectonic to D_{n+1}. On the other hand, xenoblastic garnet is syntectonic to D_n, whereas idioblastic garnet probably grew either before or early during D_{n+1}. Garnet porphyroblasts may have an inclusion-free rim that separates the core from the discordant external foliation (S_{n+1}), and represent the post-D_{n+1} growth. The foliation outside of garnet porphyroblasts generally displays evidence of recrystallization and grain-size coarsening respect to the inclusion trails in porphyroblasts. Small inclusion-free garnet grains appear to post-date biotite and muscovite foliation development.

Sampling localities for garnet in the central Santander Massif, including sector-zoned garnet, are illustrated in FIGURE 1.

OCCURRENCE OF SECTOR-ZONED GARNET

Photographs of textural and chemical aspects of the sector-zoned garnet are shown in FIGURE 2. In general, garnet shows an idioblastic to xenoblastic character and occurs mainly as porphyroblasts, but it shows differences in each metamorphic zone.

(1) Garnet from the garnet zone occurs as small and idioblastic grains, which usually contain inclusion trails of carbonaceous material and ilmenite that define an internal foliation (S_n) discordant to the main foliation (S_{n+1}). Large idioblastic to subidioblastic garnet porphyroblasts commonly show a pre-kynematic character with muscovite, chlorite and ilmenite of the main foliation wrapping around garnet that sometimes contain inclusion trails defined by quartz and ilmenite, which are discordant to the main foliation. The characteristic garnet from the garnet zone is almandine-rich and probably grows by a continuous reaction such as chlorite + muscovite = garnet + biotite + quartz + H_2O. The garnet isograd reaction is strongly dependent on bulk rock composition and specially the MnO and CaO contents. In rocks of high amount of those components, garnet could appear at temperatures below 450^0C whereas in rocks of low amount of them, garnet could not appear to well above 500^0C (Spear, 1993). Therefore, a very irregular garnet isograd is commonly observed in the field with some rocks at an outcrop showing garnet and other rocks lacking of garnet.

(2) In the staurolite-kyanite zone, garnet usually occurs as subidioblastic to xenoblastic porphyroblasts, with a pre-kynematic character, sometimes developing pressure shadows. Garnet rarely displays a sector zoning (FIGURE 2a), and, in other cases, it occurs as poikiloblastic porphyroblasts with abundant inclusions of quartz and ilmenite that give it a spongy appearance or as skeletal porphyroblasts formed by

very fast growth between quartz grain boundaries. Garnet also occurs as xenoblastic relicts included in staurolite, which shows numerous quartz and ilmenite inclusions that define an internal schistosity. Staurolite could have been produced by the discontinuous reaction garnet + muscovite + chlorite = staurolite + biotite + quartz + H_2O. Garnet will be partially resorbed by this reaction and a significant amount of chlorite will be removed along with the production of abundant staurolite and new biotite. Garnet occurs in post-tectonic staurolite, indicating the occurrence of reaction above, which is partially influenced by the content of MnO in these rocks and could extent to a higher temperature in 10-20°C as a result of the chemical composition of the rock (Spear, 1993). According to Yardley (1989), this reaction takes place at a fixed temperature for any given pressure since it is a discontinuous reaction, and proceeds until one of the three reactants has been consumed. Castellanos (2001), on the basis of the coexistence of kyanite-sillimanite-andalusite in staurolite-bearing rocks, the mineral assemblages and the textural observations, suggest the following sequence of occurrence of the Al_2SiO_5 polymorphs: first kyanite and staurolite, followed by breakdown of kyanite and presence of sillimanite, and last by retrograde metamorphism occurrence of andalusite after kyanite.

(3) In the sillimanite zone, garnet porphyroblasts display numerous quartz inclusions and are highly replaced by leucoxene or by an aggregate of sillimanite + biotite. Fibrolitic sillimanite has been developed in garnet with an anhedral and poikiloblastic character. Sillimanite first appears as aggregates of fibrolite. As staurolite becomes less abundant it may be preserved as inclusions or armoured relicts in muscovite to suggest the reaction staurolite + biotite = garnet + muscovite, and it may disappears as a result of the discontinuous reaction staurolite + muscovite + quartz = sillimanite + garnet + biotite + H_2O. If garnet is not involved, the staurolite breakdown is produced by the continuous reaction reaction staurolite + muscovite + quartz = Al_2SiO_5 + biotite + H_2O, which reflects lower temperatures than the previous reaction, and P-T conditions nearly independent of the MnO and CaO contents of the rock. However, if garnet breaks down as sillimanite is produced, so the initial growth of sillimanite may be considered to result from two separate continuous reactions operating simultaneously staurolite + muscovite + quartz = sillimanite + biotite + H_2O and garnet + muscovite = biotite + sillimanite + quartz.

In general, garnet occurs as porphyroblasts with idioblastic to xenoblastic character (0.25 mm to 20 mm in diameter). It is also possible to difference two type of garnets according to their texture: poikiloblastic and sector zoning garnets. According to Castellanos (2001), sector-zoning garnet growth can be interpreted as a non-equilibrium stage of progressive metamorphism, followed by late poikiloblastic garnet growth. Poikiloblastic garnet sometimes shows a trail pattern of inclusions of quartz, graphite and opaque minerals, which define a S_n almost perpendicular to the S_{n+1} of the rock and most of them are partially included in staurolite porphyroblasts. Some garnets are sub rounded to rounded and show a rotational trail of inclusions of quartz or S-shaped spiral structure. Garnets rarely show a concordant internal schistosity

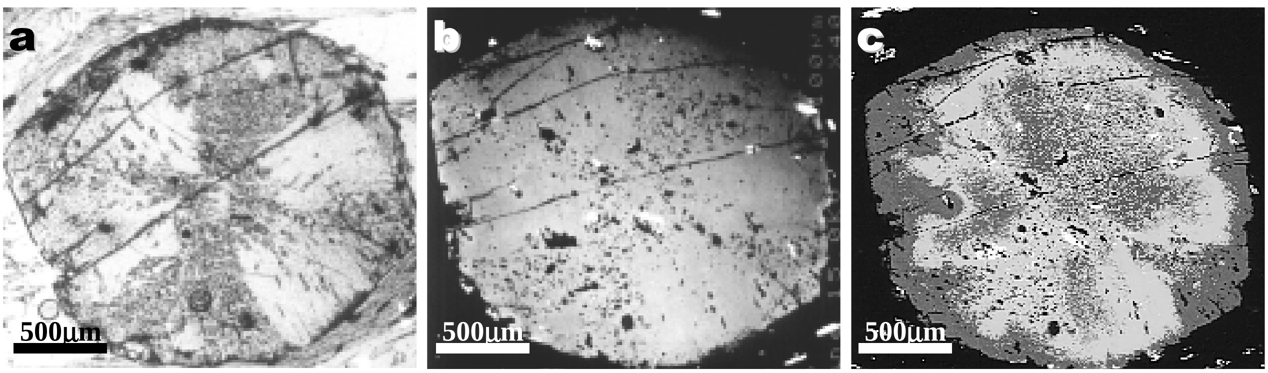

FIGURE. 2. Textural and chemical features of sector-zoned garnet in sample PCM-618. (a) Photomicrograph of a garnet displaying optical sector zoning. (b) Back-scattered electron image showing sector zoning. (c) X-ray map of Ca distribution within garnet. The light gray areas correspond to the highest Ca content and the dark gray areas, to the lowest.

trail of quartz and opaque mineral inclusions. In some porpphyroblasts is evident partial replacement by chlorite along cracks, suggesting retrograde metamorphism. Inclusions in the poikiloblastic garnets are mainly quartz, opaque minerals and plagioclase, which exhibit randomly distribution and orientation. In addition, poikiloblastic garnets sometimes show an elongated shape, suggesting a dendritic character due to high rate of growth. Sector zoning garnets are usually subrounded and show very different types in the distribution of quartz inclusions. This unusual zoning shows in general terms a radial character. It is possible to observe asymmetrical pressure shadows consisting mainly of quartz and mica, and it is also common to find garnet with rims corroded by quartz.

The concentration of inclusions at interfacial boundaries gives spectacular sector-zoned garnet porphyroblasts, which are divided into a series of pyramids, the bases of which form the crystal faces (FIGURES 2a, 3). Relatively complex sector pattern can be seen in thin sections, depending on the orientation of the section through the crystal, and within each pyramid the crystal structure is divide into a series of slightly misorientated units aligned normal or nearly normal to the crystal face.

According to Rice & Mitchell (1991), sector-zoning is revealed in minerals in three different manner: (1) textural sectoring, (2) chemical sectoring, and (3) twin sectoring. This paper is primarily concerned with features associated with the first and second types, although it is believed that all three are related. Textural sector-zoning has been described by several authors (e.g., Powell, 1966; MacQueen & Powell, 1977; Olimpio & Anderson, 1978; Finlay & Kerr, 1979; Anderson, 1984; Burton, 1986; Takasu and Kondo, 1993; Kitamura et al., 1993; Shirahata and Hirajima, 1995).

A common characteristic in many of the textural sector-zoned garnets is the presence of arcuate concentrations of graphite (or rarely other minerals) in a textural zone

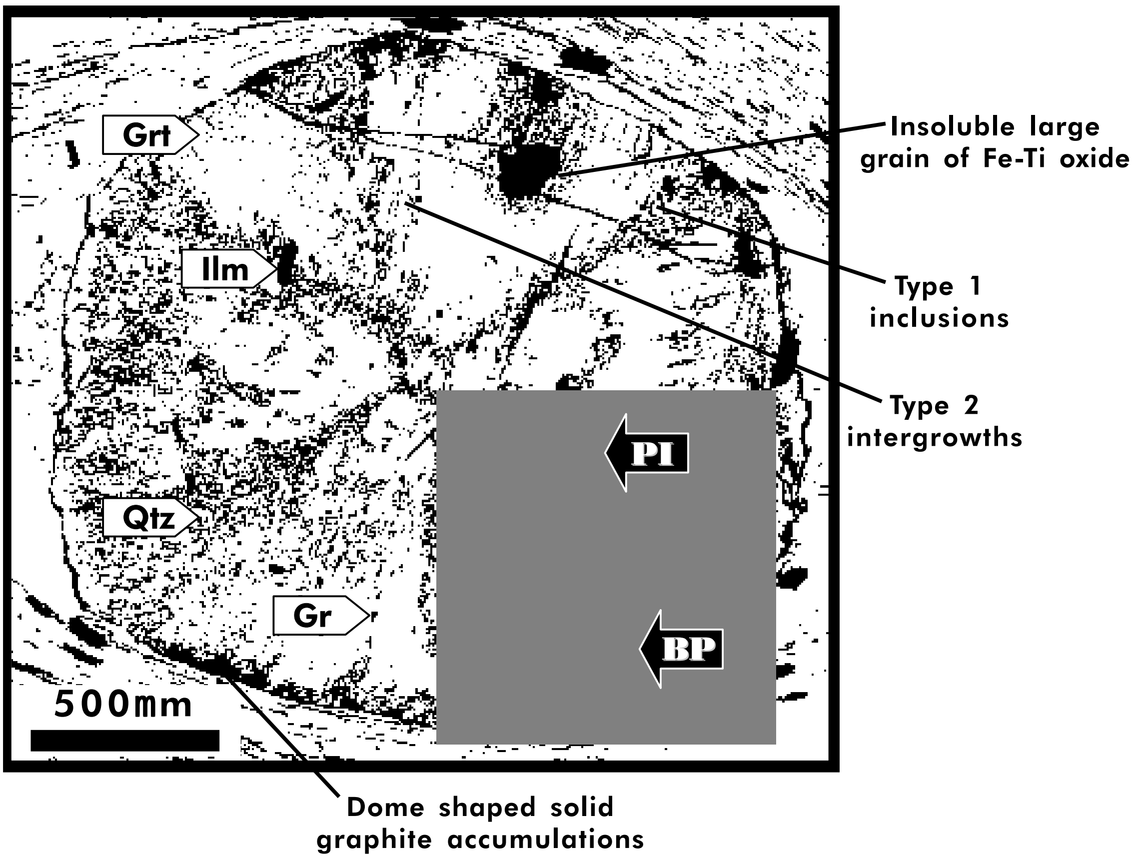

FIGURE 3. Skech of a textural sector-zoned garnet (sample PCM-618) from the Silgará Formation pelitic rocks in the central Santander Massif), showing well developed type 1 inclusions of quartz, graphite and plagioclase and type 2 intergrowths of quartz and graphite. Note the local development of cleavage domes on {110} garnet crystal faces. Shadow area displays a pyramid as well as the base of the pyramid and the pyramid interface. PI: Pyramid interface; BP: Base of the Pyramid.

(often very thin) lying immediately outside the sector-zoned region (FIGURES 2a, 3). According to Anderson (1984), within sector-zoned garnets two types of inclusions can be identified. Type 1 "blobby" inclusions of quartz, Fe-Ti oxides and graphite are found prefentially along the pyramid interfaces and were derived from the matrix. Type 2 "tubular" inclusions (or more properly "intergrowths" according to Burton (1986) consist of slender inclusions of quartz which are not relics of the matrix, but have formed simultaneously with garnet. These types of inclusions have been observed in sample PCM-618 (FIGURE 3), in which type 2 inclusions of abundant fine trails of equidimensional and tubular grains of quartz and graphite form an angle of 30º with the pyramid interfaces, where inclusions of quartz, Fe-Ti oxides and graphite occur, and approximately 90º with the base of the pyramid within which they formed. Locally, domal accumulations of graphite are observed at the end of the type 2 intergrowths on garnet {110} crystal faces (FIGURE 3).

Chemical sector-zoning, such as in sample PCM-618 (FIGURE 2b, c), is characterized by growth pyramids of different crystal habit have marginally different chemical compositions. Kochi et al. (1983) describe some mechanisms to account for chemical sectoring, based on: (1) properties relating to the ion exchange taking place at the crystal face; (2) variations in the atomic configuration of the crystal structure or adsorption layer at different faces; (3) systematic variations in growth rates at different faces and relative diffusion rates of cations in melts; (4) element partition coefficients and the roughness of crystal faces.

According to Barker (1990), ions, molecules or minerals may become attached to the growing front of a crystal by processes of adsorption and absorption. Graphite has a strong tendency to become adsorbed to porphyroblasts of garnet or staurolite and is commonly seen concentrated at their edges. However, it is also enclosed by absorption as inclusions in garnet (FIGURE 3) or staurolite porphyroblasts.

ANALYTICAL PROCEDURES

The chemical zoning of garnet in the Silgará Formation pelitic rocks has been investigated by electron microprobe analyses using a JEOL JXA 8800M electron probe microanalyzer of the Geosciences Department at Shimane University, under the following analytical conditions: accelerating voltage 15 kV, specimen current 2.5 x 10^{-8} Å, correction method after Bence & Albee (1968). Color map analysis conditions were: probe current 7.5 x 10^{-8} Å (in average), dwell time 60 msec (in average), number the pixels between 500 x 500 and 700 x 700 (depending on the grain size), and pixel size (depending on the grain size and number of pixels). This technique was applied specially for garnet. Internal micro-structures were also checked using BSE images. Compositional zoning of garnets was analyzed using traverses following different chemical sectors and radial traverses from core to rim. Sometimes new analyses were made after color mapping.

MINERAL CHEMISTRY

Representative analyses of garnet are listed in TABLE 1. Garnet is almandine-rich (X_{Fe} = 0.69-0.93) with minor pyrope (X_{Mg} = 0.06-0.15), spesartine (X_{Mn} = 0.00-0.16), and grossular (X_{Ca} = 0.00-0.11).

Castellanos (2001) reported normal, reversal and sector zoning in pelitic garnet of the Silgará Formation in the central Santander Massif. Garnet usually shows a normal zoning pattern indicating prograde growth: a strongly modified bell-shaped spessartine profile, and increasing almandine and pyrope, from core to rim. There is also an overall gradual decrease in Fe/(Mg+Fe) from core to rim.

The chemical zoning from garnets can be summarized as follows:

Type I garnet (PCM-700, from the Staurolite-Kyanite zone), which is almost almandine end member, with very low content of Mg, Mn and Ca. In addition, only a slight increase of Mn at the core was observed.

Type II garnet (PCM-651, PCM-701, PCM-971, from the Staurolite-Kyanite zone), which exhibit a normal zoning with increasing of Mg and Fe component from core to rim and decreasing of Mn and Ca component also from core to rim suggesting a prograde stage of metamorphism.

Type III garnet (PCM-47, from the Staurolite-Kyanite zone, PCM-953, from the Sillimanite zone), which exhibit a normal zoning until the inner rim, but in the outer rim the chemical zoning is inverse, reflecting effects of a retrograde stage of metamorphism.

TABLE 1. Representative mineral analyses of garnet-bearing samples in metapelitic rocks of the central Santander Massif. PS: Pelitic schists.

Lithology	PS	PS	PS	PS	PS	PS	PS	PS
Met. Zone	St-Ky	St-Ky	St-Ky	St-Ky	St-Ky	St-Ky	Sil	St-Ky
Sample No.	PCM-47	PCM-618	PCM-651	PCM-700	PCM-701	PCM-702	PCM-953	PCM-971
Weight %								
SiO_2	36.44	37.06	37.74	36.07	36.68	36.70	37.31	37.03
TiO_2	0.14	0.01	0.04	0.02	0.03	0.00	0.00	0.00
Al_2O_3	20.23	21.02	21.01	19.95	20.36	20.46	21.03	21.04
FeO*	33.69	36.37	34.29	41.06	38.08	37.09	31.24	35.41
MnO	4.04	0.79	1.07	0.03	0.88	1.62	6.07	0.14
MgO	1.88	2.53	2.69	1.37	1.57	1.72	1.96	3.75
CaO	3.46	2.92	4.09	0.37	1.58	1.62	2.97	2.21
Na_2O	0.01	0.00	0.00	0.07	0.01	0.00	0.11	0.03
K_2O	0.01	0.05	0.03	0.01	0.05	0.04	0.04	0.03
Cr_2O_3	0.00	0.00	0.03	0.01	0.00	0.01	0.01	0.04
Total	99.90	100.76	100.99	98.96	99.24	99.25	100.74	99.67
Cations per 12 O								
Si	2.975	2.979	3.006	3.000	3.015	3.011	3.002	2.983
Ti	0.009	0.001	0.003	0.001	0.002	0.000	0.000	0.000
Al	1.947	1.992	1.971	1.956	1.972	1.979	1.993	1.997
Fe^{3+}	0.085	0.049	0.012	0.041	0.000	0.000	0.003	0.038
Fe^{2+}	2.216	2.396	2.272	2.815	2.617	2.545	2.098	2.347
Mn	0.279	0.054	0.072	0.002	0.061	0.112	0.414	0.010
Mg	0.229	0.303	0.319	0.170	0.192	0.210	0.235	0.450
Ca	0.303	0.251	0.349	0.033	0.139	0.142	0.256	0.190
Na	0.004	0.000	0.000	0.023	0.002	0.001	0.036	0.009
K	0.003	0.011	0.007	0.003	0.010	0.009	0.009	0.007
Cr	0.000	0.000	0.002	0.001	0.000	0.000	0.000	0.003
Total	8.049	8.036	8.012	8.046	8.010	8.009	8.046	8.034
*Total Fe as FeO + Fe_2O_3								
X_{Mg}	0.09	0.11	0.12	0.06	0.07	0.08	0.10	0.16
Almandine	73.94	80.06	75.52	93.28	86.95	84.56	69.91	78.58
Spessartine	8.97	1.77	2.38	0.07	2.03	3.73	13.77	0.31
Pyrope	7.36	9.94	10.55	5.57	6.39	6.99	7.80	14.84
Grossular	9.73	8.23	11.55	1.08	4.63	4.72	8.52	6.27

Type IV garnet (PCM-618, from the Staurolite-Kyanite zone), which exhibits a sector-zoning with very different models of zoning even in thin section-scale, and, in some cases, distribution of elements follows a radial trend, but in other cases distribution follows a patch trend. A back-scattered electron image reveals that the garnet shows a sector structure (FIGURE 2b). A X-ray Ca map of sector-zoned garnet is shown in FIGURE 2c, reflecting also a sector structure. The sector zoning, which is developed in an intermediate domain between an indistinct core and outer rim, is due to heterogeneous distribution of Mg and Fe on the {110} faces of garnet (sample PCM-618). Mn shows less pronounced sector variation, and Ca is uniform in the intermediate domain. The rim of the grain is characterized by an increase in Mg, slight increase in Mn, and decreases in Fe and Ca. Such sector zoning, although rare in metamorphic garnet, has been described by Shirahata and Hirajima (1995) for garnet at several localities in the Sanbagawa metamorphic belt.

DISCUSSION

In the analyzed garnet-bearing pelitic schists there is no a clear textural interrelationship between the development of textural sector-zoning and the presence of matrix displacement, and is difficult to precise the occurrence of cleavage domes, except by a local development of dome shaped solid graphite accumulations. An explanation for this is that in sector-zoned garnets formed in regionally metamorphism terranes, such as the Silgará Formation metapelitic sequence, post-displacement stresses may have destroyed any cleavage domes which formed in the sense of Rice & Mitchell (1991). According to them, there is a relationship between the presence of graphite within rocks, the formation of textural sector-zoning in porphyroblasts of garnet, the development of lineage structures and/or type 2 intergrowths and the displacement of insoluble matrix grains (typically the graphite). Although textural, chemical and twin sector zoning are thought to be related, they have not been observed in conjunction in the metapelitic sequence of the Silgará Formation in the central Santander Massif.

The presence of graphite or carbonaceous material in nearly all rocks containing texturally sector-zoned garnets appears to be more significant and has been mentioned by several authors (e.g., Burton, 1986; Hollister, 1970), and this is proved in sector-zoned garnets of the Silgará Formation pelitic schists. However, the significance of graphite should be treated with some caution; syntectonic spiral garnets have been reported from graphitic schists in many areas, some of them adjacent to areas with texturally sector-zoned garnets (e.g., MacQueen & Powell, 1977), reflecting the dependence of the development of all these textures on the presence of a hydrostatic stress field.

Anderson (1984) interpreted the intergrowths as a result of non-coherent lattice bonding between quartz and garnet, with quartz added continuously during garnet growth. Type 2 intergrowths possibly nucleated from type 1 inclusions, developing with the crystal orientation of the parent grain.

Cleavage domes and growth sector zoning have been interpreted as the result of growth in local stress fields developed under bulk hydrostatic conditions (Ferguson et al. 1980). However, textural observations coupled with the style of deformation in adjacent rocks, suggest that these garnets grew under active deformation (wraps and dislocations) rather than hydrostatic conditions (http://pcwww.liv.ac.uk/microstr/aziz.html).

Based in textural features and chemical zoning, two differents types of garnets were recognized for sample PCM-618; sector-zoning garnet and poikiloblastic garnet, which in some cases exhibit also a slightly zoning. These facts suggest that growing processes for sector-zoning garnet can be interpreted as a non-equilibrium stage of progressive metamorphism, followed by the growing of poikiloblastic garnet at the last stage of this event.

In the study area, the Orthogneiss Formation exhibits concordant relationships with the middle- to high-grade metamorphic rocks, including the Silgará Formation pelitic schists, and may be interpreted as syn-tectonic intrusives emplaced at close to the peak metamorphism. We suggest that the emplacement of orthogneiss masses produced a local and abrupt heating of the pelitic schists of the Silgará Formation, which led to a rapid nucleation of sector-zoned garnets during disequilibrium growth conditions. Therefore, the development of sector-zoned garnets would be related with the emplacement of orthogneiss masses. On the other hand, we suspect that the emplacement of orthogneiss masses caused contact metamorphism in the Silgará Formation, which is reflected in the development of late andalusite porphyroblasts in pelitic schists.

There is no doubt that further petrological, geochemical and geochronological data are necessary for a better understanding of the mechanism of nucleation and growth of garnet during the tectono-metamorphic evolution of the Silgará Formation, which is also very important to develop a quantitative understanding of orogenic processes, determining metamorphic P-T-D-t conditions by means of mineralogical geothermobarometry, electron probe microanalysis of coexisting minerals, and paragenetic and thermodynamic analysis of mineral equilibria. Combined with earlier results, these studies will provide a framework for understanding the geologic-tectonic development and the metamorfic evolution of the Santander Massif.

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