

The effect of an equilibrated melt phase on the shear creep and attenuation behavior of polycrystalline olivine

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Abstract. The impact of a chemically and texturally equilibrated melt phase on the shear creep and attenuation behaviors of polycrystalline olivine has been measured experimentally at seismic-to-subseismic frequencies. The experiments were performed on aggregates that had a particularly uniform and fine grain size ($\sim 3 \mu\text{m}$). The effect of the melt phase ($\sim 5 \text{ vol}\%$) is to decrease the (Newtonian) viscosity by a factor of ~ 6 ; there is no dramatic disaggregation effect or melt-induced plummeting of the shear modulus. Both the melt-free and melt-bearing aggregates display an attenuation “band” of the form $Q_G^{-1} \propto f^{-0.4}$. This response cannot be attributed to a variation in microstructure; it is intrinsic to the diffusional creep behavior. There is no unique effect of the melt phase on the attenuation response: the slight increase in absorption of partial melt specimens is explained fully by the effect of the texturally equilibrated melt on aggregate viscosity.

Introduction and Experimental Approach

The presence of a melt phase is invoked frequently to account for the apparent mechanical weakness and the increased attenuation and reduced velocities of seismic waves under mid-ocean ridges and in the low velocity zone of the upper mantle. While the presence of basaltic melt below mid-ocean ridges is certainly beyond question, the exact impact of melting on the mechanical response(s) of mantle assemblages remains a question, and with it the interpretation of seismological data collected for the ridge environment and the mantle in general [e.g., Toomey *et al.*, 1998; Webb and Forsyth, 1998]. Required, then, is a physical understanding of the impact of partial melting on mechanical response. Both the mechanical and transport properties of partially molten, polycrystalline solids are dependent to first order on the spatial distribution of the liquid phase. At the scale of the grain size of the crystalline residuum, this spatial distribution is controlled by the relative energies of solid-liquid and solid-solid (grain and phase boundaries) interfaces. Commonly referred to as textural or microstructural (quasi)equilibrium, this spatial distribution of melt in upper-mantle assemblages has been studied extensively via experiments. There remain controversies, however. One particular issue—whether or not grain boundaries and/or phase boundaries are totally replaced by thin films of melt—has a very significant impact on the

understanding/interpretation of seismic data [cf. Vaughan *et al.*, 1982; Drury and Fitz Gerald, 1996]: a steady-state microstructure that includes “wetted” grain/phase boundaries could effect drastically the strength of the material as well as its capability of attenuating shear waves.

We report here on shear creep and attenuation measurements on very-fine-grained, polycrystalline aggregates of ferromagnesian olivine and olivine+melt. For the partial melt specimens, emphasis was placed on the achievement of textural equilibrium of the aggregates; thus the attenuation experiments probe a “steady-state” absorption response for shear waves as opposed to one associated with incipient melting. The frequencies explored in the attenuation experiments are in the seismic-to-subseismic range; thus these experiments fit into a family of studies seeking to integrate creep and attenuation responses at frequencies important in geophysics [e.g., Berckhemer *et al.*, 1982; Gueguen *et al.*, 1989; Tan *et al.*, 1997]. What is unique about the present experiments is that the materials are so fine-grained ($< 5 \mu\text{m}$) and the differential stresses employed in their fabrication and testing so low ($\leq 10 \text{ MPa}$) that there exists no lattice dislocations in the olivine [Gribb and Cooper, 1998b]; these experiments probe uniquely the creep and attenuation responses of the grain boundaries in both the nominally melt-free and melt-bearing aggregates.

Specimens were prepared by the uniaxial hot-pressing of pulverized Balsam Gap (North Carolina) dunite (Fo_{92} ; particle size significantly $< 1 \mu\text{m}$). The dunite contained $< 1 \text{ vol}\%$ each of talc and of Al-Cr spinel; in addition, x-ray fluorescence revealed the material contained (wt%) 0.1% MnO, 0.3% NiO and 0.6% CaO. Partial melt specimens involved first coating the olivine powder with an aluminosilicate glass via a sol-gel process [Cooper and Kohlstedt, 1984]. The melt phase had the composition (wt%) 42.7% SiO_2 , 15.1% Al_2O_3 , 6.7% MgO, 12.5% CaO, 11.7% FeO and 11.3% K_2O , which can be loosely described as a leucite-normative basanite. The K_2O added in excess, i.e., compared to a basalt analog, served (1) to lower the viscosity of the melt phase such that the compaction length [Richter and McKenzie, 1984] exceeded substantially the specimen size and (2) as a chemical marker of the melt phase (K^+ is incompatible in olivine). The melt was batched as $\sim 5 \text{ wt}\%$. Hot-pressing was done under vacuum conditions at 1300°C for 6 h and a (quasi)hydrostatic stress of 10 MPa [Gribb, 1998; Gribb and Cooper, 1998b].

The material that resulted from the processing, both the nominally melt-free (“MF”) and melt-bearing (“MB”) aggregates, had densities $\sim 99\%$ of the theoretical and a highly uniform grain size of $\sim 3 \mu\text{m}$ (MF: $2.8 \pm 0.4 \mu\text{m}$; MB: $2.8 \pm 0.2 \mu\text{m}$;

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