

Estimates of crustal and lithospheric thickness on Mars from gravity anomaly.

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Abstract

Using topography and gravity data on Mars obtained by Mars Global Surveyor (MGS), we calculate crustal and lithospheric thickness. At first, we evaluate reference crustal thickness, which means the thickness under 0 m elevation, assuming that topography of Hellas region is fully supported isostatically. As a result, we obtain the reference crustal thickness of 60 km. Using that value, we calculate lithospheric thickness. Because the supporting mechanism of topography depends on its wavelength, we can estimate the elastic thickness by investigating relationship between topography and gravity on wavelength domain. The resulting value is about 80 km in volcanic region, and 48 km in northern lowland, which may indicate that the martian lithosphere becomes thinner from south to north as is the case for the crustal thickness.

1. Introduction

Internal structure of the planet contains useful information about its thermal history, chemical composition, differentiation and so on. On Mars, no seismic data is available, so that correlation between topography and gravity is important constraints on the internal structure.

For example, *Zuber et al.* [2000] have calculated Bouguer anomaly, which is caused by subsurface mass anomaly, then estimated global crustal structure with reference crustal thickness of 50 km. In contrast, *Turcotte and Shcherbakov* [2002] have evaluated reference crustal thickness of 90 km under the assumption that Hellas basin is fully compensated.

Effective elastic thickness has also been estimated by the calculation of admittance (gravity/topography ratio in wavelength domain). *Turcotte and Shcherbakov* [2002] have evaluated 90 km thickness, on the other hand, *McKenzie et al.* [2002] have obtained thinner value; 61 km at Tharsis region and 15 km around the south pole.

Both crustal thickness and lithospheric thickness have not been well determined. In this study, we calculate the reference crustal thickness and

lithospheric thickness of Mars from gravity anomaly data, then consider which result is more reliable. To obtain credible results, we select relatively new and loaded region for analysis, such as volcanic region or the area resurfaced by lava flow, because we estimate lithospheric thickness by the theory of response to load on plate.

2. Data and parameter set

Mars Orbiter Laser Altimeter (MOLA) boarded onto Mars Global Surveyor (MGS) have provided detailed martian topography, and martian gravity fields have been obtained by analysis of Doppler tracking of MGS [*Lemonie et al.*, 2001, *Yuan et al.*, 2001].

We use IEG100 for the topography and JGD85F60 for the gravity (Fig. 1). IEG100 is a topographic map of Mars at a resolution of 1 by 1 degree, based on MOLA data. JGD85F60 gives the martian gravity anomaly, which is computed from a truncated MGS85F solution from degree 2 up to degree 60.

To calculate gravity anomaly, the density of crust and mantle must be determined. We adopt 2900 kg/m^3 for crustal density referring to the SNC meteorites

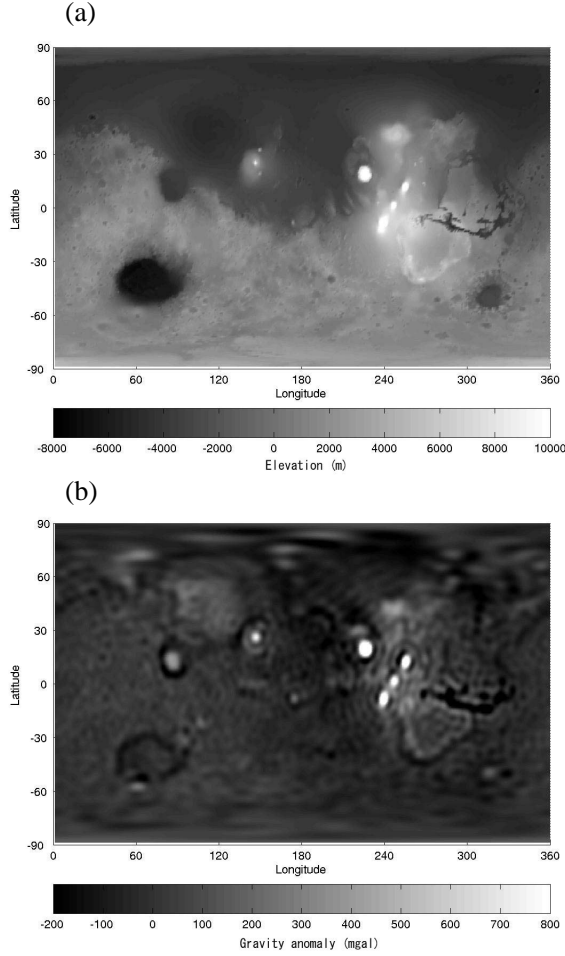


Fig. 1. Global maps of (a) topography in kilometers and (b) free-air gravity in milligals on Mars. Both are described with 1 by 1 degree griddata.

which are considered typical constituent of martian crust. As for mantle density, we adopt 3500 kg/m^3 which is consistent with martian bulk composition. Physical properties of martian crust have also been estimated from SNC meteorites. We take Young's modulus $E=70 \text{ GPa}$, Poisson's ratio $\nu=0.25$.

3. Estimate of crustal thickness

Crust is defined as the layer composed with low density material such as granite or basalt. At crust-mantle boundary (Moho), chemical composition changes, which causes gravity anomaly or seismic discontinuity. We assume that Bouguer gravity anomaly entirely derived from crust-mantle density contrast. Under such assumption, we can model

plausible Moho structure based on the observed gravity anomaly.

At first, we determine reference crustal thickness, where complete isostatic compensation occurs. Hellas basin is one of such candidates [Turcotte and Shcherbakov, 2002]. Hellas basin has more than 3000 km diameter and about 9 km depth. It is quite unlikely that martian lithosphere support elastically such a large structure. Furthermore, amplitude of free-air gravity anomaly around Hellas basin is small. These indicate Hellas basin is fully compensated. Assuming that Hellas region is supported isostatically, we can estimate Moho structure by applying airy model.

For computing gravity anomaly, we divide topography of Moho into vertical column element. Consider the vertical column element of density ρ , which has dZ height, dS base area and center of whose top face is located in (X_1, Y_1, Z_1) , center of whose base area is located in (X_1, Y_1, Z_2) . As Talwani [1973] have solved, the vertical component of gravity effect at (x, y, z) by the vertical element is written as

$$\begin{aligned}
 dg_z &= -G\rho dS \int_{Z_1}^{Z_2} \frac{(z-Z)}{\{(x-X_1)^2 + (y-Y_1)^2 + (z-Z)^2\}^{3/2}} dZ \\
 &= -G\rho dS \left[\frac{1}{\sqrt{(x-X_1)^2 + (y-Y_1)^2 + (z-Z_1)^2}} \right. \\
 &\quad \left. - \frac{1}{\sqrt{(x-X_1)^2 + (y-Y_1)^2 + (z-Z_2)^2}} \right] \quad (1).
 \end{aligned}$$

Integrating around density anomaly area, we can calculate Bouguer gravity anomaly.

By least-squares method, we seek for the best reference crustal thickness. As a result, obtained value is 60 km (Fig. 2). Cross-section of Hellas basin is described as Fig. 3. Because of airy model, topography and deflection of Moho change linearly.

4. Estimate of lithospheric thickness

Lithosphere is defined as surface elastic layer, which can support surface topographic loads. Short wavelength topography is supported elastically. However at increasing wavelength lithosphere exhibits deflection and the topography is compensated. The resulting gravity can be used to estimate the

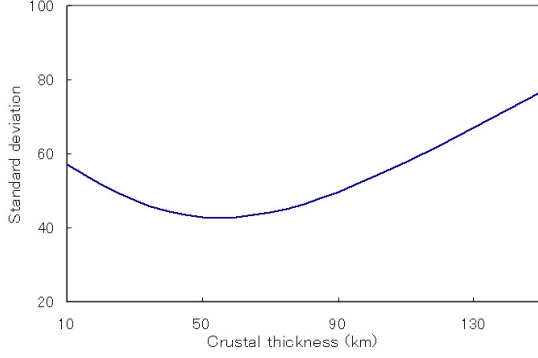


Fig. 2. Standard deviation between observed gravity anomaly and calculated one. The value making standard deviation minimum is the most plausible crustal thickness.

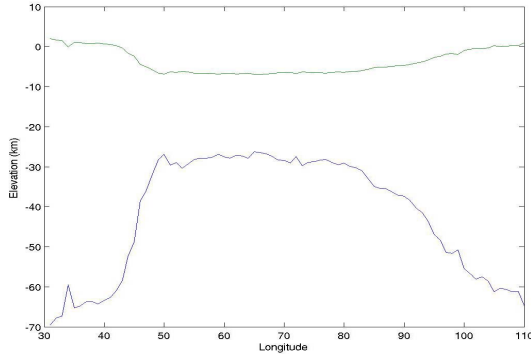


Fig. 3. Cross-section of Hellas basin along latitude line of 40°S. The upper line represents surface topography and the lower represents obtained Moho structure.

effective elastic thickness.

For estimation of elastic thickness, we calculate admittance Z (gravity/topography ratio in wavelength domain). As previously mentioned, at short wavelength lithosphere is not deformed by loads, thus gravity anomaly is almost derived from surface topography. However, at sufficiently long wavelength the support is isostatically relaxed and thus $Z \sim 0$.

Referring to *Turcotte and Shcherbakov* [2002], theoretical admittance is given by

$$Z = \frac{\Delta \bar{g}}{h} = 2\pi G \rho_c \left[1 - C_n \exp\left(-\frac{2\pi H_{c0}}{\lambda_n}\right) \right] \quad (2)$$

where ρ_c is the crust density, H_{c0} is the reference crustal thickness, λ_n is the wavelength at degree n , and

C_n indicate the compensation rate.

For a relatively small planetary body like Mars, the degree of compensation of topographic loads is controlled by both bending and shell stresses in the elastic lithosphere. *Turcotte et al.* [1981] have solved role of membrane stress in shell and found that C_n is given by

$$C_n = \frac{1 - \frac{3\rho_m}{(2n+1)\bar{\rho}}}{\frac{\sigma[m^3 - 4m^2] + \tau[m-2]}{m-1+\nu} + 1 - \frac{3\rho_m}{(2n+1)\bar{\rho}}} \quad (3)$$

where $m=n(n+1)$, $\bar{\rho}$ is the mean planetary density, ν is Poisson's ratio, σ is the bending rigidity

$$\sigma = \frac{\tau}{12(1-\nu^2)} \left(\frac{T_e}{R} \right)^2, \quad (4)$$

and τ is the shell rigidity

$$\tau = \frac{ET_e}{R^2 g(\rho_m - \rho_c)}, \quad (5)$$

where E is Young's modulus, T_e is the elastic lithosphere thickness, R is the mean planetary radius, ρ_m is the mantle density. Fitting Eq. (2) to the observed data, we find the best value of ρ_c and T_e .

2-D Fourier transformation is used for obtaining wavelength domain data of topography and gravity. We pick up some region in square, and calculate spectrum with 2-D Fast Fourier Transform (2-D FFT). Selected area are Tharsis, Elysium and northern lowland. They are relatively newly deformed topography thus suitable for estimating lithospheric thickness.

As a result, we find that elastic thickness in Tharsis region is 84 km, in Elysium region is 80 km and in northern lowland is 48 km (Fig. 4). Crust densities are all about 2900 kg/m³, that is consistent with the previous assumption for calculating reference crustal thickness.

5. Conclusion

By the analysis of Hellas basin, we conclude that reference crustal thickness is 60 km, which is consistent with the value by *Zuber et al.* [2000]. With that value, we calculate lithospheric thickness. We evaluate that effective elastic thickness at Tharsis

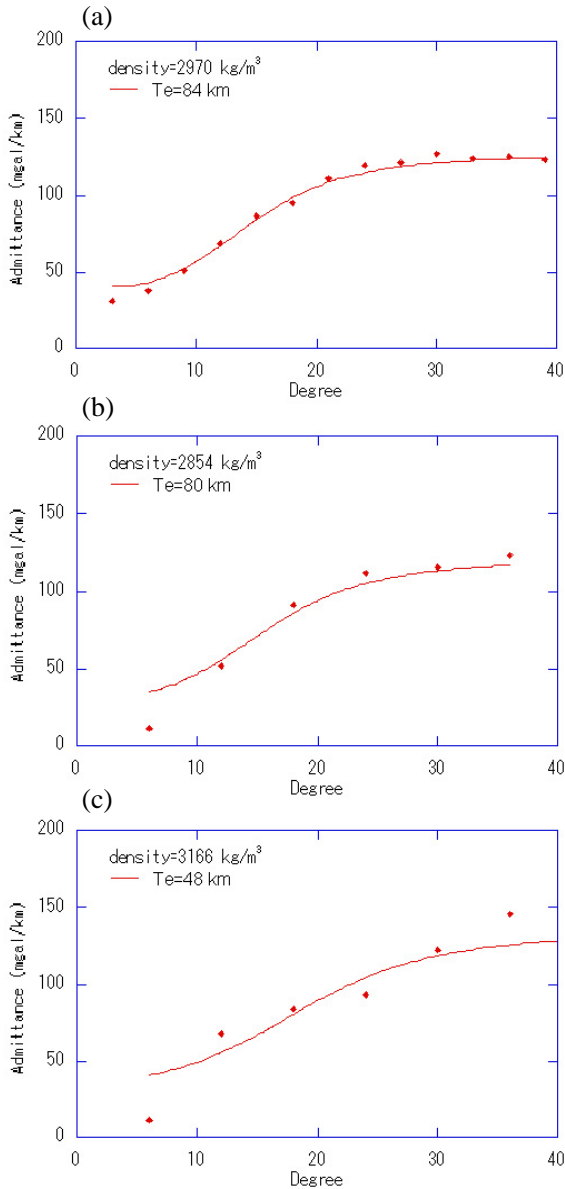


Fig. 4. Admittance at, (a) Tharsis region: 181-290°E, 49°S-60°N, (b) Elysium region: 121-180°E, 1-60°N, (c) northern lowlands: 4000 km square around the north pole. Solid lines represent theoretical curve calculated from Eq. (2).

region is 84 km, at Elysium region is 80 km and at northern lowlands is 48 km. As the previous researches have argued, martian crust becomes thinner

from south to north [Zuber *et al.*, 2000]. Our result may indicate martian lithosphere also becomes thinner from south to north as crust changes so. This supports the conclusion by Turcotte and Shcherbakov [2002] that the martian crust is also the martian elastic lithosphere.

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