AN INVERSION OF GEOID AND TOPOGRAPHY FOR MANTLE AND CRUSTAL STRUCTURE ON MARS

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Mars has the largest amplitude geoid anomalies and surface topography known on the terrestrial planets. A number of prior studies have analyzed Martian gravity anomalies and topography in terms of isostasy and flexure of the crust and lithosphere [e.g., 1, 2]. Other studies have emphasized the role of mantle convection in producing gravity anomalies and topography in some regions of Mars [3, 4]. In this study, we invert geoid and topography observations for simultaneous estimates of density anomalies in the crust and mantle of Mars. In performing this study, we make use of a recent degree 50 spherical harmonic expansion of the Martian gravity field (GMM-1) [5] and a corresponding resolution expansion of the USGS Mars topography model [6]. However, our analysis is restricted to harmonic degrees up to $L=25$, which are better determined than the higher harmonics. This provides a half-wavelength horizontal resolution of 425 km.

If density anomalies are allowed to exist at two different depths, it is always possible to solve for densities which exactly (but non-uniquely) reproduce the observed geoid and topography. Calculations of this sort were performed in several recent studies of Venus [7-9] on either a global or regional basis. In those studies, the density anomalies in the uppermost layer were interpreted as crustal thickness variations and the density anomalies in the lower layer were interpreted as due to mantle temperature variations. Our approach to the problem most closely resembles the global Venus model of Herrick and Phillips [7], although our model parameterization is somewhat different than theirs. In particular, we assume that density anomalies are distributed vertically throughout the mantle, whereas Herrick and Phillips [7] considered loading at a single interface in the mantle. It is important to allow for vertically distributed density anomalies, because different harmonic degrees are most sensitive to loading at different depths [10]. With only gravity and topography data as constraints, it is only possible to estimate two density contrasts at each spherical harmonic coefficient. However, it is possible to assume a functional form for the radial distribution of the density anomalies and simply solve for a multiplicative scaling factor. As a first approximation, we assume that the density anomalies in the mantle outside the thermal boundary layers are uniformly distributed with depth. This is a reasonable approximation of features such as mantle plumes, but it undoubtedly oversimplifies the details of the density distribution. Our results should therefore be regarded as an estimate of the vertically averaged mantle structure. We convolve this density distribution with response functions for a Newtonian viscous mantle [10] to estimate the geoid and topography produced by mantle convection.

Because the distribution of density anomalies as a function of wavelength is different in the thermal boundary layer than it is in the non-boundary layer part of the mantle [11], we parameterize the boundary layer separately from the rest of the mantle. The treatment of the lower thermal boundary layer is unimportant, because both the geoid and topography response functions go to zero at the base of the mantle [10]. At the long wavelengths considered here, the geoid and topography produced by viscous flow in the upper thermal boundary layer approaches that predicted by Pratt isostasy. Presuming that crustal thickness variations are also isostatically compensated, we are unable to distinguish the effects of thermal boundary layer structure from crustal structure. We therefore combine both effects into our parameterization of the upper density layer. The effects of lithospheric flexure are not included in our calculations.

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Model results are sensitive to a number of poorly constrained parameters, particularly the thickness of the mantle and the variation of viscosity with depth in the mantle. A broad range of structural models have been proposed for the interior of Mars [12], with mantle thicknesses ranging between about 925 and 1850 km. We consider these as limiting cases and also consider an intermediate model with a mantle depth of 1550 km. The intermediate case has a ratio of core radius to planetary radius which is the same as the earth. For viscosity models, we are guided by recent estimates of the viscosity stratification in the mantles of Earth and Venus [13, 14]. Because the pressure at the base of the Martian mantle is comparable to the pressure at the base of the upper mantle on Earth and Venus, we consider only the upper mantle portions of those viscosity models. We therefore consider an isoviscous mantle and a mantle with a factor of 30 increase in viscosity at the mid-depth of the mantle. Both models include a high viscosity layer in the upper 150 km to represent the thermal boundary layer.

For an isoviscous mantle and an intermediate size core, our results indicate pronounced hot upwellings beneath Tharsis and Elysium (temperature several hundred K higher than average), along with moderate crustal thinning. Substantial crustal thinning is predicted beneath the Hellas and Isidis impact basins. Lesser amounts of crustal thinning are required beneath the Argyre, Chryse, and Utopia basins. In the spectral domain, the deeper density layer dominates the observed geoid power at all modeled wavelengths, although the shallow layer becomes increasingly important at shorter wavelengths. Except for the lowest harmonic degrees, the shallow density anomaly typically supports 50 to 70% of the observed topography power. Changing the mantle viscosity profile or the size of the core does not substantially alter the predicted spatial patterns but does alter the required density amplitudes. Decreasing the core size slightly decreases the required range of thermal anomalies and crustal thicknesses. Including a low viscosity upper mantle significantly increases the required range of thermal variations and also requires considerable crustal thinning beneath Tharsis.

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