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Microstructural evolution during strain localization in dolomite aggregates

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Dolomite aggregates deformed by dislocation creep over a wide range of conditions ($T = 700$–1000 °C, effective pressure of 900 MPa, strain rates of $10^{-7} - 10^{-4}$/s) strain weaken by up to 75% of the peak differential stress. Microstructural study of samples shortened to different finite strains beyond the peak differential stress shows that strain becomes highly localized within shear zones by high-temperature creep processes, with no contribution of brittle cracking. At low strains (8%), dolomite deforms homogeneously by recrystallization-accommodated dislocation creep. At progressively higher sample strains, deformation is localized into narrow shear zones made up of very fine (∼3 μm) recrystallized grains and relict porphyroclasts (20–100 μm). Finely-recrystallized dolomite grains in the shear zones are largely dislocation free and localized shear is facilitated by diffusion creep. In contrast, original dolomite grains and porphyroclasts in shear zones have high dislocation densities and do not deform after shear zone formation. Calculated strain rates in the shear zones are two to three orders of magnitude faster than the imposed bulk strain rate of the samples and these strain rates are consistent with predictions of the diffusion creep flow law for fine-grained dolomite.

1. Introduction

Strain localization due to crystal plastic mechanisms is common in polyphase rocks, deformed in the Earth's crust and upper mantle and in laboratory experiments (Voll, 1976; Berthe et al., 1979; Gapais, 1989; Lonka et al., 1998; Holyoke and Tullis, 2006a,b). Ductile shear zones are generally formed when zones of initially dispersed weak phases in a matrix of a strong phase (e.g. micas or quartz in a granite) become interconnected or when preexisting heterogeneities (e.g. compositional layering) define zones of weakness within stronger surrounding rocks. The strength contrast between the shear zone and protolith is usually maintained by deformation mechanisms that are favored in the shear zone, and by changes in composition and microstructure brought about during early stages of deformation and localization (e.g. localized reactions or a switch to a grain-size-sensitive deformation mechanism: de Ronde, 2004; Holyoke and Tullis, 2006c; Newman and Drury, 2010, among many others).

In contrast to the deformation of polyphase rocks, single-phase rocks deformed by crystal plastic and dislocation creep processes commonly deform homogenously, and localized shear zones form only under limited conditions. Nucleation of strain-free recrystallized grains at the onset of dynamic recrystallization may create a matrix of fine-grained material at grain boundaries of monomineralic aggregates, initiating a component of grain-size-sensitive deformation mechanisms, such as diffusion creep and grain boundary sliding. However, subsequent growth of the new grains to a steady-state grain size limits these grain-size-sensitive mechanisms to rates that compete with rates of dislocation creep (de Bresser et al., 1998, 2001). As a result, the strength contrast between recrystallized zones and the protolith are not maintained and dislocation creep gives way gradually to a combination of dislocation and diffusion (or other grain size sensitive) creep (de Bresser et al., 1998). Relationships between mean recrystallized grain size and differential stresses that reach steady values at constant strain rate (Twiss, 1977; Schmid et al., 1980; Rutter, 1995; de Bresser et al., 1998) nearly coincide with the dislocation creep – diffusion creep boundary (de Bresser et al., 1998, 2001). More recently, these relationships have been analyzed as a balance between the nucleation of new small grains, which scales with mechanical work rate and intracrystalline defects introduced by dislocation creep, and grain growth, which is driven by surface energy and reductions in grain boundary area, in both the dislocation and diffusion creep fields (Austin and Evans, 2007).

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Strain localization by high-temperature creep processes has been observed in monomineralic aggregates made up of olivine, clinopyroxene or plagioclase, but only under special conditions. High-temperature strain localization was first noted in coarse-grained olivine aggregates deformed at high differential stresses and referred to as "ductile faulting" (Blacic, 1972; Post, 1977; Zeuch, 1982). Finely-recrystallized shear zones developed across samples as the samples strain weakened during constant strain rate deformation experiments. More recently, Hansen et al. (2012) observed that high-temperature strain localization in olivine aggregates is favored at constant differential stress, as finer grain sizes of recrystallized shear zones are maintained, and creep rates accelerate within the shear zones. Coarse-grained clinopyroxenites strain weaken and develop finely-recrystallized shear zones at high differential stresses, constant strain rates, and at temperatures just sufficient for dynamic recrystallization (Kirby and Kronenberg, 1984). The conditions for strain localization in clinopyroxenite appear to be bracketed by two regimes of homogeneous deformation: 1) deformation at low temperatures and high steady differential stresses, in the absence of recrystallization, and 2) deformation at higher temperatures and lower steady differential stresses where coarser recrystallized grains nucleate at the boundaries of original grains. Plagioclase aggregates deform by localized shear at elevated temperatures when samples are first faulted at low temperatures, and then deformed at conditions that lead to hot-pressing and recrystallization of fault gouge and activation of high-temperature, grain-size-sensitive deformation mechanisms (Tullis and Yund, 1987).

In comparison to these special cases, strain localization appears to be common in dolomite, over a wide range of high-temperature, high-pressure conditions that favor dislocation creep and dynamic recrystallization. Narrow fine-grained shear zones have been documented in dolomites that deformed in nature by dislocation creep at 250–300 °C (Newman and Mitra, 1994) and in coarse-grained dolomite deformed experimentally across the entire dislocation creep field (temperatures of 700–1000 °C and strain rates of 10^{-4}–10^{-7}/s; Holyoke et al., 2013). In contrast to the homogeneous strains and distributed recrystallization observed in calcite aggregates (de Bresser, 2002), dolomite samples experimentally deformed by dislocation creep are only homogenously deformed at strains <8%, after which narrow shear zones develop, composed of fine recrystallized grains. The development of these shear zones is contemporaneous with strain weakening of up to 75% of original peak differential stresses (Holyoke et al., 2013).

In this study, we examine the processes that caused formation of fine-grained shear zones in coarse-grained dolomite aggregates that initially deformed homogeneously by recrystallization-accommodated dislocation creep as presented in Holyoke et al. (2013). We also identify the conditions that maintain the strength contrast between the fine-grained shear zones and surrounding coarse-grained protolith. Unlike the gradual transition observed in calcite and olivine aggregates from dislocation creep to multiple mechanisms of dislocation creep and diffusion creep, the formation of fine recrystallized grains in dolomite aggregates, with little recovery to steady state creep rates or stable grain size populations, causes an increase in strain rate in the fine grains and decrease in differential stress as the dominant deformation mechanism changes from dislocation creep in coarse grains to diffusion creep in fine recrystallized grains. When viewed in a deformation mechanism map, this transition causes a significant overstep of the dislocation creep - diffusion creep field boundary, which is not observed in calcite or olivine aggregates, which generally form stable populations of recrystallized grains near the dislocation creep – diffusion creep boundary. This paper reports on the microstructural evolution of dolomite samples shortened to different total sample strains and the mechanical response is explained in terms of rheologies reported for dislocation creep and diffusion creep (Holyoke et al., 2013; Davis et al., 2008; Delle Piane et al., 2008).

2. Experimental study

The deformed samples and mechanical results we selected for this study come from triaxial compression experiments performed

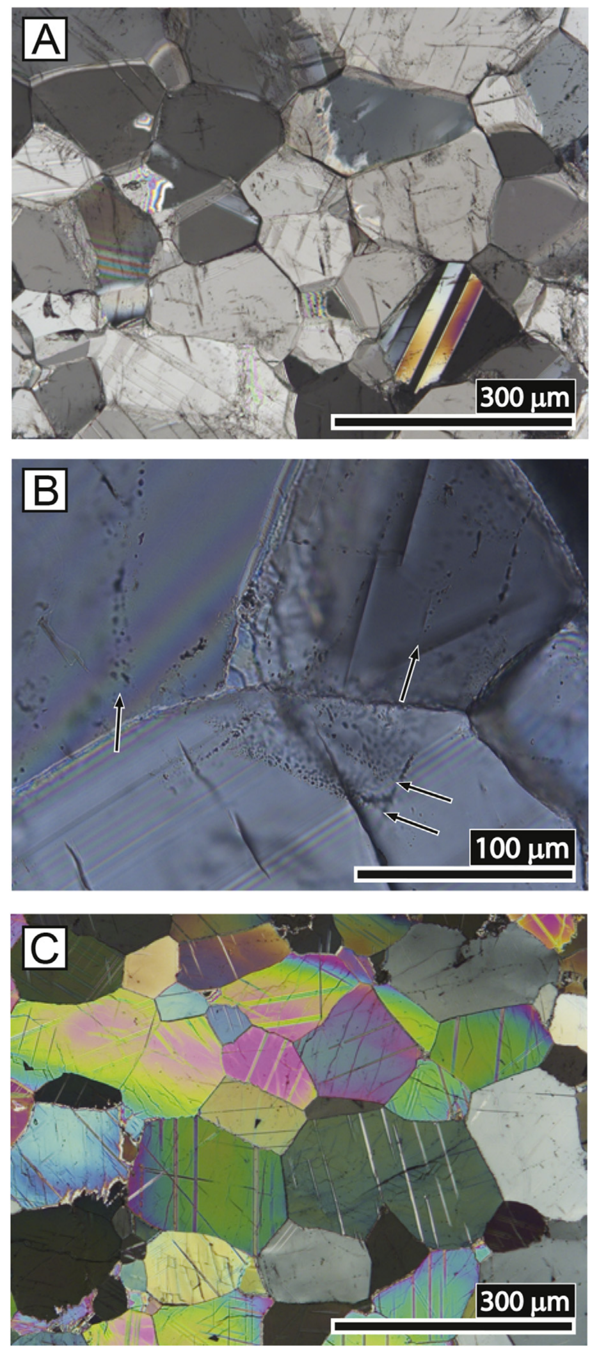

Fig. 1. (A) Madoc dolomite has a mean grain size of 240 μm, straight extinction, some twins, and straight grain boundaries. (B) Arrays of very small (<5 μm) fluid inclusions (arrows) in the starting material are likely the traces of healed cracks. (C) Microstructures in a hydrostatic experiment (D-7, 900 °C, P_c = 1120 MPa, 3600 s at conditions) are similar to those in the starting material (crossed Nicols transmitted light photomicrographs, (A) and (B) are normal thin sections, (C) is an ultra-thin section).