

THE ZONING OF GARNETS AS AN INDICATOR OF THE P.T. HISTORY OF THEIR HOST-ROCKS (*)

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(4 figures dans le texte)

ABSTRACT

This paper deals with the different types of zoning shown by metamorphic and igneous garnets. A tentative relationship between zoning and physical conditions of the host-rock during and after crystallization of garnets is inferred.

On the basis of the data presented, it is suggested that rocks whose garnets show normal zoning (i.e. a progressive decrease in Mn-content from core to rim) were subjected to no further thermodynamic activity after the crystallization of this mineral. On the other hand, garnets with Mn-enriched rims and reverse zoning (i.e. a progressive enrichment in Mn from core to rim) indicate an important change in the P and/or T conditions after the initial crystallization of garnets.

It is suggested that garnets with Mn-enriched rims were subjected to the new thermodynamic activity for a relatively short space of time. Reverse zoning suggests activity over a longer period with temperatures high enough to allow significant internal diffusion.

INTRODUCTION

Since the electron microprobe has become a widely used tool in mineralogical and petrological investigations, many unsolved problems are being now focused and some others so far unknown have been discovered. One example of this is the zoning of garnets. In fact, the electron microprobe analysis has shown that garnets display a decrease in MnO and CaO and an increase in FeO and MgO towards the edge of the crystal, though other zonation patterns are already common.

According to the interpretation proposed by HOLLISTER (1966) and ATHERTON (1968) that the decreasing Mn-content towards the crystal rim is an intrinsic feature in the mechanism of garnets growing, crystals displaying enrichment either in or towards the peripheral zones must have been generated within an environment either suddenly or progressively enriched in Mn, or, on the contrary, after their crystallization they have been subjected to P and/or T conditions very different to those under which they were generated and such conditions are responsible for the anomalous distribution adopted by Mn.

This paper deals with the different types of zoning present by garnets of metamorphic and igneous origin. An attempt is also made to establish the relationship between this zoning and the physical conditions that their host-rocks underwent during and after the crystallization of garnets.

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GARNETS IN METAMORPHIC ROCKS

Garnets of pyralpsitic composition are widespread in metapelites and meta-psammities in medium and high-pressure regional metamorphic terrains, although they also occur in some rocks of low-pressure regional metamorphism and some contact metamorphic aureoles.

In agreement with the works of BANNO (1965), DE BÉTHUNE *et al.* (1965, 1968, 1975), ATHERTON and EDMUNDS (1966), HARTE and HENLEY (1966), HOLLISTER (1966, 1969), BROWN (1967, 1969), ATHERTON (1968), EDMUNDS and ATHERTON (1971), FEDIUKOVA and VEJNAR (1971), GRANT and WEIBLEN (1971), KURAT and SCHARBERT (1972), DE PIERI and GALETTI (1972), BIRK (1972) and LOPEZ RUIZ *et al.* (1975), the garnets of metamorphic rocks display the following types of zoning (*).

- a) Normal zoning. The Mn and Ca contents decrease from core towards the crystal rim, while the Fe and Mg contents increase (Fig. 1a). In general, the variation of Mn, Mg and Fe is clearly gradual, but the Ca-profiles frequently present many irregularities, sometimes of oscillatory type.
- b) Normal zoning with Mn-enriched borders. In most of the crystal, the elements are distributed as in the type a), but in the border zone the Mn content increases, and some cases also the Ca-content, while Fe and Mg percentages decrease (Fig. 1b).
- c) Reverse zoning. The Mn-content increases and the Fe-content increases or decreases from the core towards the crystal rim, while the Mg and Ca percentages show little variation, or decrease towards the outer limit of the crystal (Fig. 1c). In some garnets this variation can only be observed in the outermost zone of the crystal, the central zone being homogeneous.

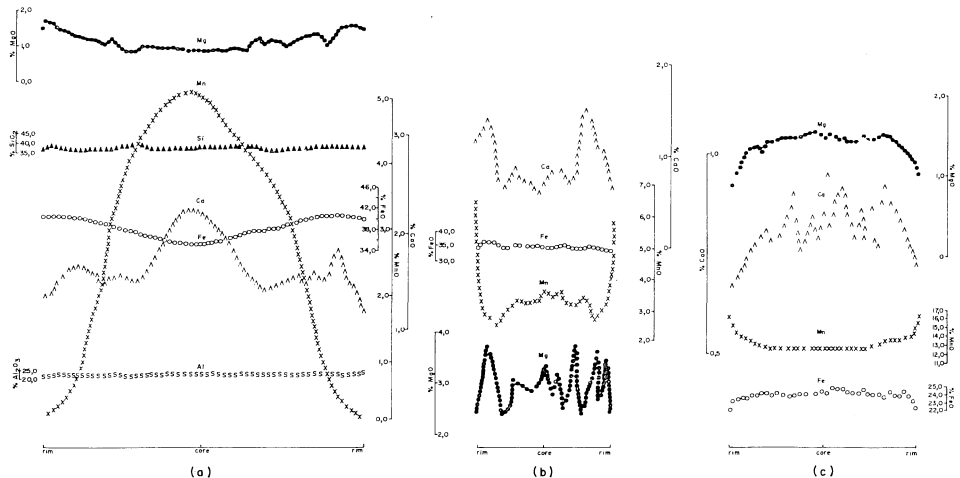


Fig. 1. — Zoning types of garnets in metamorphic rocks from Sierra de Guadarrama (after LOPEZ RUIZ *et al.*, 1975). a : normal zoning, b : Mn-enriched border, and c : reverse zoning.

(*) The zoning types are mainly based on the distribution of Mn, since this element is probably the most sensitive to the P and T changes.

Systematically garnets with normal zoning occur in low-to medium-grade rocks which have undergone progressive metamorphism (BANNO, 1965; DE BÉTHUNE, *et al.* 1965; HARTE and HENLEY, 1966; BROWN, 1967, 1969; ATHERTON, 1968; HOLLISTER, 1969; etc.).

This normal zoning, concerning Mn, has been interpreted as due to :

- 1) Growing of garnet during the metamorphic process (BANNO, 1965; DE BÉTHUNE *et al.*, 1965; HARTE and HENLEY, 1966; and BROWN, 1969).
- 2) Segregation of Mn from the matrix (other coexisting phases) to the growing garnet (HARTE and HENLEY, 1966; HOLLISTER, 1966 and ATHERTON, 1968).

The first model is based on the fact that the general pattern of this zoning shows a change of chemical composition similar to that which, according to MIYASHIRO (1953), ENGEL and ENGEL (1960), STURT (1962), BANNO (1964), NANDI (1967), ATHERTON (1968), etc., takes place in garnets with respect to metamorphic grade. Nevertheless, as MULLER and SCHNEIDER (1971), LOPEZ RUIZ and GARCIA CACHO (1974) and LOPEZ RUIZ *et al.* (1975) have recently established, there is no evident correlation between garnet composition and metamorphic grade, so the increase in pressure and temperature can not be the factor — or at least the only factor — which controls this zoning.

Concerning the second model, HOLLISTER (1966, 1969) found that the distribution of Mn in garnets obeys the model of fractionation developed by Rayleigh to determine the composition of the liquid condensed from a multicomponent vapor, while the distribution of Mg and Fe is determined by the Mn-content in the garnet. Later, ATHERTON (1968) applied the zone refining process — which HARRIS (1957) had already used in order to explain the abnormal composition of potassic magmas — to explain normal zoning in garnets.

These very similar fractionation and segregation models require the same previous conditions : little or no diffusion in the garnet, total diffusion in the matrix (that is to say, an homogeneous reservoir) and constant fractionation (segregation) factor during garnet growth.

In spite of evidence suggesting that at least two of the assumptions [homogeneous reservoir, and constant fractionation (segregation) coefficient] required by the proposed models are not satisfied in a metamorphic environment (see, MULLER and SCHNEIDER, 1971), there exists concordance between the Mn-curves theoretically calculated and those determined from analytical data. The slight divergence between the calculated and measured curves in the middle and final stages of growth, is likely due to the variation of the fractionation coefficient during garnet development. This is a probable consequence of an increase of temperature and a decrease of modal percentages of the others minerals in which Mn can also be a component (HOLLISTER, 1966, 1969 and ATHERTON, 1968).

Regarding Ca, the profiles that show the distribution of this element in some garnets (see e.g. HARTE and HENLEY, 1966; LINTHOUT and WESTRA, 1968; HOLLISTER, 1969; KURAT and SCHARBERT, 1972) are similar to Mn-profiles, whereby its distribution can also be explained by the same process of fractionation (segregation). However, the most frequent curve presented by Ca (see Fig. 1) suggests that the appearance or disappearance of calcium-bearing minerals (HOLLISTER, 1966; HARTE and HENLEY, 1966 and ATHERTON, 1968) and/or an increase in pressure (or an increase in temperature with little or no increase in pressure) during the growth

of crystal (RAHEIM, 1975), may be the factors responsible for the distribution of Ca in garnets.

Finally, MgO and FeO concentrations are conditioned by those of MnO+CaO due to diadochy (see Fig. 2).

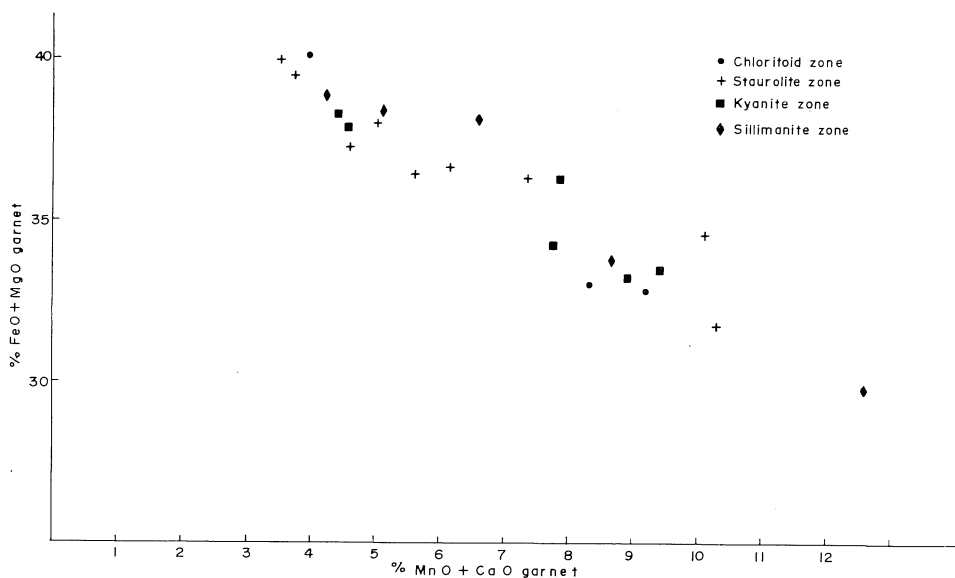


Fig. 2. — Relation between FeO + MgO and MnO + CaO percentages of garnets in metamorphic rocks from western region of Sierra de Guadarrama (according to data of LOPEZ RUIZ *et al.*, 1975).

Garnets with a Mn-enriched border have been reported by several authors (e.g. CHINNER, 1962; DE BÉTHUNE *et al.*, 1968, 1975; LINTHOUT and WESTRA, 1968; EDLUNDS and ATHERTON, 1971; BIRK, 1973; LOPEZ RUIZ *et al.*, 1975), in medium grade metamorphic rocks which have undergone plural metamorphism or just retro-metamorphism.

According to these authors, the Mn-enriched rim may be generated :

- 1) When the crystal regrows by a sudden increase in temperature, due to a subsequent thermal metamorphism, or more generally,
- 2) When the garnet undergoes resorption due to a change of P and/or T conditions, and Mn is retained or re-enters in the residual garnet.

This last process could also explain the Ca-enriched rim that some garnets present. Nevertheless, DE BÉTHUNE *et al.* (1975) have observed that this enrichment in Ca is conditioned by lack or scarcity of Ca-minerals in the rock.

In zones of high-grade metamorphism, garnets normally present reverse zoning (GRANT and WEIBLEN, 1971; KURAT and SCHARBERT, 1972; BIRK, 1973 and LOPEZ RUIZ *et al.*, 1975).

If according to the above exposed, garnets formed under progressive metamorphism shows normal zoning, those with reverse zoning can be generated by :

- 1) A progressive increase of MnO-content in the rock, supplied from outside, or

by release from some Mn-bearing minerals (ilmenite) that have become unstable (EVANS and GUIDOTTI, 1966).

- 2) Growth of the garnet under falling temperature (KURAT and SCHARBERT, 1972).
- 3) Partial garnet resorption, consequent with P, T changes, followed by internal diffusion due at the high temperatures involved in high grade metamorphic zones (GRANT and WEIBLEN, 1971; KURAT and SCHARBERT, 1972; BIRK, 1973 and LOPEZ RUIZ *et al.*, 1975).

Among these three possibilities, the first seems the most unlikely because of the lack of evidence in favour of an increase in MnO within the reservoir. Concerning hypothesis 2) and 3) — which require a progressive decrease of temperature —, both are possible, though the carious rims and the embayments of high grade metamorphic garnets suggest resorption, thus giving a stronger support to the third possibility.

Internal diffusion of Mn, as suggested above, may appear in contradiction with the evidence coming from directly zoned garnets. Nevertheless, in the case of high-grade garnets, it must be taken on account that a sudden decompressive event could have not been followed by a correspondingly descent of temperature. In these circumstances partial resorption, followed by internal diffusion may have actually taken place. This must have implied diffusion of Mg and Fe towards the crystal core and the same of Mn towards the rim. On the contrary, if the rapid descent of pressure has been followed by a rapid descent of temperature, the garnet must have been homogenized.

Apart from all the above mentioned interpretations of the genesis of the different types of zoning, ANDERSON and BUCKLEY (1973) have proposed that the diffusion in solid state between the matrix and the already formed garnet (which is supposed to be homogeneous) may have played a role in the garnet.

GARNETS IN IGNEOUS ROCKS

In igneous rocks pyralspitic garnets appear in a wide spectrum of rock, which ranges from ultrabasic types (peridotites, kimberlites, etc.), to intermediate and acid types (andesites-dacites-rhyolites and their plutonic equivalents diorites-granodiorites-granites).

While garnets of ultrabasic rocks — in which pyrope component is dominant — are interpreted by all the authors as primary igneous phenocrysts, garnets of acid and intermediate rocks — mainly of almandine composition — give rise to the problem whether their origin is xenolithic or in the contrary they have crystallized from the magma.

This controversy on the origin of garnets of intermediate and acid rocks is greatly due to the presence of inclusions of garnets-bearing schists and gneisses in these rocks (see ZECK, 1968; DIDIER, 1973 and RODRIGUEZ BADIOLA, 1973). Nevertheless, the experimental works on crystallization of andesite (GREEN, 1972) and rhyodacite liquids (GREEN and RINGWOOD, 1972), as well as the petrographic studies (e.g. OLIVER, 1956) support a magmatic origin for garnets found in intermediate and acid igneous rocks.

a) *Andesites-dacites-rhyolites*

In many calc-alkaline volcanic rocks there exists euhedral to subhedral garnet

phenocrysts, which reach more than 2 cm in size. These garnets generally show reaction corona of plagioclase + cordierite + biotite \pm spinel (LOPEZ RUIZ *et al.*, 1974), cordierite + hypersthene (GREEN and RINGWOOD, 1968), cordierite + biotite (MIYASHIRO, 1955) or plagioclase (OLIVER, 1956). The coronas may also be absent (BIRCH and GLEADOW, 1974).

According to the works of GREEN and RINGWOOD (1968), BROUSSE *et al.* (1972), FITTON (1972), BIRCH and GLEADOW (1974) and LOPEZ RUIZ *et al.* (1974) the garnets in these rocks present a Mn-enriched border whereas normal zoning is rare. In both cases, the distribution of Mg and Fe, is identical to that of garnets in metamorphic rocks which display the same type of zoning. However, these garnets generally show an enrichment of Ca from the core of the crystals outwards (Fig. 3). Additionally, FITTON (1972) and BIRCH and GLEADOW (1974) have found garnets in which the Fe-content decreases from the core to the rim, i.e. in the opposite-way as it is realized in the garnets found in metamorphic rocks.

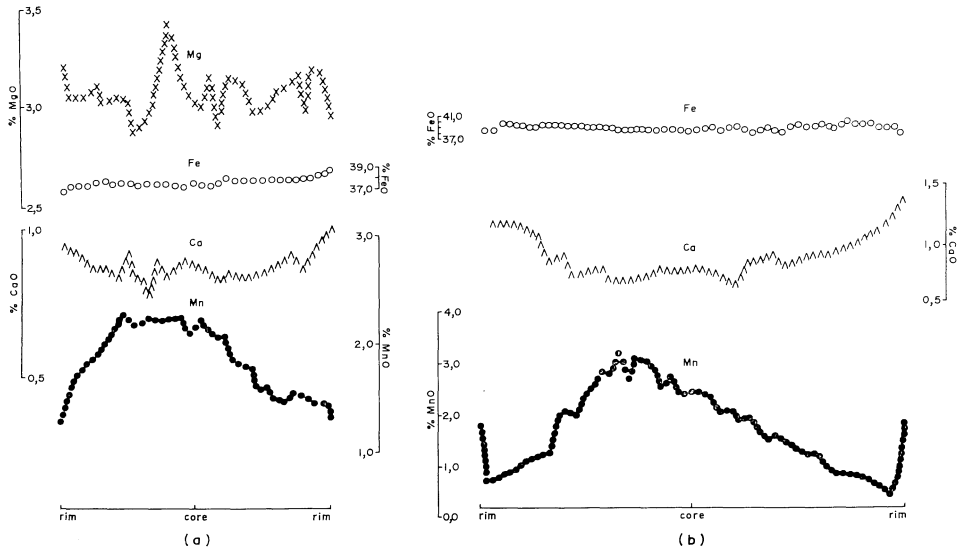


Fig. 3. — Zoning types of garnets in calc-alkaline rocks from SE de España (after LOPEZ RUIZ *et al.*, 1974). a : normal zoning, b : Mn-enriched border.

The progressive Ca-enrichment outwards of this garnets is in agreement with the variation trends experimentally established by GREEN and RINGWOOD (1968) and GREEN (1972) for the garnets crystallized from calc-alkaline liquids. The abnormal distribution adopted by Fe in some crystals may be explained by the simultaneous crystallization of Fe-rich biotite (BIRCH and GLEADOW, 1974).

The fact that garnets in these rocks generally appear as big phenocrysts, suggests that they were generated at an early stage of crystallization. This is supported by the works of GREEN (1972) and GREEN and RINGWOOD (1972) which showed that garnet is a liquidus or near-liquidus phase in melts of andesitic and rhyodacitic composition at high pressures. Hence, it seems likely that the quicker or slower pressure release which the magma undergoes when rising to shallow crustal levels, is responsible for the disequilibrium between garnet and magma, so that garnet is partially transformed into plagioclase + cordierite + biotite \pm spinel, etc.

This transformation also explains the Mn-enriched rims of garnets in calc-alkaline rocks.

b) *Granitic and associated rocks*

In some granitic massifs, some facies contain garnet as an accessory mineral. In general, such garnets are more or less euhedral, fractured and bear no reaction rims though in some cases they can be more or less transformed into chlorite and biotite.

These garnets have been studied to a lesser detail than those in metamorphic and volcanic rocks. Notwithstanding, from the works of LEAKE (1967), BIZOUARD *et al.* (1970), LOPEZ RUIZ and GARCIA CACHO (1975) and CORRETGE *et al.* (in preparation), it can be inferred that garnets in granitoids, as well as those in associated aplites and pegmatites, present normal zoning or Mn-enriched border and seldom reverse zoning.

In the three different zoning types, Fe and Mg vary in the opposite way to Mn, while Ca increases from core to rim (Fig. 4). This variation of Ca shown by garnets in granitic rocks, compares well with garnets in andesites, and makes them rather different from the garnets in metamorphic rocks.

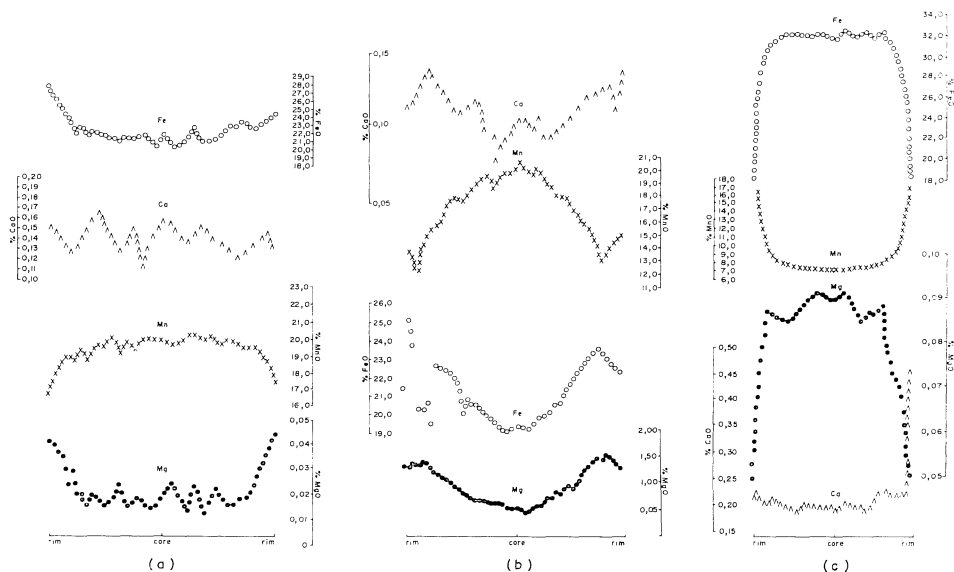


Fig. 4. — Zoning types of garnets in granitic and aplitic rocks from Sierra de Guadarrama (after LOPEZ RUIZ and GARCIA CACHO, 1975). a : normal zoning, b : Mn-enriched border, and c : reverse zoning.

According to the above mentioned studies, garnets which have not undergone any transformation or resorption show normal zoning, while those partially transformed present Mn-enriched rims. Both types of zoning evidence an igneous origin for these minerals, since, as can be inferred from the previous discussion, garnets of high-grade metamorphic rocks commonly bear reverse zoning.

Although garnets in granitoids generally bear normal zoning or Mn-enriched rims, in some areas (for example, Sierra de Guadarrama, Sistema Central, Spain),

garnets with reverse zoning have been described (LOPEZ RUIZ and GARCIA CACHO, 1975). In these case, the textural and compositional differences between the garnets with normal zoning and Mn-enriched rims (euhedral and rich in spessartine) and garnets with reserve zoning (anhedral, strongly fractured and almandine-rich) indicates that the latter have probably been developed from lightly differentiates granitic melts, whereas the spessartine-rich garnets grew from late magmatic differentiates.

CONCLUSIONS

- 1) Garnets of pyralspitic composition in metamorphic and igneous rocks always present a variation of composition from core to rim. According to the distribution of Mn, three different zoning types can be distinguished : normal, normal with Mn-enriched rims and reverse.
- 2) The existence of garnets with normal zoning in metamorphic, plutonic and volcanic rocks, shows that such a zoning is an intrinsic feature of the growing mechanism of these minerals, which is not dependent on the P, T conditions of their crystallization. Nevertheless, if after the crystallization of garnets there is an important change in the P and/or T conditions, these minerals undergo some change in their zoning, passing firstly to have a Mn-enriched border and afterwards to reverse zoning, if the conditions are maintained for sufficiently long time and temperature is high enough to allow internal diffusion.
- 3) Taking in account the conditions under which these last two types of zoning are developed, garnets in volcanic rocks will generally display Mn-enriched rims, since the P and T variations which could take place in these rocks are rapid. On the contrary, garnets in rocks of high metamorphic grade and also garnets in plutonic rocks will have a tendency to display reverse zoning, since in these rocks any P, T changes is always slower.

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