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The Importance of Grain Size to Mantle Dynamics and Seismological Observations: A Multidisciplinary Approach

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Dynamic models of Earth's convecting mantle usually implement flow laws with constant grain size, stress-independent viscosity and a limited treatment of variations associated with changes in mineral assemblage. These simplifications greatly reduce computational requirements but preclude effects such as shear localisation and transient changes in rheology associated with phase transitions, which have the potential to fundamentally change flow patterns in the mantle.

Here we use the finite-element code ASPECT [Bangerth et al., 2013] to model grain size evolution and the interplay between grain size, stress and strain rate in the convecting mantle. We include the simultaneous and competing effects of dynamic recrystallisation resulting from work done by dislocation creep, grain growth in multiphase assemblages and recrystallisation at phase transitions.

Grain size variations also affect seismic properties of mantle materials. We apply published formalisms [Jackson & Faul, 2010; McCarthy et al., 2011; Takei et al., 2014] to relate intrinsic variables (P, T, and grain size) from our numerical models to seismic velocity (Vs) and attenuation (Q). We investigate these formalisms for consistency with seismic observations at conditions beyond the range of the experiments upon which they are based; this requires constraining the range of pre-factors and activation volumes relevant for the lower mantle. Our calculations use thermodynamically self-consistent anharmonic elastic moduli determined for the mineral assemblages in the mantle using HeFESTo [Stixrude and Lithgow-Bertelloni, 2013]. We investigate the effect of realistically heterogeneous grain sizes by computing synthetic seismological data; these highlight the frequency-dependent sensitivity of seismic waves to grain size, which is important when interpreting Vs and Q observations in terms of mineral assemblage and temperature.

Our models show that grain size evolution can lead to lateral viscosity variations of six orders of magnitude due to grain size alone, in addition to the effects of temperature and strain rate. In mantle plumes, grain size reduction, caused by strain localisation at their edges, competes with fast grain growth due to high plume temperatures. As a result, the viscosity in the center of plumes reaches similar values as in the surrounding mantle, while it decreases more than an order of magnitude towards their margins. Similarly, low viscosities at the edges of slabs favor bending over thickening as mode of deformation.

Benchmarking our dynamic models against seismic observations will involve further adjustments to the grain size evolution in the lower mantle as well as the tuning of these constitutive relationships. The very slow grain growth in the lower mantle predicted by some high pressure experiments [Yamazaki et al., 1996] would produce unrealistically large attenuation in the lower mantle. We therefore explore models that include faster grain growth. A change in physical parameters such as activation volume is required across the 660 km discontinuity to match the higher Q observed seismically in the lower mantle. Dynamic recrystallisation and slow grain growth in subducting slabs results in lower seismic velocities and Q than would be predicted from purely thermal models. Negative feedbacks between thermal controls on anharmonic and (through grain size) anelastic velocity variations mean that simple mapping of tomographic velocities to temperatures may systematically underestimate true thermal anomalies.