Constraints On Global Mantle-Flow Models From Geophysical Data

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The flow in the Earth's mantle is usually studied via the numerical solution of the partial- differential equations that govern thermal convection. This approach allows the study of first-order effects such as the role of phase transitions, generation of lithospheric plates and chemical mixing, in a self-consistent manner by forward modeling. In this lecture, we will discuss another possible approach in investigating mantle convection, based on inverse modeling. This method employs available geophysical and geological data to determine the most probable values for the parameters that are included in the mantle-flow equations, and which are independent of mineral-physics experiments. During the last twenty years, most attention has been paid to determining the viscosity structure of the mantle from gravitational data (non-hydrostatic geoid and free-air gravity) and models of seismic-velocity anomalies provided by seismic tomography. These inversions, known as the "inferences of viscosity from the geoid", have led to the robust conclusion that viscosity increases with depth by 1-2 orders of magnitude. The successful prediction of the geoid, however, has raised new questions concerning the style of mantle flow. The best fit to the data has been obtained for whole-mantle flow models with a free-slip surface-boundary condition and a relatively weak lithosphere. Such a model, however, is not fully consistent with the observed velocities of plate motion, gives too-large strain rates in the lithosphere and usually also predicts excessive amplitudes of the long-wavelength dynamic topography. These points are better satisfied by layered- flow models and/or the whole-mantle flow model with imposed plate velocities that, nonetheless, fail to predict the observed gravitational signal. This apparent paradox can be reconciled by introducing a new formal parameter characterizing the partial layering of mantle flow. We discuss definitions of partial layering used by different authors, and demonstrate that the basic data are best satisfied by a mantle-flow model with imposed plate velocities in which the vertical velocity at the 660-km depth is reduced by 65% in comparison with the whole-mantle flow model.

Another issue that has been discussed in recent years is the effect of lateral-viscosity variations. This issue was not considered in the first generation of mantle-flow models, and their effect on the geoid was assumed to be of a second-order nature in comparison with radial changes in viscosity. We analyze the effect of lateral-viscosity variations on predictions of the geoid and other data, and show that small-scale lateral-viscosity variations, related to slabs and plumes, are significantly less important for predicting long-wavelength gravitational data than large-scale viscosity anomalies that are likely to exist in the boundary layers of the mantle. We present a model of lateral-viscosity variations in the asthenosphere, reflecting the viscosity contrast between continental roots and the low-viscosity zone beneath young oceans (Cadek and Fleitout, GJI 2003).

This model can significantly improve the prediction of the geoid and free-air gravity data, provided the viscosity beneath young oceans is of a value of 10^{18}-10^{19} Pa.s, thus by 2-3 orders of magnitude lower than beneath continents. The model predicts the dynamic topography with a significant degree-1 pattern, showing a maximum long-wavelength elevation located in South-east Asia. The feasibility of such a pattern is discussed. The lateral- viscosity variations in the asthenosphere significantly influence the flow-velocity field in the uppermost few hundred kilometers of the mantle. The predicted velocity field can be compared with observed 'fast' directions of seismic anisotropy, representing an integrated record of mantle flow (Kaminski et al., GJI 2004). By comparing our predictions of seismic anisotropy with those recently published by Becker et al. (GJI 2003), we find that models with partial layering and strong lateral- viscosity variations in the asthenosphere predict the observed anisotropy somewhat worse than whole- mantle flow models without lateral-viscosity variations. Another problem in predicting seismic anisotropy is that the predicted anisotropy is significantly larger than that observed, suggesting the importance of composite rheology and/or small-scale convection in the upper mantle. The difficulties in explaining the observed pattern of seismic anisotropy indicate that, despite the significant progress made over the last decade, mantle-flow models obtained from the inversion of geophysical data are still far from perfect, and require a great deal of future development.