EPSC Abstracts
Vol. 9, EPSC2014-738, 2014
European Planetary Science Congress 2014

Thickness of the crust of Mercury from geoid-to-topography ratios

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Abstract

From the gravity and topography fields of Mercury determined by the MESSENGER spacecraft, we calculate geoid-to-topography ratios (GTRs) as a means to constrain the average thickness of Mercury's crust. We assume Airy isostasy and exclude regions that might not satisfy this assumption, such as smooth plains and large impact basins. We limit our analysis to spherical harmonic degree $n \geq 5$, since lower degrees might be affected by other processes. In the analyzed regions we find that the GTR is 20±4 m/km (1-σ). For an assumed crustal density of 2900 kg m^{-3}, we infer an average crustal thickness of 79±20 km.

1. Introduction

Knowledge of the thickness of a planet's crust places important constraints on the origin, differentiation, and subsequent geologic evolution of that body. Prior to the MESSENGER mission, constraints on the thickness of Mercury's crust were inferred from the viscous relaxation of topography [<200 km; 6], the relationship between equatorial ellipticity and the low-degree gravity field [100-300 km; 1], and the depth of the brittle-ductile transition as constrained by models of thrust faults and thermal evolution [<140 km; 7].

The analysis of geoid-to-topography ratios (GTRs) has proven fruitful for the characterization of crustal thickness for the Moon, Mars, and Venus [9,10,4]. Here we perform a similar analysis for Mercury using the spherical harmonic expansion of the gravitational potential and topography as determined from measurements by the MESSENGER spacecraft. Constraining the thickness of the crust of Mercury will inform models for the formation and evolution of the crust, planetary thermal history, mantle convection, and planetary bulk composition.

2. Methods

The GTR can be expressed as [9]

$$\mathrm{GTR} = \sum_{\mathrm{n}} W_{\mathrm{n}} Z_{\mathrm{n}},$$

where W_{n} is a weighting function that depends on the measured topographic power at degree n, and Z_{n} is a degree-dependent admittance function that relates the geoid harmonic coefficients N_{nm} to the topography harmonic coefficients h_{nm}:

$$N_{\mathrm{nm}} = Z_{\mathrm{n}} h_{\mathrm{nm}}.$$

The explicit expression for Z_{n} depends on the assumed isostatic compensation model. For Airy isostasy

$$Z_{\mathrm{n}} = \frac{3}{2n+1}\frac{\rho_{\mathrm{c}}}{\rho}\left[1-\left(\frac{R-H}{R}\right)^{\mathrm{n}}\right],$$

where ρ_{c} and ρ are the density of the crust and the mean density of the planet, respectively, R is the mean planetary radius, and H is the thickness of the crust. Under the assumption of a given compensation mechanism, measurements of the GTR can be inverted for crustal thickness H.

3. Data

To perform our analysis we utilized the most recent spherical harmonic expansions of the gravitational potential and surface topography of Mercury derived from MESSENGER data and available from the Planetary Data System. The gravitational potential model (GGMES50v05), which is complete to degree and order 50, was employed and the topography model (GTMES120v02) was expanded to the same resolution. Because of the highly eccentric orbit of the MESSENGER spacecraft, the quality of both data sets is latitude dependent, with the northern hemisphere better constrained than the southern hemisphere.

Large areas of the surface of Mercury's northern hemisphere have been resurfaced by smooth plains, the majority of which are thought to be volcanic in origin [2]. If these lavas erupted when the lithosphere was sufficiently thick to support loading by plains emplacement, these regions would not satisfy our assumption of local isostasy. Large impact basins (e.g., Caloris) are also not expected to be in an isostatic state [e.g., 5].

We limit our analysis to the northern hemisphere of Mercury, where the gravity and topography are well constrained, and we exclude those regions covered by smooth plains [2] or large impact basins [3].

4. Results and Conclusions

GTRs were calculated by regressing the geoid and topography located within a circle of diameter 1500 km. To account for long-wavelength geoid signals that could be related to regional variations in crustal density or convection in the mantle, we also solved for a constant geoid offset of each region. Spherical harmonic degrees greater than or equal to 5 were used when calculating the geoid and topography, as lower degrees might have contributions from processes associated with tides, rotation, and lateral variations in crustal temperature.

In the areas analyzed, we find that the GTR has a value of 20±4 m/km. This value is insensitive to the high-pass filter applied to the geoid and topography (from $n \geq 5$ to $n \geq 6$), as well as the radius r used when regressing the two data sets (from r=1250 to 2000 km). For a crustal density of ρ_c=2900 kg/m^3, and under the assumption of Airy isostasy, this range corresponds to an average crustal thickness of 79±20 km. This range is somewhat larger than the mean thickness of 50 km adopted for a recent crustal model [8], but is consistent with the upper limits from earlier analyses [6,7].

Acknowledgements

We thank all of the individuals who designed and operated the MESSENGER spacecraft. We thank Brett Denevi for providing the locations of smooth plains, and Erwan Mazarico for sharing the latest version of Mercury's gravity field.

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