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Finite-frequency tomography, mantle plumes, and the terrestrial heat budget (Beno Gutenberg Medal Lecture)

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Classical seismic tomography has made very fruitful use of ray theory to map differences in the propagation velocities of seismic waves for length scales larger than the Fresnel zone. These zones are of the order of 1000 km in the lower mantle for long-period waves. Delays of such waves can now be measured very precisely by cross-correlation of waveforms observed with the ever increasing global network of very high quality broadband sensors, and the limitations to resolvable length scales imposed by ray theory have become palpable. Finite-frequency theory corrects to first order for the shortcomings of the ray approximation. The theory is counter-intuitive: it predicts, for example, that P wave travel times are insensitive to anomalies located on the raypath, and most sensitive when placed about halfway the width of the Fresnel zone. Some aspects of the theory have given rise to more or less heated debates among seismic tomographers.

As with many new developments, the proof of the pudding is in the eating. The first application of the new theory to short-period and long-period P wave delays led serendipitously to the discovery of more than a dozen plume-like anomalies stretching the full length of the lower mantle. Most of these are below known hotspots, but two plumes feeding the North Atlantic ridge at 20N and the Indian ridge at 100E were not known, and several 'starting plumes' have only risen to mid-mantle depth. These findings have recently been confirmed with long-period S waves.

For a number of cross-sections in the lower mantle we consider the resolution of the P velocity anomaly model good enough to try infer temperature anomalies from the seismic anomalies, and to estimate plume flux using a simple force-balance principle and Stokes' equation. At mid-mantle depth most inferred temperature anomalies are

200-250K at the center of the plume, rising to 300K near 2000 km depth. Heat flux calculations lead to estimates that are up to ten times as large as earlier estimates from surface buoyancy flux observations, depending on the value adopted for the viscosity. Possible explanations for this mismatch are the neglect of iron enrichment with its negative chemical buoyancy, or a decoupling of vertical flow between lower mantle and the surface. The latter would imply that the tomography estimates are basically correct and that plumes play a much larger role in cooling the Earth than is usually assumed.

The flux estimates derived from seismic tomography become unacceptably large as the plume widens below the 670 km discontinuity, a sign that vertical flow resistance below 670 km depth invalidates the simple Stokes' law approximation. This resistance would be similar in nature to that experienced by sinking slabs, which had already been observed by seismic tomography. These findings lead to the postulate that the phase transition at 670 km is a large enough barrier to vertical flow that it inhibits small, random transgressions of material. Mass exchange between lower and upper mantle is restricted to 'breakthrough' events, mass fluxes for slabs and plumes accross the 670 km discontinuity are on the long term equal, and mass exchange between upper and lower mantle does not exceed the 10^{15} kg per year that is subducted.