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Research paper

Cordierite from a high-temperature low-pressure shear zone of the south-western Bohemian Massif (Moldanubian terrain, Austria)

Robert Sturm

Brunnleitenweg 41, A-5061 Elsbethen, Austria

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ABSTRACT

A medium-scale shear zone exposed in the gneiss rocks of the South-western Bohemian Massif (Moldanubian Zone) contains cordierite, whose Na p.f.u. is subject to a significant increase from the centre to the edge of the deformation area, whilst other elements only show negligible variations. Coexisting mineral phases of cordierite include garnet, biotite, and sillimanite. According to the results obtained from the garnet-cordierite Fe^{2+}/Mg^{2+}-exchange thermometer a decrease of peak temperature from 639 °C in the central mylonite to 593 °C in the marginal mylonite can be observed, which indicates significant shear heating. Lithological pressures were estimated by considering the position of cordierite-forming reactions in the P-T field and the stability of coexisting sillimanite. They are subject to a reduction from 0.35 GPa in the highest deformed mylonite to 0.31 GPa at the margin of the shear zone. According to the results of comprehensive petrographic and mineralogical studies the investigated shear zone underwent a Variscan HT-LP metamorphic event implying the formation of cordierite and an Alpine MT-LP event entailing the rotation and decomposition of the cordierite phase.

1. Introduction

Ductile shear zones are planes of finite displacement between two lithological blocks and form, when the hardening capacity of the host material has been exceeded (e.g. White et al., 1980; Steyrer and Sturm, 2002; Sturm and Steyrer, 2003). Due to their rather limited sizes, ranging from few centimeters to meters, ductile shear zones offer excellent possibilities to study the metamorphic evolution of the wall rock as well as chemical and mechanical changes within a predefined transect of increasing deformation. Where shear zones cut pelitic to semipelitic rocks, calculations of metamorphic pressures and temperatures can be easily realized due to numerous mineral reactions during the shearing event. P-T estimations have been carried out for lots of shear zones in the Alps and the Bohemian Massif (e.g. Selverstone et al., 1991 and references therein; Wallbrecher et al., 1993). In the ductile shear zone of the present study, the mineral cordierite has formed during prograde and peak metamorphism and therefore will stand in the midpoint of the following investigations.

Cordierite is a (Mg, Fe)Al-silicate which is characterized by a wide range of natural occurrences. As outlined in numerous publications (see review in Deer et al., 1992; Bertoldi et al., 2004), cordierite mainly crystallizes in thermally metamorphosed rocks, particularly those derived from argillaceous sediments. Additionally, the mineral can be a major constituent of parageneses formed under high-grade regional metamorphism. Harker (1939) found that the metamorphic formation of cordierite is generally restricted to conditions of deficient or low shearing stress producing only moderate pressures. With rising pressure due to transpression cordierite often breaks down to enstatite and sillimanite or, at higher temperature, to sapphirine and quartz (Seifert, 1976; Spear, 1993). Besides its crystallization in metamorphic rocks, cordierite is also found in specific igneous rocks like peraluminous granites and related high-grade anatectic terrains (Clarke, 1995; Barbey et al., 1999). Here, the mineral is considered as a product of subsolidus metamorphic reactions (Pereira and Bea, 1994), a product of peritectic reactions at the granite source (Wall et al., 1987; Groppo et al., 2013) or a derivate of argillaceous material contaminating the granitic magma. Among some authors cordierite is also considered as a cotectic magmatic mineral (e.g. Clarke, 1981; Clemens and Wall, 1981; Groppo et al., 2013) or a mineral phase formed by metasomatism, which directly followed the process of granitization (Didier and Dupraz, 1985). Cordierite of gem quality frequently occurs in granite pegmatites, where it usually crystallizes from uncontaminated pegmatitic liquids. A previous crystallization from residual magmas enriched with Al-silicates is also discussed.

This study presents a detailed analysis of the mylonites exposed in a shear zone and, as the main feature, an extensive description of the cordierite blasts formed during the shearing event. The contribution pursues three main objectives: First, the shear zone

E-mail address: sturm_rob@hotmail.com

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described here offers the possibility of studying cordierite formation within a short-range transect of several tens of meters; second, shear-related crystallization of cordierite and its geothermobarometric evaluation have not been documented very frequently in the past and are therefore in the focus of this study; and third, due to the fact that shear zone rocks have passed two metamorphic events, besides cordierite formation also decomposition of this mineral phase is visualized.

2. Geological setting of the study area

The studied rocks as well as their surrounding lithology can be assigned to the south-western margin of the Bohemian Massif. This Variscan orogen is mainly located within the Central-European Moldanubian Zone (Kossmat, 1927; Fig. 1a), characterized by widespread high-temperature low-pressure metamorphism, partial melting processes and extensive plutonism. As outlined by numerous authors (e.g. Matte, 1986; Franke, 1989, 2000), the central part of the Bohemian Massif mainly consists of the Moldanubian unit which includes the Teplá-Barrandium primarily acting as a micro-continent (Fig. 1b). The Moldanubian unit can be subdivided into the high-temperature high-pressure Gföhl unit (Medaris et al., 1995, 1998, 2005, 2006; Schulmann et al., 2005, 2008; Štípská et al., 2008), the Ostrong unit (Monotonous Series) containing high-temperature low-pressure migmatites and gneisses, and the Drosendorf unit, a gneiss complex with marbles, calc-silicates, and amphibolites (Varied series; Zoubek, 1965; O'Brien and Vrána, 1995; O'Brien, 1997; Petrakakis, 1986, 1997; Schulmann et al., 2008).

The geology of the study area is characterized by Variscan migmatites and gneisses of the Monotonous series that were intruded by post-Variscan granite bodies (Frasl and Finger, 1991 and references cited therein; Fig. 1c). Another essential feature of the regional geology are the tertiary, NW-SE tending strike-slip faults (Pfahl and Danube fault) with variable shear sense, which divided the lithology into three main granitic bodies (Fuchs and Thiele, 1968; Fuchs and Matura, 1976; Wallbrecher et al., 1993; Fig. 1c). The rocks of the present study were formed in a local dextral shear zone that can be interpreted as a side branch of the Pfahl fault which itself runs from the Bavarian forest to the Rodl valley (Fig. 1c). The quarry, in which the cordierite-bearing mylonites are accessible, is located near the village Unterurasch, around 50 km northwest of Linz. It consists of two orthogonal walls, which are between 60 and 80 m long and up to 30 m high (Fig. 2). On the WSW-ENE-tending wall mylonites with increasing grades of deformation are exposed. The centre of the shear zone is indicated by a fine-grained, blue- to grey-coloured ultramylonite with only few clasts of K-feldspar relics (Fig. 3a, b). When approaching the shear zone walls, the number and size of these clasts increases continuously. The protolith of the shear zone could not be found in the quarry itself, but was sampled about 100 m away from the centre of deformation (Fig. 1c). This educt rock determined by chemical analyses and comparative zircon studies (Sturm, 2004) represents a remarkably layered granitoid that mainly consists of K-feldspar, plagioclase and biotite (Fig. 3a). As outlined by Sturm (1995, 2004, 2010), the respective granitoid can be recognized as a specific variety of the so-called Pearl Gneiss which is one of the main granitoid bodies in the study area (see above).

3. Rock sampling and analytical methods

Samples of the cordierite-bearing rocks were collected in the quarry described above. Besides the highest deformed mylonite in the center of the shear zone also rocks showing lower grades of deformation were sampled along a defined transect (Fig. 2b). The protolith of the shear zone was sampled about 100 m outside the center of deformation. All investigated rocks are quite homogeneous as concerning the grain size, and therefore sample size was generally limited to ca. 10 kg, respectively. Part of the samples was used for the production of oriented thin sections, and part was crushed for the separation of cordierite and accessory minerals. From each sample at least one polished thin section was produced for microchemical analysis. This was carried out on a JEOL JXA-8600 microprobe at the Institute of Geology, University of Salzburg. Operating parameters were 30 nA beam current, 15 kV accelerating voltage, 10 s counting time for each element except Ti and Na (30 s), and a constant beam diameter of 1 μm. Natural and synthetic silicates and oxides served as standards for the main element analysis. Correction of the raw analyses was conducted by the application of an internal ZAF-4 procedure. The produced element analyses were affected by an average error not exceeding 0.1 wt.%. For Na_2O the detection limit was 0.050 wt.% employing operating parameters as detailed above. Backscattered electron imaging (BSEI) of altered cordierites was carried out by using a beam current that ranged from 30 nA to 40 nA in order to increase the contrast for photography.

Calculation of peak temperatures within the shear zone was mainly conducted by application of the garnet-cordierite Mg/Fe^{2+}-exchange thermometer published by Perchuk and Lavrent'eva (1983). Estimation of a minimum pressure was realized using the cordierite stability field and the cordierite-involving reactions as published in conventional petrogenetic grid (Spear, 1993). In addition, pressures could be determined by using the original P-T diagram of Holdaway and Lee (1977) as well as the related refinements recently published by Dachs and Geiger (2008).

Modal compositions of the studied rocks were estimated by using an eyepiece with counting grid and applying appropriate stereological methods (determination of the total number of points hitting the mineral phases of interest, respectively). In order to obtain highly accurate modal amounts for each mineral phase occurring in a specific rock, thin sections with variable orientations (N = 3) were subjected to the counting procedure. For estimation of the clast/matrix ratio in mylonites with different grades of deformation, it was clarified first that [1] clasts include all mineral grains exceeding a diameter of 5 mm and [2] K-feldspar, plagioclase, and cordierite (formed during the late-Variscan HT-LP metamorphic event) represent the main mineral phases producing such large grains. Relative volumes of clasts and matrix minerals contained in the sample rocks were again found by stereological techniques. The quantity-based relationship between quartz relics and recrystallized quartz grains was determined in a similar fashion. Differentiation between relic grains and recrystallized grains was conducted with the help of characteristic recrystallization textures occurring in the mylonite samples and extensive grain size analyses.

4. Petrography and mineral chemistry of the analyzed rocks

The cordierite-bearing mylonites are grey- to blue-coloured rocks characterized by a weak stretching lineation. The metamorphic schistosity is evident in the oriented thin sections. The mylonites uniformly display assemblages containing the mineral phases K-feldspar + quartz + plagioclase + cordierite + biotite + white mica + sillimanite (fibrolite) + garnet + chlorite + ilmenite (Table 1). Under the microscope the investigated samples show a matrix formed by very fine-grained quartz and biotite. Both minerals are recrystallized in high amounts (Fig. 5b, 6a–d) and can be concentrated to specific domains or layers. Biotite is often associated