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Grain size evolution in the mantle and its effect on geodynamics, seismic velocities and attenuation

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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 use several published formulations to relate intrinsic variables (P, T, and grain size) from our numerical models to seismic velocity (Vs) and attenuation (Q). 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 body wave travel times, ray paths, and attenuation (t*) at different frequencies. We 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 rapid metamorphic reactions in mantle upwellings and downwellings lead to high lateral viscosity contrasts, as a result of gradual grain size evolution. Positive feedback between grain size reduction and viscosity reduction results in shear localisation. As a result, the edges of thermal plumes have smaller grain sizes and lower viscosities than their cores. Dynamic recrystallisation in subducting slabs results in lower seismic velocities and Q than would be predicted from purely thermal models. 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. The very slow grain growth in the lower mantle predicted by high pressure experiments produces unrealistically large travel time delays (>20 s) and t* values (>4 s) in our synthetic calculations with our current constitutive relationships for deriving Vs and Q. 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.