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The effect of deformation history on the evolution of olivine CPO

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ABSTRACT

Olivine crystallographic preferred orientation (CPO) is the primary cause of seismic anisotropy in the upper mantle. In tectonic environments with complex flow patterns, for example corner flow near mid-ocean ridges or subducting slabs, the interpretation of seismic anisotropy may be complicated by evolving thermochemical deformation conditions and the integrated deformation history. To understand how deformation history influences CPO evolution, deformation experiments were conducted on samples of Åheim dunite, which has a strong pre-existing texture. Experiments were performed in a triaxial geometry using a Griggs apparatus at $P = 1$ GPa, $T = 1473$ K, up to a maximum strain of ~ 0.7. To simulate different deformation histories, samples were deformed in three different configurations, with the pre-existing foliation perpendicular, oblique, and parallel to the shortening axis of deformation. Distinct patterns of CPO development are observed for each experimental configuration. Likewise, texture strength, symmetry, and orientation evolved differently in each set of experiments. These data are interpreted as evidence that CPO did not reach steady state and that achieving steady state texture requires larger strains than previously thought. It is concluded that the integrated deformation history plays a significant role in CPO evolution and the consequent interpretation of seismic anisotropy in Earth's mantle.

1. Introduction

Olivine is the most abundant mineral in the upper mantle and its rheology plays an important role in mantle convection and the dynamics of Earth's tectonic plates (Hirth and Kohlstedt, 2003; Karato and Wu, 1993). Over a wide range of deformation conditions, strained crystal lattices align themselves in particular patterns described as crystallographic preferred orientation (CPO). The formation and evolution of CPO in olivine is related to the kinematics of flow (Karato, 1988; Wenk and Christie, 1991), the magnitude of strain (Nicolas et al., 1973; Skemer et al., 2012; Zhang and Karato, 1995), and the thermodynamic conditions of deformation (Couvy et al., 2004; Jung et al., 2006; Katayama and Karato, 2006; Raterron et al., 2007). The CPO generated by olivine deformation is widely considered to be the primary cause for seismic anisotropy in the upper mantle (Karato et al., 2008; Long and Becker, 2010; Mainprice et al., 2000; Nicolas and Christensen, 1987; Savage, 1999), and may also play an important role in the generation of rheological anisotropy (Hansen et al., 2012; Montési, 2013; Skemer et al., 2013; Tommasi et al., 2009).

The most common olivine texture, which is developed by the dominant activity of the [100](010) slip system, aligns the olivine's seismically fastest crystallographic axis [100] with the direction of flow. This A-type texture has been widely observed in both natural samples (Ben Ismaïl and Mainprice, 1998; Nicolas and Christensen, 1987) and laboratory deformation experiments (Zhang and Karato, 1995). The ubiquity of these observations provides a strong basis for the inferring mantle flow patterns from seismic anisotropy (Montagner, 2002; Montagner and Tanimoto, 1991; Savage, 1999; Silver et al., 1999; Tanimoto and Anderson, 1985) and for the parameterization of models that predict seismic anisotropy from numerical simulations of mantle flow (Becker et al., 2003, 2006; Conrad et al., 2007; Faccenda and Capitanio, 2012; Kaminski and Ribe, 2001; Tommasi et al., 2000).

To infer mantle flow from seismic anisotropy, important assumptions must be made about the rate that CPO evolves. Specifically, it is necessary to assume that a steady state texture develops quickly and does not lag significantly behind changes in kinematics (Kaminski et al., 2004). However, recent experimental (Hansen et al., 2014; Skemer et al., 2011), geological (Skemer et al., 2010; Warren et al., 2008; Webber et al., 2010), and numerical studies (Castelnau et al., 2009) have shown that olivine CPO may evolve more slowly than previously thought. Of particular importance may be the influence of pre-existing olivine CPO on subsequent texture evolution (Skemer et al., 2012). In settings of complex

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mantle flow, such as mid-ocean ridges and mantle wedges of subduction zones, the kinematics and the conditions of deformation change rapidly over short length scales (Di Leo et al., 2014; Li et al., 2014). Yet in spite of its importance to the interpretation of seismic anisotropy, the effect of deformation history on subsequent texture evolution is poorly understood.

To explore the influence of deformation history on texture evolution in olivine, we have conducted high pressure/temperature laboratory deformation experiments on dunite with a pre-existing CPO. Experiments were conducted in three different configurations, to simulate three deformation histories. These experiments demonstrate that the accumulation of CPO depends strongly on the initial orientation of the pre-existing CPO, with respect to the geometry of deformation.

2. Methods

2.1. Starting material and experimental procedure

Triaxial deformation experiments were performed using a solid medium Griggs apparatus at a confining pressure of 1 GPa, temperature of 1200 °C, and strain rates of 3.9–5.4 × 10^{-6} [1/s] (Table 1). The starting material for these experiments is the Åheim dunite, which is composed mainly of olivine (∼95%), with small amount of orthopyroxene (∼2%), chlorite (∼2%), and spinel (∼1%) (Chopra and Paterson, 1981), and has been used in numerous laboratory experiments (Berckhemer et al., 1982; Chopra and Paterson, 1981, 1984; Druiventak et al., 2011; Jackson et al., 1992; Jin et al., 1994; Keefner et al., 2011; Van der Wal et al., 1993; Wendt et al., 1998). The Åheim dunite was chosen specifically for its coarse grain-size (∼0.3 mm) (Fig. 1A) and for its relatively strong initial texture (Fig. 1B).

Samples were obtained from the same block characterized by (Jackson et al., 1992). Cores, extracted using a diamond coring bit, were ground into right cylinders with a diameter of 5.1 mm and with a length of 12.0 mm. Samples were cored in three different orientations with respect to the sample foliation. In the first orientation, the sample's long axis, which is also the axis of shortening and the coring direction, is perpendicular to the foliation plane (Fig. 1C, henceforth this geometry is described to be "perpendicular"). In the second orientation, the sample core is at 45° to the foliation plane (Fig. 1C, "oblique"). In the third orientation, the sample core is parallel to the foliation plane (Fig. 1C, "parallel").

Samples were encased in a nickel capsule with a small amount of NiO powder added at the top of the capsule to buffer oxygen fugacity within the stability field of olivine (Nitsan, 1974). Prior to the experiment, samples were dried in a vacuum oven for a minimum of 24 h at 120 °C to evaporate any adsorbed surface water. For high pressure and temperature experiments in the Griggs apparatus, soft-fired pyrophyllite, porous MgO, and barium carbonate, were used to form the confining pressure medium. This assembly is employed for its stability at high temperatures, allowing us to achieve maximal strains at strain-rates consistent with deformation by the dislocation creep mechanism. However, this pressure medium imposes substantial friction on the sigma-1 piston, limiting the utility of the mechanical data collected by the load cell. For each experiment, the sample was pressurized and heated slowly, over a period of 12 hours, in order to minimize premature deformation of the sample. When the target temperature and pressure was achieved, deformation was initiated at a constant strain-rate. A hit-point was observed in the load–displacement record after a run-in of ∼4 mm. Samples quenched at the hit-point confirm some pre-hit strain ($\varepsilon \sim 0.2$), but with relatively little recrystallization or modification of the microstructure. Experimental conditions and data are summarized in Table 1.

Table 1
Summary of experiments parameters and texture elements. All experiments are under conditions of ∼1 GPa and 1200 °C respectively.

Experiment #	Shortening axis vs. foliation	Natural strain	Strain-rate [1/s]	Θ[a] [°]	*M*-index	[100] *P*	[100] *G*	[100] *R*	[010] *P*	[010] *G*	[010] *R*	[001] *P*	[001] *G*	[001] *R*
Undeformed	–	0.000	–	0	0.13	0.012	0.517	0.471	0.450	0.160	0.390	0.065	0.384	0.449
WUG 116	Perpendicular	0.217	[b]	0	0.10	0.008	0.300	0.692	0.374	0.103	0.524	0.037	0.459	0.505
WUG 114	Perpendicular	0.328	4.55E−06	0	0.09	0.108	0.256	0.636	0.362	0.032	0.606	0.112	0.271	0.617
WUG 125	Perpendicular	0.406	4.27E−06	0	0.08	0.083	0.228	0.690	0.336	0.065	0.599	0.102	0.293	0.605
WUG 122	Perpendicular	0.507	3.91E−06	0	0.12	0.082	0.380	0.538	0.424	0.049	0.527	0.072	0.346	0.582
WUG 126	Perpendicular	0.653	4.43E−06	0	0.11	0.073	0.449	0.478	0.409	0.087	0.503	0.033	0.333	0.634
WUG 130	Oblique	0.187	[b]	33	0.09	0.033	0.361	0.607	0.368	0.074	0.558	0.061	0.319	0.620
WUG 128	Oblique	0.410	4.08E−06	30	0.08	0.065	0.258	0.677	0.327	0.105	0.567	0.018	0.401	0.581
WUG 129	Oblique	0.482	3.77E−06	18	0.14	0.171	0.297	0.533	0.437	0.084	0.479	0.148	0.306	0.546
WUG 143	Oblique	0.685	5.35E−06	17	0.15	0.211	0.292	0.497	0.450	0.127	0.423	0.149	0.316	0.534
WUG 127	Oblique	0.717	4.78E−06	0	0.15	0.209	0.315	0.476	0.446	0.069	0.486	0.178	0.254	0.568
WUG 138	Parallel	0.207	[b]	80	0.06	0.032	0.156	0.812	0.217	0.227	0.556	0.140	0.220	0.640
WUG 133	Parallel	0.360	4.50E−06	50	0.06	0.107	0.114	0.779	0.141	0.379	0.480	0.207	0.136	0.657
WUG 146	Parallel	0.370	4.45E−06	55	0.06	0.125	0.121	0.754	0.180	0.332	0.488	0.117	0.165	0.718
WUG 134	Parallel	0.415	4.27E−06	25	0.05	0.076	0.126	0.798	0.044	0.486	0.471	0.210	0.063	0.727
WUG 147	Parallel	0.610	4.94E−06	40	0.06	0.142	0.179	0.679	0.061	0.544	0.395	0.139	0.020	0.841

[a] Angle between the normal to the shear plane and the [010] point maxima.
[b] Strain occurred during initial loading of the sample and strain-rate is poorly constrained.