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FORMATION OF ATOLL GARNET IN THE ARDARA AUREOLE, NW IRELAND

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Abstract

The formation of atoll garnet in the Ardara aureole, NW Ireland, is discussed using the textural, chemical and Electron Backscatter Diffraction (EBSD) data. Textural evidence suggests the possibility of incipient of garnet replacement from the core. In addition, the presence of staurolite and andalusite in the core of small atoll garnets as well as the occurrence of sillimanite in the core of large atoll garnet reveal the prograde nature of atoll formation. The microprobe analyses and EBSD data also indicate that atoll garnets in the Ardara aureole developed by pre-existing idioblastic garnets being replaced by mainly biotite to produce atoll forms.

Keywords: Atoll garnet; Aureole; EBSD

1. Introduction

Atoll garnet commonly consists of a complete or almost complete rim of garnet with an interior filled with any combination of biotite, muscovite, feldspar, quartz and iron oxide [23]. In several cases garnet islands can be seen inside the rims. As a general rule, atoll garnets show an idioblastic outline, which in some cases has been breached.

Well-documented examples of atoll garnet in the literature include:

(i) contact metamorphosed pelitic rocks: in the British Isles [21,19,3,22,20] and SE Tuva [25]

(ii) regional metamorphosed pelitic rocks: Canigou massif, Pyrenees [7]; Torrox unit, Western Alpujarrides, Betic Cordilleras [4];

(iii) Barrovian-type quartzofeldspathic gneiss, New Zealand [5];

(iv) eclogites in the Armorican Massif, France [8].

Studies on atoll garnet have so far resulted in disagreement about its origin [23]. Pioneer works [21,19] emphasised the selective replacement of the core of what used to be a complete garnet as the mechanism for atoll garnet formation. Atherton and Edmunds [3] used the uniform composition across both complete and atoll-shaped garnet from the Ben Lui schist at Pitlochry, Scotland, to argue against the selective replacement of garnet. They attributed the homogeneous nature of garnet to the rapid crystallisation and suggested that the atoll rims and garnet islands had probably resulted from separated nucleation.

Cooper [5] in his study in metabasic schist from the Haast area, New Zealand found that, unlike Dalradian atoll garnets reported by Atherton and Edmunds [3], chemical zoning exists within the atoll rim and isolated core. However, in the lack of textural evidence to support selective replacement of the garnet, Cooper [5] concluded that the atoll shell and garnet island were produced by separate nucleation.

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Smellie [22] carried out a petrographic and microprobe study on atoll-shaped garnets from the aureole of the Ardara pluton. The textural evidence and microprobe data led him to believe that the atoll garnets formed by replacement mainly by biotite and some quartz, plagioclase and iron oxide.

Godard [8] favoured corona or reaction rims as a mechanism for atoll garnet formation in quartz eclogites of the Hercynides.

Atoll garnets were also reported from a contact aureole in the south-east of Tuva by Ushakova and Usova [25, English abstract]. They attributed the atoll garnet formation to a skeletal growth at a short time temperature increase in the contact aureole.

More recently prograde breakdown of garnet due to a clockwise P-T path has been suggested as a mechanism for the production of atoll garnet in regional metamorphosed pelitic rocks [7,4].

From the preceding literature review it is clear that there is not a general agreement on how atoll garnet is formed. Here, we address the problem of atoll garnet formation by presenting textural, chemical and crystallographic data for atoll garnet from the Ardara aureole. Atoll garnet is developed widely throughout the Ardara aureole, thus making it an excellent place to study the factors involved in its development.

2. Geological Setting

The Donegal region is located in the north west of the Republic of Ireland. The geology of the Donegal region has been comprehensively reviewed by Pitcher and Berger [16]. The country rocks of Donegal granites consist of Dalradian metasedimentary and meta-igneous rocks that range in age from Late Precambrian to Middle Cambrian. This group of rocks subsequently underwent major deformation (the Caledonian orogeny) during Late Cambrian to Late Ordovician. The granites of Donegal have been divided into six units having different ages, composition and modes of emplacement.

The northern Ardara aureole, which is the focus of the present study, consists of a pelitic horizon (locally referred to as the Clooney Pelitic Group) and an adjacent limestone unit (the Portnoo Limestone). Pitcher and Berger [16] correlated these units respectively with the Upper Falcarragh Pelites and the Falcarragh Limestone which are members of the Creeslough Succession. The Upper Falcarragh Pelite and the Falcarragh Limestone were correlated by Harris and co workers [9] with the Appin Group (Lower Dalradian) of Dalradian rocks of Mainland Scotland. In detail, the pelitic horizon of the northern Ardara aureole consists of interlayered aluminous pelites and semipelites. Lenses and pods of metadolerite are also common in a zone extending about 200 m from the contact with the Ardara pluton [1].

The Ardara pluton, which is the southernmost of the Donegal granites, has a tear-drop shape and is about 8 km in diameter. It consists of two units, an outer ring of quartz-monzodiorite and an inner core, with the composition varying from quartz-monzodiorite to granodiorite. The Ardara aureole represents a forcibly emplaced, diapiric intrusion [2].

The contact metamorphism of the Ardara pluton has been studied in detail by many previous workers [2,17,14,11]. In brief, the metamorphic effects of the Ardara pluton extend nearly 1.5 km from the intrusion contact. The rocks of the aureole show a strong foliation. The regional structures, S_1, S_2 and S_3, are steepened and intensified in the aureole [16]. The steepening of regional structures can be seen from 800 m to 1 km from the contact [26]. Akaad [1,2], Pitcher and Berger [16] and Holder [10] attributed the squeezing and reinforcing of regional structures in the contact aureole to the emplacement of the granite pluton. However, Vernon and Paterson [26] suggested the possibility of syn- or post-emplacement regional deformation.

The Ardara aureole has been divided into two units [2]:

(a) an outer unit which is made up of the non-porphyroblastic rocks showing minor contact effects and characterised by new thermal biotite flakes crosscutting the regional schistosity;

(b) an inner unit which comprises three zones [14] (Fig. 1) on the basis of prismatic Al_2SiO_5 polymorphs found;

I. an outer kyanite-bearing andalusite zone,
II. a middle kyanite-free andalusite zone,
III. an inner prismatic sillimanite zone.

Naggar and Atherton [14] demonstrated that kyanite in the Ardara aureole is restricted to rocks with MgO/(MgO+FeO) values higher than 0.50 and lower bulk-rock MgO/(MgO+FeO) ratios precluded kyanite as a phase in the assemblage.

3. The Petrography of the Metapelitic Rocks from the Ardara Aureole

The details of textural and mineralogical characteristics of aluminium silicate-bearing rocks from the contact aureole of the Ardara pluton were given elsewhere [11]. In brief, dark porphyroblastic schists with conspicuous andalusite on most surfaces characterise the outer kyanite-bearing andalusite zone. In thin section, typical rocks consist of quartz +

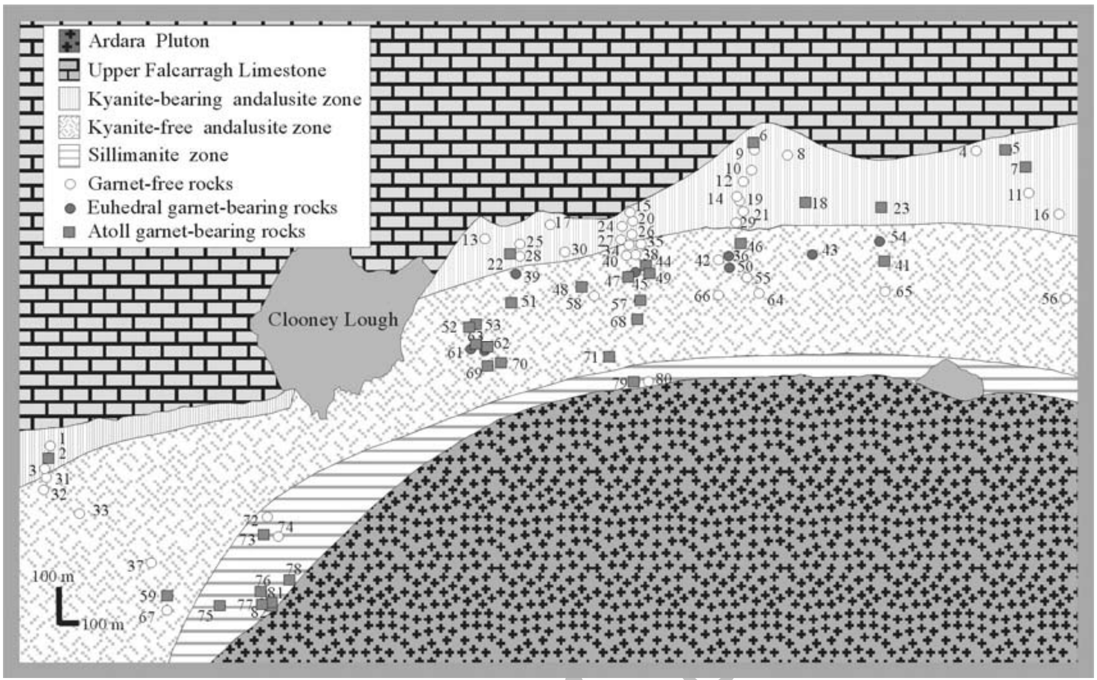

Figure 1. Sample localities in the inner aureole of the Ardara pluton showing position of euhedral and atoll garnet-bearing rocks.

plagioclase + biotite + muscovite ± chlorite ± staurolite ± garnet ± kyanite ± andalusite ± fibrolite. Graphite and ilmenite are also present. Kyanite takes place as small idioblastic to subidioblastic prisms (0.15-0.35 mm in length). Crosscut by kyanite, biotite is usually not disturbed along the kyanite boundaries. Idioblastic kyanite occurs as inclusions within andalusite porphyroblasts. Kyanite is also found included in plagioclase poikiloblasts. Staurolite commonly takes place as small (0.12 - 0.35 mm in diameter) subidioblastic generally inclusion free grains. In some slides staurolite can be seen as irregular grains, or clusters of grains, disseminated throughout the rock. Staurolite is also found as relatively large porphyroblasts (0.4 – 0.9 mm in diameter) containing continuous curved trails of quartz inclusions. Staurolite, with good crystal faces, is commonly included in andalusite and plagioclase porphyroblasts. Garnet occurs only in kyanite-free rocks i.e., kyanite and garnet never occur together in the same rock. It develops as tiny (0.09-0.13 mm in diameter) idioblastic crystals in the groundmass. It also occurs as inclusions in andalusite, plagioclase and staurolite suggesting garnet was formed earlier than these minerals. Andalusite comes as large porphyroblasts (1-5 mm in diameter) and includes quartz, staurolite, kyanite, garnet and ore minerals. Fibrolite occurs as bundles dominantly decolouring and replacing biotite. It is found anastomosing around plagioclase porphyroblasts. Fibrolite also occurs as discontinuous folia anastomosing between lenticular grains of quartz in the groundmass. In some instances it appears that andalusite encloses fibrolite or parts of the fibrolitised biotite. Plagioclase always takes place as porphyroblasts (0.5-4 mm in diameter). It generally shows "S"-shaped inclusion trails of quartz. The textures exhibited by plagioclase could easily be mistaken as textures evolving from rotated porphyroblasts. However, these textures are clearly formed by overprinting regional microfolds (S_2-S_3) in the groundmass.

Within the kyanite-free andalusite schists, andalusite can be seen to consist of an inclusion-free pink pleochroic core with the mantle of colourless poikilitic andalusite. A common feature in idioblastic andalusites is the development of textural sector-zoning and matrix displacement [11]. Other common minerals are garnet, staurolite and fibrolite. Staurolite and garnet display textural features similar to those in the kyanite-bearing andalusite zone. In many examples fibrolite folia are concentrated in narrow high strain zones between andalusite porphyroblasts where the presence of tight crenulations in the fibrolite folia is evident. Fibrolite is also found anastomosing around andalusite porphyroblasts. This textural evidence suggests syn-deformational growth of fibrolite [12].

The inner sillimanite zone is characterised by dark brown hornfelses with biotite, garnet and occasionally sillimanite visible in hand specimens. Under the microscope the overall textures of the rock suggest that the transformation from the kyanite-free andalusite zone to the sillimanite zone was accompanied by a wholesale textural reconstitution [13]. Sillimanite appears as long prisms, growing from the groundmass as well as large grains to show symplectic intergrowth with quartz in the groundmass. In some of the specimens, sillimanite is formed by the coarsening of fibrolite groundmass. In one slide, square areas about 4 mm in diameter may be presumed from the resemblance of the morphology to be andalusite, pseudomorphed by sillimanite. Fibrolite is commonly concentrated in folia that anastomose between pods rich in biotite, quartz and plagioclase Staurolite occurs as tiny subhedral grains throughout the groundmass. Garnet in most of the samples from the sillimanite zone displays two different habits. Away from the contact it occurs as small idioblastic to subhedral crystals in biotite clusters after regional garnet. At the immediate contact with the pluton, garnet is present as large porphyroblasts (1-1.5 mm in diameter) which contain inclusions of biotite, quartz and fibrolite. Cordierite can be seen as xenoblastic grains throughout the groundmass. It also occurs as large porphyroblasts (4-8 mm in diameter) which contain inclusions of fibrolite and biotite.

4. Petrographic Characteristic of Atoll Garnets from the Ardara Aureole

Atoll garnets occur throughout the Ardara aureole in the outer kyanite-bearing andalusite zone, the middle kyanite-free andalusite zone and the inner sillimanite zone, (Fig. 1). Out of 68 garnet-bearing samples collected from the Ardara aureole only seven lack atoll forms. Smellie [22], considered that atoll forms in the Ardara aureole are absent in rocks that contain andalusite but lack staurolite or vice versa. However, in this study the author found no relation between the occurrence of atoll form and presence of both andalusite and staurolite in the samples. As a matter of fact, in two atoll garnet-bearing samples andalusite is present but staurolite is absent and in one sample staurolite is present but andalusite is absent. In addition, atoll garnet was not found in four samples which contain both andalusite and staurolite.

In the Ardara aureole garnet appears as small grains (<0.25 mm) that occur in the outer kyanite-bearing andalusite and the middle kyanite-free andalusite zone, and as large porphyroblasts (>1.5 mm) which can be seen in the inner sillimanite zone.

Small garnets typically have cloudy cores (Fig. 2a) or cores that are mostly occupied by biotite (Fig. 2b) and quartz (Fig. 2c) and sporadically by plagioclase (Fig. 2d) resulting in an atoll texture. In general the rim of atoll garnet shows an idioblastic outline which has been breached (Figs. 2b & 2d). Atoll garnet with a central core or island can be seen in many examples (Figs. 2b & 2d). They are either scattered in the matrix (Fig. 2e) or as inclusions within porphyroblasts of plagioclase and andalusite (Fig. 2f), indicating they were produced before the completion of these porphyroblasts [22]. The presence of andalusite in the core of atoll garnet is evident where atoll garnets occur within porphyroblasts of andalusite (Fig. 2f). In some examples staurolite was also found within the core of atoll garnet (Fig. 2g). As staurolite and andalusite are minerals with higher temperature than garnet in the Ardara aureole [14,11], the occurrence of these two minerals in the core of atoll garnet most probably indicates the prograde replacement of the garnet core by these higher grade phases.

Large garnets from the inner sillimanite zone usually have an inclusion-rich core surrounded by a clear, inclusion-poor rim (Fig. 3a). In many examples garnet porphyroblasts contain cores of mainly plagioclase, biotite, fibrolite and a little quartz and opaque minerals resulting in an atoll texture (Figs. 3b-e). The large atoll garnets locally contain a central core of garnet (Fig. 3f). In some rocks sillimanite can be found within the core (Figs. 3g & h) probably indicating the prograde nature of growth of the garnet core. In one example (sample 82) garnet porphyroblasts occur as ellipsoidal aggregates of small garnets, quartz and biotite (Fig. 3i). In this case smaller individual garnet crystals together with quartz, biotite and fibrolite are mantled by larger garnet crystals to produce atoll forms. This type of ellipsoidal garnet aggregate has been well documented by Spiess *et al*. [24].

5. Compositional Characteristics

Garnet crystals from the Ardara aureole are chemically variable and they may be divided into relatively Mn-rich, Ca-rich and Mg-rich garnets [11]. Complete garnets usually display normal zoning characterised by increasing Mg but decreasing Mn away from the core (Fig. 4). However, outermost parts of these garnets show inverse zoning (Fig. 4).

Atoll garnets especially small atoll garnets extensively display reverse zoning at their margin distinguished by increasing Mn and decreasing Mg at the atoll garnet outer edges (Fig. 5). Remarkably compositional maps of atoll garnets (Fig. 6) display high concentration of Mn and low concentration of Mg in the contact of garnet with biotite.

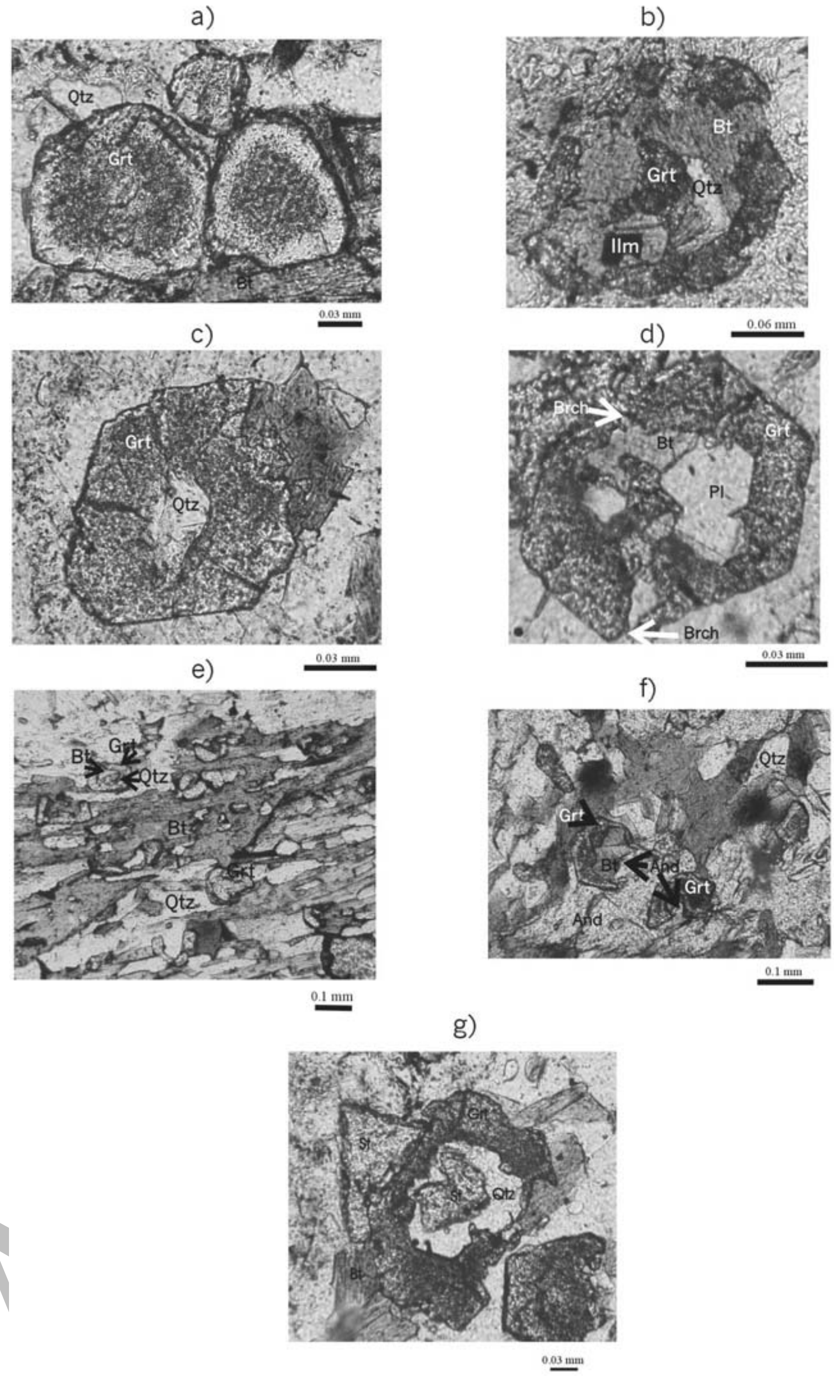

Figure 2. a. Tiny garnets (Grt) with an inclusion-rich core surrounded by an inclusion-free rim. Other minerals are biotite (Bt) and quartz (Qtz). (PPL. sample 53, the Kyanite-free andalusite zone). **b.** The core of small garnet occupied mainly by biotite and a little quartz and ilmenite (Ilm). The rim has been breached in several places but the euhedral outline remains. Garnet "island" can be seen in the centre of the atoll. (PPL. sample 7, Kyanite-bearing andalusite zone). **c.** The core of a small garnet occupied by quartz. (PPL. sample 53, Kyanite-free andalusite zone). **d.** The core of small garnet occupied by biotite and plagioclase (Pl). The rim has been breached (Brch) but the euhedral outline remains. Garnet "island" can be seen within the rim. (PPL. sample 7, Kyanite-bearing andalusite zone). **e.** Small atoll garnets within the groundmass. The cores of atoll garnets are occupied by biotite and quartz. (PPL. sample 53, Kyanite-free andalusite zone). **f.** Small garnets included within andalusite (And) porphyroblast, with cores of biotite and andalusite. Inclusions of quartz also can be seen within the andalusite porphyroblast. (PPL. sample 53, Kyanite-free andalusite zone). **g.** Staurolite (St) growth within atoll garnet. Other minerals are biotite and quartz. (PPL. sample 7, the kyanite-bearing andalusite zone).

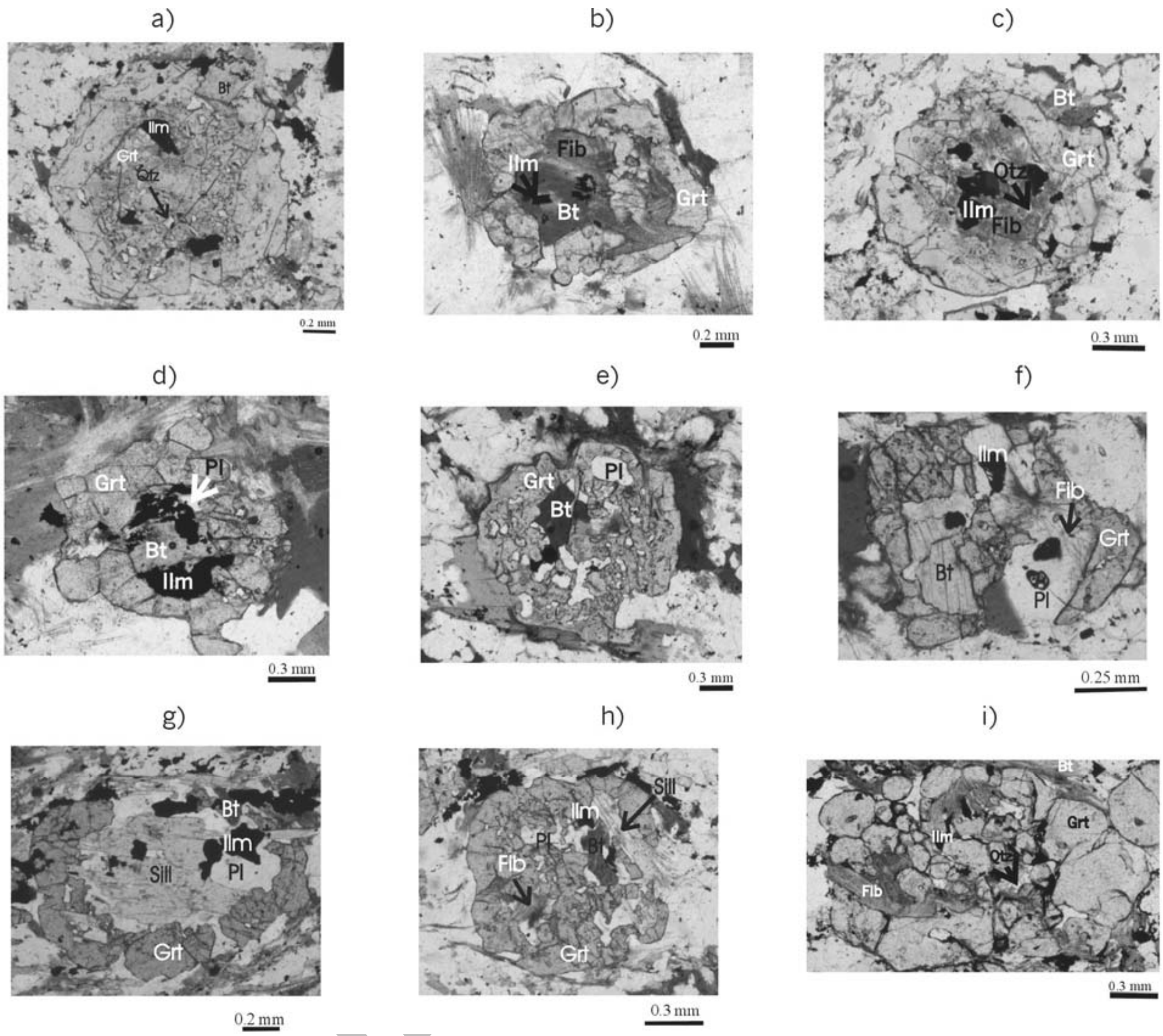

Figure 3. a. Garnet porphyroblast showing an inclusion-rich core surrounded by a clear inclusion-poor rim. Other minerals are biotite, quartz and ilmenite (Ilm). (PPL. sample 73, the sillimanite zone). **b.** The core of large garnet is mainly biotite and fibrolite (Fib) and a little ilmenite. (PPL. sample 76, the sillimanite zone). **c.** The core of garnet porphyroblast has been occupied mainly by fibrolite and ilmenite and a little quartz and biotit. (PPL. sample 73, the sillimanite zone). **d.** Garnet porphyroblast contains core of mainly ilmenite and biotite and a little plagioclase. (PPL. sample 73, the sillimanite zone). **e.** Garnet porphyroblast contains a core of mainly plagioclase and biotite. (PPL. sample 82, the sillimanite zone). **f.** Atoll garnet enclosing a core of plagiocl-ase, biotite, and a little ilmenite and fibrolite. Note that the atoll contains a central core of garnet. (PPL. Sample 82, the sillimanite zone). **g.** Sillimanite (Sil) growth within atoll garnet. Other minerals are quartz, biotite, plagioclase and ilmenite. (PPL. sample 73 the sillimanite zone). **h.** Atoll garnet enclosing a core comprising sillimanite (Sil), plagioclase, biotite, fibrolite and ilmenite. (PPL. sample 82, the sillimanite zone). **i.** Ellipsoidal aggregate of small garnets. Note that smaller individual garnet crystals together with quartz, biotite and fibrolite are mantled by larger garnet crystals. (PPL. sample 82, the sillimanite zone).

To check whether or not the compositions of biotite in the groundmass are different from those in atoll garnets, Mg/(Mg+Fe) *vs*. Al^6 of the two types of biotite were plotted for four samples (Fig. 7). Notably biotites within atoll garnets show higher values of Mg/(Mg+Fe) compared to biotites in the groundmass.

6. Orientation Contrast Images and Crystallographic Orientation

Electron backscatter diffraction (EBSD) and orientation contrast (OC) imaging are SEM-based, crystallographic methods that employ the backscattered

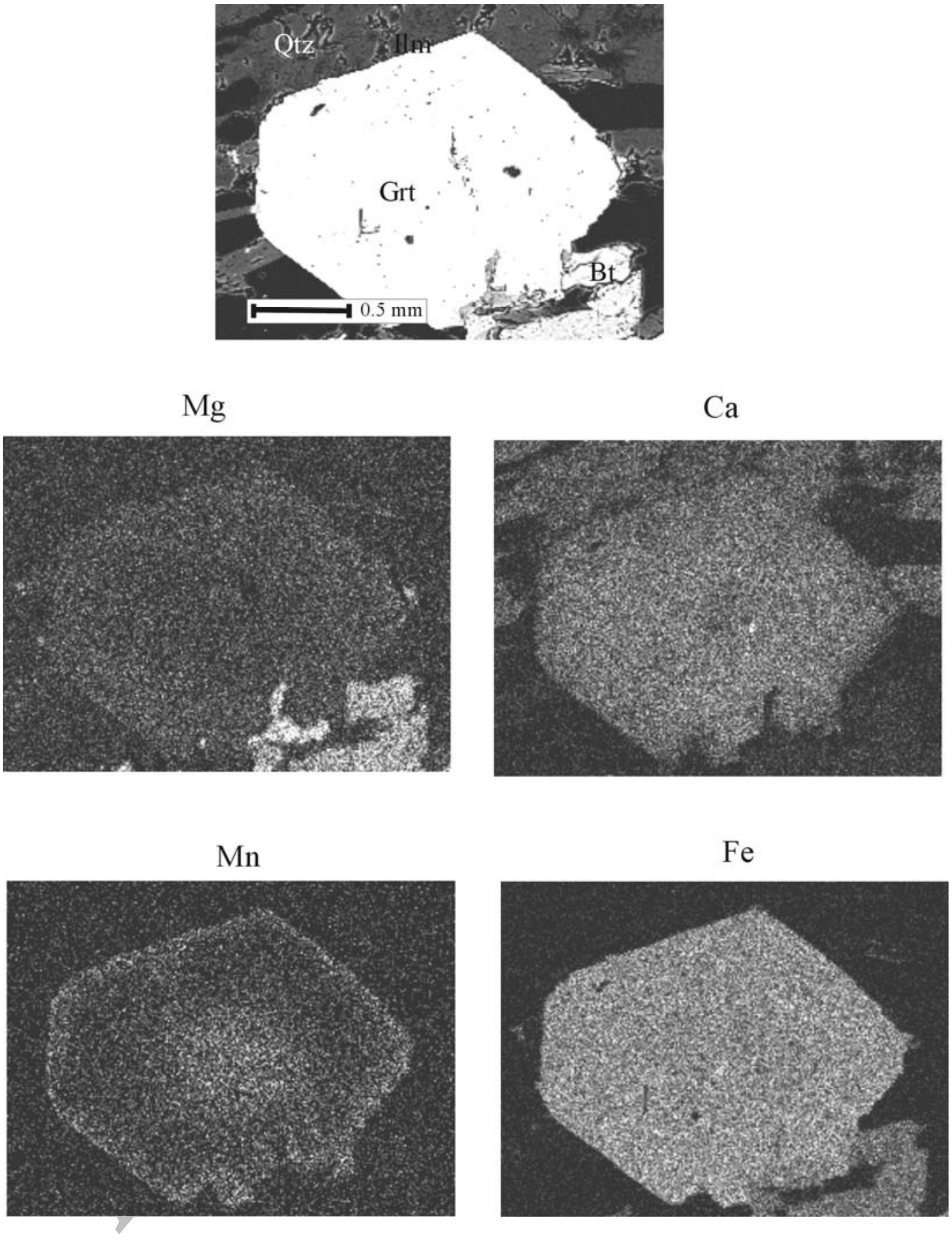

Figure 4. X-ray maps showing the distribution of Mg, Ca, Mn and Fe in a complete garnet from sample 7. Note that the garnet is largely concentrically zoned.

electron (BSE) signal [18]. The crystallographic orientation of discrete minerals as small as 1 μm can be measured by EBSD [18]. EBSD and OC studies were performed at the University of Liverpool using a Philips XL30 SEM. EBSD patterns were indexed using the program CHANNEL+. OC and EBSD were used in the present study for one sample from the sillimanite zone (samples 73) to investigate if apparently complete porphyroblastic garnets, comprise of one single garnet crystal or more than one garnet crystal (Fig. 8). These methods also are applied to find whether the rims and central core of atoll garnets have the same crystallographic orientation or not.

OC image of the porphyroblastic garnets illustrates that individual garnets comprise a series of sub-domains with variable crystallographic orientations (Fig. 8). The {100} pole figures from garnet porphyroblasts illustrate that orientations of sub-domains within any one grain are very strongly grouped (Fig. 8). In porphyroblastic atoll garnets an identical crystallographic orientation can be seen between atoll rims and central atoll garnet (Fig. 8d) indicating replacement nature of atoll formation.

7. Genesis

The most feasible explanation for the formation of atoll form in the Ardara aureole is discussed here using the textural, chemical and EBSD results presented earlier.

It is very difficult to draw any definite conclusion for mechanism of atoll formation in the Ardara aureole using textural evidence. However, the presence of cloudy cores in many small and porphyroblastic garnets suggests the possibility of incipient of garnet replacement from the core. In addition, the presence of staurolite and andalusite in the core of small atoll forms as well as the occurrence of sillimanite in the core of large atoll garnet may reveal the prograde nature of atoll formation as staurolite, andalusite and sillimanite are typically minerals with higher temperature than garnet in the thermal history of the Ardara aureole.

The microprobe analyses provide more obvious evidence for genetic interpretation of atoll garnets. On the basis of these data complete garnets generally have normal zonation. However, the outermost rims of complete garnets often show inverse zoning. In agreement with Smellie [22] we believe that garnet crystals were essentially normally zoned, but as a consequence of garnet replacement by mostly biotite, reverse zoning was formed at the margins of complete garnets.

The reverse zoning at the margin of atoll garnets especially small atoll garnets has been extensively found during the present study. In these cases Mn increases and Mg decreases at the atoll garnet outer edges. Such a reverse zoning in the atoll garnet rims has been reported by some workers [22,7,4]. Smellie [22], Gibson [7] and Casco and Roldán [4] attributed such a reverse compositional zoning to prograde breakdown of original garnets. The present author in agreement with Smellie [22], believes that core-to-rim inverse composition profile in the atoll garnets of the Ardara aureole resulted from variable degrees of diffusional modification of a pre-existing normal pattern during prograde resorption of garnet.

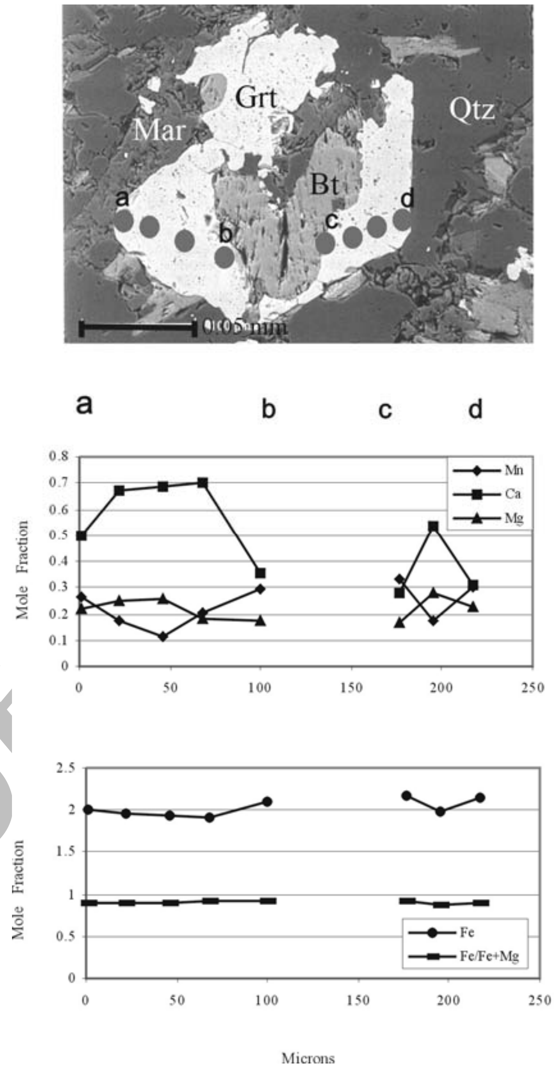

Figure 5. Microprobe traverse across an atoll garnet from sample 7 from the kyanite-bearing andalusite zone. Minerals are garnet (Grt), biotite(Bt) quartz (Qtz) and margarite (Mar). In this atoll garnet, Ca and Mg decrease whilst Mn and Fe increase from the centre of atoll rims towards the edges. An interesting aspect is that Mg shows lower values but Mn displays higher values at biotite/garnet interfaces (b and c) than those at quartz/garnet and margarite/garnet interfaces (d and a).

The most interesting evidence supporting this conclusion comes from the fact the Mg and Mn in atoll garnets are strongly dependent upon the proximity to biotite. As discussed earlier Mg decreases but Mn increases in the parts of garnet close to biotite. One-sided asymmetric profiles in garnet with Mg lower against biotite have been reported by Florence and Spear [6] from a pelitic gneiss in the Adirondack Mountains and O'Brien [15] from granulites of southern

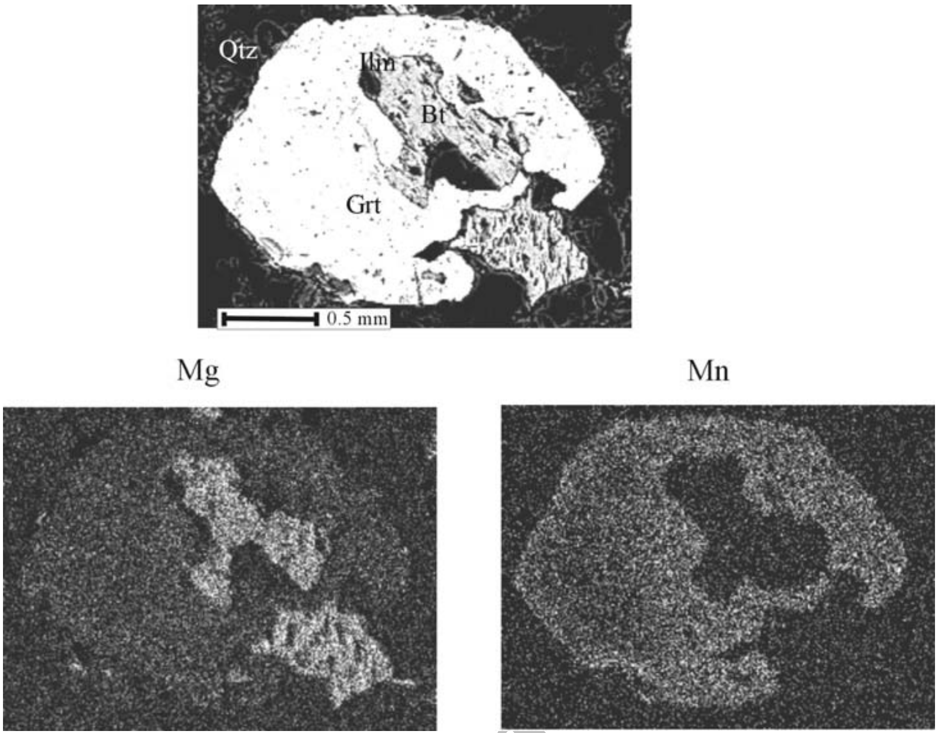

Figure 6. X-ray maps showing the distribution of Mg and Mn in an atoll garnet from sample 7. Note high concentration (area with high contents are light) of Mn but low concentration of Mg in the contact of garnet with biotite.

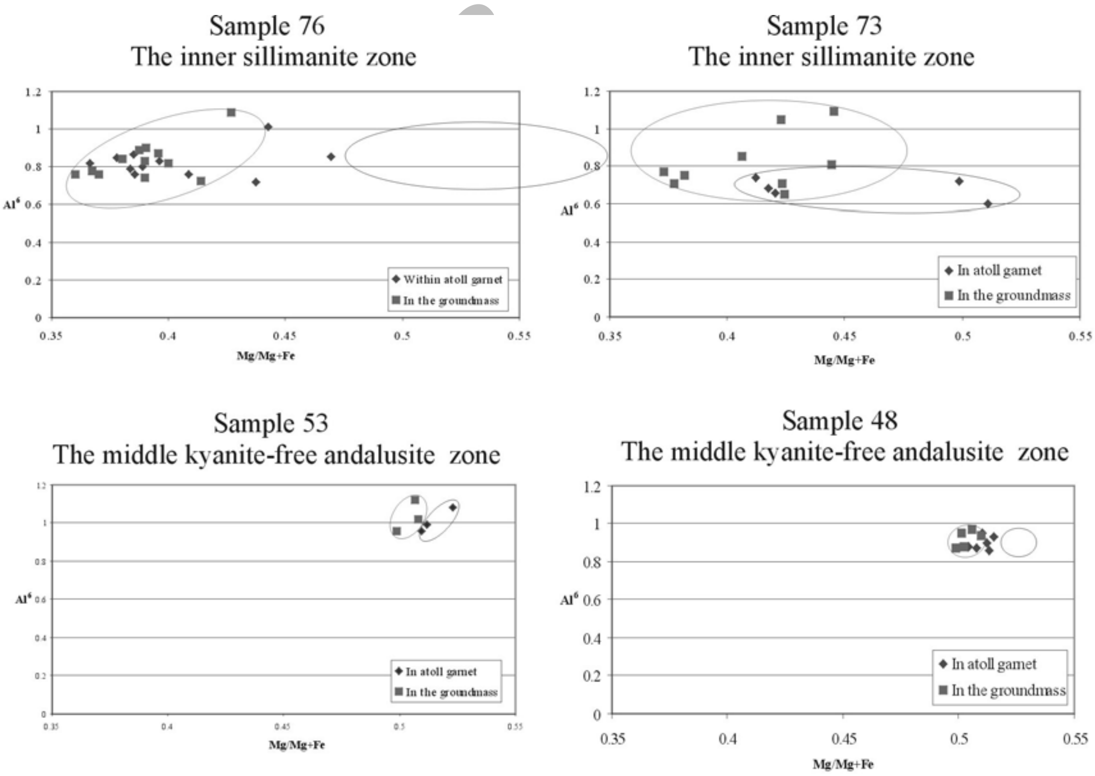

Figure 7. M/FM *vs.* AlVI plot for matrix biotites as well as biotites enclosed within the atoll garnet cores from four samples of the Ardara aureole. Note that biotites within atoll garnets show higher values of Mg/Mg+Fe compared to biotites in the groundmass.

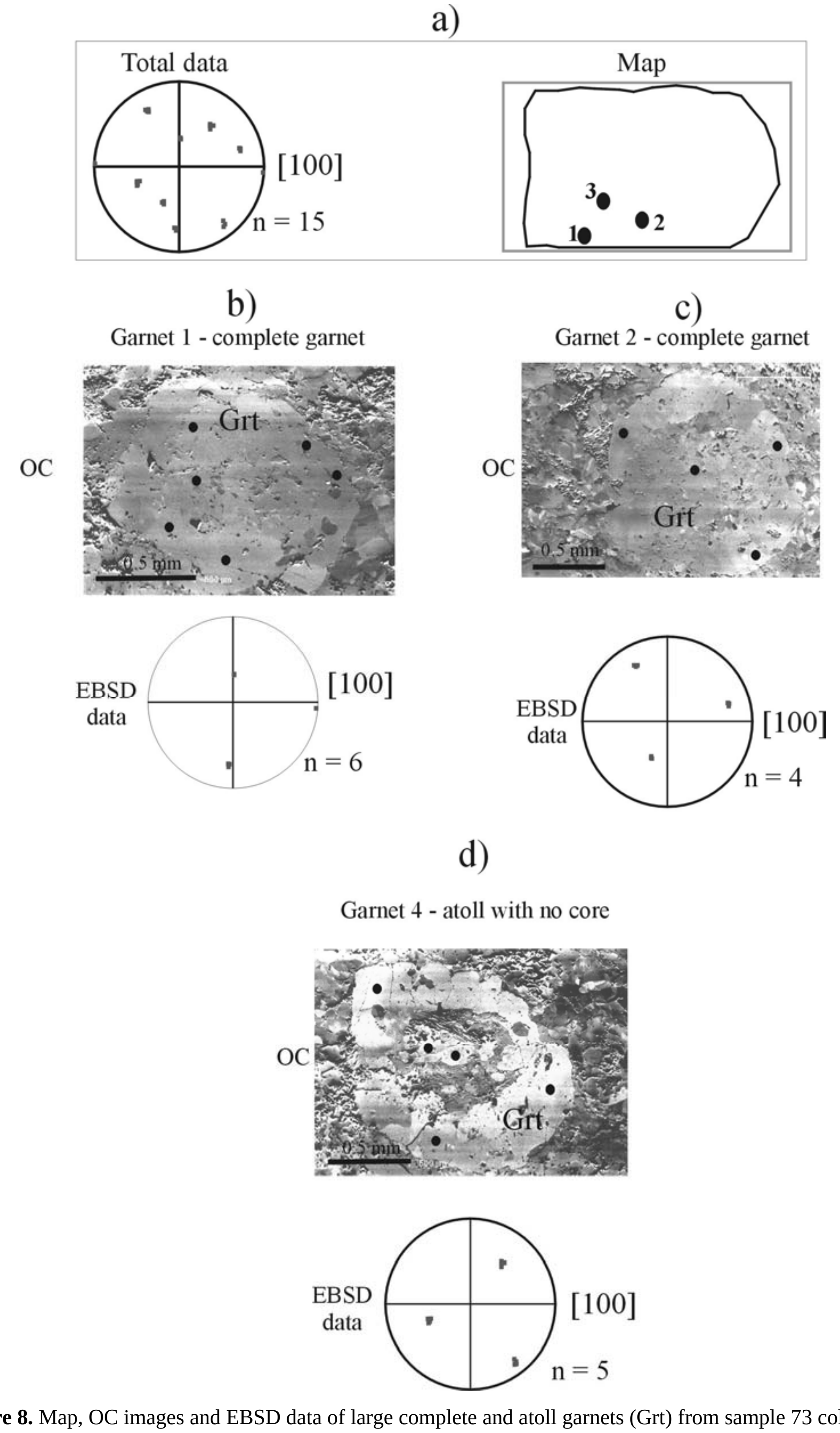

Figure 8. Map, OC images and EBSD data of large complete and atoll garnets (Grt) from sample 73 collected from the inner sillimanite zone of the Ardara aureole. Note that tens of individual grains comprise sub-domains. Different grayscale display, qualitatively, crystallographic orientations. From EBSD data it is evident that orientations of sub-domains within any one grain are very strongly grouped.

Bohemia, Czech Republic who attributed this feature to relatively slow grain-boundary diffusion during garnet replacement by biotite.

Interesting data also come from analysed biotites. Biotites within atoll garnets show higher values of Mg/(Mg+Fe) in comparison with those from the groundmass.

The evidence mentioned above is consistent with Mg being removed from the garnet to contribute to the formation of biotite whilst Mn is partitioned preferentially into garnet as it is not necessary for biotite formation.

EBSD data examined in this study also support replacement of pre-existing idioblastic garnet rather than separate nucleation of atoll and central core. Different crystallographic orientation between atoll rims and central core would be expected if these two were formed by separate nucleation. However, on the basis of EBSD data, atoll rims and central atoll garnet always show identical crystallographic orientation.

8. Conclusion

From textural evidence, microprobe and EBSD data it can be concluded that atoll garnets in the Ardara aureole developed by pre-existing idioblastic garnets being replaced by mainly biotite some quartz and plagioclase to produce atoll forms. The presence of incomplete diffusional modification as a first step of the garnet-replacement process matches well the development of atoll textures where dissolution-replacement is supposed to have progressed faster or more extensively upon those parts of garnet (core of garnet crystals) that had failed to change their composition. As noted by Smellie [22] the garnet-consuming reaction could be slowed down or prohibited in any place by localised closing of diffusion channels and subsequent shortage of the large hydroxyl groups and potassium ions necessary for biotite formation. The breakdown of garnet most likely occurred during prograde metamorphism as staurolite and sillimanite, which are both minerals with higher temperature than garnet in the Ardara aureole, have been found in the core of atoll garnets.

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