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Garnet crystal growth in sheared metapelites (southern Calabria - Italy): relationships between isolated porphyroblasts and coalescing euhedral crystals

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Abstract. — Three different generations of garnet (Type 1a, Type 1b and Type 2) occur in sheared metapelite of the Cardeto Metamorphic Complex (CMC), cropping out in the southern sector of the Aspromonte Massif (southern Calabria, Italy). Main differences are their size, chemical trends, inclusion trails geometry, and crosscutting relationships with different foliations. All of these aspects were used to discriminate between garnet typologies. The CMC was metamorphosed under greenschist to low-amphibolite facies conditions. The peculiar feature of the whole complex is the presence of a pervasive mylonitic foliation. Alternation of quartz and mica domains, the latter essentially consisting of chlorite, muscovite and subordinately of biotite, gives the main schistosity. Besides these minerals garnet, plagioclase, epidote and amphibole complete the typical rock assemblage. Microstructural evidences associated with mineral-chemical data suggest multistage garnet growth. The first garnet generation (Type 1a) is represented by pre-mylonitic porphyroblasts (up to 8 mm in diameter), usually characterized by plane-parallel inclusion trails. The second generation consists of syn-mylonitic garnets (Type 1b), characterized by spiral-shaped inclusion trails, which give to them the classical snowball appearance. Internal foliations are commonly defined by aligned grains of quartz and ilmenite. A multistage growth was recognized for these garnets by means of both compositional traverses and X-ray maps revealing concentric zonation patterns. The second garnet generation (Type 2) consists of smaller euhedral garnets, usually 100 μm in diameter (occasionally up to 400 μm). They typically occur as several adjacent crystals coalescing around Type 1a and 1b garnets. In samples the outer edge of garnet porphyroblasts (Type 1a and 1b) is the indentation of the adjoining borders of many small idioblastic coalescing grains (Type 2). Layers of small euhedral garnets, concentrically chemically zoned, parallel to the mylonitic foliation were also observed. They could have been developed through different processes: (1) mechanical alignment of already existing Type 2 garnet grains due to the shear deformation or (2) they represent a further stage of crystallization prevalently localized into small domains parallel to the main foliation, favoured by a high mobility elements flux along these surfaces.

The process of coalesced euhedral garnets over pre-existing garnet porphyroblasts, here described, could be a widespread crystallization mechanism inside shear zones. The elevated fluid concentration typically present within shear zones could promote the sustenance of chemical elements which support either overgrowth or multistage crystal growth processes.

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Riassunto. — Nelle metapeliti milonitiche del Complesso Metamorfico di Cardeto (CMC), affiorante nel settore meridionale del Massiccio dell'Aspromonte (Calabria meridionale, Italia), sono state riconosciute tre differenti generazioni di granato (Tipo 1a, 1b e Tipo 2). Le principali differenze sono costituite dalle dimensioni, dalle variazioni composizionali nucleo-bordo, dalle geometrie delle inclusioni preservate all'interno dei cristalli e dalle relazioni tessiturali che esse mostrano con le principali foliazioni metamorfiche. Tutti questi aspetti sono stati utilizzati come criteri discriminanti. L'evento metamorfico principale rinvenuto nelle rocce del CMC si è sviluppato in condizioni comprese tra la facies scisti verdi e la facies anfibolitica inferiore. Il carattere peculiare dell'intero complesso consiste nella presenza di una pervasiva foliazione milonitica definita dall'alternanza di domini quarzosi e micacei, gli ultimi dati essenzialmente da clorite, muscovite e subordinatamente biotite. Granato, plagioclasio, epidoto ed anfibolo completano la paragenesi tipica di queste rocce. Le evidenze microstrutturali e i dati minero-chimici suggeriscono un processo multistadiale di crescita del granato, cristallizzato sia antecedentemente che contemporaneamente rispetto alla fase milonitica. La prima generazione di granato (Tipo 1a) è rappresentata da porfiroblasti pre-milonitici (con diametro fino a 8 mm) che generalmente mostrano una foliazione interna piano-parallela. La seconda generazione è costituita da granati sin-milonitici (Tipo 1b) caratterizzati da una geometria a spirale della foliazione interna che conferisce a questi granati l'aspetto classicamente definito a palla di neve. Le foliazioni più antiche, comunemente definite dall'allineamento di individui di quarzo e ilmenite, si rinvengono all'interno dei nuclei dei granati. Per questa tipologia di granato, attraverso profili e mappe composizionali che rivelano un andamento concentrico della distribuzione degli elementi, è stata riconosciuta una crescita pluristadiale. La seconda generazione di granato (Tipo 2) consiste in piccoli individui euedrali generalmente di 100 μm di diametro (raramente fino a 400 μm), che tipicamente formano accrescimenti coalescenti attorno ai granati del Tipo 1. In molti campioni è evidente come il bordo più esterno dei porfiroblasti di granato di Tipo 1a e 1b sia costituito dall'indentazione dei bordi adiacenti dei più piccoli idioblasti di granato coalescenti (Tipo 2). Si osserva inoltre come i piccoli granati euedrali (Tipo 2), caratterizzati da una zonatura concentrica, formino livelli paralleli alla foliazione milonitica principale. L'organizzazione in livelli dei granati di seconda generazione è attribuibile a processi differenti: (1) un allineamento per cause meccaniche di granati pre-cinematici rispetto alla fase di shear che sarebbe quindi responsabile di tale tessitura o (2) l'evenienza di un ulteriore stadio di cristallizzazione localizzato preferenzialmente in domini paralleli alla foliazione principale, probabilmente favorito da un'elevata mobilità di elementi in corrispondenza di queste superfici.

Il processo di nucleazione qui descritto di granati euedrali coalescenti su porfiroblasti di granato preesistenti, potrebbe essere una modalità di cristallizzazione potenzialmente molto comune nelle zone di taglio crostali, favorita dall'elevata concentrazione di fluidi tipicamente associata ad esse, che garantendo un continuo supporto di nutrienti chimici consentirebbe questo tipo di crescita dei cristalli.

Key words: *Coalesced garnets; Crystal growth; Shear zone; Inclusion trails; Southern Calabria.*

Introduction and geological background

Relationships between blastesis and deformation episodes have long stimulated the interest of people that works on collisional belt. Information derived from microstructures became a time signature when they are properly correlated with crystal growth, thus facilitating the reconstruction of the succession of deformation and crystallization episodes that occurred in a metamorphosed area. Also very complex histories can be recorded into rocks and they can be unravelled via a careful microstructural study (Bell and Chen, 2002, Prior *et al.*, 2002). Usually, within high strain zones it is more difficult deciphering crystallization-deformation relationships because a possible transposition of pre-existing structures might occur. Anyway, in particular conditions, remnants of the previous structures together with corresponding assemblages can survive to a complete obliteration. These relics may indicate important constraints for the reconstruction of the textural evolution of a metamorphic rock and, with all due cautions, of an orogenic area. In this context, although shear zones and correlated mylonites represent a complex set for applying microstructural technique, they are a fascinating opportunity for studying this kind of relationships. Indeed, the time linkage between crystallization and shear episode in these highly deformed rocks, can help petrologists to understand the evolution of metamorphic terrains involved in mountain belts orogenesis.

A good opportunity to study the process of crystal grow inside a shear zone comes from metapelites outcropping near the village of Cardeto, situated in the Aspromonte Massif (Fig.1). Three types of garnet have been distinguished in the greenschist to low amphibolite-facies sheared metapelites of the Cardeto Metamorphic Complex (CMC) (Fazio *et al.*, 2008) on the basis of their typology, textural relationships and chemical zoning.

The CMC occupies the lower position of a stacking nappes edifice that characterizes the framework of the Aspromonte Massif (Pezzino *et al.*, 1990; Bonardi *et al.*, 1980, 1992; Graeßner and

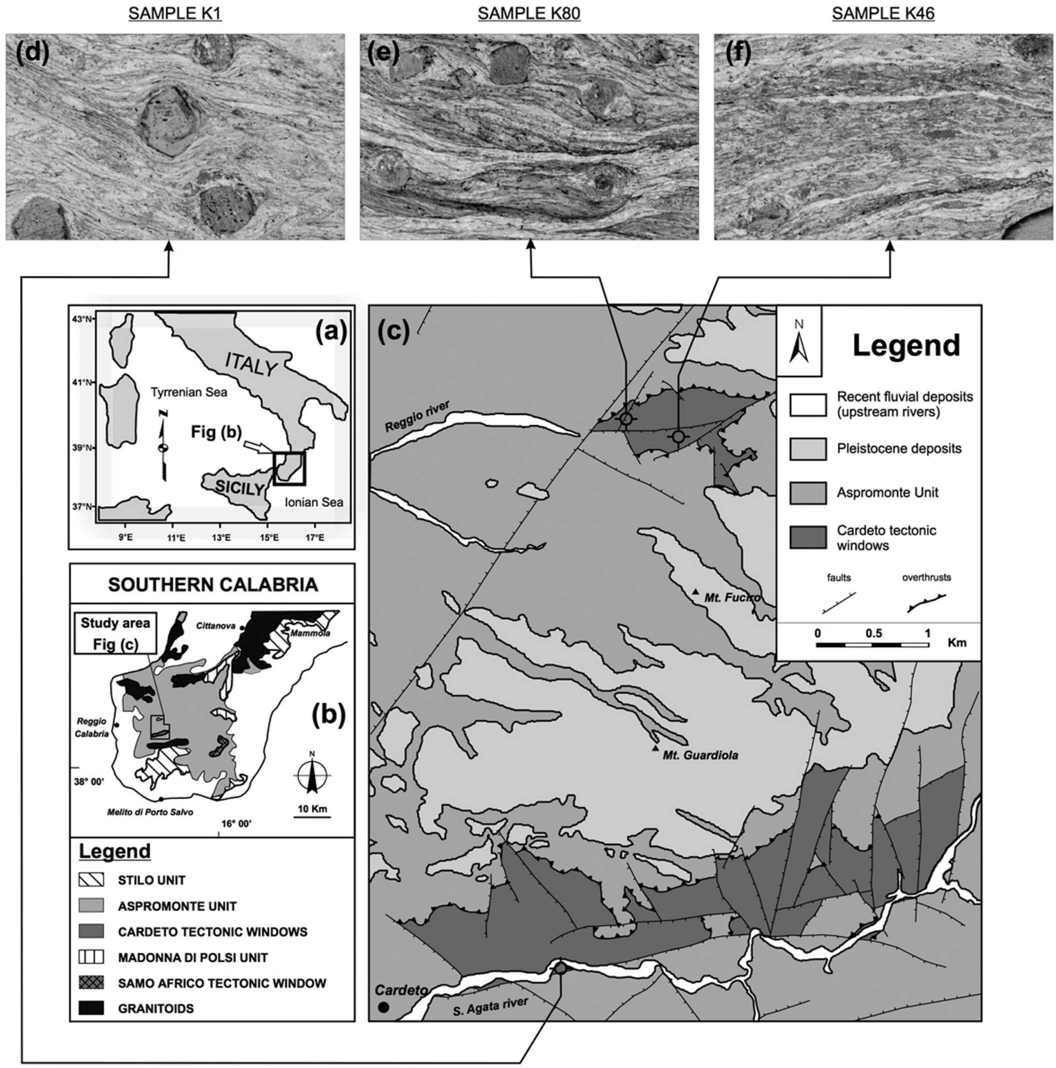

Fig. 1 – (a) Location map of the study area in the southern Mediterranean area; (b) simplified geological map of southern Calabria (modified after Graeβner & Schenk, 1999); (c) detailed geological map of the Cardeto area (modified after Fazio *et al.,* 2008) with sample locations; (d), (e) and (f) scans of thin sections (plane-polarized light) of samples K1, K80 and K46.

Schenk, 1999; Ortolano *et al.*, 2005; Russo *et al.*, 2006), a piece of the Calabrian Peloritani Orogen (CPO), constituting an intricate collage of Variscan basement terrains locally reworked during Alpine orogeny (Atzori *et al.*, 1984; Festa *et al.*, 2004) and representing a complex orogenic structure in the western Mediterranean realm (Ogniben, 1973).

In more detail, the Aspromonte Massif consists, from top to bottom, of crystalline basement rocks belonging to three different units: the Stilo Unit (SU, Dietrich *et al.*, 1976), the Aspromonte-Peloritani Unit (APU, Pezzino *et al.*, 1990) and the Madonna di Polsi Unit (MPU, Pezzino *et al.*, 1990; Pezzino *et al.*, 2008). Near the tectonic contact between different units, cataclastic to mylonitic rocks usually occur. The CMC crops out in two main tectonic windows of a few square kilometres and corresponds only to a portion of the wider MPU (Pezzino *et al.*, 2008).

A detailed microstructural and chemical study of garnet grains of the CMC mylonites was made in order to establish relationships existing between crystallization episodes and deformational phases, attempting to cast a new light on crystal growth processes operating within shear zones. With this aim we have monitored the microstructural and chemical evolution of different typologies of garnet crystals in mylonitic rocks from the Aspromonte Massif. In particular a widespread overgrowth of coalescing smaller crystals at the rim of earlier porphyroblast was observed. Similar situations are broadly illustrated in the petrological literature (Feenstra *et al.*, 2007; Spiess *et al.*, 2001; Storey and Prior, 2005; Whitney *et al.*, 2008) and the results presented in this paper contribute to give an evidence of this matter.

MESO- AND MICRO- STRUCTURES

The chapter briefly summarizes the essential characteristic of structures visible both at meso- and micro-scale (for a more complete description refer to Fazio *et al.*, 2008). Four principal deformational phases (D_1-D_4) have been recognized by the detection of related structures in the field. Meso- and micro-structural analysis (Figs. 2, 3 and 4) made on CMC rocks indicates a main shear deformation episode (D_3), which sometimes obliterates earlier structures. The first one (D_1) consists of an isoclinal folding (B_1 axis) of a pre-existing surface (S_0), which generates a new axial plane surface (S_1). The S_1 foliation appears successively folded (D_2) at millimetre scale (B_2 axis), with consequent formation of a crenulation cleavage foliation (S_2). The successive deformational event (D_3) produces a mylonitic foliation (S_3) with an associated stretching lineation (L_{str}). The last deformational event (D_4) generates asymmetrical to isoclinal folds (B_4 axis) of the S_3 foliation. Further successive deformation episodes consist of brittle-regime related structures like thrusts preferentially emplaced on pre-existing mylonitic levels and two intersecting normal fault systems (NW-SE and NE-SW oriented) that disarticulate the entire Aspromonte Massif creating a classic horst and graben structure.

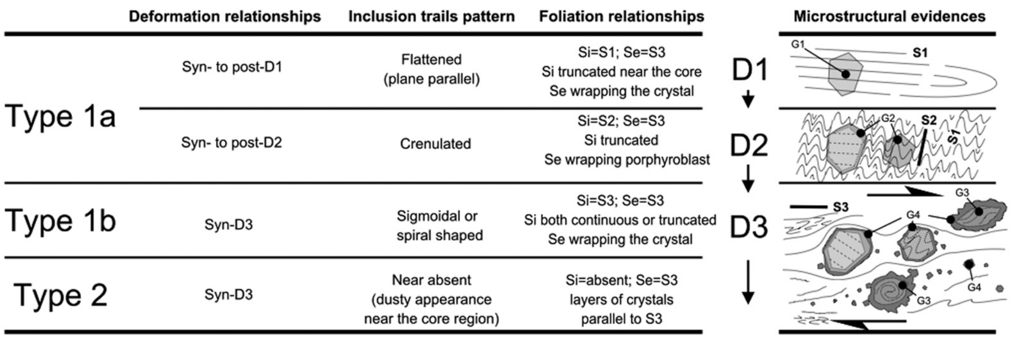

Fig. 2 – Sketch-drawing of relationships between garnet growth stages and deformation history of sheared metapelites.

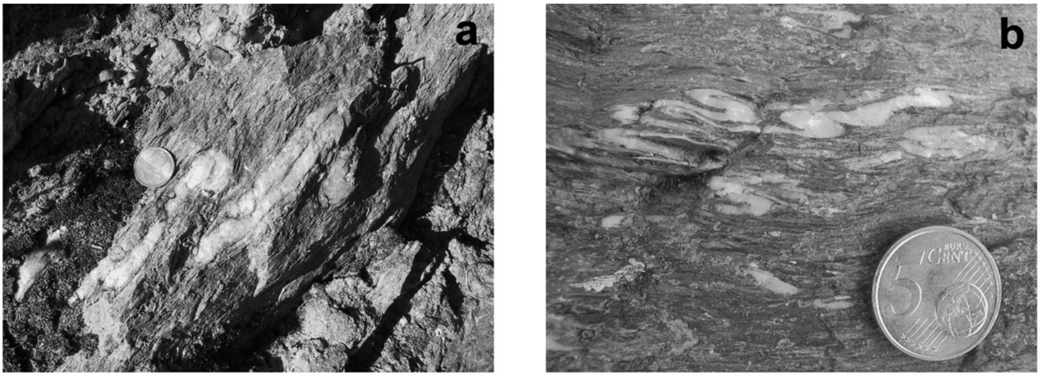

Fig. 3 – Mesostructures related to: (a) first isoclinal folding (D_1); (b) post-shear asymmetric folding (D_4).

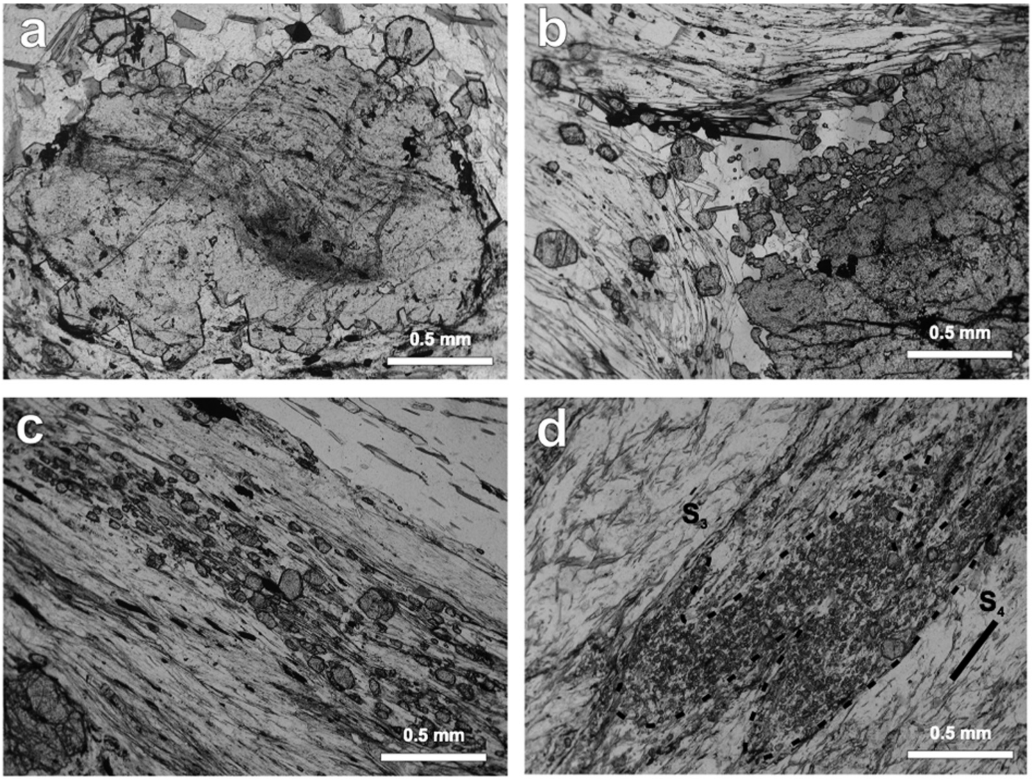

Fig. 4 – Microphotographs. (a) Type 1a garnet porphyroblast (plane-polarized light) with a rim composed by coalescing of several smaller Type 2 crystals. (b) Type 2 garnets embedded into layers parallel to the mylonitic foliation deflected around a Type 1b porphyroblast (right area of the picture). (c) Layer composed by Type 2 garnets aligned parallel to the main S_3 foliation. (d) Layer of smaller Type 2 garnets, folded during the last deformational episode (D_4).

Regarding the microstructural features, the above mentioned foliations have been wholly recognized even in thin-section, and it is noticeable that the S_3 is the most dominant schistosity surface. Details about syn-deformational assemblages will be delineated in the next chapter.

Three families of garnet were readily distinguished by microscope observations, firstly for their different dimension: a few millimetres in diameter for the first and second generations (Type 1a and 1b), forming porphyroblasts incorporating relics of early foliations; up to 400 µm for the smaller third generation (Type 2) generally inclusion free and euhedral. The difference between Types 1a and 1b is represented essentially by the geometry of the internal foliations: relics of earlier foliations enveloped within the Type 1a porphyroblasts can be (1) isoclinally folded, (2) crenulated (3) plane-parallel or (4) missing; whereas sigmoid or spiral-shaped inclusion trails are enclosed into Type 1b garnets.

Occasionally, the idioblastic outline of an early crystal (G1 growth phase) has been observed inside the inner core of Type 1a garnet, marked by a corona of very tiny inclusions that usually confers a clouded appearance to its external edge. A second (G2) and sometimes a third (G3) growth stage are also present. They are marked by the alternation of concentric limpid and clouded shells. We believe that the third stage of growth (G3) is mostly coeval with respect to the initial phases of the shear event (D_3) and represents the oldest stage of growth of the snowball garnet (Type 1b), which are classically considered syn-kinematic crystals. At the margin of the outermost shell of large Type 1a and 1b porphyroblasts, Type 2 garnets occur. They begin to nucleate and grow (G4) around the rim of early porphyroblasts as well as in the matrix. All of these growth stages take place during the whole successions of deformational events characterizing the tectonic history of CMC rocks. On the basis of microstructural observations we suppose that: G1 and G2 crystallization episodes grew syn-tectonically with respect to the first and second deformational phases (D_1 and D_2); G3 and, in part, G4 stages of growth were developed during the shear deformational event (D_3). The last episode of blastesis (G4), possibly postdating the shear event, is to be restricted to the Type 2 garnets and occasionally to the external rim of Type 1a and 1b porphyroblasts. Type 2 garnets often coalesce together to form a mosaic structure wrapping-around the edges of early porphyroblasts. In order to establish if these assumptions are valid a mixed petrographic and petrochemical study was made.

Salient petrographic features

Detailed petrographic analyses were performed over about fifty samples collected in the Cardeto Metamorphic Complex CMC. All studied samples are metapelites consisting of quartz, white mica, plagioclase, chlorite and garnet, minor biotite, amphibole, epidote and tourmaline. Accessory minerals are rutile, apatite, zircon and opaque phases (mineral abbreviations after Kretz, 1983).

The pre-mylonitic assemblage (Qtz + Ms + Grt + Pl + Bt + Amph + Chl + Ep + Ilm), developed during the isoclinal folding related to the first deformation episode D_1, occurs along the S_1 foliation, preserved into small domains less affected by the subsequent shear deformational event (D_3). Occasionally, the syn-D_1 paragenesis is also visible like inclusion trails, mostly consisting of ilmenite needles and quartz grains within cores of large garnet (Type 1a) porphyroblasts (Fig. 5).

No significant assemblages were observed along the S_2 crenulation cleavage surface associated with D_2 deformational phase. During the shear deformational phase (D_3) the grain size reduction was accompanied by a syn- to post-shear blastesis of Qtz + Grt + Ms + Bt + Pl + Chl + Ep ± Tur ± Amph. The syn-shear S_3 foliation is defined by the preferred orientation of mica flakes and elongated quartz grains that drape early garnet (Type 1a) porphyroblasts.

Beside the above-described garnets, some specimens contain porphyroblasts (average diameter size of 2.5 mm) with peculiar inclusion trails patterns that are different with respect to that previously illustrated. They are mostly characterized by a sigmoid shape and sporadically by spiral shaped inclusion trails, which could be possibly related to a rotation during crystallization (snowball garnet). These garnets (Type 1b; Fig. 6) could entrap microstructures generated during the deformational shear phase, like asymmetric crenulation cleavage, shear bands or S-C textures. This kind of garnet, often called 'rotating' garnet

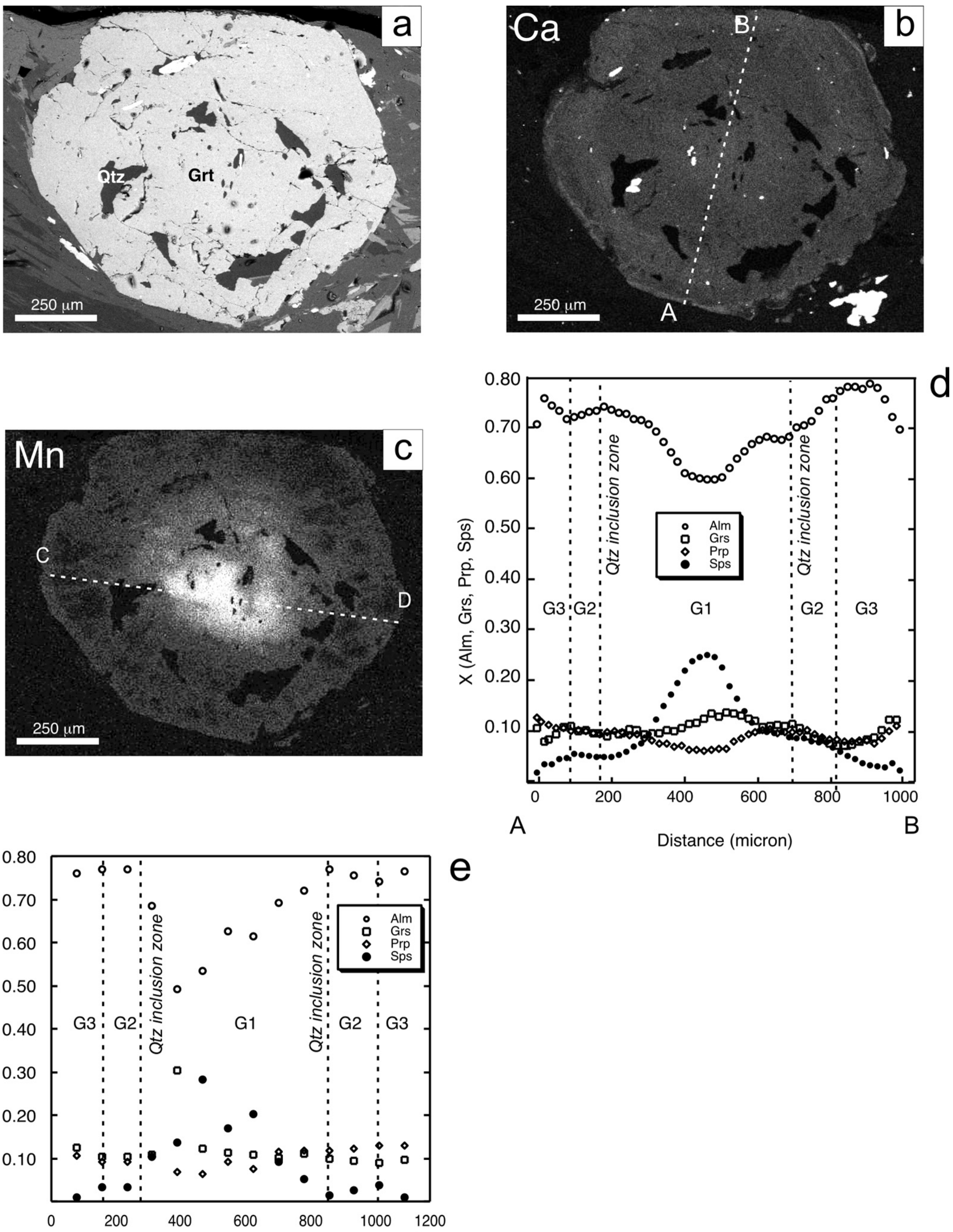

Fig. 5 – (a-c) BSE image, Ca and Mn compositional maps of Type 1a porphyroblast highlighting three stages of growth (G1, G2, G3). Mn distribution pattern reveals the first stage of growth (G1) corresponding to the inner core region enclosed within a circle made by quartz inclusions. Compositional traverses AB and CD are shown in (d) and (e), respectively.

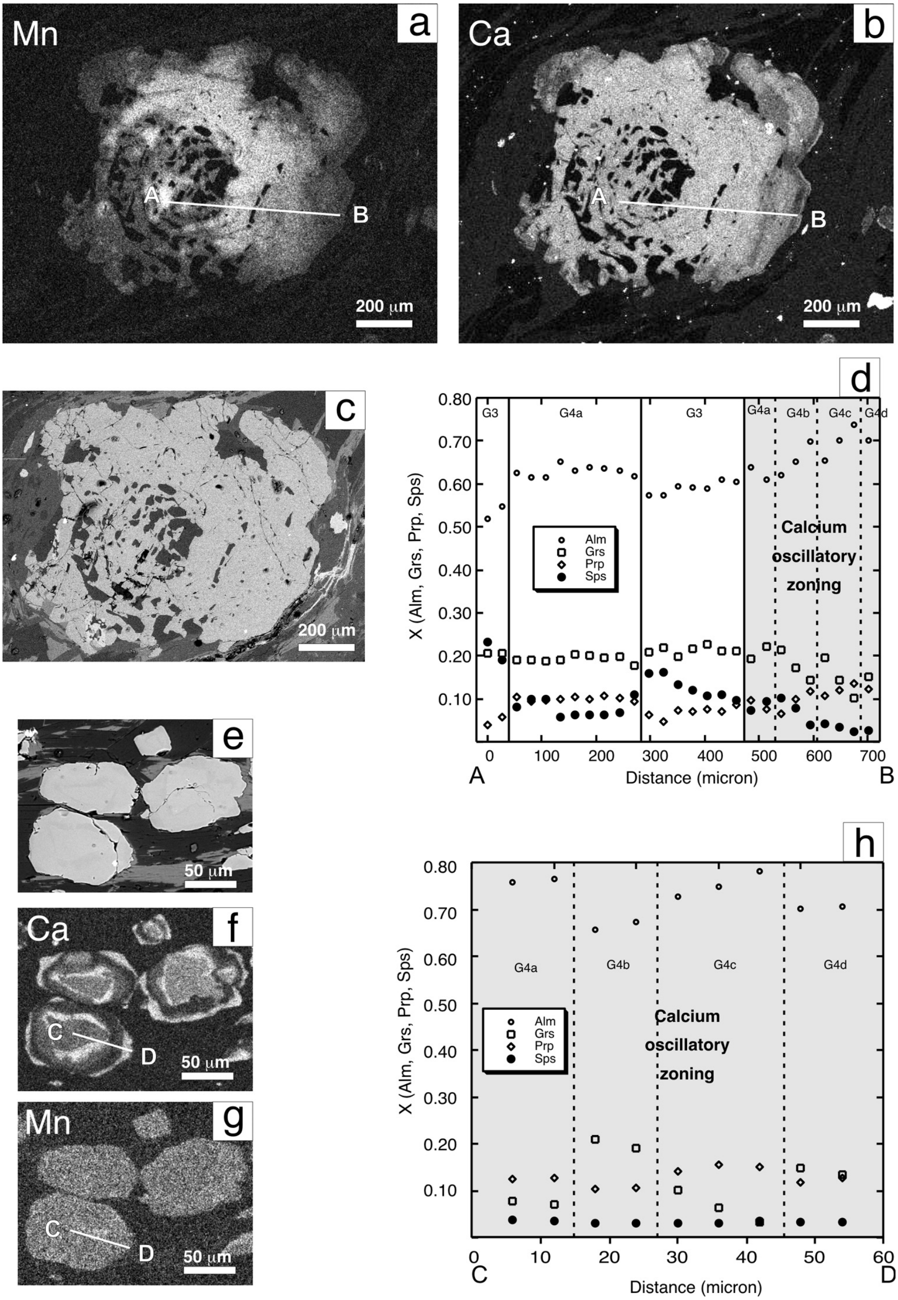

Fig. 6 – (a-c) Mn, Ca and BSE maps of a Type 1b porphyroblast. Multiple stages of growth (G3, G4a-d) were recognized into this garnet porphyroblasts put in evidence by inclusion trails patterns and also by alternating concentric crystal regions of different Ca compositions. (d) Compositional profile AB of garnet shown in (a) and (b). (e-g) BSE, Ca and Mn maps of Type 2 garnets. (h) Compositional traverse CD of a Type 2 garnet showing an oscillatory Ca zoning and an almost flattened core-rim profile of Mn.

in the literature, is very commonly observed in sheared rocks.

Type 2 garnets constitute either aggregates around earlier garnet crystals (Type 1a and 1b) or form layers which are interbedded to micaceous and quartz-rich domains. The textural relationship of these garnets with respect to the S_3 foliation allow to assess that they are from pre-D_3 to syn-D_3.

Type 2 garnets show peculiar features: they occur at the outer shell of large pre-existing garnet porphyroblasts (Type 1a and 1b) and are characterized by euhedral shape and regular outline. In most of cases it is possible to discern the margins of adjoining idioblastic smaller crystals, which form a coronitic texture around the rim of large porphyroblasts (Fig. 4a). Type 2 crystals also appear in the rock matrix, sometimes arranged into layers parallel to the mylonitic foliation. In a few of samples these garnet levels show isoclinal to asymmetric folding related to a subsequent deformational event (D_4) (Fig. 4d). Sporadically, on the S_4 axial plane surface related to this last folding event, a blastesis of Qtz + Ms + Pl + Chl + Ep occurred. Locally, a static growth of muscovite and biotite produces grains crosscutting the S_3 mylonitic foliation.

Timing of porphyroblast growth

The metamorphic rocks of CMC show three distinct foliations (S_1, S_2 and S_3) developed during different deformational phases (D_1, D_2 and D_3). The main foliation is the third one (S_3): typical shear associated microstructures, like stretching lineation, S-C texture, and evidences of rotation of pre-existing rigid objects support the mylonitic nature of this foliation. The D_3 deformation often obliterates the previous structures causing their transposition. Relicts of previous microstructures are occasionally preserved within discrete domains aligned with the mylonitic foliation, as well as they are frozen into porphyroblasts (Fig. 7a, b). Quartz rich levels have widely experienced a subgrain boundary migration recrystallization process.

Type 1a garnets show inclusions usually consisting of quartz and opaque minerals. This foliation interpreted to be the S_1 foliation generated by the isoclinal folding of an early (S_0) surface (Fig. 7a, b). The inclusion trails, occurring in the central portion of porphyroblasts, are often plane-parallel. We assume that these inner regions represent the first stage of garnet growth (G1). This internal foliation, defined by aligned minerals, sometimes appears folded. These microfolds of sub-millimetre wavelength (300 µm) were ascribed to the S_2 crenulation cleavage, which appears to be enclosed into Type 1a porphyroblasts (G2). These observations confirm that Type 1a porphyroblasts grew during the development of both D_1 and D_2 deformational phases. In particular, the G1 crystallization stage could be restricted in the time span from syn-D_1 to pre-D_2; the G2 overgrowth should be considered to be from syn- to post-D_2.

The presence of a third garnet growth stage (G3) has been attributed to the syn-shear crystallization phase. Since garnets showing spiral shaped inclusion trails (Type 1b) are not so widespread in the CMC rocks, they were considered as the result of particular local strain situations and will be therefore treated differently, as suggested by Paterson and Vernon (2001). They emphasized that rare and complex internal foliation patterns (S_i) should be distinguished from the common patterns, because the former could represent the overgrowth of locally developing structural heterogeneities. The above-mentioned Authors have identified some spectacular examples of how porphyroblasts can act as rigid objects and strongly concentrate strain along their margins, testified by the presence of crenulations in mica-rich layers that markedly increase in intensity near porphyroblasts. They argued that continued porphyroblast growth would record strongly curved, locally orthogonal foliation patterns, even though these structures are absent from quartz-rich layers just a few millimetres away, like was observed in the rocks of CMC. In this view, complex internal foliation pattern could represent different stages of a single deformation episode rather than separate phases of deformation, even if clear truncations of S_i are present (Paterson and Vernon, 2001).

The asymmetric cleavage congealed inside one of these garnets could be related to an initial growth stage immediately subsequent to the development of shear bands probably generated during an incipient phase of simple shear deformation. The spiral shaped inclusion trails with a clockwise asymmetry (Fig. 6a, b,

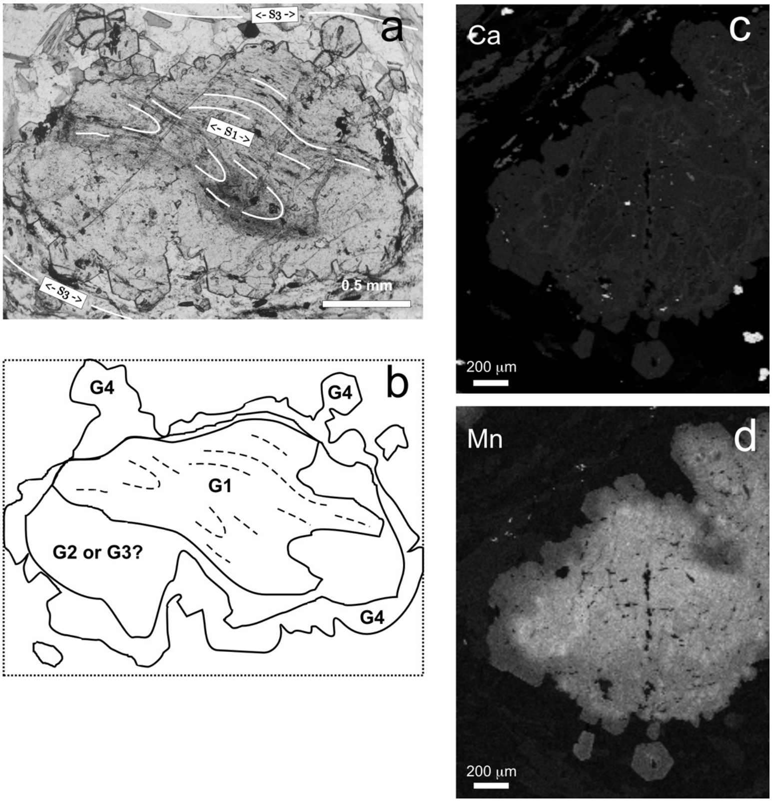

Fig. 7 – (a-b) Stages of growth and inclusion trails geometries in a Type 1 garnet porphyroblast surrounded by a secondary corona made by a mesh of Type 2 well faceted garnet crystals. (c-d) Ca and Mn distribution maps of the same porphyroblast shown in (a). A relative lower spessartine composition characterizes the external porphyroblast edge with respect to the inner region.

c) should have crystallized coevally with the following progressive simple shear deformation phases, testifying possibly a rotation during crystallization (Johnson, 1999). The internal foliation related to the first kind of microstructure (asymmetric crenulation cleavage) seem to be approximately continuous with the external mylonitic foliation S_3, even if it could be present more than one stage of growth evidenced by the clouded appearance of core and rim region respect to the intermediate limpid zone of garnet. The observed features could be the result of different processes: 1) several discrete steps of growth, 2) slight chemical variation of garnet, 3) variable rates of growth.

Remnants of the spiral shaped inclusion trails are often enclosed in the core of the porphyroblasts circumscribed by quartz patches that isolate the inner region from the rest of the garnet, the latter usually made by a lot of faceted sub-grains (G4). An X-ray map of a snowball garnet illustrates (Fig. 6a, b) a inner region revealed by the Mn distribution, entrapping a spiral shaped inclusion trail, which could represent a previous episode of blastesis (pre- to syn-D_3) surrounded by an additional stage of growth (G4). The internal region outlined by means of X-ray maps suggests a pre- to syn-kinematic (pre- to syn-D_3) feature for the core of porphyroblast (G3) succeeded by an overgrowth phase (G4). The above-mentioned microstructures suggest a pre- to syn-D_3 deformation feature for the snowball garnets, which preserve a detailed timing of blastesis, principally occurred during the shear event.

The external region of garnet porphyroblasts, related to the fourth stage of growth (G4), clearly reveals a border made by a mesh of several small garnet crystals (Type 2) (Fig. 7). Also optically it is possible to distinguish a mosaic-like domain of smaller garnet grains coinciding with the outermost region of Type 1a and 1b porphyroblasts, in which it is possible to recognize a coalescence of distinct crystals often characterized by well-developed facets (Fig. 7). In most cases, Type 2 garnets, isolated from the neighbouring Type 1a and 1b rim and probably involved into D_3 deformation, are arranged parallel to the S_3 mylonitic foliation (Fig. 4b, c).

Inside some Type 1a porphyroblasts, large quartz domains forming inclusions occur (Fig. 5). They confer to the garnet a skeleton appearance and were interpreted as relics of pressure shadows related to a temporarily cessation of blastesis followed by a further crystal overgrowth. The region between these quartz inclusions and the external edge of garnet grain was interpreted as corresponding to another stage of growth (G3). The external edge of these crystals is sometimes affected by an overgrowth stage (G4) revealed by an appreciable modification of the chemical composition towards garnet periphery. In a few specimens, the boundary between the outermost and its adjacent stage of growth (G3-G4, G2-G4 or G1-G4) into garnet porphyroblasts is frequently well delineated by patches of graphitic inclusions and more rarely is marked by a corona of rutile.

Furthermore, the large Type 1a and 1b porphyroblasts are enveloped by the S_3 mylonitic foliation, that appears deflected around them (Fig. 6c), producing strain caps at their margins marked by ilmenite grains, as well as pressure shadows consisting of quartz, chlorite and muscovite. The above features allow establishing that S_3 foliation, developed during the shear episode D_3, dates the last stage of growth (G4).

Garnet chemistry and zoning patterns

Chemical data and elements distribution maps were collected by a Cameca SX-100 equipped with five spectrometers installed at the Institut für Mineralogie und Kristallchemie of Stuttgart University. Operating conditions were an acceleration voltage of 15 kV and a beam current of 15 nA. Natural minerals were used as standards. X-ray maps have different resolution, however not lower than 10 μm for pixel.

High Fe content (XAlm 0.52-0.89), low Mg and variable Mn and Ca contents (XPrp 0.2-0.15, XSps 0.02-0.28, XGrs 0.02-0.28) for three groups of texturally differentiated garnets (Type 1a, 1b and Type 2) were observed (Fig. 8). The core compositions of Type 2 garnets fit well the compositional range of the rims of Type 1a pre-mylonitic garnets as well as Type 1b snowball syn-shear crystals, showing a compositional evolution towards more iron rich composition associated with a corresponding depletion of manganese and calcium concentration during crystals growth. On the ternary diagram of Fig. 8, analyses of Type 2 garnets define an area, corresponding to the G4 growth stage, characterized by a very low spessartine composition. Similar evolutionary trends were also documented by Russo *et al.* (2006), who studied garnet grains belonging to metapelites of the Cardeto area.

Large porphyroblastic garnets (Type 1a)

These kind of garnets initially grew syn-tectonically respect to the D_1 deformation phase, continuing to grew during the next episodes of

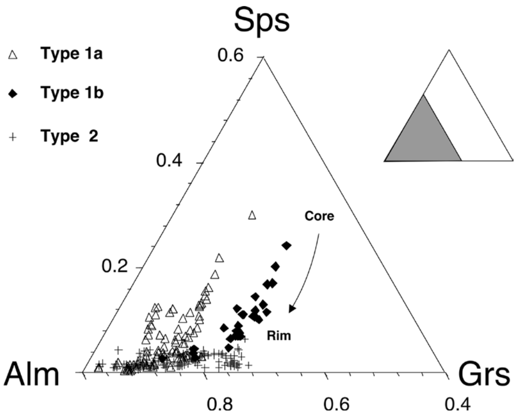

Fig. 8 – Spessartine–grossular–almandine (Sps–Grs–Alm) ternary diagrams showing compositions of three recognized garnet generations (Type 1a, 1b and Type 2). Note the overlapping of Type 1a and 1b rim areas with Type 2 garnet compositions, which are characterized by very low spessartine content.

deformation (D_2 and D_3), actually representing porphyroblasts enveloped by S_3 foliation.

Type 1a garnets (Fig. 5 and Table 1) are a solid solution of almandine (XAlm = 0.53–0.77), grossular (XGrs = 0.05–0.14), spessartine (XSps = 0.01–0.28) and pyrope (XPrp = 0.06–0.14). These garnets display three stages of growth (Fig. 5). The first one (G1) is put in evidence by the highest Mn concentration (lower XSps = 0.11). The second one (XSps range = 0.10–0.05) shows a zoning

Table 1

Representative garnet (Type 1a, 1b and Type 2) analyses expressed as weight molar percent. Compositions of four endmembers almandine, grossular, spessartine and pyrope are expresses as mole fraction (XAlm, XGrs, XSps and XPrp)

Type	1a	1a	1a	1a	1b	1b	1b	2	2
Stage	G1	G2	G3	G4 over-growth	G3	G3	G4 over-growth	G4	G4
Region	inner core	outer core	outer core	rim	inner core	outer core	rim	core	rim
Analysis	#74_a2_8	#72_a2_6	#78_a2_12	#100_a1_13	#1_a8_1	#23_a8_23	#26_a8_26	#29_a9_18	#28_a9_17
XAlm	0.53	0.69	0.72	0.76	0.52	0.70	0.74	0.75	0.67
XGrs	0.12	0.11	0.11	0.08	0.21	0.14	0.10	0.07	0.20
XSps	0.28	0.10	0.05	0.02	0.23	0.04	0.02	0.03	0.03
XPrp	0.06	0.10	0.12	0.14	0.04	0.12	0.14	0.15	0.11
SiO_2	38.65	39.22	39.18	39.32	39.39	39.22	39.08	38.89	39.27
TiO_2	0.10	0.11	0.22	0.15	0.22	0.24	0.26	0.11	0.21
Al_2O_3	20.75	21.00	20.74	21.45	20.76	21.25	20.87	21.25	21.23
FeO	22.94	29.25	31.06	32.27	22.05	29.98	32.00	32.45	28.53
MnO	11.95	4.35	2.21	0.76	9.75	1.70	1.01	1.12	1.19
MgO	1.51	2.46	2.88	3.34	0.96	2.84	3.31	3.65	2.60
CaO	4.09	3.60	3.71	2.57	6.86	4.77	3.45	2.30	6.63
Total	99.99	99.99	100.00	99.86	100.00	100.00	100.00	99.77	99.66
Si	6.40	6.49	6.47	6.48	6.57	6.44	6.42	6.37	6.45
Ti	0.01	0.01	0.03	0.02	0.03	0.03	0.03	0.01	0.03
Sum	6.41	6.50	6.50	6.50	6.60	6.47	6.45	6.39	6.48
Al	4.05	4.10	4.04	4.17	4.08	4.11	4.04	4.10	4.11
Sum	4.05	4.10	4.04	4.17	4.08	4.11	4.04	4.10	4.11
Mg	0.37	0.61	0.71	0.82	0.24	0.70	0.81	0.89	0.64
Fe^2	3.18	4.05	4.29	4.45	3.08	4.12	4.40	4.45	3.92
Mn	1.68	0.61	0.31	0.11	1.38	0.24	0.14	0.16	0.17
Ca	0.73	0.64	0.66	0.45	1.23	0.84	0.61	0.40	1.17
Sum	5.95	5.90	5.96	5.83	5.92	5.89	5.96	5.90	5.89

characterized by CaMn-1 (MgMn-1 and FeMn-1) exchange (G2). The third stage (G3) (XSps range= 0.05–0.03), corresponding to the outer rim region, shows an increase in Ca at the expense essentially of Fe but also of Mg (average XGrs = 0.10). This stage of growth (G3), even if often partly covered by the G2, is well documented on X-ray maps (Ca and Mg) and also optically by the occurrence of a very fine inclusion-rich region. An overgrowth stage (G4) made by coalesced smaller euhedral garnets of Type 2 is sporadically observed at the external edge of porphyroblasts (XSps range = 0.03–0.01).

Snowball garnets (Type 1b)

Type 1b garnets characterized by sigmoid or spiral shaped inclusion trails were already described separately respect to Type 1a garnet, which has an ordinary feature.

The garnets with internal inclusion trails marking out a "snowball" appearance are also characterized by more than one stage of growth. They exhibit an inner core region in which inclusion trails geometries display to have undergone a rotation during growth, which is characterized by high spessartine composition (XSps range of G3 = 0.10–0.23). These garnets usually have higher grossular composition (XGrs range= 0.10–0.23) with respect to the Type 1a. In addition to the G3 stage of growth they also show a further syn-D_3 crystallization stage (G4) characterized by coalesced wraparound garnet grains forming an armoured like structure. Calcium oscillatory zoning occurs towards the external border of snowball garnet (Fig. 6b, d). The same zoning has been observed for Type 2 smaller garnets too (Fig. 6f, h). The Ca distribution is qualitatively different from those of Mn, Fe and Mg and we interpreted observed patterns potentially related to: 1) different length scales of equilibration of various elements; 2) differences between element fractionation along the crystallization path; 3) highly localized changes in the precursor assemblages during growth. The grossular content could decrease rapidly due to the contribution of garnet growth from epidote and sodic calcic amphibole (Gaidies *et al.*, 2008) occurring as constituting phases of the CMC metapelite assemblages.

Small euhedral garnets (Type 2)

This generation of garnet mainly grew during the shear phase (D_3), characterized by well faceted coalesced crystals, often embracing early Type 1a and 1b porphyroblasts. The coalescence of smaller grains is put in evidence by microscopic observations allowing discerning the outline of single adjacent crystals (Fig. 7a, b) and by X-ray maps (Fig. 7c, d). They occur, in several circumstances, as inclusion free external region of pre-existing garnet grains.

In some specimens they appear to be detached from the external edges of early porphyroblasts and consecutively disposed into layers parallel to the S_3 mylonitic foliation. An X-ray map of Type 2 garnets (Fig. 6) reveals the presence of a concentric oscillatory calcium zonation pattern distinguishable also inside these smaller grains, testifying their origin as single growing crystals excluding their nature of broken fragments separated from early garnets. This zoning is probably due to the interplay of dissolution and diffusion in reactant mineral of the matrix and growth and diffusion rates within product garnet, plausible mutual processes during metamorphism that in turn will affect minerals composition.

Type 2 small garnets (Table 1) are a solid solution of almandine (XAlm=0.65–0.78), grossular (XGrs=0.03–0.21), spessartine (XSps=0.01–0.04) and pyrope (XPrp=0.10–0.16). Probably the most discriminating chemical feature of this type of garnets is represented by their spessartine-poor composition. Crystals display also a zoning pattern: the (Fe,Mg)(Ca,Mn)-1 exchange with Fe or Mg rises at the edge of the crystals. It is worth noting that the chemical compositions measured at the periphery of the first generation of garnets (Type 1a and 1b) are similar to those concerning the cores of the third-generation smaller garnets (Type 2) (Table 1 and Fig. 8).

Discussion

The timing of nucleation of garnet porphyroblast (as well as its successive growth) relative to the development of foliations represents one of decisive factors to reveal the microstructural history of a rock (Zwart, 1962; Bell, 1985; Stallard, 1998). Deformation localized within shear zones generally lead to the transposition of early structures, yielding more difficult the recognition of pre-existing deformational episodes. However, in a small number of favourable circumstances some "low strain domains" could remain preserved and keep relics of early foliations (e.g. inside porphyroblasts), allowing to reconstruct, almost at all, the sequence of the deformational events of a rock. In this view, a careful observation of porphyroblasts and above all of their inclusion trails geometries as well as their internal and external foliations, should be a good way to solve these questions.

Several studies were carried out about the crystallization of garnet within metapelitic assemblages (Hyslop and Piasecki, 1999; Gaidies *et al.*, 2008) and a lot of them treat the argument of coalescing crystals (Spiess *et al.,* 2001; Feenstra *et al*., 2007, Whitney *et al*, 2008).

Hyslop and Piasecki (1999) illustrated a complex garnet growth in a shear zone of the Scottish Central Highlands very similar to the situation here described. They recognized three different garnet generations, establishing that garnet growth was initiated at several stages during the evolution of the shear zone, also suggesting that the growth of garnet was promoted by enhanced fluid activity and resultant supply of elements within the shear zone.

Chemical evidences confirmed the growth model hereby proposed for garnets of the CMC rocks, supposed primarily by means of microstructural features. Compositional paths of studied garnet depict a general trend that starting from rich Mn composition and relatively low Mg concentration (first and second stage of growth, G1 and G2) evolves towards compositions with lower content of Ca and Mn and higher Mg and Fe values (third and fourth stages of growth, G3 and G4). Concerning the XAlm distribution pattern, it reveals an initial slight increase followed by a successive progressive depletion of Fe, very pronounced towards the external rim, probably related to the coeval crystallization of another Fe-rich phase during garnet growth history (Chernoff and Carlson, 1997; Hirsch *et al.*, 2003).

The zoning patterns of Type 1a and 1b garnets, emphasized by the collected X-ray maps, are characterized by a concentric decrease of Mn from core to rim suggesting a prograde growth of garnet during continuous fractionation. The compositional garnet profile of Fig. 5 shows the presence of a slight annulus marked by an increase of XGrs in correspondence of the idioblastic outline linked to the first stage of growth. This fact could represent the consumption of a Ca-rich phase (possibly plagioclase or epidote) during garnet growth and also a pressure increase followed by a temperature increase. The contemporary depletion of XAlm and XGrs associated with an increase of XPrp and XSps, observed at the outer rim of the Type 1, suggests a possible rise in temperature that had contributed to the Type 2 nucleation.

Regarding to the second generation of garnet there are several microstructural features that confirm the presence of a nucleation region that preferentially coinciding with the rim of early porphyroblasts (Fig. 4a, b). This hypothesis was furthermore confirmed by X-ray maps (Fig. 6) in which small euhedral Type 2 crystals show a concentric zonation of Mn, Ca, Fe and Mg, thus excluding their possible character of fragments (cf. Fazio *et al*., 2008).

A more accurate study of the same rocks and microstructures (e.g. by means of EBSD technique) might consent to develop a theoretical model capable to explain why external edges of pre-existing porphyroblast (Type 1) are favourite sites for the nucleation of new garnet generation (Type 2).

Conclusions

The observed microstructural features suggest that the metapelites of the Cardeto Metamorphic Complex (CMC) are characterized by the presence of three generations of garnet, here named Type 1a, 1b and 2.

The first one (Type 1a) consists of large porphyroblasts usually characterized by two and occasionally up to three stages of growth (G1-G2-G3), highlighted by compositional traverses and X-ray maps. They were interpreted as pre-mylonitic porphyroblasts, grown during D_1 and D_2 deformational event.

A second typology of garnet, here called "snowball" (Type 1b), we assumed grew syn-tectonically with respect the shear phase (G3), are not so widespread. Syn-shear (D_3) overgrowth

(G4) corresponds to a chemical variation observed towards the outer rim of these large crystals in which Mn, Fe and Mg decrease is associated with Ca increment, accompanied by the nucleation of a new generation of garnet (Type 2).

Garnets of third generation (Type 2) are generally small-sized appearing as inclusion free euhedral crystals. Petrographic observations, supported by chemical analyses suggest that the outer rim of the Type 1a and 1b garnet represents the nucleation region of the new smaller Type 2 crystals. The zoning pattern, characterized by Mn and Ca enriched core and Fe and Mg enriched rim, observed for these smaller garnets (Type 2) demonstrates that they are new formed crystals rather than fragments detached from the periphery of early pre-mylonitic large garnets (Type 1a and 1b).

The final remark we would underline is the possibility that coalesced garnet crystallizing over pre-existing porphyroblasts could be a common process inside shear zones in which the mobility of cations could be promoted thanks to the high fluids concentration if a concurrently rise in temperature favours an overriding of the nucleation barrier for the nucleation and growth of new crystals.

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