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# A thin, dense crust for Mercury

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ABSTRACT

Crustal thickness is a crucial geophysical parameter in understanding the geology and geochemistry of terrestrial planets. Recent development of mathematical techniques suggests that previous studies based on assumptions of isostasy overestimated crustal thickness on some of the solid bodies of the solar system, leading to a need to revisit those analyses. Here, I apply these techniques to Mercury. Using MESSENGER-derived elemental abundances, I calculate a map of grain density (average 2974 ± 89 kg/m$^3$) which shows that Pratt isostasy is unlikely to be a major compensation mechanism of Mercury's topography. Assuming Airy isostasy, I find the best fit value for Mercury's mean crustal thickness is 26 ± 11 km, 25% lower than the most recently reported and previously thinnest number. Several geological implications follow from this relatively low value for crustal thickness, including showing that the largest impacts very likely excavated mantle material onto Mercury's surface. The new results also show that Mercury and the Moon have a similar proportion of their rocky silicates composing their crusts, and thus Mercury is not uniquely efficient at crustal production amongst terrestrial bodies. Higher resolution topography and gravity data, especially for the southern hemisphere, will be necessary to refine Mercury's crustal parameters further.



## 1. Introduction

A planet's crustal thickness is a critical piece of geophysical information for a variety of geological investigations. On Mercury, a number of estimates for crustal thickness have been proposed. Analysis of Earth-based radar imaging and gravity coefficients obtained from the Mariner 10 spacecraft implied a crust 100–300 km thick (Anderson et al., 1996). This range now seems implausible on the basis of Mercury's interior structure (Smith et al., 2012), and is likely too high because the analysis assumed Mercury's degree-2 topography is isostatically compensated. Later work argued that Mercury's crustal thickness must be <200 km in order for observed topography to survive over long geologic timescales (Nimmo, 2002). This upper bound was subsequently revised to 140 km to satisfy observed faulting depths (Nimmo and Watters, 2004).

The Mercury Surface, Space Environment, Geochemistry, and Ranging (MESSENGER) spacecraft collected a wealth of observations to study the planet's crust (Solomon et al., 2001). In particular, gravity data from radio tracking (Smith et al., 2012) and topography data from the Mercury Laser Altimeter (MLA) (Zuber et al., 2012), while effectively confined to the northern hemisphere because of MESSENGER's highly elliptical orbit, allowed better estimates of Mercury's crustal thickness than ever before. These data were combined to produce a relative crustal thickness map in Mercury's northern hemisphere (Smith et al., 2010, 2012), subsequently updated with newer MESSENGER data (Mazarico et al., 2014; James et al., 2015), but these maps assumed semi-arbitrary mean crustal thickness values of 50 km and 40 km, respectively, in order to display absolute values of thickness.

Absolute values of Mercury's crustal thickness were explicitly estimated using geoid-topography ratios (GTRs) (Padovan et al., 2015). Localized GTRs can be used to study a crust's compensation state, thickness, and density using admittance, the transfer function between gravity and topography (Wieczorek and Phillips, 1997). This technique has previously been used to study crustal structure on the Moon (Wieczorek and Phillips, 1997; Wieczorek et al., 2006; Sori et al., 2018) and other planets (e.g., James et al., 2013). For Mercury, Padovan et al. (2015) performed linear regression between geoid and elevation in spatially localized windows to infer an average GTR of ∼9 m/km. This analysis excluded volcanic plains, large impact structures, and the southern hemisphere. Interpreting this GTR value using spectrally-weighted admittances, the authors assumed topography was predominantly compensated locally by Airy isostasy to conclude an average crustal thickness of 35 ± 18 km.

In creating models of isostatic support to interpret the observed GTRs, Padovan et al. (2015) assumed a classical formulation of Airy isostasy, where columns contain equal masses. Although the

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admittances predicted for this model of isostasy can account for spherical geometry of a planet (Wieczorek and Phillips, 1997), the model still only applies to the Cartesian limit because it does not minimize deviatoric stress (Dahlen, 1982; Beuthe et al., 2016) or lateral flow at depth (Hemingway and Matsuyama, 2017). An alternate approach is to produce equal pressures at equipotential surfaces at depth (Turcotte et al., 1981; Hemingway and Matsuyama, 2017). The "equal masses" approach underestimates admittances, and therefore overestimates compensation depth, compared to this "equal pressures" approach. This difference in resulting compensation depth scales with increasing crustal thickness and decreasing planetary radius; the equal masses approach is valid for cases where the crustal thickness is very small compared to the planetary radius. Hemingway and Matsuyama (2017) quantified this discrepancy for different bodies: for Earth it is negligible, for the Moon's highlands it is 27%, and for Enceladus it is a factor of $\sim$2. Beuthe et al. (2016) also studied Enceladus, formulating isostasy by minimizing deviatoric stress in the icy shell, and similarly found a discrepancy of a factor of $\sim$2 compared to the equal masses approach. The discrepancy has not been quantified for Mercury. It is important to note that the above formulations consider fully isostatic support, and should only be applied to cases where there is evidence that isostasy is the dominant mechanism of compensation (e.g., the regions of Mercury interpreted by Padovan et al., 2015). If flexural support of topography is significant, the effects of the lithosphere must be considered (e.g., Turcotte et al., 1981).

In this paper, I improve analysis of Mercury's crust in two ways. First, I quantitatively assess the possibility of Pratt isostasy by searching for a characteristic negative relationship between crustal density and elevation (Solomon, 1978). To do this, I calculate a map of grain density using normative minerology and MESSENGER-derived elemental abundances (Weider et al., 2012). Second, I use the equal pressures approach to model GTRs for various compensation models and compare them to the 9 m/km value observed in a previous study (Padovan et al., 2015). The result is a new estimate of Mercury's crustal thickness. I compare my results to those from previous studies and discuss the geological implications of any discrepancies.

## 2. Grain density and Pratt isostasy

Topography is often compensated, which is evidenced on Mercury (Smith et al., 2012). For long-wavelength topography formed early in planetary evolution, isostatic support, rather than flexural support, is likely. Many studies assume an Airy mechanism of support, in which surface relief is compensated by variations in thickness of a compositional layer (usually the crust, with subsurface-relief at the crust-mantle interface). However, a Pratt mechanism, in which compensation is a result of lateral density variations, is also possible and can be tested. Airy and Pratt mechanisms arise under different conditions and identification of which mechanism is at play can thus elucidate geologic history. A Pratt mechanism can be detected by establishing a negative correlation between crustal density and elevation, as was searched for on the Moon (Solomon, 1978; Sori et al., 2018).

I searched for the negative correlation between density and elevation characteristic of Pratt isostasy on Mercury. Elevation data come from a global digital elevation model (Becker et al., 2016) derived from stereo image observations from the Mercury Dual Imaging System (MDIS), a MESSENGER instrument (Hawkins et al., 2007). Density is not directly measured and must be inferred from other datasets. Crustal bulk density (and therefore also porosity) is not possible to reliably infer from current gravity data; the best available gravity field is expanded to degree and order 50 (Mazarico et al., 2014). Calculation of crustal bulk density on the Moon, for example, used degrees >150 (Wieczorek et al., 2013). Instead, grain density is used. The grain density $\rho_g$ is related to the bulk density $\rho_b$ and the porosity $\phi$ by the equation

$$\rho_b = (1-\phi)\rho_g. \tag{1}$$

Because the distribution of porosity in Mercury's crust is unknown, the grain density estimated here cannot be directly converted into a bulk density. Nonetheless, for the purposes of searching for a negative correlation between density and elevation, grain density may be used as a proxy for bulk density if porosity is assumed to not strongly correlate with topography. As described below, large impact basins are excluded from analysis (where lateral variations in crustal porosity may correlate with topography over large length scales, Wieczorek et al., 2013), and such an assumption is likely valid for this analysis.

To calculate grain density, I analyzed surface composition measurements collected from MESSENGER's X-Ray Spectrometer (XRS). Previous analysis reported the abundances of Mg, S, Ca, and Al relative to Si at 205 locations on Mercury's surface (Weider et al., 2012). An estimate of grain density can be inferred from these chemical abundances using normative mineralogy. XRS measurements (Nittler et al., 2011) only sample the composition of the upper $\sim$100 microns of regolith, although their general agreement with MESSENGER's Gamma-Ray Spectrometer (GRS) measurements imply those results apply to depths of at least 10 s of cm (Evans et al., 2012). This restriction necessitates an assumption for this work that surface composition is representative of underlying crustal columns. Such a constraint is not ideal, and will require the exclusion of some regions from the density-elevation analysis. It is also stressed that normative mineralogy only represents an estimate of composition. However, in the absence of high-resolution gravity data from which bulk density can be derived or samples from which composition can be directly studied, normative mineralogy represents the best currently available observational estimate of crustal density.

The XRS measurements are supplemented with constraints on abundances of other elements from GRS analyses. Relative abundances of Na have been mapped and found to have a latitudinal trend (Peplowski et al., 2014). I assign a relative Na abundance to each of the 205 locations corresponding to the XRS measurements based on their latitudes. The Na abundance measurements only exist in the northern hemisphere; for the 19 XRS measurements in southern latitudes, I used the measured Na abundance of the corresponding northern latitude. Peplowski et al. (2014) presented a forward model where Na varies as a function of geochemical terrane that is consistent with GRS observations, but I chose to only use the direct observations of Na abundance in order to minimize the number of assumptions made in this analysis.

Other relevant elements are also constrained by GRS and Neutron Spectrometer (NS) analyses. In particular, abundances of Si, Mn, K, Ti, Cr, and Fe have been presented for different geochemical terranes (Peplowski et al., 2015). For each of the 205 XRS measurements of Mg, S, Ca, and Al abundances, I assign an abundance of Si, Mn, K, Ti, Cr, and Fe according to the geochemical terrane that is mapped at the center of XRS measurement. While it would be ideal to have a high-resolution map of the abundances of all elements, Mg is mapped and is the element that is most variable across Mercury's surface (e.g., Vander Kaaden et al., 2017), and Mn, K, Ti, and Cr are sufficiently low in abundance such that they should not have large effects on density estimates.

Using normative mineralogy (Johannsen, 1931), I estimated grain density at each of the 205 locations of chemical abundance measurements of Mg, S, Ca, and Al (Weider et al., 2012) assuming abundances of other elements according to their latitude and