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

Lars N. Hansen\textsuperscript{a,b,*}, Yong-Hong Zhao\textsuperscript{a,c}, Mark E. Zimmerman\textsuperscript{a}, David L. Kohlstedt\textsuperscript{a}

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

**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 of \( > 10 \), a much higher value than previously thought necessary. Fabrics characterized by girdles of \([100] \) 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.

© 2013 Elsevier B.V. All rights reserved.

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
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 rocks exhibiting an A-type pattern were not strained to a suffi-

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 inter-

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 likeli-

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 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.

Fig. 1. Schematic depiction of A-type (top) and D-type (bottom) crystallographic fab-

[41x550]\[\{010\}

[41x550]\[\{001\}

\[\{100\}\]

\[\{010\}\]

\[\{001\}\]

\[\{100\}\]

A-type

D-type
<table>
<thead>
<tr>
<th>Sample</th>
<th>Shear strain (MPa)</th>
<th>Shear stress (10^{-4}) s(^{-1})</th>
<th>Shear strain rate (10^{-4}) s(^{-1})</th>
<th>Grain size ((\mu)m)</th>
<th>Shape parameter, (K)</th>
<th>(\ln(S_1/S_2)) [100]</th>
<th>(\ln(S_1/S_2)) [100]</th>
<th>M-index</th>
<th>J-index (\langle Y_{50}/Y_{90}\rangle) 0% Pk/40% Pk</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>PT0535</td>
<td>0.0</td>
<td>-</td>
<td>-</td>
<td>33.2</td>
<td>1.2</td>
<td>1.3</td>
<td>2.9</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>PT0248_1b</td>
<td>0.3</td>
<td>34</td>
<td>0.2</td>
<td>13.5</td>
<td>1.0</td>
<td>3.4</td>
<td>0.8</td>
<td>0.3</td>
<td>0.6</td>
<td>0.2</td>
</tr>
<tr>
<td>Bystricky</td>
<td>0.5</td>
<td>250</td>
<td>1.2</td>
<td>20.0</td>
<td>1.1</td>
<td>0.9</td>
<td>1.5</td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>PT0655b</td>
<td>1.0</td>
<td>150</td>
<td>3.6</td>
<td>12.6</td>
<td>1.4</td>
<td>0.6</td>
<td>1.6</td>
<td>0.3</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>PT0248_2b</td>
<td>1.0</td>
<td>43</td>
<td>0.5</td>
<td>11.2</td>
<td>1.8</td>
<td>0.5</td>
<td>1.0</td>
<td>0.6</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td>PI-284b</td>
<td>1.1</td>
<td>80</td>
<td>1.0</td>
<td>7.0</td>
<td>0.4</td>
<td>0.4</td>
<td>0.9</td>
<td>0.4</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>PT0248_3b</td>
<td>2.1</td>
<td>52</td>
<td>1.1</td>
<td>11.1</td>
<td>4.6</td>
<td>0.7</td>
<td>1.7</td>
<td>1.2</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>PT0503_5b</td>
<td>2.7</td>
<td>49</td>
<td>0.2</td>
<td>24.2</td>
<td>1.5</td>
<td>0.5</td>
<td>0.4</td>
<td>1.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>PT0248_4b</td>
<td>2.9</td>
<td>55</td>
<td>1.6</td>
<td>9.7</td>
<td>16.0</td>
<td>0.4</td>
<td>0.8</td>
<td>2.2</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>PT0248_5b</td>
<td>3.9</td>
<td>56</td>
<td>2.1</td>
<td>7.1</td>
<td>5.9</td>
<td>0.2</td>
<td>0.5</td>
<td>2.1</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>PT0503_6b</td>
<td>3.9</td>
<td>48</td>
<td>0.4</td>
<td>21.1</td>
<td>2.9</td>
<td>0.2</td>
<td>0.2</td>
<td>2.5</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td>PT0640b</td>
<td>4.0</td>
<td>117</td>
<td>3.3</td>
<td>19.5</td>
<td>9.4</td>
<td>0.2</td>
<td>0.3</td>
<td>2.7</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>PT0503_3b</td>
<td>4.9</td>
<td>46</td>
<td>0.4</td>
<td>21.3</td>
<td>0.1</td>
<td>0.3</td>
<td>1.2</td>
<td>0.8</td>
<td>1.5</td>
<td>0.8</td>
</tr>
<tr>
<td>Bystricky</td>
<td>5.0</td>
<td>225</td>
<td>1.2</td>
<td>4.3</td>
<td>15.7</td>
<td>0.2</td>
<td>0.4</td>
<td>1.5</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>PT0494b</td>
<td>5.9</td>
<td>278</td>
<td>54.0</td>
<td>15.0</td>
<td>18.1</td>
<td>0.4</td>
<td>0.8</td>
<td>2.3</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>PT0538b</td>
<td>6.8</td>
<td>96</td>
<td>2.1</td>
<td>11.5</td>
<td>8.6</td>
<td>0.4</td>
<td>0.7</td>
<td>2.7</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>PT0503_2b</td>
<td>6.8</td>
<td>48</td>
<td>0.6</td>
<td>16.8</td>
<td>16.2</td>
<td>0.9</td>
<td>0.8</td>
<td>2.8</td>
<td>1.4</td>
<td>1.3</td>
</tr>
<tr>
<td>PT0541b</td>
<td>7.6</td>
<td>82</td>
<td>0.8</td>
<td>13.5</td>
<td>24.6</td>
<td>0.3</td>
<td>0.4</td>
<td>3.0</td>
<td>0.8</td>
<td>0.7</td>
</tr>
<tr>
<td>PT0503_1b</td>
<td>8.2</td>
<td>41</td>
<td>0.8</td>
<td>13.1</td>
<td>13.9</td>
<td>0.8</td>
<td>0.9</td>
<td>1.9</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>PT0633b</td>
<td>8.7</td>
<td>82</td>
<td>0.6</td>
<td>17.8</td>
<td>18.1</td>
<td>0.8</td>
<td>1.2</td>
<td>2.0</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>PT0552b</td>
<td>8.8</td>
<td>138</td>
<td>8.8</td>
<td>7.4</td>
<td>16.1</td>
<td>1.0</td>
<td>1.0</td>
<td>2.0</td>
<td>1.2</td>
<td>1.0</td>
</tr>
<tr>
<td>PT0505b</td>
<td>10.2</td>
<td>115</td>
<td>3.3</td>
<td>17.0</td>
<td>13.0</td>
<td>1.0</td>
<td>1.0</td>
<td>3.3</td>
<td>1.9</td>
<td>1.8</td>
</tr>
<tr>
<td>PT0651b</td>
<td>10.6</td>
<td>112</td>
<td>3.8</td>
<td>19.9</td>
<td>12.7</td>
<td>2.7</td>
<td>2.1</td>
<td>2.6</td>
<td>2.0</td>
<td>1.9</td>
</tr>
<tr>
<td>PT0499b</td>
<td>10.9</td>
<td>168</td>
<td>5.0</td>
<td>11.5</td>
<td>6.5</td>
<td>0.9</td>
<td>0.8</td>
<td>2.9</td>
<td>1.6</td>
<td>1.5</td>
</tr>
<tr>
<td>PT019b</td>
<td>14.2</td>
<td>220</td>
<td>105.7</td>
<td>5.3</td>
<td>6.4</td>
<td>1.0</td>
<td>1.4</td>
<td>2.2</td>
<td>1.4</td>
<td>1.3</td>
</tr>
<tr>
<td>PT0484b</td>
<td>18.7</td>
<td>173</td>
<td>56.1</td>
<td>6.5</td>
<td>15.9</td>
<td>2.5</td>
<td>14.4</td>
<td>2.1</td>
<td>1.7</td>
<td>1.8</td>
</tr>
</tbody>
</table>

\(^{a}\) Data from axial sections of samples deformed in torsion.

\(^{b}\) References are given for studies in which the corresponding fabric was first published. 1: Zhang and Karato (2005), 2: Bystricky et al. (2000), 3: Hansen et al. (2012a), 4: Hansen et al. (2012b), 5: Hansen et al. (2012c), 6: This study.

\(^{b}\) Experiment conducted at constant stress. \(^{c}\) Experiment conducted at constant strain rate.
as a function of radius and therefore as a function of strain, strain rate, and stress. Sections were first polished with diamond lapping film and then finished by polishing for 40 min with colloidal silica (0.04 μm). Polished samples were carbon coated for analysis with a JEOL 6500 scanning electron microscope fitted with a field emission electron source. Crystallographic orientation maps were constructed using the HKL Channel5 software package to analyze electron-backscatter diffraction (EBSD) patterns at a step size of 0.25 to 0.8 μm. The fraction of each map for which diffraction patterns could be indexed ranged from 75 to 92%. Orientation maps were processed according to the methods outlined by previous studies (Hansen et al., 2011, 2012b, 2012a). Orientation distributions used to construct pole figures and for the eigenvalue analysis were resolved with one data point per grain. Each orientation distribution included 500 to 2600 individual grains.

To quantify the shape of the distribution of crystallographic axes, we used an eigenvalue analysis following Woodcock (1977). An orientation tensor, A, is defined by

\[
A = \frac{1}{N} \left[ \sum \frac{l_i^2}{m_{i1}} \sum m_{i1} \sum m_{i1} m_{i2} \sum m_{i2} m_{i3} \right],
\]

where \( l_i, m_{i1} \), and \( m_{i1} \) are the components of the unit vector that describes the orientation of the \( i \)th crystallographic axis in a Cartesian reference frame. \( N \) is the total number of measured orientations. The normalized eigenvalues, \( S_i \), are calculated such that

\[
S_1 + S_2 + S_3 = 1
\]

and

\[
S_1 \geq S_2 \geq S_3.
\]

The shape of the ellipsoid that describes the distribution of orientations in \( A \) can then be quantified by comparing \( \ln(S_1/S_2) \) to \( \ln(S_2/S_3) \). Thus, the shape parameter, \( K \), is defined by

\[
K = \frac{\ln(S_1/S_2)}{\ln(S_2/S_3)}.
\]

\( K > 1 \) for ellipsoids that are more prolate (i.e., distributions of orientations that form a cluster on a pole figure) and \(<1 \) for those that are more oblate (i.e., distributions of orientations that form a girdle on a pole figure). Values of \( \ln(S_1/S_2) \), \( \ln(S_2/S_3) \), and \( K \) are given in Table 1. Errors associated with each of these values were estimated by conducting the same eigenvalue analysis on 300 randomly selected orientations from each sample for 1000 iterations and calculating the standard deviation of the resulting distributions of values. Similar eigenvalue analyses have been used to quantify crystallographic fabric shapes in a variety of studies on natural peridotites (e.g., Vauchez et al., 2005; Soustelle et al., 2010; Higgie and Tommasi, 2012).

To quantify the strengths of the distribution of crystallographic axes, we used both the M-index (Skemer et al., 2005) and J-index (Bunge, 1982). The M-index has a value of 0 (random) to 1 (single crystal) and is based on the distribution of uncorrelated misorientation axes. The J-index (also known as the texture index) has a value of 1 (random) to infinity (single crystal) and is based on a calculated orientation distribution function. Orientation distribution functions were calculated using the MTEX toolbox for MATLAB and a kernel half width of 10° (Bachmann et al., 2010).

Grain sizes were measured using the linear intercept method on grain-boundary maps produced from EBSD data. The mean grain size was estimated by multiplying the mean intercept length by a factor of 1.5 to account for the underestimated inherent in measuring grain size from a 2-dimensional section (Underwood, 1970, pp. 80–93). Intercept lengths were measured along two sets of transects, one parallel to the shear plane and one parallel to the torsion axis.

2.4. Calculation of elastic properties

Elasticity tensors and seismic velocities were calculated using the measured distribution of crystallographic orientations. Elasticity tensors determined at room pressure and temperature for single crystals of olivine and orthopyroxene were taken from Abramson et al. (1997) and Chai et al. (1997), respectively. Average elasticity tensors for the aggregate were calculated from single crystal tensors using the MTEX toolbox for MATLAB (Mainprice et al., 2011). The Voigt average (homogeneous-strain assumption) was used since it has been experimentally demonstrated to best approximate the macroscopic elastic properties of textured mantle rocks (Crosson and Lin, 1971). Elastic properties were initially calculated only for pure olivine aggregates. However, to better approximate the elastic properties of mantle rocks elastic properties were also calculated assuming an orthopyroxene content of 40% by volume. Elasticity tensors for olivine and orthopyroxene aggregates were calculated separately, and a composite tensor was then calculated using the Voigt average. The elastic properties of orthopyroxene aggregates were calculated in the same manner as those for olivine using the orthopyroxene crystallographic fabric measured in sample PT0651. The pyroxene fabric from only one sample was used because all pyroxene fabrics measured in our sample set are relatively weak (M-index ≤ 0.05).

Average elasticity tensors were used to calculate magnitudes of seismic anisotropy. In Voigt notation, the stiffness tensor is described by the 36 components in \( C_{ij} \), where \( i \) and \( j \) range from 1 to 6. In our reference frame, subscripts 1, 2, and 3 correspond to the shear direction, normal to the shear plane, and the vorticity direction, respectively. We calculate the radial anisotropy, \( (V_{SH}/V_{SV})^2 \), assuming the shear plane is horizontal. \( V_{SH} \) and \( V_{SV} \) are the velocities of S-waves polarized parallel to the shear plane and the normal to the shear plane, respectively. Following Montagner and Nataf (1986), we calculated the radial anisotropy using components of the average stiffness tensor through the relationship

\[
\frac{V_{SH}^2}{V_{SV}^2} = \frac{1}{8} (C_{11} + C_{22}) - \frac{1}{4} C_{12} + \frac{1}{2} C_{66} - \frac{1}{8} (C_{44} + C_{55}) \quad (5)
\]

3. Results

3.1. Crystallographic fabric evolution

Torsion experiments resulted in a range of shear strains up to \( \gamma = 18.7 \), as summarized in Table 1. Throughout these experiments, the strain rate exhibited a non-linear dependence on stress and on grain size (Hansen et al., 2012b). Because of their similarity to theoretical predictions (e.g., Langdon, 1994), these rheological observations have been interpreted to indicate that dislocation-accommodated grain-boundary sliding was the dominant deformation mechanism (Hirth and Kohlstedt, 1995, 2003; Wang et al., 2010; Hansen et al., 2011, 2012b).

We tracked the evolution of the distributions of crystallographic axes with increasing strain. The pole figures in Fig. 2 illustrate the distinctive progression of fabric shape. In the starting material, all axes are randomly distributed. At a shear strain of \( \sim 2 \), all axes gather into diffuse clusters. Between a shear strain of 3 and 5, the [100] axes form strong point maxima and [010] and [001] axes are strongly girdled: these fabrics are similar to those observed in previous torsion experiments (Bystricky et al., 2000). Surprisingly, above a shear strain of \( \sim 5 \), the [010] axes become less girdled and gather into strong clusters. Pyroxene crystallographic fabrics are generally weak throughout the data set. The strongest pyroxene fabric (\( M = 0.05 \)) is presented in Fig. 3.
Fig. 2. Pole figures for distributions of [100], [010], and [001] axes for olivine in all samples in the data set organized by the total shear strain, \( \gamma \). Data corresponding to sample names with an underscore are from axial sections. All other data are from tangential sections. The data set includes samples of San Carlos olivine deformed in torsion (Bystricky et al., 2000) and direct shear (PI-284) (Zhang and Karato, 1995; Zhang et al., 2000). The shear sense is top to the right, and the torsion axis is vertical. Data are one point per grain and colored by multiples of uniform distribution. All pole figures are equal-area lower-hemisphere projections.

Fig. 3. Pole figures for distributions of [100], [010], and [001] axes for pyroxene in sample PT0651. This fabric represents the strongest pyroxene fabric observed in the entire data set. The shear sense is top to the right, and the torsion axis is vertical. Data are one point per grain and colored by multiples of uniform distribution. All pole figures are equal-area lower-hemisphere projections.

To better assess the fabric evolution with increasing shear strain, we employ the eigenvalue analysis described above (Woodcock, 1977) to quantify the shape of the distributions of each of the primary crystallographic axes and plot their evolution on a Flinn-type diagram (Flinn, 1965) in Fig. 4. With increasing shear strain, the [100] axes remain well into the clustered field and reach an approximately steady-state fabric shape after a shear strain of \( \sim 4 \). The [010] axes continually progress into the girdled field until a shear strain of \( \sim 6 \), at which point they begin to advance toward the clustered field. By a shear strain of \( \sim 9 \), the [010] axes reach the girdle/cluster transition. Although the [010] axes in most of the high strain samples plot near the girdle/cluster transition, the [010] axes in the sample deformed to the highest strain (\( \gamma = 18.7 \)) are clearly more clustered than girdled. The [001] axes evolve in a similar manner to the [010] axes, with some distributions crossing the girdle/cluster transition after a strain of \( \sim 8 \). We note that the distance from the origin on the plots in Fig. 4 is an additional measure of the overall strength of the fabric.

The relationship between the shape of [010] axis distributions and strain is additionally assessed in Fig. 5 using the shape parameter, \( K \), as defined in Eq. (4). The value of \( K \) approaches zero for strongly girdled fabrics and infinity for strongly clustered fabrics. The girdle/cluster transition occurs at a value of \( K = 1 \). The magnitude of \( K \) for distributions of [010] axes follows a distinct evolution as a function of strain. As anticipated from Fig. 2, \( K \) progresses from values >1 at very low strain (although errors are
Fig. 4. Eigenvalue analysis of the crystallographic fabrics measured from deformed olivine aggregates. $S_1$, $S_2$, and $S_3$ are the eigenvalues of the orientation tensor as defined by Woodcock (1977). Fabric strength increases with increasing distance from the origin, and the degree of girdling increases with proximity to the abscissa. The gray arrows indicate the interpreted evolution of fabric shape. Circles are from tangential sections of torsion samples, triangles are from axial sections of torsion samples (up pointing are from sample PT0248 and left pointing are from sample PT0503), the diamond is from a direct shear experiment, PT-284 (Zhang and Karato, 1995; Zhang et al., 2000), and the stars are from torsion experiments on San Carlos olivine (Bystricky et al., 2000). Errors are one standard deviation determined by a bootstrapping method with a subsample size of 300 grains.

Fig. 5. Evolution of the shape parameter, $K$, for distributions of [010] axes as a function of shear strain. Values of $K$ vary systematically from >1 at low strain, to a minimum at a shear strain of ~5, and finally to ≥1 at a shear strain of ~10. The observed progression in fabric shape is consistent with fabrics measured in previous studies. Error bars and marker shapes are defined as in Fig. 4.

Fig. 6. Variation in olivine crystallographic fabric strength as a function of shear strain. Fabric strength is quantified using the M-index (a and c) or the J-index (b and d). Markers are colored according to grain size (a and b) or shear stress (c and d). Marker shapes are defined as in Fig. 4.

Fig. 7. Magnitude of radial anisotropy as a function of shear strain. Radial anisotropy is calculated assuming the shear plane (i.e., plane normal to the torsion axis) is horizontal. Open markers indicate anisotropies calculated assuming the aggregate is entirely olivine. Closed markers indicate anisotropies calculated assuming the aggregate is 40% pyroxene. The pyroxene fabric presented in Fig. 3, the strongest pyroxene fabric observed, was used for all calculations. Elastic properties of olivine/pyroxene composites were calculated using a Voigt average. The gray region indicates the range of strains examined in previous laboratory studies of the development of seismic anisotropy in olivine aggregates.

3.2. Seismic anisotropy

Calculations of radial seismic anisotropy are presented in Fig. 7. Values of $(V_{SH}/V_{SV})^2$ for 100% olivine aggregates increase from ~1.00 in undeformed samples to ~1.15 after at a shear strain of ~5. Notably, values of $(V_{SH}/V_{SV})^2$ remain approximately constant at shear strains >5. Fig. 7 additionally illustrates that values of $(V_{SH}/V_{SV})^2$ calculated for our samples are in relatively good agreement with those of previous studies. The magnitude of anisotropy follows a similar evolution when 40% orthopyroxene is included in the calculation, reaching maximum values at a shear strain of ~5. The elastic properties of pyroxene aggregates were calculated using the pyroxene crystallographic fabric depicted in Fig. 3. Previous studies of natural rocks have similarly demonstrated that the addition of secondary mantle minerals tends to reduce the magnitude of anisotropy while maintaining the symmetry and orientation of anisotropy (Mainprice and Silver, 1993;
Barruol and Mainprice, 1993). Values of \((V_{SH}/V_{SV})^2\) are reduced by about 6% when pyroxene is included in the calculation.

### 4. Discussion

#### 4.1. Comparison to previous studies

In addition to our analysis of aggregates of Fo\(_{90}\) deformed in torsion, we applied the same technique to fabrics measured from samples of San Carlos olivine deformed in both direct shear (primarily simple shear with a component of compression) (Zhang and Karato, 1995; Zhang et al., 2000) and torsion (Bystricky et al., 2000). The sample deformed in direct shear (PI-284) is part of the set of experimental samples used to define A-type fabrics (Zhang and Karato, 1995; Zhang et al., 2000; Jung et al., 2006). The distributions of [010] and [001] axes in this sample are similar to those observed in the low strain portion of our data set. K values indicate that axis distributions in this sample are slightly more girdled than clustered, but not as girdled as data from our samples deformed to moderate strains. Interestingly, [100] distributions are significantly more girdled in this direct shear sample than in our data set. We suggest that the observed girdling of [100] axes is due to a component of compression inherent to direct shear experiments. This particular sample (PI-284) experienced 23% compressional strain at a shear strain of 1.1 (Zhang et al., 2000). Several previous laboratory-based studies demonstrated that axial compression of olivine aggregates results in clusters of [010] axes and girdles of [001] axes (Ave'Lallemant and Carter, 1970; Nicolas et al., 1973; Keefer et al., 2011; Hansen et al., 2011). Correspondingly, numerical simulations of olivine crystallographic fabric development suggest that transpression of olivine aggregates will result in fabrics similar to those observed in PI-284 (Tommasi et al., 1999, 2000). Fabrics from samples deformed in torsion experiments on San Carlos olivine (Bystricky et al., 2000) are also plotted in Fig. 4 and Fig. 5 as stars. Data from these samples are often used as examples of a D-type fabric. Axis distributions in these published results agree well with those in the moderate strain portion of our data set.

We note that the primary distinction between an A-type and D-type fabric is the character of the [010] axis distributions. Although sample PI-284 analyzed in this study does exhibit girdled [010] axes, many of the fabrics measured by Zhang and Karato (1995) and Zhang et al. (2000) exhibit qualitatively more distinct [010] point maxima. Because these direct shear experiments include a component of compression, we suggest that the primary difference between [010] distributions observed in direct shear experiments and those in torsion experiments is the difference in strain geometry rather than subtle differences in mechanism. The observed difference between strain geometries emphasizes the point that our results best describe simple shear and care should be taken if applying our conclusions to systems with more complex kinematics.

The range of olivine compositions presented here (Fo\(_{50}\) to Fo\(_{90}\)) does call into question the robustness of comparing our data to those of previous studies. However, we emphasize that increasing the Fe content in olivine primarily acts to increase diffusivities and lower the melting temperature. All olivine compositions in the forsterite–fayalite solid solution tend to exhibit the same deformation mechanisms (Zhao et al., 2009) and have the same primary slip systems with similar relative strengths (Kohlstedt and Ricoult, 1984; Ricoult and Kohlstedt, 1985). Although the rate controlling point defect populations will likely be different in the pure Mg end member than in Fe-bearing olivines (Kohlstedt and Ricoult, 1984), there is likely little difference between Fo\(_{50}\) and Fo\(_{90}\).

#### 4.2. Mechanism of fabric evolution

We interpret the observed fabric evolution to represent the competition between the two easiest slip systems in olivine, [010][100] and [001][100]. Because these two slip systems are of similar strengths (Durham et al., 1977; Bai et al., 1991), most grain orientations with [100] parallel to the shear direction will be “soft orientations” leading to girdles of [010] and [001] axes. The transition to an A-type fabric at high shear strains suggests that [010][100] is indeed the weakest slip system, and we suggest that it is the similarity in strength between the two slip systems that prolongs the fabric evolution. To further justify this conclusion, misorientation axes from subgrain boundaries in 10 samples are plotted in Fig. 8. The distribution of subgrain misorientation axes provides information on the dominant types of dislocations in subgrain walls (Lloyd et al., 1997; Prior et al., 2002; Hildyard et al., 2009). Misorientation axes in our samples are distributed between [010] and [001] early in the deformation and are dominantly clustered near [001] at high strain. Most of the observed subgrain boundaries are oriented vertically in tangential sections (see Fig. 4 in Hansen et al., 2012b), and most of the subgrain misorientation axes are oriented normal to tangential sections (Fig. 8). If we assume that most subgrain boundaries are also near perpendicular to tangential sections, then we can conclude that subgrains at moderate strain are characterized by tilt walls built of either [010][100] or [001][100] dislocations, whereas subgrains at high strain are characterized by tilt walls built primarily from [010][100] dislocations. Fig. 9 depicts two grains from sample PT0541 (γ = 7.6), exhibiting near vertical subgrain boundaries. The dispersion of crystallographic axes in Fig. 9 clearly demonstrates that strain in grain 1 is primarily accommodated by rotation around [010] while that in grain 2 is primarily accommodated by rotation around [001]. Thus, these subgrain boundaries are consistent with the occurrence of both [001][100] tilt walls (grain 1) and [010][100] tilt walls (grain 2). Although [010] misorientations could be related to twist walls built from [010][100] and [001][100] dislocations (twist walls require screw dislocations from two independent slip systems), subgrain boundaries would all have to be nearly parallel to tangential sections to be perpendicular to misorientation axes. Additionally, it is unlikely that most of the subgrain walls with [001] misorientation axes are of twist rather than tilt character since [001][100] is the only slip system in olivine that slips on [001] (see compilation in Tommasi et al., 2000). Thus, our observations are consistent with a transition from simultaneous operation of [010][100] and [001][100] dislocations to dominant contribution from [010][100] dislocations. We also note that many authors have attributed the formation of girdles of [010] axes to simultaneous operation of a variety of dislocations in the [0kl][100] family of slip systems, often referred to as pencil glide (e.g., Ave'Lallemant and Carter, 1970; Ismail and Mainprice, 1998; Mehl et al., 2003; Michibayashi et al., 2006). Although [010][100] and [001][100] dislocations are within the [0kl][100] family, clusters of misorientation axes near [001] and [010] suggest that other dislocations in the [0kl][100] family are not common. Because grain-scale simulations of crystallographic fabric development in olivine track the activities of different slip systems (Tommasi et al., 2000; Castelnau et al., 2008; Leibensohn et al., 2010), our results can be used to calibrate models that are carried out to very high strain.

The specific mechanism responsible for a change in the relative activities of the [010][100] and [001][100] slip systems is difficult to determine from our set of observations. One possibility is that, if the critical resolved shear stress for [001][100] dislocations is slightly higher than for [010][100] dislocations, then grains optimally oriented for slip on the former system would experience a larger stress. Differences in stress state among populations of
Fig. 8. Misorientation axis distributions from deformed samples plotted in the crystal reference frame and the sample reference frame. Data are for neighbor-pair misorientation axes with misorientation angles between 2° and 15°, which are misorientations associated with subgrain boundaries. Only data collected from tangential sections are plotted.

Grains with different orientations should lead to differences in dislocation density (e.g., Kohlstedt and Goetz, 1974). Thus, grains optimally oriented for ⟨001⟩[100] slip would have higher dislocation densities and therefore be consumed during grain-boundary migration in favor of grains oriented for ⟨010⟩[100] slip that would have lower dislocation densities. Previous studies have demonstrated the relationship between grain orientation and dislocation density in deformed olivine aggregates is not always systematic (Farla et al., 2011). However, a weak correlation between grain orientation and dislocation density may explain the necessity for very large strains before the crystallographic fabric is clearly dominated by the influence of one slip system.

We also emphasize that the differences between A-type and D-type fabrics are not necessarily the result of different deformation conditions. Results from early experiments of Carter and Ave'Lalllemant (1970) suggest that at low temperatures [high stresses] the ⟨0kl⟩[100] family of slip systems becomes dominant. Therefore, the association between D-type fabrics and high-stress conditions has led several authors to conclude that the difference between A-type and D-type fabrics is a result of subtle changes in the dominant deformation mechanism. Since grain size and applied shear stress also vary among the experiments in our dataset, it is possible that these conditions influence the relative activity of different deformation mechanisms. To confirm that strain is the main factor determining fabric shape, we assessed the dependence of fabric shape on grain size and shear stress. As demonstrated in Fig. 10, K for ⟨010⟩ axes does not exhibit a systematic dependence on either the mean grain size or the applied shear stress. We note that fabric strength, as opposed to fabric shape, does appear to have a subtle dependence on grain size, as depicted in Fig. 6. This dependence may result from either (1) changes in relative contributions of different deformation mechanisms or (2) differences in the amount of grain-size reduction that has occurred through dynamic recrystallization. In the first case, increasing amounts of diffusion creep...
at smaller grain sizes may contribute to randomization of fabrics, although to our knowledge this behavior has not yet been demonstrated experimentally. In the second case, the amount of recrystallization may also affect crystallographic fabric development (Kaminski and Ribe, 2001). In practice, it is difficult to establish which of these two mechanisms is responsible for the slight dependence of fabric strength on grain size, although the role of recrystallization could be tested in future experiments by using samples with starting grain sizes smaller than the steady-state grain size such that grain growth accompanies deformation.

Furthermore, some fabrics in our data set were measured from the interiors of solid cylinders deformed in torsion. These interior regions could potentially be deforming by a different deformation mechanism than the outer edge of the sample because shear stress and shear strain rate are correlated with radius (Paterson and Olgaard, 2000). To test this point, Fig. 11 presents a comparison of flow laws for diffusion creep and dislocation-accommodated grain-boundary sliding along the radii of two solid cylinders deformed in torsion. Stresses were calculated at each point along the radius based on published flow laws using the applied strain rate and the observed grain size. Dislocation-accommodated grain-boundary sliding is the dominant (i.e., lowest stress) mechanism at all points but one (center of PT0248, γ = 0.3), confirming that a transition in mechanism is not responsible for differences in fabric shape. Although the fabric shape is not related to changes in deformation mechanism, we do observe systematic variation in fabric strength with changes in grain size and stress (Fig. 6). Thus, at smaller grain sizes, an increased contribution of sliding on grain boundaries to the total strain may contribute to weakening the fabric. We note that the inverse correlation between fabric strength and stress is simply related to the inverse relationship between stress and the recrystallized grain size.

### 4.3. Implications of systematic fabric evolution

These conclusions have three main implications. First, our results demonstrate that deformation in the dislocation-accommodated grain-boundary sliding regime can produce both A-type and D-type fabrics and is therefore potentially responsible for the occurrence of both fabric types in naturally deformed olivine-rich rocks. Because these fabric types are so commonly observed in nature (Ismail and Mainprice, 1998), this conclusion increases the robustness of recent experimental studies that suggest that grain-boundary sliding is a ubiquitous mechanism of deformation in the upper mantle (Hansen et al., 2011, 2012b). Therefore, even the viscosity of strongly anisotropic upper mantle rocks is sensitive to grain size.

Second, our results provide the calibration necessary for using the shape of crystallographic fabric as a proxy for strain magni-

---

**Fig. 9.** Misorientation within two grains from sample PT0541. Each grain is colored according to the misorientation angle relative to a reference point (red dot). White lines denote subgrain boundaries defined by neighbor-pair misorientations $>2^\circ$. Pole figures indicate orientations of the three primary crystallographic axes for all points within each grain. Note that measurements in grain 1 are primarily misoriented around [010] while those in grain 2 are primarily misoriented around [001].

**Fig. 10.** The shape parameter, $K$, for [010] axis distributions as a function of (a) shear stress and (b) grain size. The dashed lines at a value of $K = 1$ corresponds to the girdle/cluster transition. $K$ does not vary systematically as a function of (a) shear stress or (b) grain size. Error bars and marker shapes are defined as in Fig. 4.

**Fig. 11.** Stress predicted for diffusion creep and for dislocation-accommodated grain-boundary sliding along axial transects of two samples deformed in torsion. Stresses were calculated based on the measured grain size and the applied strain rate, which is a linear function of the radius, using flow laws for dislocation-accommodated grain-boundary sliding (closed markers) and diffusion creep (open markers) from Hansen et al. (2012b) and Zhao et al. (2009), respectively. The flow law that predicts the lowest stress for any combination of grain size and strain rate corresponds to the mechanism that contributes the most to sample deformation. Based on this analysis, all points, except the innermost point for PT0248, were dominantly deforming by dislocation-accommodated grain-boundary sliding.
tude. If it can be demonstrated for a suite of naturally deformed rocks that the deformation conditions were anhydrous, the deformation kinematics were approximately simple shear, and the dominant deformation mechanism was dislocation-accommodated grain-boundary sliding, then we expect any associated fabric evolution to be comparable to the observations presented in this study. Values of $K$ and fabric strength for natural rocks can then be compared with our results to provide an estimate of the amount of strain experienced by the natural rocks. The complicated fabric evolution demonstrated here will allow shear strains to be estimated up to a value of $\sim 20$. We suggest that strains estimated in this way are minima since pre-existing fabrics can prolong fabric development (Warren et al., 2008; Knoll et al., 2009; Webber et al., 2010). The girdled [100] axes in direct shear experiments also imply that the relative magnitudes of the components of the strain tensor can be determined for deformations other than simple shear with a similar analysis to that employed here, although a dataset of crystallographic fabrics for such a purpose does not yet exist.

Third, the observed fabric evolution has important ramifications for investigations of upper-mantle seismic anisotropy. The observed changes in fabric symmetry suggest that regions of the upper mantle subject to large amounts of predominantly simple shear (e.g., Couette-style flow just beneath the oceanic lithosphere; Podolefsky et al., 2004; Behn et al., 2009) would be characterized by crystallographic fabrics with orthorhombic symmetry. This implication is supported by the recent argument (Song and Kawakatsu, 2012) that the coexistence of strong radial and azimuthal anisotropy throughout the oceanic asthenosphere is best explained by anisotropy with orthorhombic symmetry. Thus, the results presented here suggest that the large regions of the oceanic upper mantle with orthorhombic anisotropy have been deformed to sufficient strain to develop an A-type fabric.

Furthermore, although previous investigations of the development of seismic anisotropy in laboratory experiments demonstrated that the magnitude of anisotropy increases with increasing shear strain (Zhang and Karato, 1995; Bystricky et al., 2000), Fig. 7 demonstrates that the magnitude of anisotropy saturates at shear strains just larger than those attained in previous studies. The observed saturation of anisotropy suggests that regions of the upper mantle in which the magnitude of anisotropy does not change as a function of the duration of deformation (e.g., as function of distance from a mid-ocean ridge in the sublithospheric oceanic mantle) can be interpreted to have developed a steady-state crystallographic fabric, which corresponds to a critical value of shear strain ($\gamma \approx 5$ for anhydrous, simple shear in the dislocation-accommodated grain-boundary sliding regime). We note again that any estimates of the magnitude of shear strain would be a minimum since pre-existing fabrics can prolong fabric development, and there are very few geodynamic scenarios in which deformation begins with initially untextured mantle rocks.

5. Conclusions

We analyzed crystallographic fabrics from a large set of experimentally deformed olivine aggregates. Samples were deformed in torsion up to a shear strain of $\gamma = 18.7$, exploring considerably higher strains than previous studies. We observed a systematic evolution in olivine crystallographic fabrics that does not reach a steady state until a significant strain is reached ($\gamma > 10$). Notably, [010] and [001] axis distributions become progressively more girdled until a shear strain of $\sim 5$, at which point those distributions begin to become more clustered. This evolution in fabric symmetry is confirmed through an eigenvalue analysis. In addition to this evolution in fabric symmetry, the fabric strength and magnitude of seismic anisotropy are only observed to reach a steady state after a significant amount of deformation.

We suggest that the protracted fabric evolution results from the similar strengths of the two dominant slip systems, [010][100] and [001][100]. Analysis of misorientations associated with subgrain boundaries suggests that both slip systems are initially active but that [010][100] eventually dominates the deformation at high strain. Comparison of quantitative measurements of fabric shape to shear stress and grain size do not reveal any indication that changes in deformation mechanisms are responsible for the observed changes in fabric shape.

The documented evolution of olivine crystallographic fabrics yields several important ramifications. (1) The dominant mechanism in these experiments, dislocation-accommodated grain-boundary sliding, can potentially be the dominant deformation mechanism in the upper mantle since many of the naturally observed olivine fabrics are encapsulated in our observations. (2) Our analysis provides a means to use measurements of fabric shape as a proxy for strain in both field and laboratory settings for a specific set of deformation conditions. (3) We demonstrate that the magnitude of radial seismic anisotropy reaches a steady state at $\gamma > 5$, which indicates that relatively small changes in the magnitude of upper-mantle anisotropy with increasing durations of deformation could be used to indicate that enough strain has been accumulated to reach a steady-state crystallographic fabric.

Acknowledgements

This work benefited greatly from discussions with Ben Holtzman, Marshall Sundberg, and Jacob Tielke. We thank Misha Bystricky for providing previously published EBSD data and Jessica Warren for the use of EBSD facilities at Stanford University. The quality of this work benefited greatly from comments from Andrěa Tommasi and an anonymous reviewer. Comments from David Prior significantly improved an earlier version of this manuscript. Parts of this work were carried out in the Characterization Facility, University of Minnesota, which receives partial support from NSF through the MRSEC program. This research was supported by NSF grants EAR-1015343 (to M.E.Z.) and EAR-1214876 (to D.L.K.) and NSF grants 41274094 and 40821062 (to Y.H.Z.).

References


