Is There a Crustal Thickness Dichotomy on Mars? L. Ojha[1], E. Mazarico[2], S. Goossens[2]. [1]Department of Earth and Planetary Sciences, Rutgers, The State University of New Jersey (luju.ojha@rutgers.edu). [2]NASA Goddard.

Introduction: A fundamental question regarding the Martian topographic dichotomy is whether the surficial manifestation of the dichotomy is also reflected in the internal structure of Mars. In the last few decades, crustal thickness dichotomy has been proposed as a fundamental feature of Mars [e.g., 1], however, is there really an unambiguous evidence for it? A variety of crustal thickness models have been constructed using the available Martian gravity data. An explicit assumption in these crustal thickness models of Mars is that the density of the Martian crust is either constant or that they do not significantly vary laterally [e.g., 2,3]. With this assumption, crustal thickness models are derived by assuming that the lateral heterogeneities in Bouguer anomaly are entirely due to differences in crustal thickness [e.g., 4].

One of the first crustal thickness models of Mars that was derived using this assumption was presented in Zuber et al. [2000]. The model of Zuber et al [2000], assuming a constant crustal density of 2900 kg m^{-3}, varied from a minimum of 3 km to a maximum of 92 km thickness, with the northern lowlands characterized by a relatively uniform 35-km thick crust. However, Zuber et al [2000] did acknowledge an alternative interpretation to a constant crustal density, that compensation could occur by a spatial variation in crustal density (i.e., Pratt Compensation). This alternative interpretation has however been largely ignored and the idea of a crustal thickness dichotomy has largely been accepted in the Mars science community.

Another key line of evidence presented in support of the crustal thickness dichotomy is the ~3.1 km center-of-mass/center-of-figure offset of the planet suggesting a planetwide distribution of mass [e.g., 5]. Previously, it has been posited that a northern lowland denser by ~200 kg m^{-3} can explain the ~3.1 km center-of-mass/center-of-figure offset of the planet **[6]**. Summarily, the evidence presented in support of the crustal thickness dichotomy could equally be explained by a Pratt-like compensation mechanism.

More recently, spectral and gravity investigation of Mars have shown that the composition and density of the Martian crust does vary significantly [7]. Lower crustal densities for Mars have been advocated for several areas on Mars on the basis of gravity data [e.g., 7]. On the other hand, volcanic complexes on Mars such as the Tharsis province are found to have higher densities [6-8] and known observations from wide-spread Martian meteorites and petrological modeling from gamma ray data also favor higher densities [9], indicating that strong lateral density variations are likely. Goossens et al. [2017] suggest that the global density variations are broadly consistent with earlier findings: densities over the volcanic complexes are relatively high, while the northern hemisphere is in general denser than the southern hemisphere [e.g., 6].

Thus, while an Airy-like model for the Martian crust cannot be ruled out, in light of the recent findings that the crustal density of Mars varies significantly, it is equally plausible that the topographic dichotomy is compensated by lateral heterogeneity in crustal density (i.e. pratt isostasy). In fact, Figure 3 (c) of Goossens et al. [2017] shows a crustal thickness model of Mars assuming significant spatial variation in the density of crust. As expected, the signature of the purported crustal thickness dichotomy is completely absent in that map.

A theoretical test that may allow us to ascertain whether Mars has a crustal thickness dichotomy is presented here. The validity of the theory is first confirmed in terrestrial GRACE data. We then apply the theory to the Martian gravity field and show that unambiguous evidence for crustal thickness dichotomy is not present in the gravity data. Thus, we argue that crustal thickness dichotomy may not be present on Mars. A robust verification or rebuttal of the crustal thickness dichotomy hypothesis will require a dedicated gravity mission to Mars that can map the lateral variations in the density of Martian crust.

Theory: Consider a topographic variation $\boldsymbol{h(x)}$ along a single interface at the crust-mantle boundary at depth, z = d (z positive down). Based on the Bouguer slab formulation, the first-order gravity effect of the topographic variation $\boldsymbol{h(x)}$ measured on the observed gravity at an observational plane z=0 in the frequency domain is given by [10]: $\boldsymbol{|g(k)|^2 = 4\pi^2 G^2 \Delta\rho^2 e^{-2kd} |H(k)|^2}$; (*Eqn. 1*) where k is the wave number, g(k) is the power spectrum of the observed gravity, $\boldsymbol{\Delta\rho}$ the density contrast across the layer, and H(k) the Fourier transform of the topography h(x). For a very likely natural scenario, where compensating sources are spread over multiple interfaces $\boldsymbol{h_1(x), h_2(x), \ldots, h_n(x)}$, the gravity power spectrum is given by the following: $\boldsymbol{\langle |g(k)|^2 \rangle = 4\pi^2 G^2 \langle \Delta\rho^2 \rangle \langle e^{-2kd} \rangle \langle |H(k)|^2 \rangle}$; (*Eqn. 2*) where the symbols $\boldsymbol{\langle g(k) \rangle}$ and $\boldsymbol{\langle H(k) \rangle}$ represent the expectation. Taking the natural logarithm of each side of *Eqn. 2* yields: $\boldsymbol{\ln\langle |g(k)|^2 \rangle = \ln(4\pi^2 G^2 \langle \Delta\rho^2 \rangle) - 2kd + \ln(\langle |H(k)|^2 \rangle)}$ (*Eqn. 3*). Previously, Karner and Watts (1983) assumed that the slope of the natural log of gravity power is solely due to the attenuation of the high-frequency signals in the relief by upward continuation.

In other words, the spectrum of the relief on the density contrast in assumed to be white. However, it is commonly observed that for real surfaces on many scales: $\ln(\langle|\boldsymbol{H}(\boldsymbol{k})|^2\rangle) = \Upsilon \ln(k)$; (*Eqn. 4*) where Υ is almost always close to -2 (e.g. Sayles and Thomas, 1978; Bechtel et al., 1987). The spectrum of the relief of density contrast in either Martian or terrestrial Moho is unknown, thus, we consider two different plausible scenarios. In the first scenario, we assume that the relief at the Moho mimics the surface topography (i.e. Airy isostasy). In such case, we derive the value of Υ by running a regression between the observed topography and wavenumber. Alternatively, we assume that the relief at the source of the gravity anomaly is flat (i.e. white spectrum). In that case, Υ is assumed to be 0. For both cases, we solved for d using the following:

$$d = \frac{\ln\langle|g(k)|^2\rangle - \Upsilon \ln(k)}{-2k} \quad \textit{(Eqn. 5)}$$

Terrestrial Validation: The above technique has been frequently used in terrestrial gravity surveys to ascertain the depth to the crust-mantle boundary [e.g., 10]. While the resulting estimate of the crust-mantle interface depth will invariably have a large range of uncertainty due to assumptions regarding the slope of the Moho, to the first order, the localized Bouguer power spectrum from areas with different crustal thicknesses should show contrasting slopes. As a validation of this simple theory, consider the localized Bouguer power spectrum from three different regions on Earth (Fig. 1): (i) Himalayas, (ii) Pacific floor, and (iii) the Andes. The mean-depth from using Eqn 5 for the three regions are also annotated in the plot. While the estimated depths from this technique differ from seismically constraints, which are much more robust, to the first order the examples from Figure 1 illustrates that crustal thickness variations are manifested in the power spectrum of the gravity data.

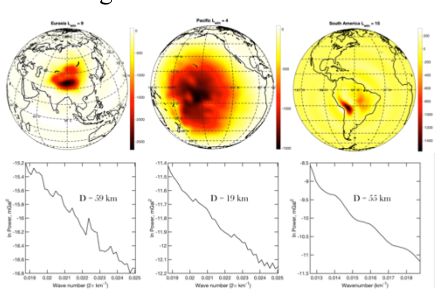
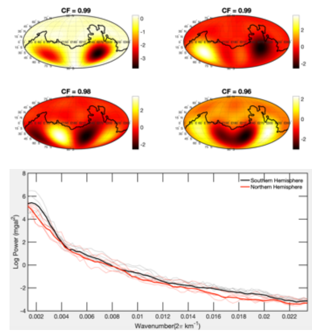


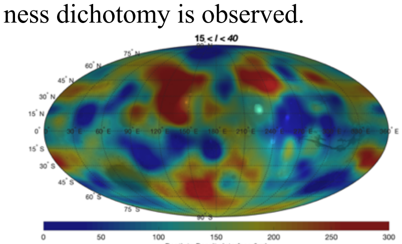
Figure 1. *Top row show the tapers used to localize the bouguer power spectrum from the Himalayas, Pacific floor, and the Andes. Bottom row show the logarithm of the bouguer power spectrum as a function of the wavenumber.*

Application to Mars: We used multitapers to localize the gravity data originating from the north and south of the hypothesized Martian crustal dichotomy (Figure 2). In contrast to Figure 1, for Mars, we use the free-air gravity maps as Bouguer correction requires knowledge of the crustal density. While the effect of topography is present in free-air gravity maps, the low spherical harmonic degree gravity (degree and order < 40) considered are not notably affected by the topography for most cases.



An example of the tapers used to localize gravity from the southern hemisphere is shown in Figure 2. The individual power spectrum from the tapered regions and their weighted mean are also shown in Fig. 2. Neither the individual power spectrum nor their weighted mean from the two hemispheres of Mars exhibit any obvious differences in their slopes (Fig. 2).

We also ran a global simulation using 20° radius windows and a L_{win} of 12 (Fig. 3). An automated routine found the steepest segment in the resulting power spectrum and computed the depth to the crust-mantle depth using equation 5. The result is shown in Figure 3. While significant variations in the depth to the interface with the largest density contrast is observed, no unambiguous evidence for north-south crustal thickness dichotomy is observed.



Conclusion: The topographic dichotomy of Mars is one of the oldest and fundamental features of Mars, the origin of which is hotly debated. Both endogenic and exogenic processes have been proposed as the formation mechanism for the dichotomy. Preliminary results from our work suggest that Mars may not have a crustal dichotomy. Updated results and implications will be presented at the meeting.

References: [1] Watters et al., *Annu. Rev. Earth Planet. Sci* 35, 621–52 (2007). [2] Zuber *et al. Science (80).* 287, 1788–1793 (2000). [3] Neumann *et al. J. Geophys. Res. E Planets* 109, (2004). [4] Wieczorek, M. A. in *Treatise on Geophysics* 10, 165–206 (2007). [5] Smith & Zuber, *Science (80).* (1996). doi:10.1126/science.271.5246.184. [6] Belleguic et al.,. *Geophys. Res. E Planets* 110, 1–22 (2005). [7] Goossens *et al. Geophys. Res. Lett.* 44, 7686–7694 (2017). [8] Beuthe et al., (2012). doi:10.1029/2011JE003976. [9] Baratoux *et al. J. Geophys. Res. Planets* 119, 1707–1727 (2014). [10] Karner & Watts. *J. Geophys. Res.* (1983). doi:10.1029/JB088iB12p10449