Earth and Planetary Science Letters 387 (2014) 157–168

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Protracted fabric evolution in olivine: Implications for the relationship among strain, crystallographic fabric, and seismic anisotropy

Lars N. Hansen [a,b,*], Yong-Hong Zhao [a,c], Mark E. Zimmerman [a], David L. Kohlstedt [a]

[a] Department of Earth Sciences, University of Minnesota, Minneapolis, MN 55455, USA
[b] Department of Earth Sciences, University of Oxford, Oxford, OX1 3AN, England, UK
[c] Department of Geophysics, Peking University, Beijing, 100871, China

ARTICLE INFO

Article history:
Received 20 August 2013
Received in revised form 8 November 2013
Accepted 10 November 2013
Available online 7 December 2013
Editor: P. Shearer

Keywords:
crystallographic-preferred orientation
electron-backscatter diffraction
experimental rock deformation
upper-mantle seismic anisotropy
grain-boundary sliding
torsion

ABSTRACT

Crystallographic fabrics in olivine-rich rocks provide critical information on conditions and mechanisms of deformation as well as seismic properties of Earth's upper mantle. Previous interpretations of fabrics produced in laboratory experiments were complicated by uncertainty as to whether the steady-state fabric was attained. To examine the systematics of the evolution of olivine crystallographic fabrics at high strain, we conducted torsion experiments on olivine aggregates to shear strains of up to $\sim$20. Our results demonstrate that a steady-state fabric is not reached until a shear strain >10, a much higher value than previously thought necessary. Fabrics characterized by girdles of [010] and [001] axes or by clusters of [010] and [001] axes are both observed. Until now, these fabrics were associated with either two different deformation mechanisms or two different sets of deformation conditions. Here we establish that both fabrics are, in fact, part of the same evolutionary process. An eigenvalue analysis allows the fabric shape to be quantitatively correlated with the magnitude of shear strain. Misorientation analysis suggests that the observed fabric evolution results from the competition of the two easiest slip systems in olivine, (010)[100] and (001)[100]. Our results open up the possibility of using olivine crystallographic fabrics or seismic anisotropy to quantitatively evaluate strain histories in both field studies and geophysical investigations of upper-mantle rocks.

1. Introduction

The high-temperature viscous deformation of rocks involves the production and motion of defects in the crystalline grains that make up those rocks. In many cases, these defects are dislocations, the motion of which produces rotations of the crystallographic axes of individual grains. The resulting distribution of grain orientations contains information about the nature and number of dislocations acting during deformation. Therefore, the crystallographic fabrics produced by preferred grain orientations are a key microstructural parameter for inferring the deformation history of a rock.

For mantle rocks, analysis of crystallographic fabrics is an important tool for assessing the mechanisms and conditions of deformation as well as the associated sources of seismic anisotropy in Earth's upper mantle. The correspondence between olivine fabrics derived through numerical simulation (Tommasi et al., 2000) and those obtained in laboratory experiments (Zhang and Karato, 1995; Bystricky et al., 2000) permits researchers to confidently apply laboratory-derived flow models to natural rocks with similar crystallographic fabrics (Toy et al., 2010; Webber et al., 2010). In some cases, comparison of crystallographic fabrics measured in samples collected in the field with those developed in laboratory experiments has yielded constraints on possible deformation conditions such as stress, strain rate, and water content in the Earth (Warren and Hirth, 2006; Skemer et al., 2010). Additionally, regional variations in the pattern and magnitude of seismic anisotropy have been used to constrain the active deformation mechanism in the upper mantle (Karato, 1992; Podolefsky et al., 2004; Behn et al., 2009) and assess mantle flow patterns (Hess, 1964; Tanimoto and Anderson, 1984; Becker et al., 2006).

Laboratory-based deformation experiments have provided the key insight necessary to interpret observations of natural crystallographic fabrics and seismic anisotropy. Early triaxial compression experiments demonstrated that crystallographic fabrics could be developed in olivine aggregates deforming at high temperature (Ave'Lallemant and Carter, 1970; Nicolas et al., 1973). The first direct shear experiments on olivine aggregates, which reached moderate strains of <3, revealed [100] axes clustered near the shear direction and [010] axes clustered near the normal to the shear plane (Zhang and Karato, 1995; Zhang et al., 2000). This pattern, depicted in Fig. 1 and often referred to as an A-type fabric (Jung et al., 2006; Karato et al., 2008), is very similar to fabrics observed

* Corresponding author. Tel.: +44 775 901 0866.
E-mail address: lars.hansen@earth.ox.ac.uk (L.N. Hansen).

0012-821X/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.epsl.2013.11.009

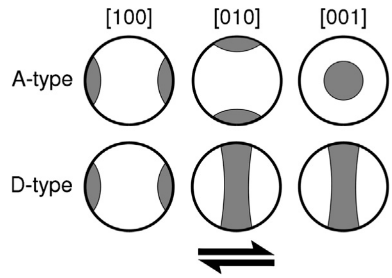

Fig. 1. Schematic depiction of A-type (top) and D-type (bottom) crystallographic fabrics in olivine. Pole figures are shown for each of the three principal crystallographic axes. Gray regions denote the dominant orientations of grains for each fabric type. The shear sense is top to the right.

in many naturally deformed mantle rocks (Ismail and Mainprice, 1998). Subsequent torsional shear experiments on olivine aggregates (Bystricky et al., 2000), which reached shear strains of ∼5, demonstrated that [010] and [001] axes formed girdles in a plane normal to the shear direction rather than clusters. This pattern, depicted in Fig. 1 and often referred to as a D-type fabric (Jung et al., 2006; Karato et al., 2008), was interpreted by Bystricky et al. (2000) to represent the true steady-state fabric for deforming olivine aggregates. This interpretation has two main implications. First, because of the girdled axis distributions, crystallographic fabrics in strongly deformed regions of the upper mantle (and therefore the resulting seismic anisotropy) will relate to the shear plane less clearly than an A-type fabric. Second, naturally deformed mantle rocks exhibiting an A-type pattern were not strained to a sufficient magnitude to reach a steady-state microstructure and therefore only record fabrics produced by low-strain deformation.

However, controversy remains as to whether A- and D-type fabrics are generated by the same microphysical mechanisms. Results from early studies on the relative activities of olivine slip systems (Carter and Ave'Lallemant, 1970) imply that the A-type fabric should be common at low-stress (high-temperature) conditions whereas the D-type fabric should be common at high-stress (low-temperature) conditions. This implication is in agreement with later laboratory experiments exploring both high-stress (Bystricky et al., 2000) and low-stress conditions (Zhang and Karato, 1995; Zhang et al., 2000). Therefore, the D-type fabric has been interpreted as an indicator of dislocation creep under dry, high-stress conditions (Jung et al., 2006). In accord with laboratory-based studies, the D-type fabric appears to be relatively common in lithospheric shear zones (Ismail and Mainprice, 1998; Warren et al., 2008), which are generally interpreted to be dry and deforming at relatively high stress based on field setting and grain-size piezometry (Jaroslow et al., 1996; Warren and Hirth, 2006; Toy et al., 2010).

Alternatively, recent laboratory experiments (Hansen et al., 2011, 2012b) demonstrate that both the low-strain direct shear experiments (Zhang and Karato, 1995) and the moderate-strain torsion experiments (Bystricky et al., 2000) were conducted in a regime in which dislocation-accommodated grain-boundary sliding is the dominant deformation mechanism. Numerical simulations of the development of fabrics in olivine have been able to generate girdles of [010] and [001] axes by relaxing strain compatibility constraints on grain-to-grain interactions (Tommasi et al., 2000). Braun (2004) and Warren et al. (2008) suggested that relaxing those constraints simulates a contribution of grain-boundary sliding to the total strain. They therefore suggested that D-type fabrics are the result of deformation dominated by dislocation-accommodated grain-boundary sliding. Thus, it is currently unclear whether a change in stress (Jung et al., 2006) and/or in deformation mechanism (Braun, 2004; Warren et al., 2008) is responsible for the change in fabrics and how to interpret girdled fabrics in natural samples. Here we address this gap in knowledge through a series of torsion experiments in which we track fabric evolution to very large strains.

2. Methods

2.1. Sample preparation

Aggregates of Fo_{50} olivine were synthesized following the methods outlined in previous studies (Zhao et al., 2009; Hansen et al., 2012a, 2012b). Powders of Fe_2O_3 were mechanically mixed with powders of SiO_2 and fired for 100 h at 1410 K in a gas-mixing furnace with a 1.15:1 mixture of CO:CO_2. The ratio of Fe_2O_3 to SiO_2 was intentionally set to produce Fo_0 olivine with a small amount (∼1%) of orthopyroxene in the final samples to buffer the silica activity. The resulting powders of Fo_0 olivine were reground and mechanically mixed with powders of San Carlos olivine (Fo_{91}) in the appropriate ratio to produce Fo_{50}. The powder mixture was then fired for 40 h at 1673 K with a 1:1 mixture of CO:CO_2. To ensure chemical homogeneity, a sample of the reaction product was analyzed with an electron microprobe. The resulting Fo_{50} powders were uniaxially cold-pressed into a right-cylindrical Ni can with 100 MPa of pressure. Some samples were fabricated as thin-walled cylinders by including a central Ni post in the cold press (Hansen et al., 2012a, 2012b). We did not observe a systematic difference between the results obtained from solid cylinders and those obtained from thin-walled cylinders. Cold-pressed samples jacketed in Ni were then isostatically hot-pressed in a gas-medium apparatus (Paterson, 1990) at 300 MPa confining pressure and 1200 °C for 3 to 8 h to promote densification and grain growth. The mean grain size was ∼40 μm after hot-pressing. The hot-pressed cylinder was then sectioned into discs from 2 to 5 mm in thickness for subsequent deformation experiments.

2.2. Deformation experiments

Deformation experiments were conducted following the methods outlined in previous studies (Hansen et al., 2012a, 2012b). Hot-pressed samples, still jacketed in Ni, were stacked between porous alumina, dense alumina, and zirconia pistons, and the entire assembly was inserted in a steel tube. Sample assemblies were then inserted into the same internally heated, gas apparatus equipped with a servo-controlled torsion actuator (Paterson and Olgaard, 2000). Olivine with a relatively high Fe content was used for deformation experiments because of its reduced strength relative to Mg-rich olivine, which allows deformation experiments to be conducted at faster strain rates and lower shear stresses. Lower stresses are especially important because they reduce the likelihood of decoupling between sample and porous alumina pistons.

Torsional deformation was carried out at a confining pressure of 250 to 300 MPa and a temperature of 1200 °C. Deformation was controlled at either constant strain rate or constant stress (Table 1). Reported shear stress and shear strain rates were calculated for the outermost portion of the sample assuming the twist rate is homogeneous throughout the sample and the mechanical response is characterized by a single stress–strain rate relationship, following Paterson and Olgaard (2000).

2.3. Microstructural analysis

Microstructures were assessed from tangential and axial sections of samples before and after deformation. Tangential sections just intersect the cylindrical surface of the sample normal to the radius and provide a reference frame that approximates simple shear. Axial sections intersect the center of the sample on a plane parallel to the torsion axis and allow analysis of microstructures