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Low-Temperature Deformation Mechanisms of Forsterite Aggregates and Implications for the Rheology of the Upper Mantle

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The uppermost lithospheric mantle can be subject to temperatures as low as 500°C. However, deforming mantle rocks experimentally at such low temperatures is a major challenge in rock physics since the strain rates needed to achieve steady-state dislocation creep at those temperatures are too low to be performed in the laboratory. Consequently, deformation experiments providing insights into the "cold" rheology of olivine have been performed at large stresses without achieving steady state and the strain rate dependence is difficult to assess. It is therefore crucial to identify possible deformation mechanisms at the lab by characterizing the samples post-mortem. This approach can, for instance, point out to certain dislocation slip systems in order to later implement them in numerical dislocation dynamics models.
In this regard, deformation experiments were carried out on forsterite aggregates using a gas-medium deformation apparatus (Paterson press) at 300 MPa, 900-1200°C and strain rates of ∼ 10–5 s–1. The starting material was a synthetic iron-free forsterite aggregate with an average grain size of ∼2.8 μm. The maximum stresses obtained range from ∼480 to 1800 MPa. Mechanical data show that forsterite aggregates have greater strengths than their iron-bearing olivine counterparts, with a maximum strength close to ∼1800 MPa at 900°C. Results show a transition from brittle to ductile deformation around 1000-1050°C. At high temperature (>1050°C), the temperature dependence of creep obtained here for forsterite is similar to the one of the iron-bearing counterpart reported in previous studies. Towards lower temperatures (≤1000°C), however, the strength of forsterite becomes greater than that of iron-bearing olivine.
At 1100-1200°C, where pseudo-steady state could be achieved, microstructures reflect creep by dislocation glide, resulting from the activation of several dislocation slip systems. Below 1000°C, in response to differential stresses largely exceeding the confining pressure, i.e. beyond the Goetze criterion, deformation is brittle. A form of grain boundary mediated creep is observed, with textures showing evidences of sliding and cavitation (gaping) at grain boundaries. Since grain boundary sliding is related here to large differential stresses and extensive cavitation, similar creep of olivine is therefore not expected to occur under regular upper mantle conditions, where lithostatic pressures consistently exceed differential stresses. However, around the brittle-ductile transition –here at 1050-1100°C, high resolution TEM images of grain boundaries suggest that grain boundary mediated plasticity results from complex interactions between grain boundaries, dislocations and possibly grain boundary diffusion.