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Development of lattice preferred orientation in clinoamphiboles deformed under low-pressure metamorphic conditions. A SEM/EBSD study of metabasites from the Aracena metamorphic belt (SW Spain)

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Abstract

The mechanical properties of the lower continental crust are intimately related to the rheology of calcic clinoamphibole. Naturally deformed clinoamphibole typically shows brittle behaviour under a wide range of deformation conditions, whereas crystal plasticity is rarely observed. In this study, the microfabric of clinoamphiboles from metabasites deformed under low-pressure/medium-to-high temperature metamorphic conditions is presented. Amphiboles from all samples have developed LPO that can be attributed to different deformation mechanisms depending on deformation temperature, fluid content, structure and phase-strength contrasts. Rigid body rotation of amphibole prisms within a weaker plagioclase matrix corresponds to metabasites deformed under medium deformation temperatures that show a weak layer structure and a high phase strength-contrast between plagioclase and clinoamphibole. Lower temperatures and the presence of fluids mean that one of the studied rocks was affected also by dissolution-precipitation creep and cataclastic flow. In the final sample, dislocation creep was accommodated by recovery and subgrain rotation dynamic recrystallization in monomineralic hornblende layers at higher temperatures, which could be representative of the rheology of amphiboles in a lower continental crust at high temperature conditions.

Keywords: Cataclastic flow; High-temperature deformation; Misorientation; Phase-strength contrast; Rigid body rotation; Subgrain rotation dynamic recrystallization

1. Introduction

The mechanical behaviour of the lower continental crust, which is closely related to the formation and evolution of crustal-scale structures (e.g., Wilks and Carter, 1990), is considered to be basically controlled by polyphase rocks composed primarily of plagioclase and hornblende (e.g., Kirby and Kronenberg, 1987; Ranalli and Murphy, 1987). Whilst the behaviour of plagioclase is relatively well-known (e.g., Stünitz and Fitz Gerald, 1993; Rybacki and Dresen, 2004; Terry and Heidelbach, 2006), a better knowledge of the rheology of calcic amphibole is crucial in improving understanding of the mechanical properties of the lower continental crust. Furthermore, some physical properties of this part of the lithosphere (namely, seismic lamination and seismic anisotropy) are intimately related to the lattice preferred orientation (LPO) of anisotropic minerals (e.g., Mainprice et al., 2000; Meissner et al., 2006 and references therein), with hornblende being perhaps the most important phase.

Calcic clinoamphiboles are thought to be one of the strongest lower crustal minerals (e.g., Brodie and Rutter, 1985; Shelley, 1994). Nevertheless, there is significant disagreement on the mechanisms taking place during hornblende deformation.

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Experimentally deformed clinoamphiboles under very high strain rates typically show $(\bar{1}01)$ mechanical twinning, together with (100)[001] dislocation glide without dynamic recrystallization (Rooney et al., 1970, 1975; Dollinger and Blacic, 1975; Morrison-Smith, 1976). However, these deformation mechanisms are likely to play a role in naturally deformed amphiboles only under extreme deformation conditions, such as shock-loaded rocks (Chao, 1967). Additionally, under high temperature conditions, dislocation glide, incipient dynamic recrystallization and fracturing have also been reported (Hacker and Christie, 1990). In contrast, naturally deformed amphiboles typically show brittle behaviour, sometimes along with solution mass transfer, under low greenschists to amphibolites facies conditions (Allison and La Tour, 1977; Brodie and Rutter, 1985; Nyman et al., 1992; Lafrance and Vernon, 1993; Stünitz, 1993; Babaie and La Tour, 1994; Berger and Stünitz, 1996; Kruse and Stünitz, 1999; Imon et al., 2004), as well as (100) mechanical twinning at temperatures ranging from 350 to 540 °C (Dollinger and Blacic, 1975; Biermann, 1981; Cumbest et al., 1989). Kinking has been reported only rarely (Imon et al., 2004; Baratoux et al., 2005). Crystal plasticity has been observed occasionally for temperatures ranging from 450 to >650 °C, including dynamic (although usually chemically enhanced) recrystallization (Cumbest et al., 1989), dislocation creep on (100)[001] (Skrotzki, 1992) and subgrain formation by dislocation glide on (hk0)[001] (Biermann and van Roermund, 1983). Finally, deformation by dissolution-precipitation creep under upper greenschist – lower amphibolite facies conditions has been described in amphibolites from the Ryoke Belt (Imon et al., 2002).

In this study, LPO of calcic amphiboles from the Aracena metamorphic belt (SW Spain) are analysed. These amphiboles are found in metabasites (amphibolites and mafic schists) that were deformed under low-pressure metamorphic conditions ($P < 6$ kbar), at temperatures ranging from 650 °C to 970 °C.

2. Geological setting

The Aracena metamorphic belt (AMB) is a long and narrow band located at the contact between the Ossa-Morena zone (OMZ) and the South-Portuguese zone (SPZ), two of the main units forming part of the Iberian Massif (SW European Variscan Chain). The limits of the AMB lie parallel to the main regional structures, which trend in a WNW-ESE direction. According to the division proposed by Castro et al. (1999), two domains can be distinguished in the AMB: an oceanic domain (OD) to the south and a continental domain (CD) to the north (Fig. 1). In the northern part of the OD, the Acebuches metabasites are in contact with the CD. The Acebuches metabasites were derived, according to various geochemical studies, from the high-temperature/low-pressure (HT/LP) metamorphism of former oceanic crust with MORB affinities (Bard and Moine, 1979; Dupuy et al., 1979; Quesada et al., 1994; Castro et al., 1996).

The Acebuches metabasites were affected, during the Variscan orogeny, by three main tectono-metamorphic events (Castro et al., 1996; Díaz Aspiroz and Fernández, 2005). The first stage involved a HT/LP metamorphic event (AM-M_1), which reached the amphibolite-granulite facies transition, along with a ductile shear deformation (AM-D_1). Subsequently, the structural base of the Acebuches metabasites was affected by a retrometamorphism (AM-M_2) related to a mylonitic deformation (AM-D_2). This second deformation event was responsible for the juxtaposition of the Acebuches metabasites onto the Pulo do Lobo accretionary prism, through the formation and activity of the Southern Iberian shear zone (SISZ) (Crespo-Blanc and Orozco, 1988). The characteristics of the structures generated during AM-D_2 in the SISZ suggest that: (1) the SISZ is an oblique transpressional shear zone with triclinic symmetry (Díaz Aspiroz and Fernández, 2005); and (2) the finite strain was higher toward the structural base of the Acebuches metabasites (Díaz Aspiroz and Fernández, 2003, 2005). Finally, the Calabazares shear zone (AM-D_3) affected the top of the series, at the contact between the Acebuches metabasites and the CD.

The CD is composed of a variety of high and medium grade metamorphic rocks, including schists, gneisses, migmatites, calc-silicates, amphibolites and marbles, as well as various intermediate to basic intrusive rocks (Fig. 1). The El Rellano amphibolites (Castro et al., 1996), which are part of the CD, show cross-cutting relationships with foliated calc-silicate rocks, suggesting an intrusive (gabbroic) origin for these rocks.

The CD underwent, during Variscan plate convergence, a complex tectonic evolution that comprised up to four ductile deformation phases (Díaz Aspiroz et al., 2006). The first stage (CD-D_1) has been traditionally related to km-scale recumbent folds (e.g., Bard, 1969). In the high-grade rocks of the AMB, the CD-S_1 foliation is only preserved within some CD-S_2 foliation microlithons. The second tectonic event (CD-D_2) is associated with widespread extension that caused generalised axial flattening and discrete shear zones with a normal sense of displacement. A penetrative metamorphic foliation (CD-S_2) is present throughout the CD, whereas within shear zones a localized mylonitic foliation (also CD-S_2) and a related stretching lineation (CD-L_2) have developed. This deformation phase was accompanied by a high-temperature/low-pressure (HT/LP) metamorphism that affected the CD (Díaz Aspiroz et al., 2006). The third stage (CD-D_3) generated symmetric upright folds with variable fold axial trace orientations but only in some minor fold hinges in the marbles has a weak axial-planar foliation (CD-S_3) developed (Díaz Aspiroz et al., 2003). The last ductile deformation event (CD-D_4) resulted in km-scale, SW-verging antiforms and several reverse shear zones. A penetrative mylonitic foliation (CD-S_4) and a related stretching lineation (CD-L_4) developed within these shear zones.

3. Rock types and samples

According to their structural features, the Acebuches metabasites can be divided into two main groups (Fig. 1, Table 1): (1) banded amphibolites that were unaffected by AM-D_2 and show therefore structures formed only by AM-D_1; and (2) mylonitic metabasites that were affected by AM-D_2 (Díaz Aspiroz and Fernández, 2005). The banded amphibolites