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Direct shear of olivine single crystals

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ABSTRACT

Knowledge of the strengths of the individual dislocation slip systems in olivine is fundamental to understanding the flow behavior and the development of lattice-preferred orientation in olivine-rich rocks. The most direct measurements of the strengths of individual slip systems are from triaxial compression experiments on olivine single crystals. However, such experiments only allow for determination of flow laws for two of the four dominant slip systems in olivine. In order to measure the strengths of the (001)[100] and (100)[001] slip systems independently, we performed deformation experiments on single crystals of San Carlos olivine in a direct shear geometry. Experiments were carried out at temperatures of 1000° to 1300 °C, a confining pressure of 300 MPa, shear stresses of 60 to 334 MPa, and resultant shear strain rates of 7.4×10^{-6} to $2.1 \times 10^{-3}\ \mathrm{s}^{-1}$. At high-temperature (≥1200 °C) and low-stress (≤200 MPa) conditions, the strain rate of crystals oriented for direct shear on either the (001)[100] or the (100)[001] slip system follows a power law relationship with stress, whereas at lower temperatures and higher stresses, strain rate depends exponentially on stress. The flow laws derived from the mechanical data in this study are consistent with a transition from the operation of a climb-controlled dislocation mechanism during power-law creep to the operation of a glide-controlled dislocation mechanism during exponential creep. In the climb-controlled regime, crystals oriented for shear on the (001)[100] slip system are weaker than crystals orientated for shear on the (100)[001] slip system. In contrast, in the glide-controlled regime the opposite is observed. Extrapolation of flow laws determined for crystals sheared in orientations favorable for slip on these two slip systems to upper mantle conditions reveals that the (001)[100] slip system is weaker at temperatures and stresses that are typical of the asthenospheric mantle, whereas the (100)[001] slip system is weaker at conditions typical of the lithospheric mantle. These observations demonstrate that the relative strength of the dislocation slip systems in olivine and, thus, the development of lattice-preferred orientation and anisotropic viscosity in olivine-rich rocks are strongly dependent upon temperature and stress.

1. Introduction

The rheological and microstructural properties of olivine-rich rocks reflect the strength of dislocation slip systems. One means of measuring the strength of dislocation slip systems is by carrying out deformation experiments on single crystals that are oriented to promote the motion of dislocations on specific slip systems. Many experiments have been performed on olivine single crystals in uniaxial or triaxial compression (e.g., Young, 1969; Kohlstedt and Goetze, 1974; Durham and Goetze, 1977; Darot and Gueguen, 1981; Kohlstedt and Hornack, 1981; Poumellec and Jaoul, 1984; Ricoult and Kohlstedt, 1985; Mackwell et al., 1985; Bai et al., 1991; Raterron et al., 2007, 2009; Demouchy et al., 2009, 2013; Girard et al., 2013). These experiments are usually carried out in three orientations, referred to as $[110]_c$, $[101]_c$, and $[011]_c$, where a compressive stress (σ_1) is applied at 45° to specific crystallographic axes of olivine. These orientations allow for activation of the four dominant dislocation slip systems in olivine, which operate on the (100), (010), and (001) planes and have either [100] or [001] Burgers vectors. For the $[110]_c$ orientation, σ_1 is orientated at 45° to both the [100] and [010] axes, activating the (010)[100] slip system. In a similar manner, the $[011]_c$ orientation has σ_1 at 45° to the [010] and [001] axes, activating the (010)[001] slip system. However, the $[101]_c$ orientation has σ_1 at 45° to the [100] and [001] axes, which simultaneously activates both the (001)[100] and the (100)[001] slip system.

To activate the (001)[100] and (100)[001] slip systems independently, we performed deformation experiments on single crystals of San Carlos olivine in a direct shear geometry, as illustrated in Fig. 1. The direct shear geometry allows for isolation of one of these slip systems at a time. The data derived from these experi-

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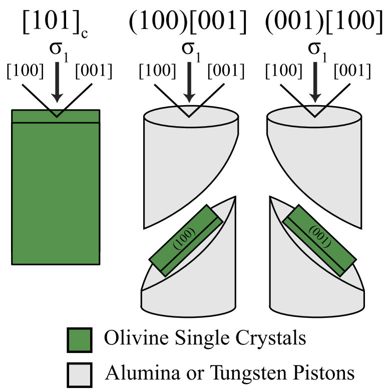

Fig. 1. Illustrations of crystals oriented for deformation in triaxial compression in the $[101]_c$ orientation (left) and for crystals oriented for direct shear (middle and right) on the (100)[001] and (001)[100] slip systems, respectively. During triaxial compression of crystals in the $[101]_c$ orientation, both the (100)[001] and the (001)[100] slip systems operate simultaneously, whereas in the direct shear geometry, only one of the slip systems is activated.

ments provide information essential to understanding the development of lattice-preferred orientation (LPO) in upper mantle rocks.

1.1. Applications to LPO

Physical properties of mantle rocks are strongly influenced by the strength of the LPO of their constitutive minerals. The presence of an LPO causes anisotropy in the propagation of seismic waves (Ismail and Mainprice, 1998; Becker et al., 2006), in attenuation of seismic waves (Farla et al., 2012), in viscosity (Hansen et al., 2012a, 2016), and in electrical conductivity (Pommier et al., 2015). Field based measurements of these properties, combined with data from laboratory experiments and numerical simulations of LPO development, form a framework for interpreting the structure and flow behavior of Earth's upper mantle.

Numerical simulations that implement the relative activity of dislocation slip systems inferred from deformation experiments carried out on olivine single crystals successfully reproduce the nature of the LPO observed at asthenospheric mantle conditions (Tommasi et al., 2000). The results from these numerical simulations predict the development of an LPO with crystallographic axes aligned in similar orientations with respect to an externally applied stress as those observed in high-temperature deformation experiments on olivine aggregates (e.g., Zhang and Karato, 1995; Bystricky et al., 2000; Hansen et al., 2011, 2012b, 2014) and observed in many exposed mantle rocks (e.g., Ismail and Mainprice, 1998; Warren and Hirth, 2006; Précigout and Hirth, 2014).

1.2. The power-law creep regime

At conditions of high temperature and low stress, the strain rate of olivine crystals follows a power-law relationship with stress and an Arrhenius relationship with temperature. The strain rate of crystals deforming in a power-law regime, $\dot{\varepsilon}_{\text{power}}$, is expressed as

$$\dot{\varepsilon}_{\text{power}} = A_p\sigma^n \exp\left(\frac{-Q_p}{RT}\right), \tag{1}$$

where A_p is a material-specific parameter, σ is stress, n is the stress exponent, Q_p is the activation energy, R is the gas constant, and T is the temperature in K (e.g., Durham and Goetze, 1977; Darot and Gueguen, 1981; Bai et al., 1991). Strain in materials that deform in this manner is consistent with glide of dislocations, with strain rate limited by the mean velocity at which dislocations climb to overcome obstacles such as other dislocations in the crystal lattice (e.g., Poirier, 1985, pp. 103–107). The rate of climb of dislocations is controlled by diffusion of the slowest diffusing ionic species along its fastest diffusive pathway, which for the case of olivine under anhydrous conditions at high temperatures is silicon diffusing through the cores of dislocations (Hirth and Kohlstedt, 2015).

1.3. The exponential creep regime

Deformation experiments carried out at low temperatures and high stresses on olivine single crystals (Phakey et al., 1972; Evans and Goetze, 1979; Demouchy et al., 2009, 2013) and olivine aggregates (e.g., Raterron et al., 2004; Mei et al., 2010; Druiventak et al., 2011) yield mechanical behavior markedly different from experiments performed at high-temperature and low-stress conditions. At low temperatures and high stresses, the strain rate of olivine single crystals follows an exponential dependence on stress. The strain rate of crystals deforming in an exponential regime, $\dot{\varepsilon}_{\text{exp}}$, is expressed as

$$\dot{\varepsilon}_{\text{exp}} = A_e\sigma^{1.4}\exp\left[\left(\frac{-Q_e}{RT}\right)\left(1-\left(\frac{\sigma}{\sigma_e}\right)^p\right)^q\right], \tag{2}$$

where A_e is a material dependent parameter, Q_e is the activation energy, σ_e is the stress needed to move dislocations in the absence of thermal energy, and p and q are parameters describing the shape and spacing of the impediments to dislocation motion. Stress is raised to the power of 1.4 in Equation (2) because, for olivine, dislocation density, ρ, is proportional to $\sigma^{1.4}$ rather than σ^2, as is often assumed (Hirth and Kohlstedt, 2015); and strain rate is given by the Orowan equation, $\dot{\varepsilon} = \rho b v$, where b is the Burgers vector (Frost and Ashby, 1982, pp. 6–9). Values of p range from 0.5 to 1 and values of q range from 1 to 2 (Kocks, 1976). Deformation of materials in this regime is rate limited by the ability of gliding dislocations to move through obstacles such as other dislocations or to overcome lattice resistance (Frost and Ashby, 1982, pp. 6–9).

1.4. Inferring slip system activity

In this paper, we are primarily concerned with determining flow laws for the (001)[100] and (100)[001] slip systems in both the power law and exponential creep regimes. Previous researchers have used microstructural analyses and measurements of shape change to evaluate the activity of the slip systems that operate during deformation of crystals in the $[101]_c$ orientation. The most direct evidence of the relative activity of the (001)[100] and (100)[001] slip systems is from strain analyses carried out on deformed crystals (Durham and Goetze, 1977). Measurements of shape change and rotation of crystallographic planes resulting from compressive creep experiments on crystals in the $[101]_c$ orientation at 1600 °C are consistent with most of the deformation occurring by glide of dislocations on the (001)[100] slip system. This conclusion is supported by microstructural observations of crystals that were deformed at high temperature, which reveal that dislocations with Burgers vectors parallel to [100] are more common than those with Burgers vectors parallel to [001] (Durham et al., 1977; Bai and Kohlstedt, 1992).

At lower temperature and higher stress conditions, microstructural evidence suggests the activity of the (100)[001] slip system is greater than the (001)[100] slip system. Transmission electron microscopy (TEM) analyses of a crystal deformed in the $[101]_c$ orientation at 1150 °C demonstrates dislocations operating with [001] Burgers vectors are at least equally as prevalent as dislocations with [100] Burgers vectors (Durham et al., 1977). Measurements of the preferred orientation of low-angle boundaries and shape change in a crystal deformed in the $[101]_c$ orientation at 1000 °C