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Recrystallization fabrics of sheared quartz veins with a strong pre-existing crystallographic preferred orientation from a seismogenic shear zone

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ABSTRACT

Microstructural investigations were carried out on quartz veins in schist, protomylonite, and mylonite samples from an ancient seismogenic strike-slip shear zone (Sandhill Corner shear zone, Norumbega fault system, Maine, USA). We interpret complexities in the microstructural record to show that: (1) pre-existing crystallographic preferred orientations (CPO) in the host rock may persist in the new CPO patterns of the shear zone and (2) the inner and outer parts of the shear zone followed diverging paths of fabric development.

The host rocks bounding the shear zone contain asymmetrically-folded quartz veins with a strong CPO. These veins are increasingly deformed and recrystallized with proximity to the shear zone core. Matrix-accommodated rotation and recrystallization may position an inherited c-axis maximum in an orientation coincident with rhomb <a> or basal <a> slip. This inherited CPO likely persists in the shear zone fabric as a higher concentration of poles in one hemisphere of the c-axis pole figure, leading to asymmetric crossed girdle or paired maxima c-axis patterns about the foliation plane.

Three observed quartz grain types indicate a general trend of localization with decreasing temperature: (1) large (>100 μm), low aspect ratio (<~5) and (2) high aspect ratio (~5–20) grains overprinted by (3) smaller (<~80 μm), low aspect ratio (<~4) grains through subgrain rotation-dominated recrystallization. In the outer shear zone, subgrain rotation recrystallization led to a well-developed c-axis crossed girdle pattern. In the inner shear zone, the larger grains are completely overprinted by smaller grains, but the CPO patterns are relatively poorly developed and are associated with distinctively different misorientation angle histogram profiles ("flat" neighbor-pair profile with similar number fraction for angles from 10 to 90°). This may reflect the preferential activation of grain size sensitive deformation processes in the inner-most part of the shear zone where transient deformation associated with the seismic cycle may have localized.

1. Introduction

Shear zones in the continental crust provide important natural laboratories for investigating mineral deformation mechanisms and their potential role in strain localization. Quartz deformation has been particularly well documented due to its common and widespread natural occurrence and the relative ease with which it can be experimentally deformed. These studies have led to a broadly accepted understanding of how quartz recrystallization mechanisms and resulting crystallographic preferred orientation (CPO) patterns relate to deformation conditions in shear zones. Experimental and observational studies (Hirth and Tullis, 1992; Hobbs, 1968; Lloyd and Freeman, 1994; Stipp and Kunze, 2008; Stipp et al., 2002a,b; White, 1976) identified and described a progression of dynamic recrystallization quartz microstructures with increasing temperature or decreasing strain rate in water present conditions (Stipp et al., 2002b): grain boundary bulging (BLG; ~280–400 °C for water present strain rates of 10^{-12} to 10^{-14} s^{-1}), subgrain rotation (SGR; ~350–500 °C for water present strain rates of 10^{-12} to 10^{-14} s^{-1}), and grain boundary migration (GBM; begins at the upper range of SGR around ~400–500° for water present strain rates of 10^{-12} to 10^{-14} s^{-1}). Quartz CPO patterns when plotted relative to the kinematic reference frame (i.e. XY plane parallel to shear zone foliation, X is parallel to lineation direction, and Z is normal to foliation) change with temperature through the temperature-dependent

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dominance of certain slip systems [basal <a> slip forming a c-axis peak at the edge of the figure near the pole to the foliation (Z-axis), rhomb <a> slip plotting between the Y- and Z-axes, prism <a> slip plotting at the Y-axis, and prism <c> slip plotting at the X-axis] that represent the slip directions with the lowest critical resolved shear stress and the highest calculated Schmid factor (Baëta and Ashbee, 1969; Barth et al., 2010; Hobbs, 1968; Law, 1990; Law et al., 1990; Lister and Dornsiepen, 1982; Lister and Hobbs, 1980; Lister et al., 1978; Lloyd et al., 1992, 1997; Mainprice et al., 1986; Schmid and Casey, 1986; Toy et al., 2008; Tullis et al., 1973). Flow stress affects the mean size of the recrystallized grains (Stipp and Tullis, 2003) and, at the lowest temperatures, may also affect recrystallization mechanisms (Stipp et al., 2002b; Stipp and Tullis, 2003). Therefore, explanation of shear zone development relies on an interpretation of the quartz microstructure and CPO patterns within the context of these progressions and relationships.

The strength of a pre-existing fabric and the path of fabric development are among the factors that affect the type of quartz microstructure and CPO that is produced by non-coaxial strain during shear deformation. The persistence of the host rock CPO or parent grain orientation in the CPO of the recrystallized grains can lead to a pattern that is similar to, but more diffuse than, the parent grain or host fabric (e.g. Halfpenny et al., 2006; Heilbronner and Tullis, 2006b; Menegon et al., 2008; Michibayashi and Mainprice, 2004; Pauli et al., 1996; Stipp and Kunze, 2008; Stipp et al., 2002a; Webber et al., 2010). Parent grain orientations and host rock fabrics persist in quartz even with static recrystallization and annealing (Heilbronner and Tullis, 2006a; Kruhl and Peternell, 2002). Furthermore, a large proportion of parent grains may facilitate the development of the new fabric and affect the mechanical evolution of the system if their orientations coincide with the activity of slip systems that have the lowest critical resolved shear stress for the range of grain orientations present (e.g. Michibayashi and Mainprice, 2004; Toy et al., 2008; Webber et al., 2010).

Various studies have also shown that quartz microstructure, CPO, and rheology evolve with strain as the parent grains are completely recrystallized and as grains with "hard" orientations are progressively replaced by grains with "soft" or "weak" orientations in the grain population of a quartz-rich sample (Heilbronner and Tullis, 2006b; Kruhl and Peternell, 2002; Takeshita et al., 1999). "Soft" refers to grains that, for given conditions of deformation (e.g. temperature, strain geometry), would preferentially recrystallize via slip systems with the highest Schmid factor (e.g. Heilbronner and Tullis, 2006b; Law et al., 1990). For these "soft" orientations, the c-axis pole figure pattern changes from maxima at the periphery (Z-axis) to paired maxima along the crossed girdle between the Y- and Z-axes and ultimately to a single peak at the center of the pole figure (Y-axis) with increasing strain, indicating a transitional sequence of slip system dominance from basal <a> to rhomb <a> to prism <a> slip with strain (Heilbronner and Tullis, 2006b; Kruhl and Peternell, 2002; Law et al., 1990; Lloyd and Freeman, 1994; Lloyd et al., 1992; Takeshita et al., 1999). Lloyd and Freeman (1994) and Trimby et al. (1998) both describe a change from SGR-dominant to GBM + SGR-dominant deformation with progressive strain. The quartz microstructure under SGR recrystallization has also been described as progressing from ribbon grains with high aspect ratios through core–mantle dominated microstructures towards complete replacement by new polygonal grains with layered grain orientation domains (Halfpenny et al., 2004, 2006; Law, 1986; Law et al., 1984; Pauli et al., 1996; Trimby et al., 1998). These and other studies collectively indicate that it is important to take into account all steps along the path of fabric development when interpreting quartz microstructures, particularly from areas with complex or overprinting deformational fabrics.

We examine the evolution of quartz microstructure and crystallographic orientation data for quartz-rich volumes (referred to in this study collectively as quartz veins) in samples collected from within a shear zone exhumed from frictional-to-viscous transition depths (~10–15 km; Schmid and Handy, 1991) of a major crustal fault zone (Sandhill Corner shear zone of the Norumbega fault system in Maine, USA; Price et al., 2012). The frictional-to-viscous transition is effectively interchangeable with terms such as the brittle-ductile or brittle-plastic transition, but we prefer its use in the present geological context (Handy et al., 2007). This study shows that: (1) the pre-existing host rock CPO (i.e. the wall rock that hosts the shear zone) likely persisted in the CPO of the sheared samples and (2) the subsequent path of recrystallization, and thus the resultant CPO, of the sheared samples was different between the inner- and outer-most parts of the shear zone. We interpret the data based on the potential impact of transiently-elevated stresses and strain rates associated with the seismic cycle on the differences in quartz fabrics from the inner- and outer-most parts of the shear zone.

2. Geologic setting

2.1. Regional geology

The eastern margin of the Appalachian orogen in Maine, USA is defined by northeast-striking lithotectonic belts that preserve evidence for a complex orogenic history (Fig. 1; Gerbi and West, 2007; Hibbard et al., 2006; Hussey et al., 2010; Tucker et al., 2001; van Staal et al., 2009). Siluro-Devonian subduction-related shortening led to early thrusts and recumbent folds followed by later upright, isoclinal folds (Tucker et al., 2001). Crustal thickening and plutonism caused high-temperature, low-pressure regional metamorphism and local contact metamorphism (Gerbi and West, 2007; Guidotti, 1989). Peak metamorphic grade decreases across Maine from upper amphibolite facies in the southwest to greenschist and sub-greenschist facies in the northeast, representing differential exhumation of an exposed estimated depth range of ~8–25 km along strike (Guidotti, 1989; Hubbard et al., 1995; Ludman and Gibbons, 1999; Swanson, 1999a,b; Wang and Ludman, 2004; West and Hubbard, 1997; West et al., 1993, 2008).

Following dominantly orthogonal convergence in the Late Silurian-Early Devonian (Bradley et al., 2000; Tucker et al., 2001), a shift to west-directed, dextral transpressive shortening began in Middle-to-Late Devonian time (Gerbi and West, 2007; West et al., 2003), coincident with development of the Norumbega fault system. The primary structural evidence for this shift to dextral transpression is the widespread and common occurrence of outcrop-scale, asymmetric folds of compositional layering and quartz veins that indicate progressive dextral shearing (e.g., Short and Johnson, 2006; Frieman et al., 2013). Although the regional tectonic context of this dextral transpression is poorly constrained (e.g., Kuiper, 2016), it was interpreted to have been syn- to post-metamorphic in south-central Maine but prior to regional cooling below muscovite mineral closure temperatures (West and Lux, 1993).

The Norumbega fault system includes a 5–40 km wide zone characterized by heterogeneously-distributed non-coaxial, viscous, dextral deformation that occurred near peak (sillimanite grade) metamorphic conditions. Superimposed on this early, higher-temperature history are narrow (≤2 km), near-vertical strands of highly-localized deformation that formed parallel to the pre-existing compositional layering and higher-temperature foliation of the broader zone of non-coaxial dextral shear. As a result of the differential exhumation noted above, the nature of this localized deformation depends on the along-strike location within the fault system, with central and southern localities characterized by mylonites and ultramylonites, and more northern localities characterized by phyllonites, cataclasites, and breccias (Hatheway, 1971; Ludman, 1998; Short and Johnson, 2006; Short et al., 2011; Swanson, 1988, 1992, 1999b, 2006a,b; Wang and Ludman, 2004; West and Hubbard, 1997). Intense strain localization is thought to have occurred prior to or coincident with regional exhumation (West, 1999; West and Hubbard, 1997). ^{40}Ar/^{39}Ar, U–Pb zircon, and monazite ages (Ludman et al., 1999; West and Hubbard, 1997) constrain the timing of dextral shearing and faulting to between Middle Devonian and