A Dynamical Model for Generating Sharp Seismic Velocity Contrasts Underneath Continents: Application to the Sorgenfrei-Tornquist Zone

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Global and regional seismic tomographic models consistently show significant variability in P- and S-wave velocity at all depths and especially in the uppermost mantle. Mineral physics experiments and thermodynamic calculations indicate that the variability in the mantle above the transition zone must be mostly due to temperature. Differences in composition (for likely mantle materials) can only account for seismic velocity perturbations of about 1%. While large temperature differences are expected in dynamically active regions such as subduction zones, mid-ocean ridges, rifts, and mantle plumes, variations in seismic wave speed of the same magnitude are commonly found also in tectonically quiet regions.

We present seismic velocity models of the Sorgenfrei-Tornquist Zone (between Denmark and Sweden) based on teleseismic traveltime tomography. Between 100 and 250 km depth, the models show a sharp lithospheric boundary with P-waves about 4% faster and S-waves 6% faster within the cratonic lithosphere to the north. The standard, static type of lithospheric temperature and heat flow modeling cannot account for such seismic velocity differences because the last major tectonic event was at least 200 Myrs ago and heat diffusion over this timescale would have largely equilibrated any initial temperature contrast. In order to explain the observations, we propose a dynamical model of convection in the upper mantle that is consistent with rheological data and that satisfies the seismic observations by maintaining an abrupt lateral temperature contrast over 100s of Myrs. A step-like increase in lithospheric thickness from 100 to 250 km is assumed to have formed in a Triassic rifting event at the Sorgenfrei-Tornquist Zone (around 220 Ma) and is subsequently exposed to active convection below. A lithosphere that is distinct from the mantle in terms of temperature and composition remains stable against convective erosion. Heat advection to different depth beneath the thin and the thick lithosphere leads to a maximum horizontal contrast of 500°C at 150 km depth over a lateral transition distance of 100 km, sufficient to generate 5% and 8% in maximum P- and S-wave velocity perturbation, respectively. A purely conductive model under the same conditions yields only $\Delta v_p \approx 1\%$ and $\Delta v_s \approx 2\%$, while a lithospheric evolution simulation without a compositional effect on the rheology leads to significant thermo-mechanical erosion of the lithosphere giving $\Delta v_p \approx 2\%$ and $\Delta v_s \approx 4\%$.

In our study, we use the Sorgenfrei-Tornquist Zone as an example because of the high-resolution seismic data available. The results are of course applicable to other regions as well where lateral differences in compositional lithospheric thickness allow mantle convection to reach different depth levels. However, while our model provides a plausible explanation for horizontal variations in seismic velocity at the lithosphere-asthenosphere interface, significant velocity variability extends much deeper. Lateral temperature differences of several hundred degrees within the convecting mantle (away from subduction zones) are difficult to reconcile with most models of mantle convection. More work is required to bring convection models and mantle tomography into agreement.