Quartz grainsize evolution during dynamic recrystallization across a natural shear zone boundary

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ABSTRACT

Although it is widely accepted that grainsize reduction by dynamic recrystallization can lead to strain localization, the details of the grainsize evolution during dynamic recrystallization remain unclear. We investigated the bulge size and grainsizes of quartz at approximately the initiation and the completion stages of bulging recrystallization across the upper boundary of a 500 m thick mylonite zone above the Vincent fault in the San Gabriel Mountains, southern California. Within uncertainty, the average bulge size of quartz, 4.7 ± 1.5 μm, is the same as the recrystallized grainsize, 4.5 ± 1.5 μm, at the incipient stage of dynamic recrystallization, and also the same within uncertainties as the recrystallized grainsize when dynamic recrystallization is largely complete, 4.7 ± 1.3 μm. These observations indicate that the recrystallized grainsize is controlled by the nucleation process and does not change afterwards. It is also consistent with the experimental finding that the quartz recrystallized grainsize paleopiezometer is independent of temperature.

1. Introduction

During dynamic recrystallization, newly formed grains are often smaller than the original ones as shown in both experimentally and naturally deformed rocks (e.g., Hirth and Tullis, 1992; Stipp et al., 2002). As a result, the average grainsize of a sample decreases after dynamic recrystallization. Grainsize reduction resulting from dynamic recrystallization may lead to changes in deformation mechanism (e.g., Vissers et al., 1995; Platt and Behr, 2011a), strength of samples (e.g., Poirier, 1980), and may cause strain localization (e.g., Tullis and Yund, 1985; Rutter and Brodie, 1988; Jin et al., 1998; Drury, 2005). However, the grainsize evolution during dynamic recrystallization is still under debate. Derby and Ashby (1987) proposed a theoretical model of dynamic recrystallization, arguing that the recrystallized grainsize is controlled by two microscopic processes: nucleation of new grains, and grain-boundary migration driven by strain energy. In this model, nucleation of new grains results in grainsize reduction while migration of grain boundaries leads to grain growth. The word “nucleation” used in this paper refers to the process of forming new grains during dynamic recrystallization by mechanisms including subgrain rotation and grain-boundary bulging. A nucleation-and-growth model was also proposed by Shimizu (1998, 2008, 2011), where nucleation takes place by subgrain rotation while grain growth is driven by the distortional strain energy associated with subgrain walls and free dislocations. De Bresser et al. (1998, 2001) argued that the recrystallized grains will grow after nucleation until the strain rates contributed by diffusion creep and dislocation creep are the same. Austin and Evans (2007) suggested a somewhat different model, in which the steady-state recrystallized grainsize is a result of the balance between increasing surface energy caused by nucleation and decreasing surface energy resulting from grain growth. All of the above models predict that recrystallized grainsize should depend on temperature as well as stress.

An alternative approach was that of Twiss (1977), who equated the dislocation strain energy in the grain boundary to that in the enclosed volume, and concluded that both grainsize and subgrain size are simply functions of stress. The experimental recrystallized grainsize paleopiezometers for minerals have employed the grainsize-stress relation and are temperature-independent within uncertainty (Van der Wal et al., 1993; Post and Tullis, 1999; Stipp and Tullis, 2003; Stipp et al., 2006, 2010), though the recrystallized grainsize of some metals may be temperature dependent (e.g., Kodzhaspirov and Terentyev, 2012). Platt and Behr (2011b) argued that because strain-energy-driven grain-boundary migration increases grain-boundary curvature, whereas surface-energy-driven grain-boundary migration decreases it, the two processes cannot normally operate at the same time in a recrystallized aggregate. If dynamic recrystallization is driven by strain energy, then grainsize should be set by the nucleation process. This implies that in the dislocation creep regime, the grainsize evolution should not involve surface-energy driven grain growth, and therefore may not be temperature dependent.

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A key difference between the nucleation and growth models (Derby and Ashby, 1987; De Bresser et al., 1998, 2001, Shimizu, 1998, 2008; Austin and Evans, 2007) and other models is whether the recrystallized grains grow after nucleation. Stipp and Kunze (2008) reported that the recrystallized grain size produced by bulging recrystallization in naturally deformed quartz is about the same as grain boundary bulges and subgrains, but their results lacked quantitative measurements for subgrains and bulges. In order to investigate the grainsize evolution during dynamic recrystallization, one could examine the size of recrystallized grains, either in one sample at various temporal stages of recrystallization, or in two samples deformed at the same conditions but recording different stages of recrystallization. The latter approach was made possible by the mylonites above the Vincent fault in the San Gabriel Mountains, southern California. This paper investigates the grainsize of recrystallized quartz in two samples from either side of the upper boundary of the mylonite zone, which are only 8 m apart but show approximately the initiation stage and the completion stage of dynamic recrystallization, respectively. With these two samples, we aim to examine the grainsize evolution during quartz dynamic recrystallization.

Fig. 1. Geologic setting of the mylonite zone above the Vincent fault in the San Gabriel Mountains, southern California. (a) Major faults (red lines) and Laramide subduction related schists (grey areas) of southern California. Modified after Jennings (1977). (b) Geologic map of the East Fork area of the San Gabriel Mountains. Modified after Debblee (2002a, 2002b, 2002c, 2002d) and Xia and Platt (2017). (c) Transect along A-A’ in panel (b). Modified after Xia and Platt (2017). (d) Photo of the mylonitic front outcrop and sample locations. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)
2. The Vincent fault mylonites in the San Gabriel Mountains, southern California

The Vincent fault in the San Gabriel Mountains (Fig. 1) separates the late Cretaceous-Paleocene subduction-associated Pelona schist in the lower plate from the Mesozoic magmatic arc consisting of a Mesoproterozoic gneiss complex and Mesozoic granitoid rocks in the upper plate (Ehlig, 1981; Jacobson, 1997; Xia and Platt, 2017). The bottom 100–1000 m of the upper plate gneiss is mylonitized with a few weakly deformed lenses, forming a mylonite zone (Ehlig, 1981; Xia and Platt, in review). The bottom 100–1000 m of the upper plate gneiss is mylonitized with a few weakly deformed lenses, forming a mylonite zone (Ehlig, 1981; Xia and Platt, in review). The mylonites are argued to have been formed during the eastward normal sense shear of the mylonite zone based on deformation fabrics, kinematic indicators, deformation conditions, and geochronological evidence from the Pelona schist in the lower plate and the rocks in the upper plate (Xia and Platt, 2017, in review). Amphibole and white mica Ar/Ar cooling ages and detrital zircon fission track ages of both plates indicate that the mylonite zone was active between ∼58 Ma and ∼51.1 Ma (Jacobson, 1990; Grove and Lovera, 1996; Grove et al., 2003; Xia and Platt, 2017).

About 90% of the quartz grains in the upper-plate mylonites are recrystallized, dominantly by subgrain rotation (SGR) in the Lower Mylonite Zone (Fig. 2a) and bulging (BLG) in the Upper Mylonite Zone (Fig. 2b). In a sample from the base of the Upper Mylonite Zone, some of the quartz grains were recrystallized by SGR and others by BLG, indicating that the Upper Mylonite Zone overprinted the Lower Mylonite Zone. The recrystallized quartz grain sizes range between 19.3 ± 3.2 μm and 46.4 ± 7.4 μm in four samples from the Lower Mylonite Zone and between 4.7 ± 1.3 μm and 9.2 ± 1.6 μm in four samples from the Upper Mylonite Zone (Fig. 3).

The Upper Mylonite Zone is structurally overlain by unmylonitized gneiss, where the minerals are coarse grained and show little to no evidence of plastic deformation. The boundary between the top of the Upper Mylonite Zone and the bottom of the overlying unmylonitized gneiss is a zone a few meters thick, and we refer to this as the mylonitic front. Quartz grains in gneiss right above the mylonitic front exhibit undulose extinction with serrate grain boundaries. Two samples, PS111 (34.279917 °N, 117.75125 °W) and PS114 (34.279859 °N, 117.74741 °W), approximately 8 m apart, were collected below and above the mylonitic front, respectively (Fig. 1d). About 2% of quartz in PS114 from the gneiss is recrystallized and represents the incipient stage of recrystallization (Fig. 4a). Quartz grains in PS111 from the Upper Mylonite Zone, on the other hand, are almost completely recrystallized by BLG (Fig. 4b). Dynamic recrystallization of quartz in PS114 is likely to be coeval with the mylonites, as there is no other recognized deformation event producing similar microstructures in this area. We assume that the P-T conditions prevailing during recrystallization at the mylonitic front were the same as those determined in the Upper Mylonite Zone, and considering the short distance between our two samples bracketing the front, it is reasonable to assume that the P-T and stress conditions of these two samples were the same when dynamic recrystallization occurred.
3. Methods

The samples were sectioned parallel to lineation and perpendicular to foliation. The thin sections were prepared using colloidal silica on a Buehler VibroMet 2 in order to remove the surface crystal lattice damaged during mechanical polishing. Quartz crystallographic orientation was collected using a Hikari electron backscatter diffraction (EBSD) detector mounted on a JEOL-7001F scanning electron microscope (SEM) at the Center for Electron Microscopy and Microanalysis of University of Southern California. The acceleration voltage was between 20 and 25 kV, the working distance between 15 and 17 mm, and the step size 0.15–0.40 μm. The data collection and processing were performed using EDAX OIM software. Grain boundaries are defined as having a misorientation of 10° or higher. Grain size is treated as the diameter of a circle with the same area as the grain, while the average grain size of a sample is the root mean square (RMS) of all the measured grains in that sample. Grain size was measured using the OIM Analysis program. The relict grains were distinguished from the recrystallized ones following the procedure outlined by Behr and Platt (2011) and Cross et al. (2017). A value of 2.05° was used for the grain orientation spread threshold (Cross et al., 2017), which is a quantitative measurement of the lattice distortion. The area of a bulge is defined by the area of either the bulge-related subgrain when a subgrain boundary is shown at the root of the bulge, or the portion of a grain that intruded into an adjacent grain if there is no subgrain wall formed at the root of the bulge. Bulge size is defined as the diameter of a circle with the same area as the bulge. Only elongate-shaped bulges were measured using ImageJ, because bulges smaller than D_{min}, defined by Platt and Behr (2011b) may shrink and disappear due to surface energy; the elongate shape of the bulges, however, indicates that they are above D_{min} and are able to eventually form new grains. The average bulge size is the RMS of all the measured bulges in the sample.

Data were expressed as mean ± standard deviation. Student’s unpaired t-test was performed to identify significant differences. F-test was performed to examine if the variances of two populations are equal. P < 0.05 is considered significant. All data analyses were performed using Stata Statistical Software: Release 13. College Station, TX: StataCorp LP.

4. Results

In the gneiss sample PS114, most quartz is coarse-grained, showing some internal variation of crystallographic orientation and subgrain boundaries (Fig. 4a; Fig. 5a and b; also see the supplementary file). The host grain boundaries are serrated. Bulges are shown by the sutured grain boundaries. The root of a bulge, where the bulge meets its host grain, may form a subgrain wall (Fig. 5a and c), as reported by Stipp and Kunze (2008). The average size of the bulges is 4.7 ± 1.5 μm (Fig. 6a). The average aspect ratio (long axis/short axis) of the bulges is 1.33 ± 0.25. Scattered recrystallized quartz grains are developed along the relict grain boundaries in this sample, taking up approximately 2% of the entire quartz (Figs. 5a and 4b). The average grain size of recrystallized quartz is 4.5 ± 1.5 μm (Fig. 6b) and the average aspect ratio is 1.90 ± 0.46. Because of the very low strain, and hence low degree of recrystallization, the number of measurements of bulges (n = 24) and recrystallized grains (n = 103) is small, but the low variance in the measurements suggests that the mean values we have obtained are robust.

In the mylonite sample PS111, quartz is close to completely recrystallized (Figs. 4b, 5e and 5f; also see the supplementary file), forming very fine-grained new crystals with an average grain size of 4.7 ± 1.3 μm (Fig. 6c), based on a statistically significant sample size (n = 193). This grain size corresponds to a shear stress of 97.8 ± 20.9/–13.5 MPa using the EBSD-based calibrations of the Stipp and Tullis (2003) piezometer (Cross et al., 2017), or 71.4 ± 15.3/–9.8 MPa with the apparatus correction of Holyoke and Kronenberg (2010). The shear stress in a plane stress setting is the differential stress divided by √3 (Behr and Platt, 2013). The misorientation angle distribution (Fig. 5d) shows that grain boundaries < 15° are dominant, suggesting the operation of subgrain rotation. The peak between 40° and 70° may reflect the preservation of original high angle grain boundaries. On the orientation maps (Fig. 5e), relict grains, often over 10 μm in size, exhibit variation in intragranular orientation, subgrain boundaries, and have irregular grain boundaries. Recrystallized grains may contain grain boundaries curved both toward and away from the grain center (Fig. 5f). The crystallographic preferred orientation (CPO) of quartz grains in this sample shows asymmetric small-circle girdles around the normal to foliation (Z axis), indicating a top-to-the-southeast sense of shear (Fig. 5g).

Student’s t-test was used to compare the bulge size and the recrystallized quartz grain size in PS114. As a premise of the t-test, F-test was performed first to examine the equality of variances between the bulge size and recrystallized grain size, and no significant difference was found. There is no statistically significant difference between the average bulge size and the average recrystallized grain size (p = 0.46) assuming equal variance as validated by the F-test in the first step. That is, the average bulge size is the same as the average size of the recrystallized grains within uncertainty in PS114.
5. Discussion

The EBSD analysis confirms that quartz in both PS114 and PS111 was recrystallized by the bulging mechanism. As shown by the data analysis, the average bulge size is not significantly different from the average size of recrystallized grains in PS114. This implies that the size of recrystallized grains is controlled by the bulges, and hence by the nucleation process, at least during incipient recrystallization.

Fig. 5. (a) Orientation map along part of a grain boundary in PS114 showing a bulge and subgrain boundary at its root. (b) Orientation map along part of a grain boundary in PS114 showing a newly recrystallized grain which preserves the bulge shape. (c) Misorientation along Line A’A’ crossing a bulge in panel (a). (d) Frequency distribution of misorientation angles for PS111. (e) Orientation map and grainsize distributions (inset, frequency computed as number fraction of grains) of PS111. (f) Enlarged part of panel (e). Black arrows show the portion of grain boundaries curved toward the center of the pink grain while grey arrows show the outward curvature of grain boundaries with respect to the pink grain. (g) Quartz c-axis pole figure (lower-hemisphere and equal-area projection) of panel (e). Contour intervals are as shown in the legend where numerals indicate multiples of random distribution (m.r.d.). The orientation maps are color coded in (a), (b), (e) and (f) as shown in the inverse pole figures (legend), where the crystallographic orientations are shown with respect to the sample Y-axis (parallel to foliation and normal to lineation). Also, the grain and subgrain boundaries are as shown in the legend, where numerals indicate the misorientation angles between adjacent grains or subgrains. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)
recrystallized grains. The average grain size of recrystallized quartz in the mylonite sample PS111 is the same as that in PS114 within uncertainty, and the recrystallized grain size distributions of both samples are similar (Fig. 6b and c). These similarities imply that there is no significant change in grain size during dynamic recrystallization. This conclusion is supported by other evidence from both naturally and experimentally deformed rocks where the recrystallized grain sizes are independent of either the amount of recrystallization or the amount of strain (Johanesen and Platt, 2015; Valcke et al., 2015; Heilbronner and Kilian, 2017; Platt and De Bresser, 2017).

Several models propose that grain boundary migration driven by either surface energy or strain energy can result in grain growth during dynamic recrystallization after nucleation (Derby and Ashby, 1987; Derby, 1991, 1992, De Bresser et al., 1998, 2001, Shimizu, 1998, 2008). However, this is not consistent with our observation that the grain sizes of recrystallized quartz in both samples are the same within uncertainty, and the lack of evidence supporting grain growth after nucleation. In addition, the recrystallized quartz grains do not show 120° triple junctions with straight grain boundaries, indicating that surface-energy-driven grain boundary migration (γ-GBM) was not dominant. Instead, the fact that inward and outward curvature of grain boundaries occurs in the same recrystallized quartz grains (Fig. 5d) imply that dislocation-density-driven grain boundary migration (ρ-GBM) was dominant.

Our observations are consistent with the suggestion that dynamic recrystallization by the BLG mechanism occurs in a region of stress—grain size space where grain-boundary migration is primarily driven by lattice strain energy (i.e., ρ-GBM) (Bailey and Hirsch, 1962; Drury et al., 1985; Hirth and Tullis, 1992; Stipp and Kunze, 2008; Platt and Behr, 2011b). In this region, surface energy does not contribute to grain size evolution, and hence does not lead to grain growth (Platt and Behr, 2011b). No experimental or theoretical grain-growth law has been derived for ρ-GBM, and this process is unlikely to lead to a significant change in grain size after nucleation.

The concept of a temperature-independent recrystallization grain size paleopiezometer was challenged by theories that relate dynamically recrystallized grain size to the rate of energy dissipation (e.g., Austin and Evans, 2007), to the field boundary between grain size sensitive and grain size insensitive creep (e.g., De Bresser et al., 1998, 2001), or to a balance between grain size reduction and grain growth (e.g., Derby and Ashby, 1987; Shimizu, 1998), because all these processes involve a temperature dependence related to the activation energies for creep and grain-boundary migration (or in the case of the field boundary hypothesis, the difference in the activation energies of the creep mechanisms involved). The existing experimental recrystallized grain size piezometers are independent of temperature within the uncertainties, however (Van der Wal et al., 1993; Post and Tullis, 1999; Stipp and Tullis, 2003; Stipp et al., 2006, 2010). Also as shown by this study, the grain size of recrystallized quartz does not change after nucleation, which appears to invalidate the nucleation-and-growth model, and may rule out the possible roles of strain rate and surface energy in grain size evolution after nucleation. Therefore, temperature is unlikely to be incorporated in the recrystallized grain size paleopiezometer for quartz, at least in the BLG regime.

6. Conclusions

Two samples associated with the Vincent fault in the San Gabriel Mountains, southern California allowed us to investigate quartz grain size evolution during dynamic recrystallization in the BLG regime. We conclude that:

1. At the initiation of dynamic recrystallization by the BLG mechanism, the average size of the bulges (4.7 ± 1.5 μm) is the same as the recrystallized quartz grains (4.5 ± 1.5 μm) within uncertainty. When dynamic recrystallization is largely complete, the average grain size of recrystallized grains (4.7 ± 1.3 μm) remains the same as that at the initiation stage within uncertainty.
2. The recrystallized grain size of quartz is controlled by the nucleation process and does not change after nucleation.
3. The recrystallized grain size paleopiezometer for quartz is unlikely to be temperature-dependent, confirming earlier experimental findings.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jsg.2018.01.007.

References
