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Mimicking syntectonic growth: cordierite overgrowth of earlier rotated staurolite porphyroblasts, strain caps and deflected foliation

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ABSTRACT

Monoclinic shape fabrics and inclusion trail geometries of porphyroblasts are regarded as reliable shear-sense indicators, provided that timing and sequence of growth can be established. In the southern Bossòst dome of the Central Pyrenees, staurolite and cordierite porphyroblasts in mica schists contain inclusion trails oblique to, but continuous with the external foliation, indicating porphyroblast rotation. Straight inclusion trails in staurolites record growth between formation of the main schistosity and subsequent shear, i.e. an intertectonic origin. Strain caps and deflection of foliation around porphyroblasts show a distinct asymmetry with uniform sense of shear. Cordierite porphyroblasts are significantly larger than staurolites and contain curved inclusion trails which would suggest syntectonic growth and a similar shear of sense. However, staurolite and cordierite do not belong to the same paragenesis and textural evidence, corrosion of staurolite rims and relict inclusions in cordierites, suggest partial consumption by cordierite. Complete overgrowth of staurolite with preservation of its inclusion trails and adjacent foliation deflection results in curved inclusion trails that mimic syntectonic growth of cordierite. Actually, the larger cordierites statically overgrew rotated staurolites during post-tectonic contact metamorphism.

1. Introduction

Recognition of shear-sense is crucial for the reconstruction of the deformational evolution of orogenic core zones. In discrete zones of strong deformation, shear zones *s. l.*, displaced or deflected markers or foliation curvature provide in most cases reasonable information on the direction of shear (Carreras, 2001). Deformation at deeper crustal levels is commonly distributed across broader zones lacking undeformed wall rocks that limit shear zones. There, the most common macroscopic shear-sense indicators are shear band cleavages, shape-preferred orientation of quartz or calcite, and rotated porphyroclasts and porphyroblasts. Porphyroclasts of magmatic origin, e. g. feldspar augen in metagranites, or sedimentary clasts, such as pebbles in metaconglomerates, are recognizable and clearly predate deformation. Metamorphic porphyroblasts are more difficult to interpret, but they have the potential to reveal more comprehensive information, due to sequential growth of metamorphic phases. Timing of their nucleation with respect to observed deformation events distinguishes pre-, syn-, inter- and post-tectonic porphyroblasts, a concept developed nearly half a century ago by Zwart (1960, 1962), and which until today remains a very powerful, low-cost tool to recognize orogenic events, both in time and space (Hanmer and Passchier, 1990; Passchier and Trouw, 2005).

Correct interpretation of sense of shear from porphyroblasts in the field requires a favourable outcrop plane, oriented orthogonal to the schistosity, the inferred flow plane, and parallel to the mineral or stretching lineation, which represents the shear direction (Passchier and Trouw, 2005). The deflection of external foliation around porphyroblasts, inclusions within porphyroblasts preserving older fabrics, and their relation with the external foliation have to be recognized. It has to be taken into account that reactivation of schistosity during subsequent deformation phases may obscure or rotate stretching lineations, so that rotation axes of porphyroblasts are not necessarily oriented perpendicular to lineations anymore (Bell et al., 1995). A further very important aspect, the sequence of growth of the metamorphic minerals involved, is the most difficult to establish in the field. This paper reports a case where interpretation of monoclinic shapes and inclusion trails from field observations yields apparent unequivocal shear-sense and timing of cordierite porphyroblast growth which were refuted later by close inspection of thin

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sections and thermobarometric calculations. The results emphasize the necessity to examine microstructural and petrological evidence of fabrics involving deformation and metamorphism. Field observations alone, even if they seem to be unequivocal, do not yield sufficient information, and can lead to wrong conclusions.

2. Initial field observations from the southern Bossòst dome

Mica schists with large, centimetre-sized porphyroblasts of andalusite, staurolite and cordierite, and smaller garnets, crop out in the eastern part of a structural and metamorphic dome in the central Pyrenees. The Bossòst dome, also known as the Garonne dome, is one of several structural and metamorphic domes which evolved during the main phase of the Variscan orogeny in the Axial Zone of the Pyrenees. These structures possess a core of pre-Variscan orthogneisses or, as in the case of the Bossòst dome, Variscan granite plutons, mantled by Cambrian to Devonian metasedimentary rocks. The development of these Pyrenean dome structures is still a matter of debate, as summarized in detail by Mezger and Passchier (2003) and Mezger (2009). Relevant for the understanding of the problem discussed here, it is sufficient to know that the rocks of the metasedimentary mantle have experienced polyphase metamorphism and deformation, resulting from pre-Variscan regional metamorphism and intrusion of orthogneiss protoliths (Castiñeiras et al., 2008; Denèle et al., 2008), main phase Variscan ductile deformation (Carreras and Capella, 1994), late main phase Variscan plutonism (Gleizes et al., 1997, 1998), late Variscan shear zone development and Alpine deformation and faulting (Lamouroux et al., 1980; McCaig and Miller, 1986; Soula et al., 1986).

The mica schist outcrop of particular interest for this study is located along a forestry road on the northeastern side of the Spanish Aran valley, 800 m northwest of the village of Arres and approximately 2.5 km south of Bossòst (0°42′26” E, 42°45′40” N; Mezger et al., 2004). A well-developed continuous schistosity is formed by a fine-grained matrix (ca. 200 μm) of aligned muscovite, biotite and elongated quartz. Distributed equally throughout are numerous reddish brown idioblastic staurolite crystals up to 6 mm in diameter. Many of the staurolite porphyroblasts contain interpenetrating twins, whose variable orientations produce a variety of shapes. Rotation of the blasts can be inferred from deflection and drag folding of schistosity. The plane of view is oriented favourably, parallel to a distinctly recognizable mineral lineation. A smaller number of ubiquitous centimetre-sized black minerals, significantly larger than the staurolites – an important fact to keep in mind – with rounded or oblate shapes are identified as cordierite (Fig. 1). Some cordierites possess monoclinic sigmoidal shapes, which were interpreted by previously visiting geologists as δ-clasts, evident from labels on the rock face beside marked specimen. A polished rock sample from that outcrop reveals straight inclusion trails in staurolites, variably oriented with respect to the main schistosity, and larger cordierites with sigmoidal inclusion pattern (Fig. 2). The interpretation as outlined in Fig. 3 seems straightforward: staurolite grew intertectonically, overgrowing an existing schistosity, and then rotated clockwise with respect to the main schistosity, as indicated by continuation of the internal foliation S_i, preserved as quartz inclusion trails, into the external foliation S_e, which is deflected near the staurolite margin. Cordierite, on the other hand, appears to have grown syntectonically, in the same clockwise sense relative to the schistosity, evident from *S*-shaped inclusion trails, which likewise continue into S_e. One can conclude from the fact that in both phases S_i is continuous with S_e, i.e. inclusion trails in both phases represent the same foliation, staurolite nucleated earlier than cordierite and ceased growing before shearing commenced, while cordierite porphyroblasts, at least in part, grew during non-coaxial shearing. In his landmark paper on the determination of polymetamorphic mineral associations, Zwart (p. 51, 1962) arrived at the same conclusions. Furthermore, the general lack of stable staurolite-cordierite parageneses suggests that medium pressure-medium temperature regional metamorphism, which produced staurolite, was followed by contact metamorphism with coeval shearing during growth of cordierite. The growth sequence is correct, but the conclusion pertaining to deformation and cordierite formation is inconsistent with detailed microstructural observations and petrological considerations discussed in the next section.

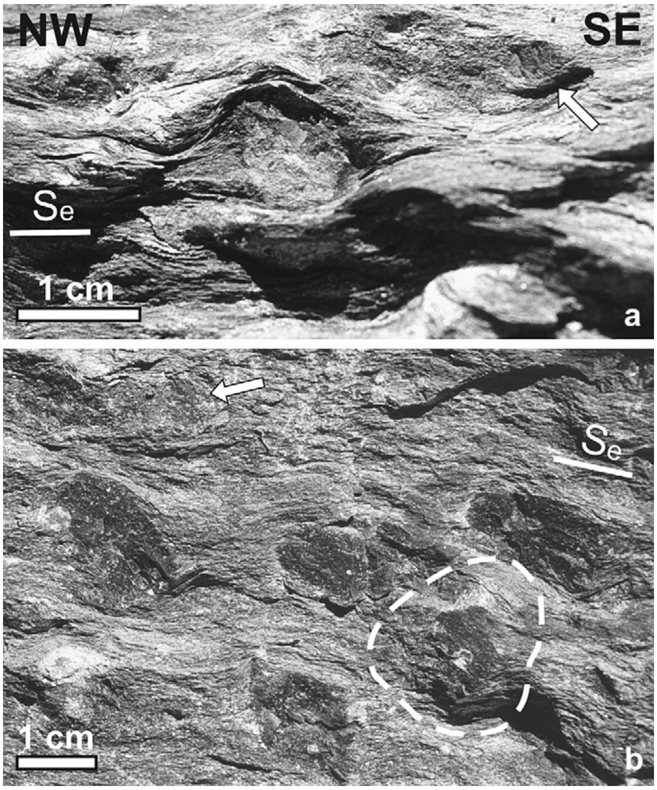

Fig. 1. Closeup photographs of the staurolite-cordierite schist along the road outcrop northwest of the village of Arres, Spain. The foliation and lineation of the schist dip moderately (20–30°) ESE–SE. The plane of view is perpendicular to schistosity and approximately parallel to the mineral lineation. Cordierite porphyroblasts form dark grey centimetre-sized ellipses, although unequivocal distinction is not easy. (a) Weathering has outlined the deflected foliation around the central crystal which displays a non-stairstepping geometry characteristic of δ-type clasts. The grain in the upper right corner (white arrow) has a similar symmetry. The sense of shear derived from such geometry would be dextral. Thin sections reveal that cordierites are porphyroblasts with sigmoidal inclusion patterns, and not δ-clasts in the true sense of Passchier and Trouw (2005). However, this does not become obvious when looking at this rock face. (b) Numerous cordierite blasts, some of them displaying similar δ-type as in (a), are circled with blue marker, which is not discernible in black and white photographs, and labelled with ‘δ’. One outline is retraced by dashed white lines. The white arrow points to a lighter coloured staurolite blast, which is hardly visible even on the natural rock face, so that it is easily overlooked.

3. Evidence from microtectonic and petrographic analyses

3.1. Petrographic and thermobarometric considerations

Doubts about the above interpretation should arise when staurolite inclusions in the same cordierite appear in a parallel section (Fig. 2d). Vernon (2004), Passchier and Trouw (2005)

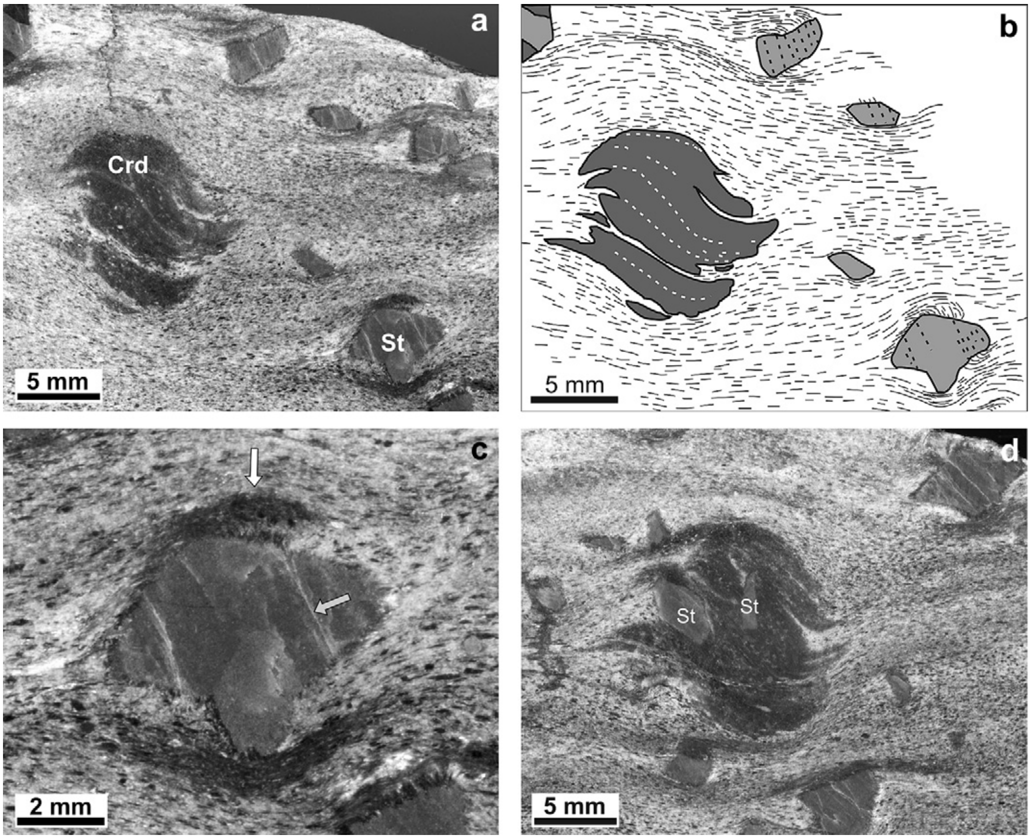

Fig. 2. Scans of polished rock slabs of the staurolite-cordierite schist from the outcrop in Fig. 1. The sections were cut orthogonal to the main schistosity and parallel to the mineral lineation. (a) The main schistosity is outlined by black flakes of biotite, oriented approximately horizontal, and curves around staurolite (St) and cordierite (Crd) porphyroblasts. (b) Interpretive sketch of (a). Straight inclusion trails in staurolite, marked by dashed black lines, continue into the main schistosity. Deflection and drag folding of schistosity in the strain caps indicate clockwise rotation of staurolite blasts with respect to the schistosity. The cordierite, whose shape resembles a *δ*-type clast at first glance, has a sigmoidal, curved S_i pattern, outlined by dashed white lines, which can be traced directly into S_e. The angle between S_i in the center and the margin would suggest a minimum rotation of 55°, also clockwise, relative to S_e. (c) Detail of lower right corner of (a). Grey arrow points to straight inclusion trails in the staurolite blast, outlined by thin light lines. Strain caps (white arrow) have a darker colour due to concentration of biotite grains and narrower spacing of schistosity than in the matrix. (d) Counterpart of rocks slab shown in (a), spaced approximately 3 mm apart. The cordierite blast envelops two staurolite inclusions.

(Fig. 7.30) and Vernon et al. (2008) have argued that different growth rates of coevally nucleating phases can result in slow growing minerals being overgrown by faster growing phases. However, in the present rocks, the observed cordierite-staurolite-muscovite-biotite assemblage can be considered metastable and is result of polymetamorphism (García-Casco and Torres-Roldán, 1999; Mezger and Passchier, 2003). Staurolites with embayed margins and rimmed by coarse muscovites suggest that retrograde metamorphic reactions took place, most likely a reversal of the initial staurolite-forming reaction involving muscovite and chlorite as reactants. This occurred after peak-metamorphism at 5.5 kbar and 580 °C, calculated for the staurolite-garnet-biotite assemblage (Mezger et al., 2004). At lower pressures and temperatures, 2 kbar and 525 °C, the stability field of andalusite-cordierite-biotite is reached. Along the retrogade path, possibly related to uplift during the formation of the Bossòst dome, cordierite and andalusite are formed at the expense of staurolite, chlorite, muscovite and quartz. Newly formed andalusites were subsequently also consumed, along with biotite, to form cordierite, and is only preserved as relict grains in cordierite (Mezger and Passchier, 2003). Staurolite abundance was too large for complete consumption, so that staurolite remains present under metastable conditions. Ilmenite inclusions in cordierite originate from the TiO_2-component in

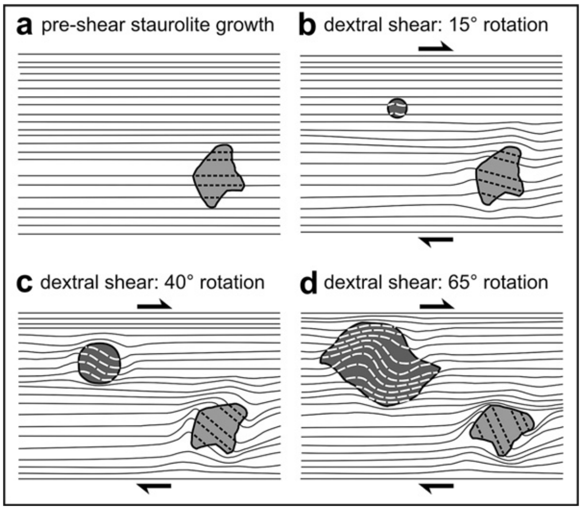

Fig. 3. Initial, field-based interpretation of the fabrics of Figs. 2a and b. (a) Staurolite grows intertectonically prior to shearing. (b) During the early phase of non-coaxial deformation, after 15° of clockwise rotation of staurolite, relative to the schistostiy, cordierite nucleation sets in. (c) Continuous dextral shearing results in *s*-shaped inclusion trails in cordierite, as the mineral continues to grow syntectonically. (d) Present stage after 65° rotation of staurolite. Cordierite inclusion trails with sigmoidal pattern decrease in magnitude of curvature from core to rim, characteristic of syntectonically grown porphyroblasts (Schoneveld, 1977).

biotite (2 vol. %) which cannot be incorporated into cordierite during the breakdown of biotite.

3.2. Microstructural observations

The cordierite porphyroblasts of this sample are several times larger than staurolites, which can be attributed to the fact that several metamorphic reactions, not all including staurolite, contributed to the formation of cordierite (Fig. 4). Inclusions in staurolite are predominantly shape-oriented, elongated, rounded quartz grains that form planar inclusion trails. In cordierite, similar quartz inclusions are also aligned, but more numerous and larger, with additional minor ilmenite and aligned biotite (Fig. 5). Different composition and size of inclusions indicate that cordierite did not always completely consume staurolite, which was probably only a minor reactant in cordierite formation. Staurolite inclusions in most cordierite grains suggest that they could have acted as nucleation sites for cordierite. In the field, staurolite inclusions in cordierite are difficult to distinguish due to negligible colour contrast between both minerals. As a consequence of their larger size and their nucleation around staurolite, cordierite grains overgrew the matrix around staurolite, including strain caps and deflected external foliation, composed of mica and elongated quartz grains. Cordierite-forming reactions consumed most of muscovite and biotite, while enough quartz remains to preserve the older foliation as inclusion trails (Figs. 4 and 5). Incorporation of continuous staurolite inclusion trails in the center and deflected external foliation at the margin yield S_i in cordierite that resemble sigmoidal inclusion patterns characteristic of syntectonic porphyroblasts (Fig. 6).

Evidence that cordierite did not simply form syntectonically comes from several smaller staurolite grains overgrown by a single large cordierite porphyroblast (Fig. 4b). Tracing the internal foliation of that cordierite grain reveals a complex curvature resulting

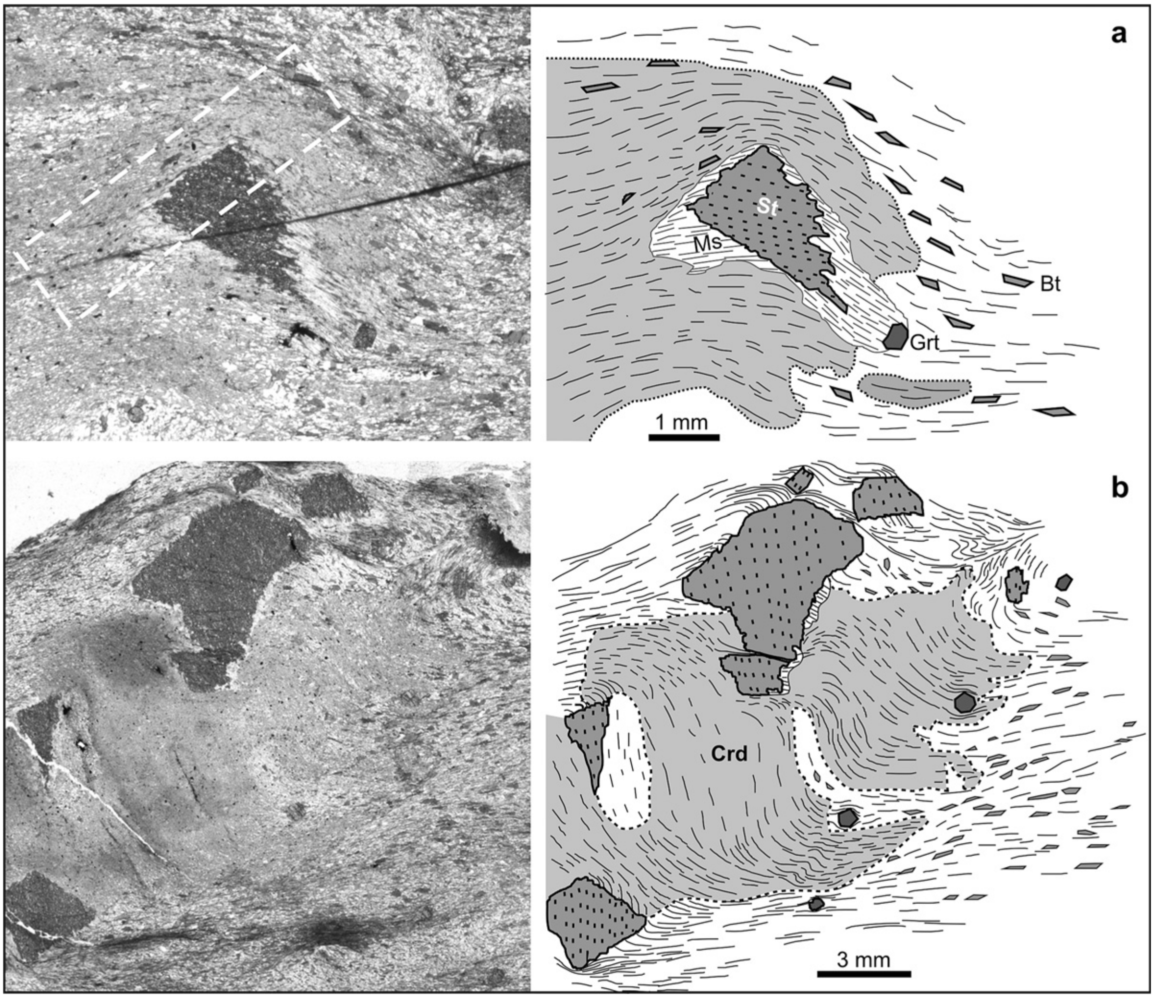

Fig. 4. Thin section scans and sketches from the same staurolite-cordierite schist sample shown in Fig. 2. (a) Relict staurolite with embayed margin, indicative of corrosion and consumption, is separated by coarse muscovites from enveloping cordierite. Low-refractive cordierite is completely altered to pinite, a fine-grained retrograde aggregate of chlorite and sericite, and characterized by low abundance of biotite (Bt) and quartz compared to the matrix, both phases being consumed to form cordierite. Breakdown of staurolite along its rim during retrogression leads to the epitaxial nucleation of coarse-grained muscovite (Ms) parallel to the external schistosity. The strain cap above the staurolite is overgrown by cordierite. No strain caps related to cordierite can be observed. Dashed white line outlines location of Fig. 5. Small idioblastic garnets (Grt) show no signs of corrosion within cordierite, indicating that they are not part of any metamorphic reaction. The diagonal black line in the scan is an artefact of a scratch in the thin section plate. (b) Large cordierite overgrowing several staurolite blasts and their individual foliation strain caps, as well as another folded part of the matrix traced from the upper right to the lower left corner. It shows that cordierite has grown post-tectonically.

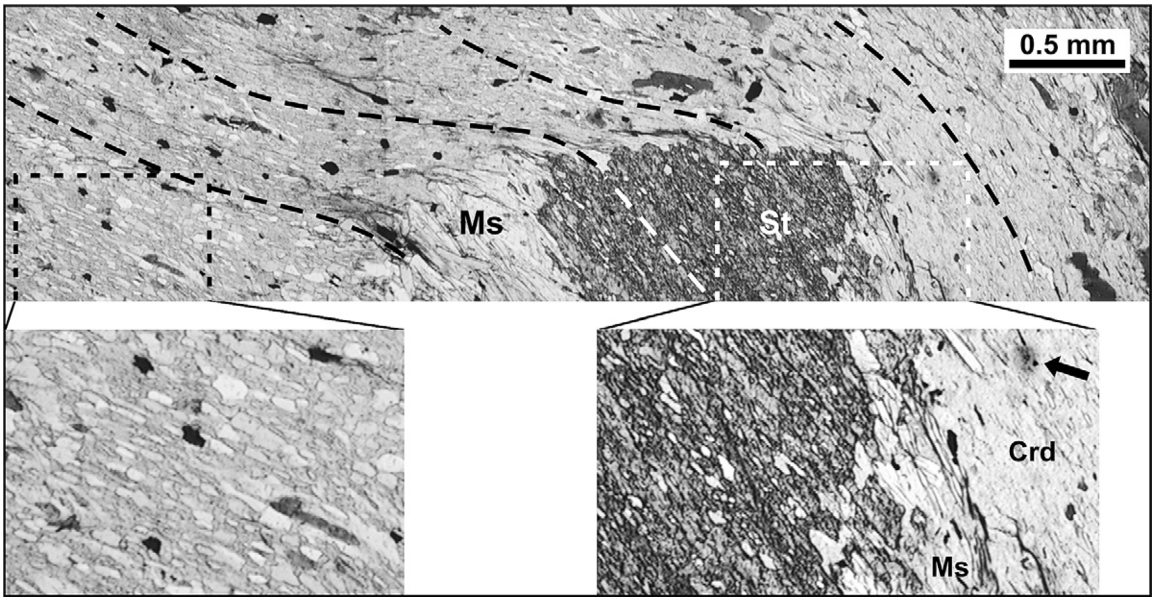

Fig. 5. Thin section photographs of the staurolite inclusion in cordierite of Fig. 4a in plane polarized light. Dashed white lines outline the straight inclusion trails in staurolite that continue directly into the curved inclusion trails in cordierite (dashed black lines), which mimic the deflected external foliation and strain caps around the previously rotated staurolite. The enlarged sections show that inclusions are predominantly made of elongated rounded quartz grains, larger and more numerous in the cordierite than in staurolite. Remnant biotite and opaque ilmenite grains are minor inclusions in cordierite. The black arrow in the right enlargement points to a pleochroic halo around a zircon inclusion in cordierite. The grain boundary of staurolite is strongly embayed due to the replacement by muscovite.

from of overgrowth of folded matrix and several foliation deflections and strain caps in the engulfed staurolites, confirming the postdeformational origin of cordierite.

4. Discussion

The observed microstructures and inferred metamorphic reactions can be summarized in a four-stage model (Fig. 6). At first, regional metamorphism, possibly related to Variscan crustal thickening, led to staurolite nucleation at a period without significant deformation. Staurolite crystals incorporated the existing foliation, its quartz components form straight inclusion trails (Fig. 6a). Different angles between crystal long axes and internal foliation are evidence of random growth directions (Mezger and Passchier, 2003). Second, non-coaxial deformation with a possible pure shear component, associated with an early phase of dome formation and exhumation along an extensional shear zone, resulted in differential rotation of staurolite grains relative to the schistosity (Fig. 6b). This can be inferred from the obliquity of inclusion trails with respect to the external foliation. Third, late in the dome evolution during the main Variscan phase, the intruding Bossòst granite produced a contact aureole coeval with coaxial deformation, preserved in convex inclusion trails of early forming andalusites (Mezger and Passchier, 2003). Subsequent cordierite nucleation, leading to partial overgrowth and replacement of andalusite and staurolite, occurred under static conditions after deformation caused by granite emplacement ceased (Fig. 6c). Fourth, continuous cordierite growth incorporated staurolite inclusion trails and engulfed adjacent deflected external foliation, forming large, centimetre-sized crystals, whose microstructures can either be recognized as post-tectonic, if folded matrix foliation is involved (Fig. 4b), or mimic curved inclusions indicative of syntectonically grown porphyroblasts (Figs. 2a, 3d). Close examination reveals inclusions that are straight in the core of the porphyroblast, and only curve in the outer parts near the rim (Fig. 6d). Careful observation of the outcrop yielded both post-tectonic and pseudo-syntectonic types.

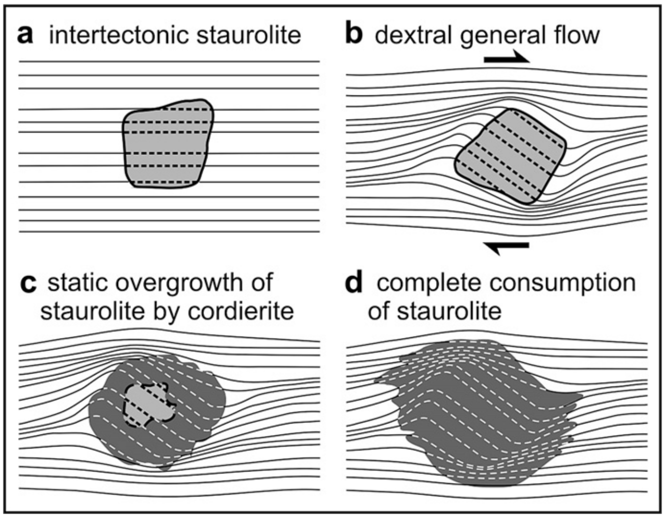

Fig. 6. Proposed model for the sequence of porphyroblast growth and deformation phases. See text for discussion.

In the quest to find shear-sense indicators, it is understandable to focus on the seemingly conclusive evidence, i.e. monoclinic fabrics providing sense of shear, while ignoring those without unequivocal shear-sense information. Thus it happened at the locality in the Bossòst dome discussed here that cordierite porphyroblasts with apparent δ-shapes were circled by thick blue and green markers and labelled accordingly (Fig. 1). Upon close inspection of samples taken, and thorough studies of thin sections, the counterfeit syntectonic porphyroblast would be exposed as a “fake”. What had been initially interpreted as syntectonic cordierite porphyroblasts turned out to be post-tectonic blasts that statically overgrew intertectonic staurolites. The shearing event occurred between growth periods of staurolite and cordierite, i. e. two metamorphic events, and not as originally thought during growth of the younger mineral, cordierite (Mezger and Passchier, 2003).

Generally, porphyroblasts with curved inclusion trails continuous with the matrix folation are considered reliable indicators for synkinematic growth (p. 109, Vernon and Clarke, 2008; Vernon et al., 2008). As the case discussed here shows, this only holds true for original, primary mineral phases, not for pseudomorphs or larger overgrowing minerals. In most cases pseudomorphs consist of mineral aggregates replacing an older mineral while preserving its shape. Retrograde pseudomorphs of coarse muscovites after staurolites are common and easily distinguished, so that misinterpretation, even at first glance, is not very likely (Guidotti and Johnson, 2002). Overgrowths, on the other hand, extend beyond the grain boundary of the engulfed mineral, incorporating the external foliation, which can be deflected if the original porphyroblast had rotated. The resulting large minerals can be very visible and possess impressive monoclinic fabrics and shapes that may be prone to misconception. Growth of metamorphic minerals, porphyroblasts, depend on many aspects: pressure, temperature, whole-rock composition, growth rate, diffusion rates, that correct interpretation, even after careful petrographic thin section studies and additional microprobe data, is not an easy task (Vernon et al., 2008). Taking this into consideration, conclusions drawn from field observations should only be the beginning of an examination and not the end.

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