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Experimental Deformation of Olivine Crystals at Mantle P and T: Evidences for a Pressure-Induced Slip Transition and Implications for Upper-Mantle Seismic Anisotropy and Low Viscosity Zone

P. Raterron (1), J. Chen (2), T. Geenen (3), J. Girard (1,2)

(1) LSPES (CNRS 8008), Bat C6, Université des Sciences et Technologies de Lille, Villeneuve d'Ascq, Cedex, France (paul.raterron@univ-lille1.fr, +33 320 436591), (2) The CeSMEC, Florida International University, University Park Campus, Blg. VH140, Miami, Florida 33199, USA, (3) Department of Theoretical Geophysics, Faculty of Geosciences, Utrecht University, Budapestlaan 4, 3584 CD Utrecht, The Netherlands

Recent developments in high-pressure deformation devices coupled with synchrotron radiation allow investigating the rheology of mantle minerals and aggregates at the extreme pressure (P) and temperature (T) of their natural occurrence in the Earth. This is particularly true in the case of olivine, which rheology has been recently investigated in the Deformation-DIA apparatus (D-DIA, see Wang et al., 2003, Rev. Scientific Instr., 74, 3002) at upper-mantle P and T conditions.

Olivine deforms by dislocation creep in the shallow upper-mantle, as revealed by the seismic velocity anisotropy observed in this region. The attenuation of seismic anisotropy at depth greater than 200 km is interpreted as a pressure-induced change in olivine main deformation mechanism. It was first attributed to a transition from dislocation creep to diffusion creep (Karato and Wu, 1993, Science, 260, 771). This interpretation has been challenged by deformation data obtained at high pressure ($P > 3$ GPa) in the dislocation creep regime (Couvy et al., 2004, EJM, 16, 877; Raterron et al., 2007, Am. Miner., 92, 1436; Raterron et al., 2009, PEPI, 72, 74), which support a second interpretation: a transition in olivine dominant dislocation slip, from [100] slip at low P to [001] slip at high P (e.g., Mainprice et al., 2005, Nature, 433, 731). Such a P-induced [100]/[001] slip transition is also supported by recent theoretical studies based on first-principle calculations of olivine dislocation slips (Durinck et al., 2005, PCM, 32, 646; Durinck et al., 2007, Eur. J. Mineral., 19, 631).

In order to further constrain the effect of pressure on olivine slip system activities, deformation experiments were carried out in poor water condition at $P > 5$ GPa and T=1400°C, on pure forsterite (Fo100) and San Carlos olivine crystals, using the D-DIA at the X17B2 beamline of the NSLS (Upton, NY, USA). Crystals were oriented in order to active either [100] slip alone or [001] slip alone in (010) plane, or both [100](001) and [001](100) systems together. Constant applied stress $\sigma < 300$ MPa and specimen strain rates were monitored in situ using time-resolved X-ray diffraction and radiography, respectively. Run products were investigated by transmission electron microscopy (TEM) in order to verify the actual activation of the tested dislocation slip systems. The obtained data were compared with rheological data previously obtained at comparable T and σ conditions, but at room P (Darot and Gueguen, 1981, JGR, 86, 6219; Bai et al., 1991, JGR, 96, 2441), resulting in creep power laws which quantify the effect of P on olivine rheology. The new data confirm the occurrence of a P-induced [100]/[001] slip transition, and suggest that [001](010) system dominates olivine deformation in the deep upper mantle. Extrapolation of the obtained rheological laws to natural σ condition along upper-mantle geotherms, shows that the [100] / [001] slip transition should occur in the Earth at $\sim$ 200 km depth, thus can explain the attenuation of seismic anisotropy in the deep upper mantle. The obtained rheological laws were also integrated into a straightforward olivine aggregate model, then extrapolated to mantle condition using a 2-D geodynamic modeling application (Van den Berg et al., 1993, Geophys. J. International, 115, 62), which is the simplest approach to investigate upper-mantle steady-state deformation. In the application, the velocity of the lower boundary (the transition-zone boundary at 410-km depth) was set to 0, while that at the Earth's surface was set to 2 cm/year. Results from this modeling suggest that the combine activity of [100] and [001] slips in olivine aggregates may significantly decrease mantle viscosity below the oceanic lithosphere, thus, may contribute to the low viscosity zone (LVZ) required in plate tectonics to decouple rigid plates from the more ductile asthenophere underneath.