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Repeated hydrothermal quartz crystallization and cataclasis in the Bavarian Pfahl shear zone (Germany)

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ABSTRACT

Field and microstructural data of the Pfahl shear zone in north-eastern Bavaria (Germany) reveal the intimate spatial-temporal connection between fragmentation, fluid influx and quartz crystallization. These processes and their interaction led to complex-structured quartz units: (i) a dense network of early quartz veins, (ii) two domains of fine-grained reddish to grayish quartz masses, (iii) an extended central zone of massive white quartz, and (iv) late cross-cutting closely spaced parallel fractures and partly open quartz veins.

The fine-grained quartz domains result from repeated and coeval cataclasis, fluidization and quartz precipitation. Material transport in these domains is at least partly governed by the flow of mobile fluid-quartz-particle suspensions. The complex internal meso-to microstructures of the massive white quartz are generated by repeated processes of fragmentation and grain growth. In general, the brittle part of the Pfahl shear zone represents a key example of cyclic dissolution/precipitation and fragmentation on large scale.

1. Introduction

Influx of large fluid volumes leading to precipitation of massive quartz and ore may result from several processes, generally connected to fluctuations of fluid pressure within fault zones (Nguyen et al., 1998; Robl et al., 2004; Sibson, 2004). In this setting dilatant fracture networks are produced by large volumes of uprising pressurized fluids. Crack formation or propagation is followed by depressurization that promotes quartz or ore precipitation sealing the previously opened fractures. This triggers renewed pressurization and subsequent hydrofracturing. Different processes leading to the cyclic formation of hydraulic fractures have been proposed, namely: (i) seismic pumping or fault-valve behavior (Sibson et al., 1975; Sibson, 1990) and (ii) rapid ascent of fluids in mobile hydrofractures (Bons, 2001) or fluid-filled fracture propagation (Dahm, 2000). Quartz veins are widespread in fault zones, which developed under diagenetic to low-grade greenschist facies conditions within the lower level of the seismogenic zone (200–450 °C and 2–4 Kbar) (Sibson, 1984; Bons, 2001). Such exhumed veins represent a source of information on quartz precipitation and fluid migration in relation to the deformation of wall rocks under brittle conditions.

The cataclastically deformed segments of the ca. 150-km-long and up to 100-m-wide brittle Pfahl shear zone in the Bavarian Forest (Germany) represent ideal examples where quartz crystallization in the frame of the relationships between long-term fluid migration and ongoing deformation in the upper crust can be studied in detail. The quartz lodes within this shear zone are evidence of an important fossil hydrothermal system deriving from the circulation of large volumes of fluid, comparable with the volume of the Baltic Sea, during an estimated period of ~160,000 years (Peucker-Ehrenbrink and Behr, 1993). The formation and evolution of such a large vein system pose questions on how permeability is maintained over such a long time and large distance (Hofmann, 1962; Horn et al., 1986). This topic is relevant for the exploitation of geothermal energy in active hydrothermal systems and for receiving further information about fluid involvement in brittle deformation and earthquake nucleation. Particularly, the

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interaction between permeability-enhancing brittle fracturing/hydrofracturing and permeability-reducing mineral precipitation is crucial for the sustainable use of geothermal systems and for research on earthquake triggering.

2. Geological setting

The Bavarian Pfahl shear zone represents an approximately NW–SE trending dextral strike-slip shear zone at the south-western margin of the Bohemian Massif (Fig. 1). It is part of a syn-to post-Variscan crustal-scale system of conjugate shear zones, which separate Variscan domains with different tectono-metamorphic characteristics. These shear zones were formed during the collisional evolution of the Variscan orogeny. Along the Pfahl, at the late stages of the Variscan orogeny syntectonic emplacement and crystallization of granodiorite generally occurred at 342–327 Ma (Siebel et al., 2005, 2006). Younger granites and granodiorites were emplaced between Regen and Patersdorf at 329–321 Ma (Fig. 2a; Siebel et al., 2006). Granitoids were later mylonitized down to greenschist-facies conditions leading to a mylonite belt with a maximum width of ca. 1 km (Brandmayr et al., 1995; Galadí-Enriquez et al., 2006). Mylonitization was followed by dextral brittle deformation in the presence of hydrothermal fluids (Brandmayr et al., 1995). These fluids led to the crystallization of quartz, which forms an up to 100-m-thick, nearly vertical and ca. 150-km-long giant lode, the so-called "Bavarian Pfahl" located in the center of the shear zone. Fluid inclusion microthermometry on latest-stage subhedral druse quartz yielded in trapping temperatures of 290–180 °C at ~160 MPa to 210–120 °C at ~50 MPa (Oppermann, 1990; Peucker-Ehrenbrink and Behr, 1993). Fluid salinities increase strongly (from less than 5 to more than 20 wt.% NaCl-equivalent) with decreasing homogenization temperature indicating the involvement of distinct fluids in the waning stage of the vein formation (Gerler, 1990; Peuker-Ehrenbrink and Behr, 1993). Based on Rb–Sr whole-rock analyses it was suggested that the Pfahl quartz was formed during late Permian to early Triassic (247 ± 21 Ma; Horn et al., 1986) consistently with geochronological data on the Wölsendorf fluorite-barite vein deposits (Fig. 1) at the northwestern section of the Pfahl zone (Brockamp and Zuther, 1985; Lippolt et al., 1985; Dill et al., 2011). These fluorite-barite veins formed from fluids showing strong geochemical similarities with those responsible for precipitation of the Pfahl quartz (Horn et al., 1986; Gerler, 1990; Reutel, 1992). Later deformation along the Pfahl shear zone took place in the late Cretaceous to Paleocene during reactivation of the south-western Bohemian border zone (Schröder et al., 1997), evidenced by Upper Cretaceous SW-directed thrusting along the northern extension of the Pfahl zone in Mesozoic rocks of the South German Basin near Amberg (Gudden, 1956) (Fig. 1), along Danube (Siebel et al., 2010) and the Rodl shear zones (Brandmayr et al., 1995).

The Pfahl quartz is best exposed between Regen and Harrling (Fig. 2a). The initially decameter-wide quartz lode was heavily quarried for glass production during earlier centuries and later also for the silicon and aluminum industry. Only a few ridges survived. However, in several large quarries relics of the quartz lode are present and the original structure of the Pfahl is still visible. The quartz exposures highlight that the Pfahl is not a single unit but is composed of a locally complex system of veins and numerous smaller massive lodes. In the Regen-Harrling segment, the Pfahl is ca. 30–100 m thick and trends ~125°. Detailed mapping of the Pfahl

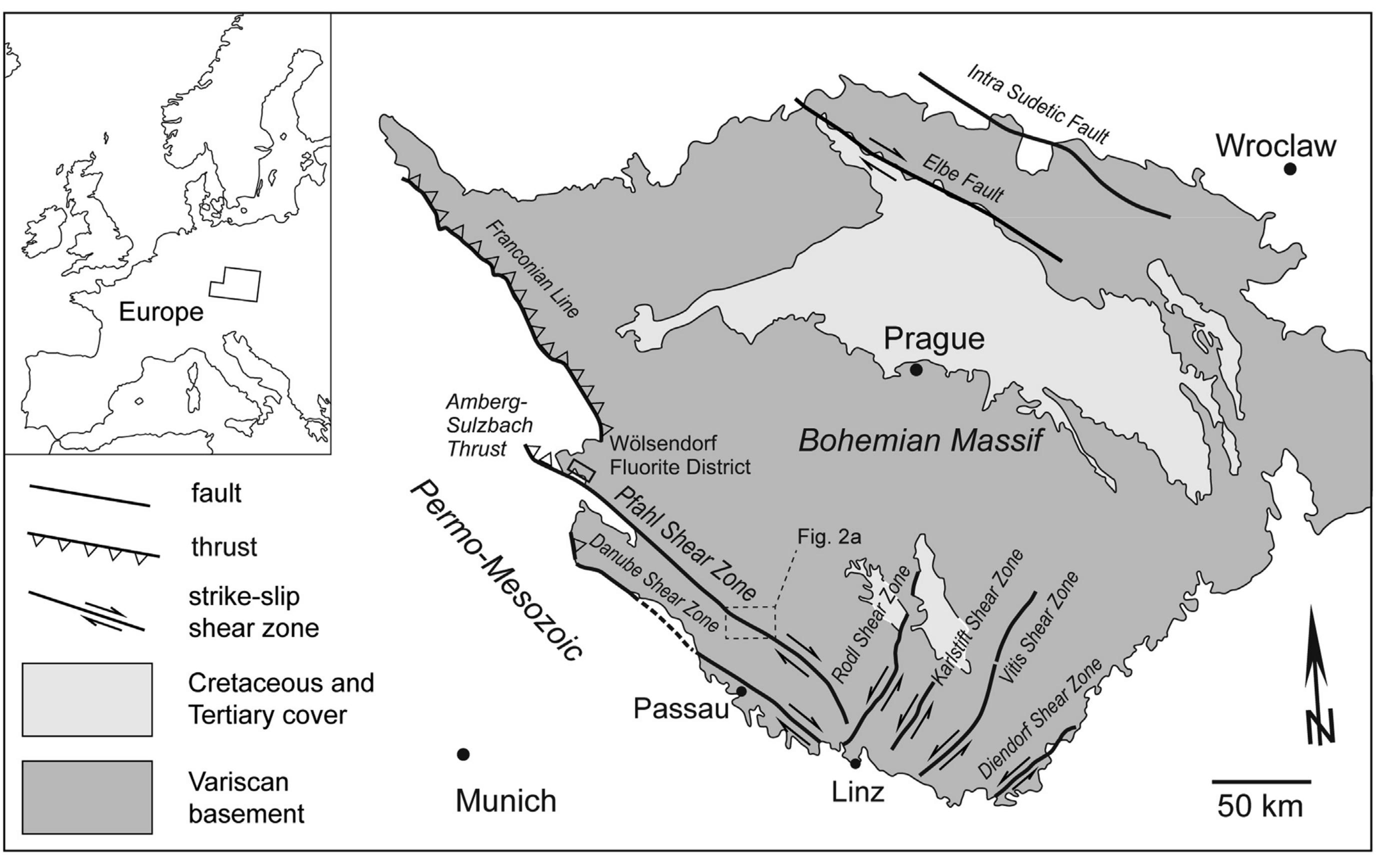

Fig. 1. Geological sketch map of the Bohemian Massif with main tectonic structures. White: undifferentiated, mostly post-Variscan rocks around the Bohemian Massif. Modified after Siebel et al. (2010).