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Reconciling Observations and Predictions of Earth's Dynamic Topography

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While the bulk of topography on Earth is generated and maintained by variations in the thickness and density of crust and lithosphere, a significant time-variable contribution is expected to result from convective flow in the underlying mantle. For over three decades, this dynamic topography has been calculated numerically from inferred density structure and radial viscosity profiles. These models predict ± 2 km of long wavelength (i.e., $\sim$ 20,000 km) dynamic topography with minor contributions at wavelengths shorter than $\sim$ 5,000 km. Recently, observation-based studies have revealed that, at the longest wavelengths, dynamic topography variation is approximately half that predicted, with ± 1 km amplitudes recovered at shorter wavelengths. This significant discrepancy between predictions and observations suggests that current knowledge of our planet's internal structure is incomplete. However, if Earth models can be found that are compatible with these new constraints, a significantly improved understanding of mantle dynamics is within reach.

Most numerical models excise the upper $\sim$ 300 km of Earth's mantle and are thus unable to reconstruct the short wavelength and fast rates of vertical motion observed in many locations. However, residual depth observations strongly anticorrelate with asthenospheric shear wave velocity anomalies suggesting a close link between surface deflections and density anomalies immediately beneath the lithosphere. Through conversion of upper mantle shear wave velocities to temperature and density using a calibrated anelasticity parameterization, we show that observed shorter wavelength (i.e., $\leq$ 5,000 km) dynamic topography is largely generated by ± 150 °C temperature anomalies in a low-viscosity asthenospheric channel. Inclusion of this anelastically-corrected density structure in whole-mantle instantaneous flow models also reduces long wavelength discrepancy between predictions and observations of dynamic topography. Residual mismatch is further reduced if the basal 300 km of large low shear wave velocity regions in the deep mantle are assumed to be basaltic in composition and therefore negatively buoyant. Importantly, these thermochemical models of mantle convection simultaneously improve fit to core-mantle boundary topography and the geoid, contradicting previous studies that suggest modest long wavelength dynamic topography cannot be reconciled with geoid observations using physically reasonable Earth models. This work provides strong evidence for large basaltic regions in the deepest mantle, corroborating recent results from inverse modelling of body tides, normal modes and seismic velocities.