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Unusual Lath-Shaped Garnet-Zoisite Intergrowth Textures from a UHP Zoisite-Quartz Fels, Dora Maira, Northwest Italy: An EBSD Case Study

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Abstract

Intergrowth textures of garnet and zoisite have been discovered in the coesite-bearing unit of the Dora Maira Massif near Bastoneri, Valle Gilba. Garnet is rich in grossular- and almandine-component and forms lath-shaped lamellae that are oriented parallel to (100) of zoisite. Electron backscatter diffraction (EBSD) studies show that zoisite/garnet symplectites typically form clusters where the crystallographical c-axes of each zoisite are characterized by a planar orientation. No epitaxial relationship between the structures of zoisite and garnet was recognized. Three different but typical examples of garnet lamellae can be distinguished where (1) one single garnet lamella has one distinct crystallographical orientation, (2) one single garnet lamella exhibits different domains of random orientations, and (3) different parts of a single garnet lamella show in general the same crystallographical orientation but contain microdomains of different orientations that were repeated by 30° along a great circle.

In all probability these garnet lamellae are exsolved from an earlier-generation epidote-group mineral. A potential mechanism of formation is the break down of the former clinozoisite/epidote precursor during metamorphism due to a reduction of trivalent iron to form grossular/almandine lamellae in zoisite. High amounts of divalent cations in the precursor may play a significant role in that their incorporation is favored by pressure. Pressure release during exhumation of the rocks could then lead to the "exsolution" of garnet from precursor clinozoisite/epidote.

Introduction

A NEW EPISODE in metamorphic petrology was initiated in the mid-eighties of the last century with the discovery of ultrahigh-pressure (UHP) metamorphic rocks in the Dora Maira Massif, Italy (Chopin, 1984) and the Western Gneiss Region, Norway (Smith, 1984). *The* indicator mineral which is intimately connected with the definition of a UHP metamorphic rock is coesite, the high-pressure polymorph of quartz; all metamorphic rocks that experienced pressure conditions under which coesite or even a higher pressure polymorph is stable may bear the prefix "UHP." The ensuing two decades were characterized by the discovery of many new UHP-provinces (for details, see Carswell and Compagnoni, 2003), which include rocks containing metamorphic diamonds (e.g., Sobolev and Shatsky, 1990; Massonne, 1999; van Roermond et al., 2002). The unusually high pressure conditions these rocks experienced led to the finding of new minerals such as ellenbergerite (Chopin et al., 1986), bearthite (Chopin et al., 1993), TiO_2 with a α-PbO_2 structure (Hwang et al., 2000; Massonne and O'Brien, 2003). Furthermore, unusual mineral compositions resulted from high pressure conditions of formation such as garnet with several mol% of majorite-component (van Roermond et al., 2001), potassium-bearing clinopyroxene (Sobolev and Shatsky, 1990), and OH-bearing topaz (Zhang et al., 2002). Because of their extraordinary whole-rock composition (high in Si, Al, Mg, extremely poor in Fe, Ca, Na; see e.g. Tilton et al., 1991; Chopin and Schertl, 1999), the whiteschist-type rocks from Dora Maira represent a natural laboratory for MASH-system compositions, thus, producing exceptional minerals like pure pyrope (Chopin, 1984), magnesiostaurolite (Chopin et al., 1992; Simon et al., 1997), magnesiochloritoid (Simon et al., 1997), and magnesiodumortierite (Chopin et al., 1995; Ferraris et al., 1995).

Recently, much attention was focused on intergrowth textures that derive from former single-phase UHP-metamorphic minerals. Examples are: K-feldspar exsolution lamellae (or later K-micas;

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Ogasawara et al., 2002) within clinopyroxene as described by Sobolev and Shatsky (1990); exsolution textures of quartz lamellae parallel to the *c*-axis of clinopyroxene from eclogite, granulite, and garnet clinopyroxenite (Smith and Cheeney, 1980; Smith, 1988; Bakun-Czubarow, 1992; Gayk et al., 1995; Zhang and Liou, 1998; Schmädicke and Müller, 2000; Janák et al., 2006); ilmenite rods in olivine (Dobrzhinetskaya et al., 1996; Green et al., 1997; Hacker et al., 1997; Risold et al. 2001; Massonne and Neuser, 2005); monazite lamellae within apatite (Zhang et al., 1999); coesite exsolution from supersilicic titanite (Ogasawara et al., 2002); and orthopyroxene lamellae in garnet as evidence for a supersilicic precursor with majorite component (e.g. van Roermond et al., 2001, see above). A recently discovered hexagonal K-feldspar polymorph, "kokchetavite," occurs in multi-phase lamellae within clinopyroxene, as revealed by transmission electron microscopy (Hwang, pers. commun., 2005).The foregoing textures often are a result of exsolution during pressure release. In this paper, we report lath-shaped garnet/zoisite intergrowth textures from felsic rocks of the UHP-metamorphic Brossasco-Isasca Unit, Valle Gilba, southern Dora Maira Massif (Schertl, 1995).

Regional Geological Background

The Dora Maira Massif, along with the Monte Rosa and Gran Paradiso massifs, is part of the former southern European plate, prior to its subduction and exhumation during collision with the African plate. The UHP metamorphic slab, the Brossasco-Isasca Unit (BIU) (Compagnoni et al., 1995) of the Southern Dora Maira Massif, measures $10 \times 5 \times 1$ km, and is sandwiched between two lower pressure units that experienced epidote-blueschist- and LT eclogite-facies conditions, respectively. Peak metamorphic conditions of the BIU are about 36 kbar/720°C (e.g., Nowlan et al., 2000; see also Chopin et al., 1991; Schertl et al., 1991; Simon et al., 1997), thus indicating subduction to about 130 km.

According to Compagnoni et al. (1995) the BIU is subdivided into monometamorphic and polymetamorphic complexes. The monometamorphic complex is mainly composed of orthogneiss with scarce relics of undeformed metagranite, and contains lenses of pyrope quartzite, the rock where Chopin (1984) first discovered metamorphic coesite. The polymetamorphic complex comprises metapelites, minor eclogites, and lenses of marble. The protoliths of the polymetamorphic complex represent the former country rocks of a granitic intrusion now forming the monometamorphic complex.

The felsic rock that contains the garnet/zoisite intergrowth textures was found as a loose block in the Valle Gilba of the southern Dora Maira Massif, north of Case Bastoneri. The discovery site is located 2 km northwest of the city of Brossasco within the monometamorphic complex, but very close to the polymetamorphic complex of the BIU.

Objectives of the Study—Analytical Methods

The type of intergrowth texture observed here is very remarkable and easy to recognize; however, it is not known from other natural occurrences. Neither the silicates, garnet, and zoisite, nor their respective compositions are "unusual." Even in rocks from other UHP metamorphic localities like the Kokchetav Massif, Kazakhstan; Dabie and Sulu Mountains, China; Western Gneiss Region, Norway; Erzgebirge, Germany; etc. such symplectites were never observed. Thus, the prime goal of this study is to obtain more detailed information on these unique textures. The aim is not only to obtain data to infer the identity of a precursor mineral (or minerals) of the symplectite, but also to find out whether there is a crystallographical relationship between the structure of garnet and the structure of zoisite. Using optical methods like polarizing microscopy and universal stage measurements, only very restricted information on crystallographic orientation can be derived because garnet is isotropic.

Thus, we applied different methods in order to gain insight into these textures. First, several polished thin sections of the zoisite-quartz fels were investigated using a polarizing microscope. The chemical compositions of typical intergrowth textures were analyzed with a CAMECA SX100 electron microprobe (EMP). Measuring conditions were: acceleration voltage 15 kV, beam current 15 nA, measuring time 20 s. In addition to using EMP, X-ray intensity mapping (MAPS) was performed where four elements were analyzed semiquantitatively at the same time during one cycle in order to measure chemical zonation (measuring time 1 s; for more information, see Schumacher et al., 1999; Schertl et al., 2004). Finally, the electron backscatter diffraction (EBSD) technique was used to obtain structural information on zoisite and on garnet but also on their potential structural relationship. For

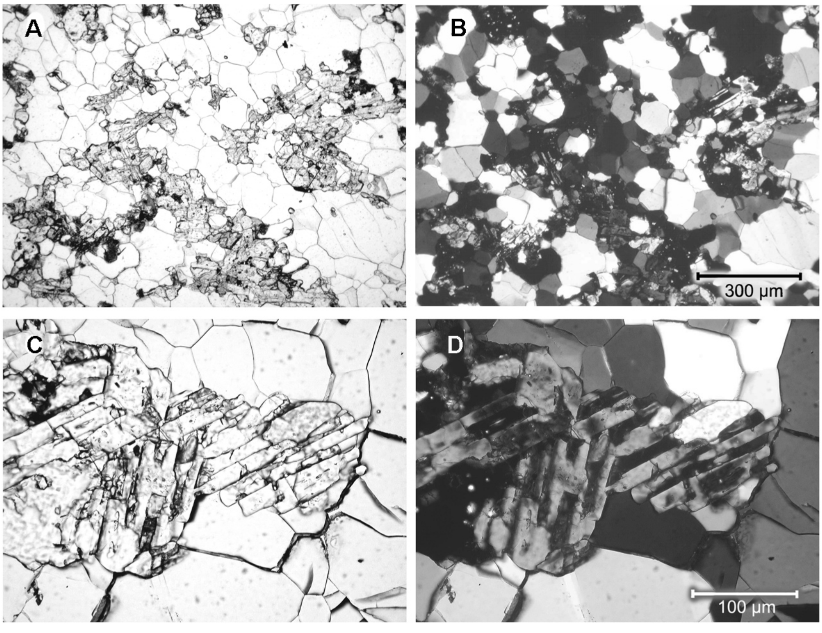

FIG. 1. Photomicrographs of the zoisite quartz fels investigated under linear polarized light (A) and crossed polars (B). Closer look at a cluster of two zoisite/garnet symplectites (linear polarized light (C) and crossed polars (D).

the EBSD studies a device provided by HKL Technology (Denmark) was used, adapted to a scanning electron microscope (SEM) (LEO 1530 Gemini). Prior to coating with carbon, the polished thin sections were etched using colloidal silica (SYTON). Operating conditions for EBSD were: acceleration voltage 20 kV, beam current 1.3 nA, aperture 60 μm, working distance 25 mm, and 70° tilt angle of the thin section (for more information, see Massonne and Neuser, 2005).

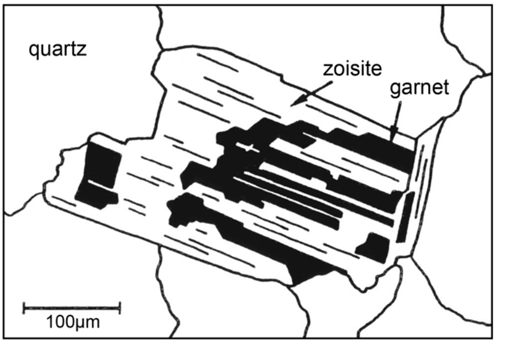

FIG. 2. Sketch map of a zoisite-garnet intergrowth texture showing trace of (100) zoisite cleavage.

Petrographic Characteristics and Mineral Compositions

Main constituents of the zoisite-quartz fels are quartz, zoisite, and garnet. Secondary amphibole, titanite, apatite, and zircon occur as minor amounts. An overview of several zoisite-garnet symplectites sitting within a quartz-rich matrix is presented in Figures 1A and 1B. A closer look and a typical example of such a symplectite is presented in Figures 1C and 1D. Under crossed polars the intergrowth texture of garnet (black, isotropic) and zoisite (grey interference colors) is quite easily distinguishable. From the crystallographical point of view it is important to note that garnet forms lath-shaped lamellae that are oriented parallel to the (100)-cleavage of zoisite (Fig. 2). In all probability, these lamellae are exsolved from a mineral of the epidote group belonging to an earlier generation.

Several typical zoisite-garnet textures were investigated, and two characteristic examples were chosen in order to measure an average garnet:zoisite volume ratio. The relative amounts of garnet and zoisite (analyzed by EMP) in the symplectites were estimated by weighing their respective constituents

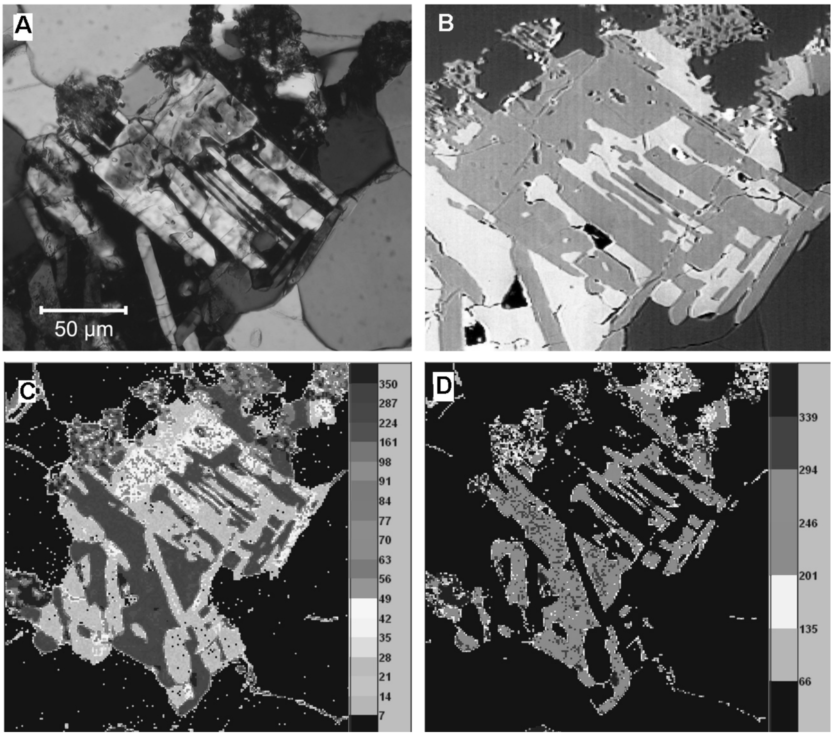

FIG. 3. Photomicrographs of example no. 1 of the three typical intergrowth textures studied. A. Crossed polars. B. BSE image (garnet = white; zoisite = grey). C and D. X-ray intensity mapping (MAPS) of Fe, where (C) focuses on the Fe-distribution of zoisite and (D) of garnet.

using microphotographs under crossed polars. The average symplectite consists of 26.5 vol% garnet and 73.5 vol% zoisite. The structural formula of a potential clinozoisite/epidote precursor was then recalculated by taking the above-mentioned amounts of garnet and zoisite into account. The average garnet composition is $gros_{58.8}$ $alm_{26.6}$ py_{10} $and_{2.6}$ $spes_{2.1}$, whereas that of zoisite is $Ca_{2.03}(Al_{2.87}Fe^{3+}{}_{0.11})_{sum=2.98}[SiO_4/Si_{1.98}Al_{0.02}O_7/O/OH]$. The resulting composition of the potential precursor is $Ca_2(Al_{2.68}Fe^{3+}{}_{0.09}Fe^{2+}{}_{0.21}Mn_{0.02}Mg_{0.08})_{sum=3.08}[SiO_4/Si_{2.01}O_7/O/OH]$. Inasmuch as the amount of divalent cations (Mg, Mn, Fe) is unusually high, the same composition was then recalculated to a structural formula where $Fe_{tot}=Fe^{3+}$. Due to this procedure a structural formula of $Ca_{1.99}(Al_{2.64}Fe^{3+}{}_{0.31}Mn_{0.02}Mg_{0.08})_{sum=3.05}[SiO_4/Si_{1.98}Al_{0.02}O_7/O/OH]$ follows. The small amounts of Mg incorporated in clinozoisite/epidote is not abnormal; even higher amounts up to $Mg_{0.13}$ per formula unit (p.f.u.) are known from the literature (e.g. Petrusenko and Padera, 1970; see also Deer et al., 1986; Franz and Liebscher, 2004, Appendix A). It is well known that zoisite represents a typical mineral of HP to UHP metamorphism (Zhang et al., 1995). Moreover, clinozoisite and even epidote are stable during UHP metamorphism, as proven by quartz pseudomorphs after coesite (Mattinson et al., 2004). Among the possibilities for a precursor mineral for the garnet-zoisite symplectites, vesuvianite may be rejected because its content of CaO is higher and Al_2O_3 lower than in clinozoisite/epidote.

EBSD Studies

Three typical examples of intergrowth textures were studied in detail using EBSD. The three sets of photomicrographs of thin sections under crossed polars, BSE, and Mg and Fe composition maps shown in Figures 3–5 correspond, respectively, to the EBSD images of Figures 6–9, with Figure 4 repeated in two EBSD images, Figures 7 and 8.

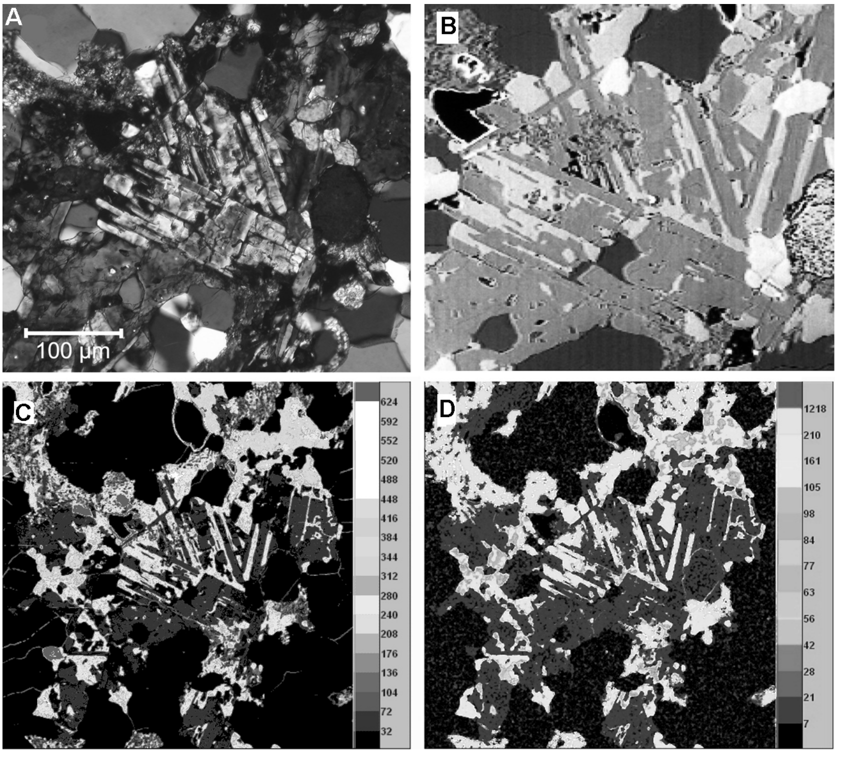

FIG. 4. Photomicrographs of example no. 2 of the three typical intergrowth textures studied. A. Crossed polars. B. BSE image (garnet = white; zoisite = grey). C. MAPS of Fe (light lamellae: garnet). D. MAPS of Mg (light lamellae = garnet).

Each different gradation of grey color in the EBSD images shown in Figures 6–9 corresponds to a clearly defined crystallographical orientation. Minerals with the same orientation are represented by the same grey color scale. The stereographic projections of zoisite presented show the respective normals of the {011}- (left) and {101}-lattice planes (right), whereas the image in the middle shows the orientation of the *c*-axis <001>. The stereographic projections of garnet show the normals of {011} as well as the a_1-, a_2- and a_3-axes <001>.

The EBSD image of the first intergrowth texture investigated (Figs. 3 and 6) demonstrates zoisite to display a homogeneous grey color; the resulting <001> projection reveals the *c*-axis to lie within the plane of the thin section. The garnet that is intergrown with this zoisite generally shows the same crystallographical orientation, mainly except for some slight differences (Fig. 6).

The second sample (Figs. 4 and 7) shows three different crystals of zoisite, each of which is intergrown with garnet; all three zoisite-garnet symplectites are accreted together, forming one cluster. It is important to note that although for each symplectite the <001> direction of zoisite is different, all three *c*-axes of the zoisite grains exhibit a planar orientation (Fig. 7) that is indicated by arrows. The garnet lamellae of the same intergrowth texture show different gradations in grey color, thus indicating a different crystallographical orientation even within one single lamella (Fig. 8, cf. Fig. 4). The different orientations of {011} and <001> along the length of a garnet lamella are given by the stereographic projections shown in Figure 8.

In the third symplectite studied (Figs. 5 and 9), the entire zoisite grain shows a homogeneous crystallographical orientation. Garnet laths, however, exhibit quite surprising results. The EBSD image of Figure 9 shows, at first glance (similar to Fig. 8), different orientations of garnet within one lamella. A closer look, however, at two different parts of the same garnet lamella shows the following peculiari-

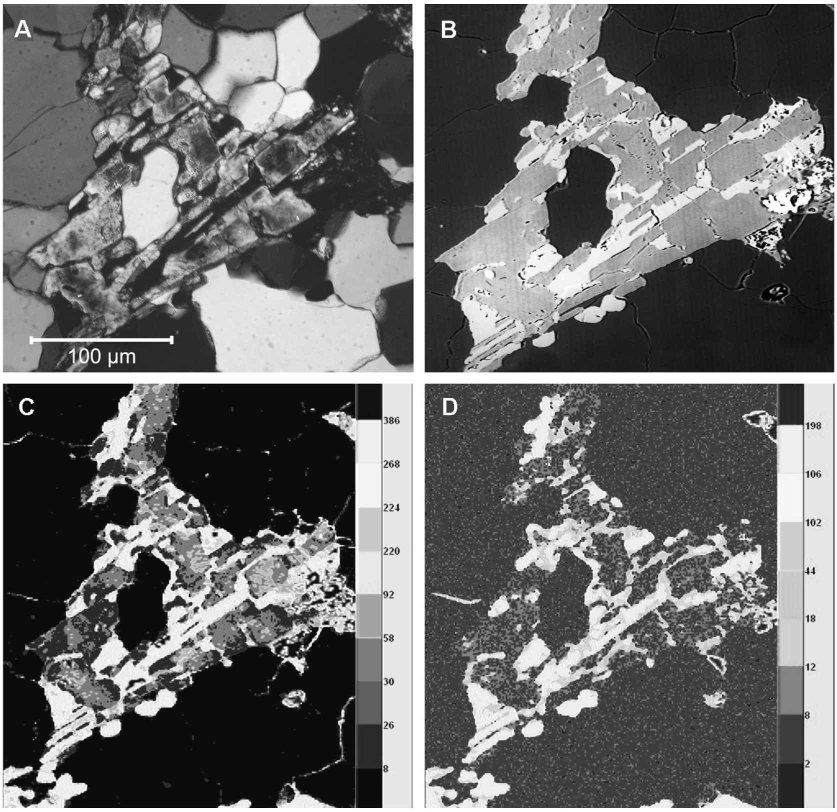

FIG. 5. Photomicrographs of example no. 3 of the three typical intergrowth textures studied. A. Crossed polars. B. BSE image (garnet = white; zoisite = grey). C. MAPS of Fe (light lamellae = garnet; grey gradations = zoisite). D. MAPS of Mg (light lamellae = garnet).

ties (Fig. 9): although the two indicated areas each display homogeneous colors, indicating uniform orientations, the stereographic nets show a more complex structure. Each area shows a dominant orientation, but subsidiary orientations were also measured. Within each of the indicated areas on the garnet lamella, {011}-normals and <001> axes are aligned along great circles at intervals of 30° (Fig. 9).

Discussion and Conclusion

The investigations performed unequivocally show proof of an oriented intergrowth of lath-like garnet lamellae parallel to the (100) direction of zoisite. Characteristically, several zoisite/garnet symplectites are intergrown among themselves, where the *c*-axes of the zoisites are oriented within the same plane. However, a crystallographical/epitaxial relationship between zoisite lattice and that of garnet was never observed; garnet and zoisite show random intergrowth textures. The EBSD technique shows that seemingly homogeneous areas of garnet lamellae may not entirely display the same crystallographical orientations. Individual garnet lamellae may be characterized by a complicated but nevertheless interrelated "rotation-like" texture. The projection points are aligned along a great circle which cannot be derived by simple twinning because a twin system in the cubic system of garnet along the three 4-fold axes does not exist. The only known twinning plane in the cubic system is that of spinel law, which is parallel to {111}, but that cannot explain the obtained EBSD pattern. Thus, although the intergrowth of different interrelated garnet orientations seems to exhibit a regularly recurrent nature, in all probability it represents a kind of periodical but random feature. In any event,

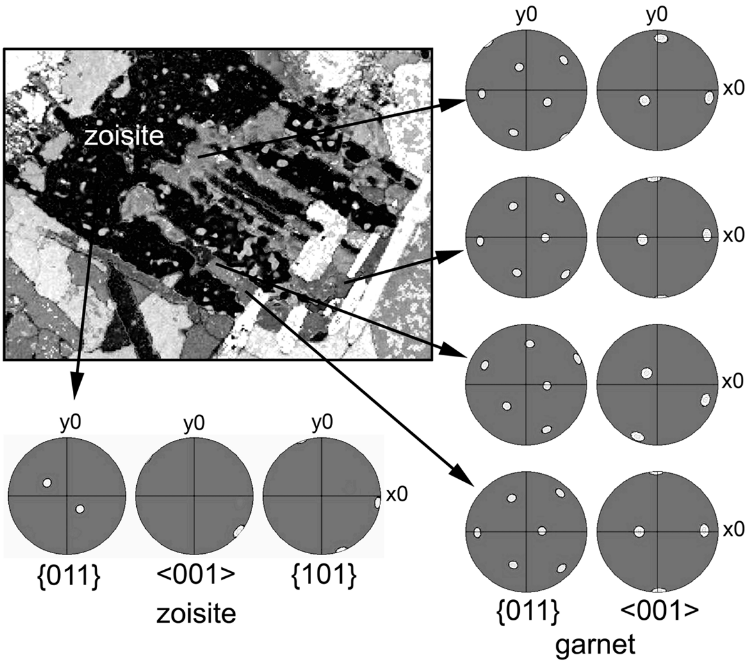

FIG. 6. EBSD image of the zoisite-garnet intergrowth from example no. 1 (where identical gradations in grey color correspond to identical crystallographical orientations) (cf. Fig. 3) and stereographic projections with the normals of the {011} and {101} lattice planes and the orientation of the *c*-axes <001>.

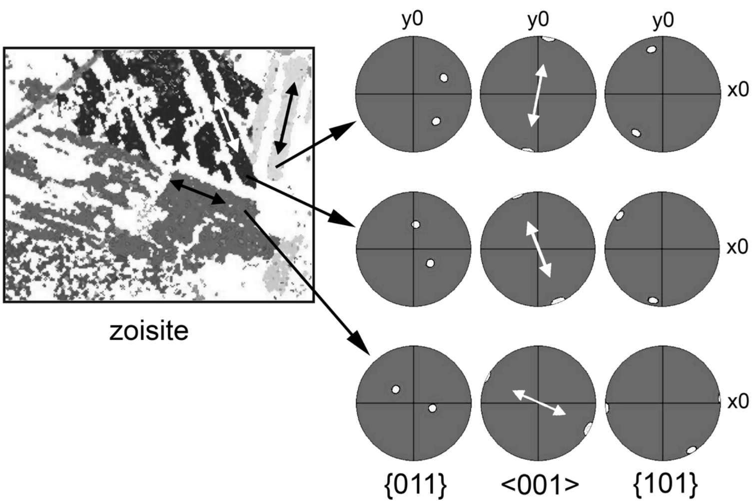

FIG. 7. EBSD image of the zoisite-garnet intergrowth from example no. 2 (cf. Fig. 4) focused on three different zoisites (zoisite = grey gradations; void = garnet) and stereographic projections with the *c*-axes indicated by arrows.

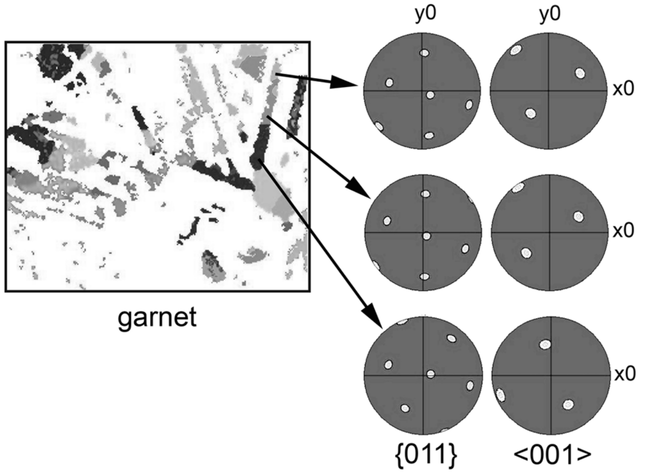

FIG. 8. EBSD image of the zoisite-garnet intergrowth from example no. 2 (cf. Figs. 4 and 7) focused on garnet (garnet = grey gradations; void = zoisite) and stereographic projections of {011} normals and <001> axes of garnet.

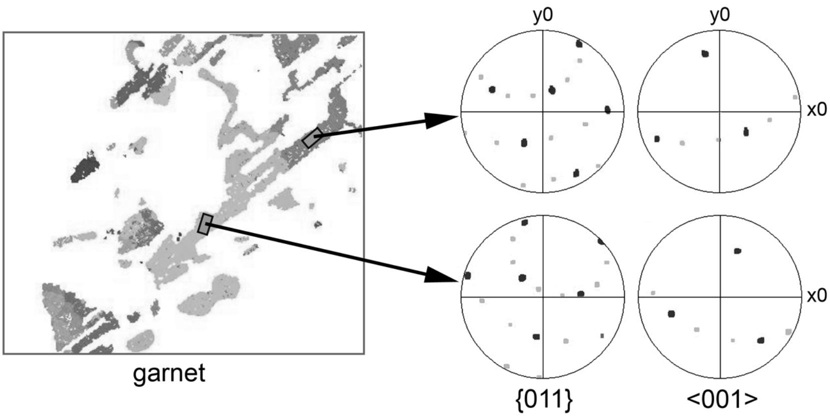

FIG. 9. EBSD-image of the zoisite-garnet intergrowth from example no. 3 (cf. Fig. 5) focused on garnet (void: zoisite, quartz). The stereographic projections of {011} normals and <001> axes from the two areas marked are shown on the right (for details, see text).

structural reasons must be responsible for these textures; it may be possible that these areas represent twinning domains of the precursor epidote/clinozoisite. Subsequently, during the transformation, these domains possibly could be inherited by the secondary garnet. These problems cannot be entirely solved using solely the EBSD technique. Much more work remains to be done; possibly some future TEM-studies may help to enlighten this problem.

It is concluded that the zoisite-garnet symplectites formed from a precursor mineral most likely belonging to the clinozoisite/epidote group. A number of additional questions are still open: why are these intergrowth textures so rare and never before observed in nature? At what stage during exhumation (or during subduction?) did these textures form? What mechanism is responsible for their formation? One interpretation of the origin of the symplectites could be related to a possible change in oxygen fugacity. During metamorphism, a reduction of trivalent iron in the former clinozoisite-epidote may result in a breakdown of this precursor to form lamellae of grossular/almandine–bearing garnet in zoisite (which of course would not simply be "exsolution"). Perhaps the high amounts of divalent cations deduced in one of the structural formulae described above play a significant role. If their incorporation is favored by pressure, the pressure release during the exhumation of the rocks could lead to the "exsolution" of garnet.

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