

# Low-frequency shear attenuation in polycrystalline olivine: Grain boundary diffusion and the physical significance of the Andrade model for viscoelastic rheology

Tye T. Gribb

Department of Materials Science and Engineering, University of Wisconsin–Madison

Reid F. Cooper

Department of Materials Science and Engineering and Department of Geology and Geophysics  
University of Wisconsin–Madison

**Abstract.** The high-temperature (1200–1285°C) torsional dynamic attenuation ( $10^{-3}$ – $10^0$  Hz) and unidirectional creep behavior of a fine, uniform grain sized ( $d \approx 3 \mu\text{m}$ ) olivine ( $\sim\text{Fo}_{92}$ ) aggregate have been measured. In all cases, the material is found to be mechanically linear (i.e.,  $\gamma(t)$ ,  $\dot{\gamma} \propto \sigma_{xy}^1$ ), indicating that diffusional processes dominate the deformation kinetics in these experiments. The creep response displays a large decelerating transient in the strain rate leading to a nominally constant “steady state.” The attenuation behavior displays a band in  $Q_G^{-1}$  that is moderately dependent on frequency ( $Q_G^{-1} \approx f^{-0.35}$ ) and temperature with  $-1.5 < \log(Q_G^{-1}) < 0.5$ . The creep and attenuation behaviors are accurately represented by a compliance function based on the Andrade model of viscoelasticity, which incorporates a power law description of anelastic strain (i.e.,  $\gamma_a \propto t^n$ , with  $n \approx 1/2$ ), and its Laplace transform, respectively. The uniformity of the material and the nature of its dynamic response allow the argument that the power law transient has a physical interpretation: because the attenuation band is not associated with a range of grain sizes or a distribution of lattice dislocations, the transient term describes the intrinsic transient in diffusional creep, which arises due to the evolution of tractions on the grain boundaries and is effected by chemical diffusion within a diminishing potential. Employing the rheological model of *Raj* [1975] for the intrinsic transient, we demonstrate that the “high-temperature background” absorption can be predicted from the creep response; a master curve description of the attenuation results. Comparison of these data to those of previous investigators, and contemplating their application to the upper mantle, raises the suggestion, explored in this paper, that the subgrain size may prove the critical microstructural variable effecting the broad attenuation band seen in all experiments as well as in the upper mantle.

## 1. Introduction

Of specific curiosity is that region of the upper mantle called the low-velocity zone (LVZ;  $\sim 40$ – $220$  km depth) that is characterized by the following features: (1) low seismic wave velocities ( $V_S$  reduced by as much as 10% [e.g., *Forsyth*, 1975]), (2) high attenuation of seismic waves (shear attenuation,  $Q_G^{-1}$  as high as 0.1 [e.g., *Chan et al.*, 1989]), (3) unusual  $Q_G^{-1}$  versus frequency dependence (an attenuation band representing a distribution of relaxation times with  $Q_G^{-1} \approx f^{-(0.15-0.4)}$  [e.g., *Andersen and Minster*, 1979; *Anderson and Given*, 1982; *Molodenskiy and Zharkov*, 1982]), and (4) anomalously high electrical conductivity. Several theories have been put forth to explain LVZ dynamics, including partial melting [cf. *Shimozuru*, 1963; *Anderson and Sammis*, 1970; *Solomon*, 1972] and dislocation mechanisms [cf. *Minster and Anderson*, 1981; *Karato and Spetzler*, 1990]. As direct probing of the asthenosphere is untenable, the elucidation of the mechanical properties of the upper mantle, and of operative attenuation/dispersion mechanisms, depends on laboratory studies.

In the present study, we report on the torsional creep and driven attenuation behavior of a fine-grained, dense olivine aggregate at high temperatures and seismic/subseismic frequencies. The material and experiments were designed specifically to isolate the contribution of grain boundaries to the dynamic response. From these data, and knowing the microstructure of the material, we argue that the description of the anelastic rheology of a Newtonian (linear) polycrystalline aggregate with an Andrade model (i.e.,  $\gamma_a \propto t^n$ , where  $\gamma_a$  is anelastic shear strain,  $t$  is time, and  $n \approx 1/2$ ) is rooted in the intrinsic response of all materials undergoing diffusional creep. The attenuation band that results and that matches well the band seen in seismic studies of the mantle is a result of a single loss mechanism, the chemical-diffusion-effected evolution of the traction on grain boundaries.

## 2. Experimental Approach

### 2.1. Material for Study

Both scientific and practical demands were placed on the material used in our experiments. Our scientific desire was to isolate the grain boundary relaxation effect in polycrystalline olivine and at the same time to minimize the impact of a broad range of grain sizes. Thus we were obligated to prepare materials with a grain

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