Journal of Structural Geology 83 (2016) 194–206

Contents lists available at ScienceDirect

Journal of Structural Geology

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

The influence of stress history on the grain size and microstructure of experimentally deformed quartzite

Steven Kidder [a,*], Greg Hirth [b], Jean-Philippe Avouac [c], Whitney Behr [d]

[a] Department of Earth and Atmospheric Science, The City College of New York, 160 Convent Ave, New York, NY 10031, USA
[b] Department of Geological Sciences, Brown University, Providence, RI 02912, USA
[c] California Institute of Technology, MC 100-23, 1200 E. California Blvd, Pasadena, CA 91125, USA
[d] Department of Geological Sciences, Jackson School of Geosciences, University of Texas, Austin, TX 78712, USA

A R T I C L E I N F O

Article history:
Received 9 April 2015
Received in revised form
4 December 2015
Accepted 11 December 2015
Available online 15 December 2015

Keywords:
Recrystallized grain size piezometry
Quartz
Dislocation creep
Microstructures
Rheology
EBSD

A B S T R A C T

Deformation of middle crustal shear zones likely varies with time as a result of the stress build-up and release associated with earthquakes and post-seismic deformation, but the processes involved and their microstructural signature in the rock record are poorly understood. We conducted a series of experiments on quartzite at 900 °C to characterize microstructures associated with changes in stress and strain rate, and to investigate the feasibility of carrying out grain size piezometry in natural rocks that experienced analogous changes. Differential stress (referred to simply as "stress") was varied in two-stage experiments by changing strain rate and by stopping the motor and allowing stress to relax. The two-stage samples preserve a microstructural record that can be interpreted quantitatively in terms of stress history. The microstructure associated with a stress increase is a bimodal distribution of recrystallized grain sizes. The smaller grains associated with the second deformation stage accurately record the stress of the second stage, and the surviving coarse grains remain similar in size to those formed during the earlier stage. The transient microstructure associated with stress decrease is a "partial foam" texture containing a larger concentration of stable 120° triple junctions than occur in samples deformed at a relatively constant strain rate. Our results indicate that microstructures preserved in rocks that experienced relatively simple, two-stage deformation histories can be used to quantitatively assess stress histories.

Grain growth rates during deformation are similar to rates observed in previous isostatic growth experiments, supporting theoretical approaches to recrystallized grain size, such as the wattmeter theory (Austin and Evans, 2007), that incorporate static growth rates. From an analysis of the experimental data for quartz recrystallized grain size, we find: 1) Recrystallized grain size quickly reaches a value consistent with ambient deformation conditions. We argue that this explains a good match between average grain sizes predicted by the wattmeter after complete recrystallization and the recrystallized grain sizes of the experiments. 2) The present formulation of the wattmeter overestimates the rates at which porphyroclasts recrystallize by as much as an order of magnitude, and 3) owing to problems with extrapolation of grain growth data for quartz, the wattmeter is not presently applicable to natural samples deformed at low temperatures. We present a simplified flow law for quartz, and suggest that the change in slope of the quartz piezometer at high stress (regime 1) is related to a switch to a linear viscous rheology.

1. Introduction

Stress in the crust is traditionally viewed to be constant at a given depth (e.g. Mercier et al., 1977; Brace and Kohlstedt, 1980; Kohlstedt et al., 1995). The existence of earthquakes and associated stress drops, and variations in pre- and post-seismic deformation (e.g. Bürgmann et al., 2002) however, make it clear that crustal stress magnitudes change with time. With the exception of pseudotachylites, the imprint that non-steady state deformation leaves on rocks is poorly understood and the processes involved are relatively unknown (e.g. Fagereng and Sibson, 2013). In this study,

* Corresponding author.
E-mail addresses: skidder@ccny.cuny.edu (S. Kidder), Greg_Hirth@brown.edu (G. Hirth), avouac@gps.caltech.edu (J.-P. Avouac), behr@utexas.edu (W. Behr).

http://dx.doi.org/10.1016/j.jsg.2015.12.004
0191-8141/

we define non-steady state deformation broadly as deformation in which stress and strain rate vary substantially over time. While brittle deformation processes mainly accommodate non-steady state deformation at shallow crustal levels, microstructural studies on rocks from the Alpine Sesia Zone (Küster and Stöckhert, 1998; Trepmann and Stöckhert, 2001, 2003) indicate that ductile processes at deep crustal levels can also accommodate markedly non-steady state deformation (c.f. Handy et al., 2007).

Quartz plays a major role in controlling the rheology of the continental crust (e.g. Lowry and Pérez-Gussinyé, 2011), and quartz microstructures have proven to be useful records of numerous aspects of deformation history (e.g. Prior et al., 1990; Dunlap et al., 1997; Trepmann and Stöckhert, 2003; Mancktelow and Pennacchioni, 2004; Stipp et al., 2004; Fitz Gerald et al., 2006; Toy et al., 2008; Menegon et al., 2011; Bestmann et al., 2012). Interpretations of quartz microstructures often rely on laboratory deformation experiments (e.g. Hobbs, 1968; Means, 1989; Hirth and Tullis, 1992; Stipp et al., 2006), but there have been few experimental studies of non-steady state deformation in the ductile regime. Notable exceptions include "kick and cook" experiments (Trepmann et al., 2007; Druiventak et al., 2012), which investigate the microstructural changes associated with annealing following a large stress pulse. Very few studies have addressed the grain-scale microstructures associated with stress changes during dislocation creep (Ross et al., 1980; Van der Wal et al., 1993; Austin and Evans, 2009). The lack of experimental results makes it difficult to assess the degree to which exhumed rocks were affected by non-steady state deformation.

Non-steady state deformation has the potential to affect recrystallized grain size. In steady state experiments on quartz (and other minerals), recrystallized grain size is strongly correlated with differential stress (Stipp and Tullis, 2003), and recent work demonstrates that the experimental relationship is accurate at geologic conditions (Kidder et al., 2012). Studies involving recrystallized grain size piezometry often focus on the finest recrystallized grains formed near the brittle–ductile transition since these grains are best preserved and provide a constraint on peak crustal stress (e.g. Weathers et al., 1979; Ord and Christie, 1984; Dunlap et al., 1997; Stipp et al., 2002; Fitz Gerald et al., 2006; Behr and Platt, 2011; Kidder et al., 2012). These stress estimates have different meanings depending on whether they are interpreted to represent constant stress or transient and decaying stresses following earthquakes (e.g. Trepmann and Stöckhert, 2003).

We present the results of a laboratory investigation of non-steady state behavior of quartz during ductile deformation. We compare the rheology and microstructures of nearly constant strain rate experiments and experiments where strain rate, and consequently differential stress (referred to below simply as "stress"), experienced a major change. These first attempts at investigating non-steady state behavior in quartz during dislocation creep allow us to address a number of open questions: can we distinguish microstructural features developed during steady vs. non-steady state deformation? How much deformation is required to obscure microstructures developed during earlier stages of deformation? Under what conditions, if any, can recrystallized grain size piezometry be applied to samples that have experienced non-steady state deformation? What are the kinetics and mechanisms of grain size change during deformation? We additionally investigate the applicability of the wattmeter (e.g. Austin, 2011) to predict sizes and rates of change of grain size.

2. Background

The term dynamic recrystallization refers to changes in grain size, shape and orientation driven by strain energy in the form of dislocations (Poirier and Guillope, 1979; Stünitz, 1998). During dynamic recrystallization the formation of new grains reduces internal strain energy associated with elevated dislocation density. Recrystallized grains are thought to form by two major processes: grain-boundary migration and subgrain rotation recrystallization (e.g. Urai et al., 1986). In experimentally deformed quartz, three dislocation creep regimes have been identified (Hirth and Tullis, 1992). At high stress levels (regime 1), new grains form predominantly by the migration or "bulging" of grain boundaries in response to large, intergranular dislocation density differences. Bulges are pinched, rotated or sheared off, thereby forming new grains (e.g. Stipp and Kunze, 2008). At moderate stress (regime 2), formation of new grains is dominated by rotation recrystallization: dislocations combine into lower energy subgrain boundaries, and misorientation increases until high-angle grain boundaries form. At low stress (regime 3), grain-boundary mobility increases and recrystallized grains form by both grain-boundary migration recrystallization and subgrain rotation recrystallization. While the dominance of subgrain rotation and grain-boundary migration recrystallization differs in the three regimes, both processes occur to some extent in all three regimes (e.g. Stipp and Kunze, 2008).

Previous experimental work on quartz indicates that the relationship between stress and recrystallized grain size (Fig. 1) is independent of temperature and water content (Bishop, 1996; Stipp and Tullis, 2003; Stipp et al., 2006). No previous experimental studies have investigated the role of changing stress on recrystallized grain size in quartz; however, such transient effects have been analyzed in other materials and natural samples. For example, Ross et al. (1980) deformed olivine under increasing and decreasing stress levels and found that recrystallized grain sizes respond in "minimal" (but unspecified) strains and times. Van der Wal et al. (1993) found that the adjustment period for olivine occurs within 3–10% strain for modest stress decreases. White et al. (1985) deformed impure magnesium to high strains and found that recrystallized grain size within shear zones in the samples remained at peak stress levels despite strain weakening. Recrystallized grains in zones bordering the shear zones however equilibrated to the new stress conditions. In experiments on calcite, Austin and Evans (2009) found that fine-grained aggregates grew during diffusion creep at the same rates that occur under isostatic conditions. Prior et al. (1990) and Cross et al. (2015) quantified rates of change in grain size associated with the deflection of quartz about porphyroclasts in a natural shear zone.

3. Methods

3.1. Experimental methods

Experiments were conducted in two modified Griggs apparatuses (Tullis and Tullis, 1986) on beige-colored Black Hills Quartzite (6.3 mm diameter, 14 mm length). The quartzite is >99% pure quartz with a grain size of ~70 μm (Stipp and Kunze, 2008). The material has no lattice preferred orientation and grains exhibit minimal or no deformation microstructures. Samples consisted of two stacked cylinders of quartzite with 0.2 weight percent water added between the pieces. Platinum jackets were annealed for 15 min at 900 °C and folded over annealed platinum disks on each end of the samples. The platinum-encased samples were inserted into a Ni sleeve and NaCl assembly identical to that described by Chernak et al. (2009). Samples were brought to pressure along a standard pressure-temperature path following Chernak et al. (2009); at 300 °C and a confining pressure of ~1.3 GPa, the deformation piston was advanced to hit the sample (i.e., a "cold hit"), and then retracted. Temperature was then increased to 900 °C where it was held for ~12 h prior to the initiation of uniaxial compression.