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Formation of lithospheric shear zones: Effect of temperature on two-phase grain damage

Elvira Mulyukova [a,*], David Bercovici [a]

[a] *Yale University, Department of Geology and Geophysics, New Haven, CT, USA*

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ABSTRACT

Shear localization in the lithosphere is a characteristic feature of plate tectonic boundaries, and is evident in the presence of small grain mylonites. Localization and mylonitization in the ductile portion of the lithosphere can arise when its polymineralic material deforms by a grain-size sensitive rheology in combination with Zener pinning, which can impede, or possibly even reverse, grain growth and thus promotes a self-softening feedback mechanism. However, the efficacy of this mechanism is not ubiquitous and depends on lithospheric conditions such as temperature and stress. Therefore, we explore the conditions under which self-weakening takes place, and, in particular, the effect of temperature and deformation state (stress or strain-rate) on these conditions. In our model, the lithosphere-like polymineralic material is deformed in a two-dimensional simple shear driven by constant stress or strain rate. The mineral grains evolve to a stable size, which is obtained when the rate of coarsening by normal grain growth and the rate of grain size reduction by damage are in balance. Damage involves processes by which some of the deformational energy gets transferred into surface energy. This can happen by (i) dynamic recrystallization (grain damage) and (ii) stretching, deforming and stirring the material interface (interface damage). The influence of temperature enters through rheological laws (which govern the rate of work and damage), grain growth kinetics, and the damage partitioning fraction, which is the fraction of deformational work that goes into creating new surface energy. We demonstrate that a two-phase damage model, in which the partitioning fraction depends on both temperature and roughness of the interface between the phases, can successfully match the field data, including the reported correlation of grain size and temperature, the increasing dominance of dislocation creep at higher temperatures and a large range of grain sizes observed across the depth of a single shear zone.

1. Introduction

The history of deformation of the Earth's crust and lithosphere is recorded in the microstructure of its constitutive rocks, which deform in response to the differential stress imposed by forces in the lithosphere and underlying convecting mantle. The heat and the mechanical work supplied by the mantle drives deformation on a multitude of scales: from the movement of the crystalline defects on the subgrain scale, associated with the solid state diffusion and dislocation creep, to the formation of mylonitic shear zones, and further to the planetary scale deformation of the Earth's lithosphere, manifested as plate tectonics.

The relative motion of the plates is almost entirely accommodated by highly localized deformation at the plate boundaries, as is, for example, geologically evident in the presence of small grain mylonites and ultramylonites (White et al., 1980). Such subdivision of the Earth's surface into largely undeformed tectonic plates, separated by narrow, strongly deformed plate boundaries, suggests that its constitutive materials experience shear localization, as can for example be caused by some self-weakening mechanism (Kaula, 1980; Bercovici, 1993; Bercovici, 1995; Tackley, 2000; Bercovici, 2003; Montési, 2013; Bercovici et al., 2015). To understand how Earth evolved to have such an exotic style of surface dynamics, we need to understand the mechanisms responsible for strain localization across the crust and the lithosphere, including their brittle and ductile regions. Localization in the brittle portion of the Earth's outer shell is an expected feature at low crustal and lithospheric pressures and temperatures (Kohlstedt et al., 1995). However, the ductile portion of the lithosphere is where the peak lithospheric strength occurs and is thus a bottle-neck to localization; in this region, deformation is also enigmatic since it involves

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* Corresponding author.
E-mail addresses: elvira.mulyukova@yale.edu (E. Mulyukova), david.bercovici@yale.edu (D. Bercovici).

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combined brittle-ductile behavior as well as mylonitization (Kohlstedt et al., 1995; Karato, 2008).

A crystalline rock deforming viscously can experience self-weakening and localization due to a number of processes, such as shear heating, presence of multiple phases (including melt) and grain size reduction (via phase transformation or dynamic recrystallization), to name a few (e.g., Hobbs et al., 1990; Hobbs et al., 1990; Montési and Zuber, 2002; Montési and Zuber, 2002; Karato, 2008; Karato, 2008, pp. 288–301; Bercovici et al., 2015; Bercovici et al., 2015, and references therein). The microstructure that develops due to the action of a given strain-localizing mechanism can reveal whether and to what degree it is active during lithospheric deformation. Such interpretations require a thorough quantitative understanding of these mechanisms at the conditions representative of the lithospheric crust and mantle. The physical conditions, characterized by temperature, composition and the magnitude of the mechanical forcing (e.g., stress), vary spatially and through time, so that the dependence of shear localizing mechanisms and their associated microstructure on these properties must also be understood.

A common geometrical quantity used to characterize the microstructure of a crystalline material is its grain size distribution. It can be readily measured in laboratory experiments, as well as in the natural samples collected from the field. From the physical point of view, the size of the grains reflects the amount of internal energy that is stored as surface energy on the grain boundaries. In particular, when the material deforms by dislocation creep and undergoes dynamic recrystallization, by mobilization of a pre-existing grain boundary or by the formation of subgrain boundaries, its grain boundary area increases (Karato et al., 1980; Van der Wal et al., 1993). This reduces the grain size and thereby stores the deformational work in the form of increased grain boundary area (Bercovici and Ricard, 2005; Austin and Evans, 2007; Ricard and Bercovici, 2009; Rozel et al., 2011). In polyphase materials, the relative movement of grains of different phases can also lead to distortion of the inter-phase boundaries, which further increases the surface energy (Bercovici and Ricard, 2012).

For shear localization to occur, there needs to be a mechanism by which deformation can cause weakening, which would increase deformation, and which would further enhances weakening. This is, for example, the case when a material deforms by dislocation-accommodated grain boundary sliding and undergoes dynamic recrystallization (Hirth and Kohlstedt, 1995; Warren and Hirth, 2006; Hansen et al., 2011; Hansen et al., 2013; Kohlstedt and Hansen, 2015; Skemer and Hansen, 2016). Another possible mechanism, which is the focus of this study, is when a polyphase material deforms by grain size sensitive diffusion creep and undergoes grain size reduction due to interface-damage and pinning, which are induced by the presence of multiple phases (Bercovici and Ricard, 2012; Cross and Skemer, 2017).

There is abundant support from field (Jin et al., 1998; Montési and Hirth, 2003; Warren and Hirth, 2006; Skemer et al., 2010; Herwegh et al., 2011; Linckens et al., 2011; Linckens et al., 2015; Hansen and Warren, 2015), experimental (Evans et al., 2001; Hiraga et al., 2010; Farla et al., 2013; Platt, 2015; Cross and Skemer, 2017) and theoretical studies (Bercovici and Ricard, 2012; Bercovici and Ricard, 2016) that secondary phases play an important role in the mechanical properties of lithospheric materials. The goal of this study is to use this observational evidence to test and further constrain the theoretical models of grain damage, with a particular focus on the effect of temperature, and effectively depth, on the grain-size dependent shear-localizing mechanisms (see alsoLanduyt et al., 2008; Behn et al., 2009; Gueydan et al., 2014).

To constrain the models presented here, we use the data from four different upper mantle shear zones, published in Jin et al. (1998) and Linckens et al. (2015). The reported microstructure, including grain size and crystallographic orientation, together with the independent temperature measurements, are used to constrain the dominant creep mechanism. In combination with the olivine flow laws and grain growth kinematics obtained from previous experimental studies (Hirth and Kohlstedt, 2003), we are able to deduce the deformation conditions, such as stress or strain rate, for a given tectonic environment. Some of the physical parameters that enter the model are less well constrained, such as the grain growth activation energy and the partitioning fraction of the mechanical work that goes into creating new grain boundaries. Here, we provide further constraints, by comparing the grain size dependence on temperature predicted by our model with that reported in the observational data.

Field observations demonstrate a correlation between grain size and temperature (with the grain size increasing by over two orders of magnitude across a few hundred degrees increase in temperature), increasing dominance of dislocation creep at higher temperatures, and a coexistence of different deformation regimes across small spatial scales (Jin et al., 1998; Linckens et al., 2015). These observations are used as constraints in the model presented below.

2. A simple shear zone model

A detailed mathematical description of the two phase grain damage model was presented previously (e.g.Bercovici and Ricard, 2012; Bercovici et al., 2015; Bercovici and Ricard, 2016). We provide a brief overview of the equations here, to introduce the governing physical processes and to highlight the main assumptions made along the way.

We consider the deformation of a polycrystalline material subject to simple shear. The material consists of a non-dilute mixture of two immiscible fluids, or phases (e.g., a peridotite mixture with volume fractions of 40% and 60% pyroxene and olivine, respectively). In the general formulation of the model, the phases have different densities, viscosities and other properties, although in this study, for simplicity, the phases are assumed to have identical material properties.

The two-phase material is characterized by a mean grain size within each phase, as well as the geometry (i.e., roughness or, specifically, the characteristic radius of curvature) of the interface that separates the two phases. The grain size and the interface roughness directly or indirectly influence the mechanical properties of the material, but also evolve in response to the applied mechanical or kinematic forcing. This introduces a non-linear coupling between the applied deformation and the effective rheology of the material.

The grain size distribution within each phase is assumed to follow a lognormal distribution, characterized by a mean grain size. Moreover, the grain size evolution is assumed to be slaved to that of the interface roughness r, as the grain growth within each phase is blocked by the presence of the other phase. This is known as the pinned state limit (Bercovici and Ricard, 2012), in which the grain size is proportional to the interface roughness. For the grain-size distribution and phase volume fraction (e.g., 60% olivine, 40% pyroxene) assumed in this study (following Bercovici and Ricard (2013, 2014, 2016, 2015)), the mean grain size is approximately $\pi/2$ times the interface roughness (the limitations of the pinned-state assumption are discussed in Appendix A.).

The model has a two-dimensional plane geometry, with shear acting parallel to the x-axis, and assumed to be infinite and uniform in the x-direction. The temperature varies with depth, increasing in the negative z-direction, while the applied stress or strain rate are constant and uniform in all directions (Fig. 1).