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# Viscous anisotropy of textured olivine aggregates, Part 1: Measurement of the magnitude and evolution of anisotropy

Lars N. Hansen [a,*], Jessica M. Warren [b], Mark E. Zimmerman [c], David L. Kohlstedt [c]

[a] Department of Earth Sciences, University of Oxford, UK
[b] Department of Geological Sciences, University of Delaware, DE, USA
[c] Department of Earth Sciences, University of Minnesota, MN, USA

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ABSTRACT

The development of crystallographic textures in olivine-rich rocks leads to a marked anisotropy in viscosity of the upper mantle, strongly influencing a variety of large-scale geodynamic processes. Most estimates of the magnitude of viscous anisotropy in the upper mantle are derived from micromechanical models that predict textural and mechanical evolution numerically. Unfortunately, relatively few data exist with which to benchmark these models, and therefore their applicability to geodynamic processes remains in question. Here we present the results from a series of laboratory deformation experiments that yield insight into the magnitude and evolution of the anisotropy of olivine aggregates during deformation along complex loading paths. Aggregates of $Fo_{50}$ olivine were first deformed in extension in a gas-medium apparatus at a temperature of 1473 K, confining pressure of 300 MPa, and a variety of stresses and strain rates. Early in the extension experiments, samples exhibited viscosities similar to those previously determined for isotropic aggregates. Extensional deformation was accompanied by formation of crystallographic textures with [100] axes dominantly aligned with the extension axis. Samples were subsequently deformed in torsion under similar conditions to shear strains of up to 15.5. Early in the torsion experiments, samples supported stresses a factor of $\sim$2 larger than measured at the end of extension experiments, demonstrating a marked anisotropy in viscosity. Textures at the end of torsion experiments exhibited [100] axes dominantly aligned with the shear direction, comparable to previous experimental observations. Evolution of the textures resulting from extension to those resulting from torsion was analyzed through examination of radial sections of torsion samples. Our results confirm that texture produces viscous anisotropy in olivine aggregates, and we provide a simple, calibrated parameterization of viscous anisotropy for use in geodynamic models. Our results also provide an extensive dataset for future calibration of micromechanical models that track the evolution of anisotropy in upper mantle rocks.



## 1. Introduction

Many large-scale phenomena in the solid Earth depend directly on the viscosity of upper-mantle rocks. Notably, spatial and temporal variability in the viscosity of mantle rocks dramatically influences a number of key processes including localization of deformation into tectonic plate boundaries (e.g., Bercovici et al., 2000; Tackley, 2000), evolution and structure of mantle flow (e.g., Lenardic et al., 2003), flexure of the lithosphere in response to loading from ice sheets or other masses (e.g., Mitrovica and Forte, 2004), and viscoelastic relaxation of stresses after seismic events (e.g., Freed et al., 2012).

Heterogeneity in the spatial and temporal distributions of upper-mantle viscosity results from the evolution of thermodynamic, chemical, and microstructural conditions. For instance, laboratory-based investigations have demonstrated that the viscosity of olivine aggregates depends on temperature, pressure, water fugacity, oxygen fugacity, melt fraction, melt distribution, and grain size (e.g., Hirth and Kohlstedt, 1995; Mei and Kohlstedt, 2000; Keefner et al., 2011; Raterron et al., 2012). In addition to these relatively well-studied state variables, aggregates in which crys-

* Corresponding author.
*E-mail addresses:* lars.hansen@earth.ox.ac.uk (L.N. Hansen), warrenj@udel.edu (J.M. Warren), zimme030@umn.edu (M.E. Zimmerman), dlkohl@umn.edu (D.L. Kohlstedt).

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tals exhibit preferred crystallographic orientations should exhibit anisotropy in their viscosity, because crystallographic alignment inherently imparts anisotropy to bulk material properties Only very recently have experiments demonstrated that crystallographic textures significantly affect the viscosity of olivine aggregates (Hansen et al., 2012a, 2012c). Thus, heterogeneity in the viscosity of mantle rocks can additionally arise either from variation in the strength of a texture or from variation in the orientation of the texture relative to that of the applied stress.

The role of viscous anisotropy in the flow of the upper mantle has been examined theoretically in a number of studies. Numerical simulations have demonstrated that viscous anisotropy in the upper mantle affects the boundary layer thickness of convection cells (Christensen, 1987), modifies the thermal evolution of the lithosphere (Hearn et al., 1997), offsets geophysical signals from mass anomalies during post-glacial rebound (Christensen, 1987), influences the horizontal component of ice sheet motion (Han and Wahr, 1997), modifies the temporal and spatial distributions of density instabilities leading to drips forming from a dense lithosphere (Lev and Hager, 2008), and modifies the thermal structure above subducting slabs (Lev and Hager, 2011). Tommasi et al. (2009) demonstrated through numerical simulation that spatial heterogeneities in crystallographic fabric can lead to the formation of large-scale shear zones. This suggestion is supported by field studies illustrating that major tectonic fabrics observed at outcrop and mountain belt scales tend to parallel the underlying upper-mantle fabric revealed by the anisotropy of seismic wave propagation (e.g., Vauchez et al., 1998. Detailed microstructural investigations of exhumed mantle shear zones also indicate that viscous anisotropy associated with texture formation plays a role in shear zone initiation (Michibayashi and Mainprice, 2004; Skemer et al., 2013).

Currently, most estimates of the viscous anisotropy of mantle rocks are derived from micromechanical simulations of olivine deformation (e.g., Tommasi et al., 2009). The main input into these simulations is the relative ease of activation of potential slip systems in olivine, which is primarily determined from deformation experiments on single crystals of olivine (Durham et al., 1977; Bai et al., 1991). There are, however, relatively few results from deformation experiments on anisotropic aggregates with which to benchmark these micromechanical models. Previous studies have investigated only a limited range of deformation paths (e.g., Wendt et al., 1998; Hansen et al., 2012a, 2012c; Boneh and Skemer, 2014). In addition, these studies do not give insight into the time evolution of viscous anisotropy after a change in the kinematic conditions, a critical aspect of complex flow in the upper mantle (e.g., Castelnau et al., 2009).

To address the lack of laboratory data for calibration of micromechanical models that would allow viscous anisotropy to be incorporated into a wide range of geodynamic simulations, we have conducted a series of deformation experiments. In this contribution, we describe laboratory experiments in which olivine aggregates are initially deformed in extension and subsequently deformed in torsion. The experiments yield microstructural data that illustrate the evolution of texture strength, orientation, and symmetry in response to a change in deformation geometry. The experiments also yield mechanical data that demonstrate the manner in which viscosity varies as a function of textural characteristics and orientation of the principal stresses relative to the texture. In a subsequent contribution, we use these data to calibrate a new set of micromechanical models for easy incorporation into geodynamic simulations.

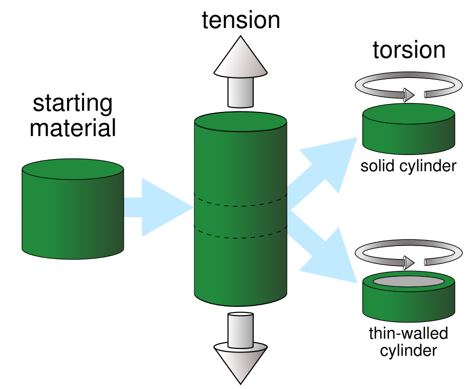


**Fig. 1.** Overview of experimental design. Hot-pressed aggregates of olivine (green) were deformed in extension. Short cylinders prepared from samples deformed in extension were subsequently deformed in torsion as either solid cylinders or thin-walled cylinders with the central region replaced with a Ni plug (gray). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

## 2. Methods

### 2.1. Sample preparation

Aggregates of $Fo_{50}$ were fabricated following the methods outlined in several previous studies (Zhao et al., 2009; Hansen et al., 2012b, 2012c, 2014). $Fo_{50}$ (rather than $Fo_{90}$) was used because of its fast grain-growth kinetics, which facilitates synthesis of coarse-grained starting materials, and for its low strength relative to San Carlos olivine ($Fo_{90}$), which reduces the likelihood of slip at piston-sample interfaces during torsion experiments. First, fayalite powders were initially synthesized by reacting fine-grained mixtures of $Fe_2O_3$ and $SiO_2$ in a gas-mixing furnace at 1410 K for 100 h with a mixture of CO and $CO_2$ specified to control the oxygen partial pressure at $P_{O_2} \approx 10^{-7}$ Pa. Then, this fayalite powder was reground and mixed with San Carlos olivine powder in a ratio suitable to produce equal amounts of Fe and Mg. Finally, this mixture of powders was reacted at 1673 K for 40 h in an one-atmosphere furnace filled with CO plus $CO_2$ in a ratio specified to control the oxygen partial pressure at $P_{O_2} \approx 10^{-4}$ Pa. This calcination process also removes any dissolved water initially present in the San Carlos olivine powders.

Aggregates of olivine used in deformation experiments were prepared from the $Fo_{50}$ powders. Powders were first uniaxially pressed into cylindrical Ni cans with a pressure of 100 MPa at room temperature. The Ni cans were capped with Ni discs and isostatically hot-pressed in an internally heated gas-medium apparatus (Paterson, 1990) at the University of Minnesota. Hot pressing was conducted at a temperature of 1473 K and confining pressure of 300 MPa for 5 to 8 h. During hot pressing, aggregates densified to $<1\%$ porosity and experienced significant grain growth. Scanning electron microscopy observations of hot-pressed samples reveal no evidence for residual glass after sintering. The ends of the cylinders of hot-pressed aggregates were subsequently ground to yield right cylinders approximately 10 mm in diameter and 20 mm in length.

### 2.2. Deformation experiments

We performed extension experiments followed by torsion experiments; this order is reversed from that used in our previous experiments (Hansen et al., 2012a). As depicted in Fig. 1, textured aggregates were initially created during extension experiments (PT0715 and PT0750) to provide material for subsequent torsion tests. Each sample deformed in extension was sectioned to