Journal of Structural Geology 68 (2014) 16–32

Contents lists available at ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

Microfabric memory of vein quartz for strain localization in detachment faults: A case study on the Simplon fault zone

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ARTICLE INFO

Article history:
Received 26 January 2014
Received in revised form
5 August 2014
Accepted 11 August 2014
Available online 23 August 2014

Keywords:
Detachment fault
Quartz microstructures
Crystallographic preferred orientation
Recrystallization
Deformation mechanisms
Shear zone evolution

ABSTRACT

This manuscript deals with the adaptation of quartz-microfabrics to changing physical deformation conditions, and discusses their preservation potential during subsequent retrograde deformation. Using microstructural analysis, a sequence of recrystallization processes in quartz, ranging from Grain-Boundary Migration Recrystallization (GBM) over Subgrain-Rotation Recrystallization (SGR) to Bulging Nucleation (BLG) is detected for the Simplon fault zone (SFZ) from the low strain rim towards the internal high strain part of the large-scale shear zone. Based on: (i) the retrograde cooling path; (ii) estimates of deformation temperatures; and (iii) spatial variation of dynamic recrystallization processes and different microstructural characteristics, continuous strain localization with decreasing temperature is inferred. In contrast to the recrystallization microstructures, crystallographic preferred orientations (CPO) have a longer memory. CPO patterns indicative of prism <a> and rhomb <a> glide systems in mylonitic quartz veins, overprinted at low temperatures (≤400 °C), suggest inheritance of a high-temperature deformation. In this way, microstructural, textural and geochemical analyses provide information for several million years of the deformation history. The reasons for such incomplete resetting of the rock texture is that strain localization is caused by change in effective viscosity contrasts related to temporal large- and small-scale temperature changes during the evolution of such a long-lived shear zone. The spatially resolved, quantitative investigation of quartz microfabrics and associated recrystallization processes therefore provide great potential for an improved understanding of the geodynamics of large-scale shear zones.

1. Introduction

Deformation of the Earth's crust and mantle often is strongly localized in fault zones, which are either dominated by ductile or brittle deformation processes (e.g., Ramsay, 1980; Ramsay and Huber, 1987 Hull, 1988; Schmid and Handy, 1990; Mitra, 1992; Means, 1995; Burlini and Bruhn, 2005; Schrank et al., 2008). Information on the rheology and shear zone evolution can be gained by quantitative analyses of microstructures and crystallographic preferred orientations of samples collected across and/or along these large-scale fault zones (e.g., Dunlap et al., 1997; Stipp et al., 2002a; Ebert et al., 2007a; Herwegh et al., 2008; Toy et al., 2008; Law et al., 2011, 2013). Often, a great variability and complexity exist in these microstructures, owing to their polymineralic character (e.g., Herwegh et al., 2011 and references therein). To reduce complexity, different studies focused on monomineralic microfabrics. Under ductile deformation conditions, in monomineralic polycrystalline aggregates intracrystalline deformation processes combined with dynamic recrystallization change initial grain sizes, grain shapes, grain shape preferred orientations (SPO) and crystallographic preferred orientations (CPO) during transient deformation stages approaching a strain invariant steady state situation at elevated shear strains (Means, 1981; Herwegh and Handy, 1996; Pieri et al., 2001; Barnhoorn et al., 2004). For given physical deformation conditions, characteristic steady state microstructures result (e.g., Herwegh et al., 1997; de Bresser et al., 2001). Their analysis therefore provides the opportunity to investigate the deformation conditions for large-scale shear zones and their changes in space an time.

Using sample series from the Simplon fault zone (SFZ), the aim of the current study is two-fold: (i) We investigate the preservation of older microstructures as a function of overprinting deformation processes during changing physical conditions. (ii) Based on these outcomes, we analyze the spatial and temporal evolution of large-

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http://dx.doi.org/10.1016/j.jsg.2014.08.001
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scale strain localization during exhumation-induced cooling for progressive ductile normal faulting. For these purposes, we use synkinematically formed polycrystalline quartz veins as monomineralic proxy. A great advantage of our approach is that veins formed at several times during the deformation history, enabling the investigation of the overprinting deformation and dynamic recrystallization processes at different stages of retrograde cooling.

2. Geological setting

2.1. Regional geology

The SFZ is a major crustal-scale extensional structure in the Swiss Alps, which separates a nappe stack of Lower Penninic from Upper Penninic units (e.g., Mancktelow, 1985; Keller et al., 2005; Steck, 2008; Campani et al., 2010a,b; in press; see Fig. 1). To the North in the Rhone valley, foot- and hanging wall of the SFZ are juxtaposed to the Aar massif. Here, the SFZ joins the Rhone dextral strike slip fault and together they are the Rhone-Simplon-Line (Steck, 1990; Steck and Hunziker, 1994). In the present study, we will focus on the central and southern part of the SFZ only (see Fig. 1).

Because of the importance of the SFZ as a major Alpine low-angle normal fault, a variety of studies analyzed its geometry, kinematic aspects, timing, metamorphic conditions and geodynamic significance (e.g., Bearth, 1956; Mancktelow, 1985, 1987a,b; 1990, 1992; Merle et al., 1986; Mancel and Merle, 1987; Steck, 1987, 1990; Steck and Hunziker, 1994; Schmid and Kissling, 2000; Axen et al., 2001; Selverstone, 2005; Grosjean et al., 2004; Schmid et al., 2004; Keller et al., 2005, 2006; Campani et al., 2010a,b; 2014; Haertel et al., 2013). In its present position, the SFZ changes from a 25–30° dipping, top-to-SW low-angle detachment in its central part (e.g., Simplon pass – Zwischbergen valley, see Mancktelow, 1985, 1987a; 1990; Grosjean et al., 2004) to a 60–80° southward dipping strike slip fault in the south (between Val Bognanco and Domodossola, Fig. 1; Campani et al., 2010a). In terms of the evolution of the SFZ, at least four major stages are recognized: (i) Multistage pre-Simplon deformation including N- to NW-directed thrusting under ductile conditions during stacking of the Penninic nappes (Milnes et al., 1981). These early structures are best preserved in the hanging wall of the SFZ, while they were least partially overprinted during SFZ footwall-related deformation. (ii) The first stage of this subsequent ductile shearing of the SFZ created a several kilometers-wide mylonite zone, which we refer to as the 'old SFZ mylonites' (Sm in the studies of Campani et al., 2010a, 2014). (iii) The old SFZ mylonites are folded by the Berisal syncline (Fig. 1), which itself is cut by a few hundred meter wide ductile shear zone, i.e. the young SFZ mylonites (e.g., Keller et al., 2005; Sm2 of Campani et al., 2010a, 2014). These mylonites are interpreted to have formed at the brittle–ductile transition (Campani et al., 2010a, 2014). (iv) Final brittle dominated deformation and the generation of a 10-m wide zone of cataclasites and fault gouges document the youngest movements of Simplon faulting (Simplon Line, SL; e.g., Mancktelow, 1985; Mancel and Merle, 1987; Steck, 1987; Zwingmann and Mancktelow, 2004).

2.2. Metamorphic and chronological evolution

During nappe stacking related to subduction and subsequent exhumation of pre-Alpine basement and Mesozoic cover units, a combined top-to-SE shearing along the roof of the nappe stack, and a top to N or NW thrusting at the base are believed to represent the D1/D2 deformation phases during high P/low T conditions (Reinecke, 1991; Keller et al., 2005). Subsequently, more thermally dominated Barrovian-type metamorphism affected the Penninic units with an increasing metamorphic grade from middle greenschist facies in the NW (Rhone valley) to middle amphibolite facies in the SE (Ossola valley; Wenk and Wenk, 1984; Todd and Engi, 1997). Peak metamorphic conditions of about 580–620 °C at 6–8 kbar (Frank, 1983) in the Lower Penninic units (footwall) and of 620–700 °C at ~5 kbar (Keller et al., 2005) in the Camughera-Moncucco unit, the structurally deepest part in the Middle to Upper Penninic units (hanging wall), were reached. In the Toce dome (SFZ footwall), Vance and O'Nions (1992) calculated an age of peak metamorphism of about 30 Ma.

Under NW–SE shortening, D3 deformation led to a first back folding phase (i.e. producing SE-vergent folds), SW–NE extensional unroofing, and the formation of two large-scale regional antiformal structures, the Lepontine dome in the East and the Toce dome in the West (Steck and Hunziker, 1994). In the NE region of the Lepontine dome, Wiederkehr et al. (2011) calculated 500–570 °C and 5–8 kbar for the Barrovian heating pulse. With an age between 18 and 20 Ma, this pulse postdates the local post-nappe folding. For the South, the proposed T_{max} occurred at around 30–25 Ma (Rubatto et al., 2009; Berger et al., 2011b; Engi et al., 2001; Brouwer et al., 2005).

The timing of the onset of SFZ shearing is controversial. While Steck and Hunziker (1994) and Steck et al. (2001) suggest a first stage of ductile shearing between 35 and 30 Ma and 18 Ma, recent thermo-chronological modeling by Campani et al. (2010b) indicates a range from 18.5 ± 2.5 to 14.5 Ma. For this period rapid exhumation and uplift is indicated (Campani et al., 2010b). Subsequent northward propagation of a southern lower crustal Adriatic indenter is proposed to have led to the back folding event, forming large-scale folds such as Glishorn antiform and Berisal synform (Fig. 1) at about 10 Ma (Campani et al., 2014). As stated above, they fold the old SFZ mylonites (Fig. 1, see also Mancel and Merle, 1987; Mancktelow, 1992). During subsequent formation the younger mylonites (Sm2), conditions were close to the ductile–brittle transition (280–300 °C, Campani et al., 2010a, 2014), which was dated by Campani et al. (2010a) at between 14.5 and 10 Ma. The final brittle deformation developed the cataclasites of the Simplon line. Brittle deformation was active down to at least 3 Ma (Soom, 1990; Mancktelow, 1992; Zwingmann and Mancktelow, 2004; Campani et al., 2010a) and might even be ongoing today as can be inferred from active seismicity in the Simplon region. In this sense, the recent studies of Campani et al. (2010a,b; 2014) interpret that the SFZ represents a telescoped crustal section, which was continuously exhumed over a period of about 15 Ma of normal faulting, starting first under ductile but ending under dominantly brittle deformation conditions.

3. Approach and theoretical background

To use quartz as monomineralic proxy, we collected synkinematic quartz veins (Fig. 2) along three sections across the SFZ and analyzed them by: (i) Using oriented thin sections to determine the dynamic recrystallization processes of quartz and quantitatively investigate the quartz microstructures (dynamically recrystallized grain sizes, grain aspect ratios); (ii) Using electron backscatter diffraction to characterize crystallographic preferred orientations (CPO) and active slip systems; (iii) Using the estimates of deformation temperature from Haertel et al. (2013) to link them with the observed microfabrics. Combining this information, we show that (i)–(iii) clearly indicate a continuous narrowing of the SFZ with progressive cooling. Despite this tendency, however, the preservation potential of microstructures and CPO vary dramatically depending on the timing of synkinematic vein formation and the degree of the deformational overprint, resulting in considerable complexity for samples in the proximity of the fault plane. To