Elastic Thickness, Paleo Heat Flow, and Curie Depth at the Tyrrhena Patera Highland Volcano

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Introduction: Tyrrhena Patera is a low-relief volcanic construct possessing an irregularly shaped summit caldera, and its morphology and topography is attributed to explosive volcanism related to phreatomagmatic processes. The entire construct was emplaced early in Martian history before 3.9 Ga, but subsequent activity occurred well into the Amazonian period. The caldera itself has a crater retention age of 3.3 Gyr, with limited resurfacing occurring around 1.5 Gyr [1].

A weak magnetic anomaly is associated with Tyrrhena Patera, indicating that the volcano formed in the presence of global magnetic field before magmatism demagnetized part of the crust [2]. A well localized positive free-air gravity anomaly is associated with the construct and a good correlation exists with the features topography (cp. Fig. 1).

Here we use the latest gravity field model for Mars [3] expanded up to degree and order 110 to model the admittance at Tyrrhena Patera and constrain the density of the volcanic load as well as the elastic lithosphere thickness at the time of load emplacement. The improved gravity field model is above the noise level for degrees up to 95, allowing for the analysis and interpretation of small scale features such as Tyrrhena Patera. Furthermore, we derive estimates for the paleo-heat flow and Curie depths at Tyrrhena Patera assuming different carriers of the observed magnetization.

Modeling: To model the observed admittance at Tyrrhena Patera we calculate the linear transfer function Q_l between gravity and topography coefficients in the spherical harmonics domain using a forward model appropriate for top loading of the lithosphere [4]. Apart from the crust and mantle densities, crustal thickness, and material parameters, Q_l is a function of the elastic lithosphere thickness and the load density and we invert for these parameters by fitting the modeled admittance to the observations.

Tyrrhena Patera is located at 106.53^{o}E and 21.36^{o}S and we use a spherical cap localization window centered around this location to perform a localized admittance analysis. The chosen localization window has a cap diameter of $\theta_0 = 7^o$ and a spherical harmonic bandwidth of $L = 37$ was chosen, such that 99% of the gravity and topography signals are localized inside the window. In the analysis we reference the gravity field to the average planetary radius at the location of interest, which for this analysis is $R = 3395.5$ km. Other parameters used in the calculations are a mantle density ρ_m of 3500 kg m^{-3}, a crustal density ρ_c of 2900 kg m^{-3}, a crustal thickness T_c of 50 km, a Youngs modulus E of 100 GPa, and a Poisson ratio ν of 0.25.

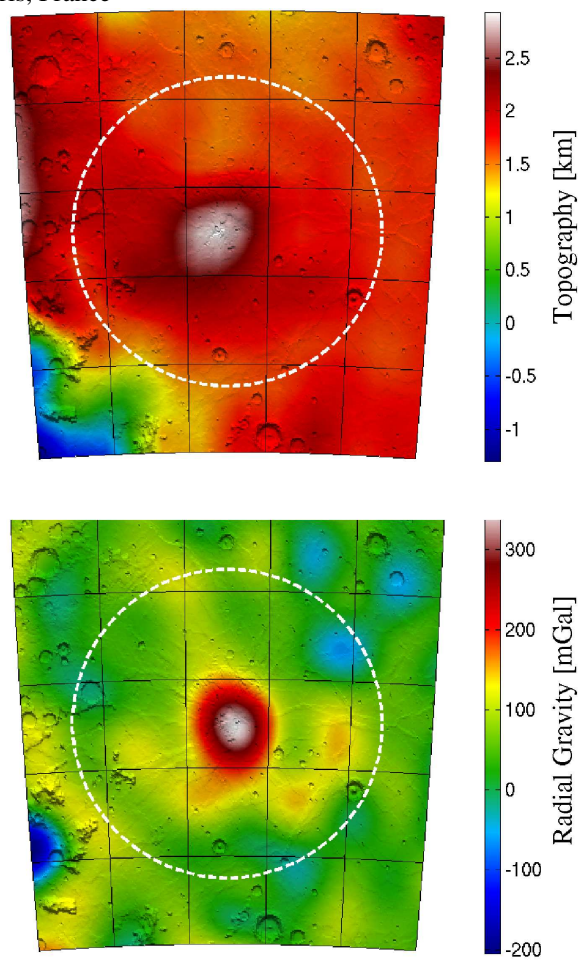

Figure 1: Topography (MarsTopo719.shape) and radial free-air gravity anomaly (MRO110b2 [3]) at Tyrrhena Patera, both referenced to a sphere of radius $R = 3395.5$ km and truncated at spherical harmonic degree 95. The circle indicates the location of the localization window.

At low degrees < 5 gravity field coefficients are strongly influenced by contribution from the Tharsis bulge, and these degrees are consequently ignored for the purpose of this study. Furthermore, the localization procedure mixes contributions of degrees larger than 95 (which are not known) to degrees 95-L and contributions

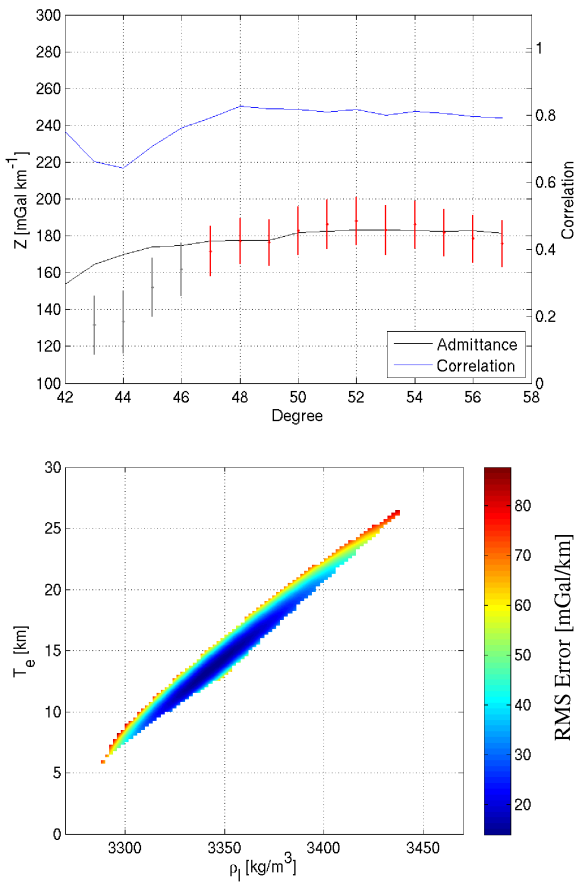

Figure 2: Top: Correlation and best fit admittance functions for the localized gravity and topography signals at degrees between 43 and 57. Observed admittance and associated errorbars are indicated in gray and red for degrees 43-46 and 47-57, respectively. Bottom: Color coded contour plot of the root mean square misfit between the modeled and observed admittance at degrees between 47 and 57.

from degrees 1 to 5 influence the localized admittances for degrees 5+L. As such, only degrees 43 to 57 can be confidently analyzed.

For the adopted top loading model, which only considers positive loads on an initially flat surface [4], the correlation between gravity and topography is expected to be nearly unity at all degrees and deviations from this value are interpreted as being caused by unmodeled gravitational signals (such as noise in the gravity field, or unmodeled geologic processes). Under this assumption the variance of the admittance can be expressed in terms of the correlation function [4], and we will use the variance as a formal error bound on the observed admittance.

Results: The best fit admittance and correlation functions are given in the top panel of Fig. 2. and the correlation function is larger than 0.775 (corresponding to a signal to noise ratio of 1.5) for degrees larger than 47. We restrict the analysis of the admittance to these degrees and the modeled admittance then is within the error bounds for elastic thicknesses $5 < T_e < 27$ km and the best fit elastic thickness is found to be $T_e = 13.25$ km. Admissible load densities are $3285 < \rho_l < 3440$ kg m^{-3}, with a best fit density ρ_l of 3342 kg m^{-3} (cp. Fig. 2). Varying the crustal density between 2700 and 3100 kg m^{-3} has little influence on the elastic thickness, but the admissible load densities are changed by +50 and -50 kg m^{-3} when choosing $\rho_c = 2700$ and 3100 kg m^{-3}, respectively.

In order to convert elastic thicknesses to heat flows we use the equivalent-moment strength envelope formalism [5], which takes brittle as well as plastic yielding of the lithosphere into account. Maximum curvatures K of the flexure profiles determined from the applied thin shell loading model are $1.3{\cdot}10^{-7}$ and $2.1{\cdot}10^{-6}$ m^{-1} for $T_e = 27$ and 5 km, respectively. Assuming a crustal thermal conductivity of 2 W m^{-1} K^{-1} and a wet diabase crustal rheology, these T_e and K values correspond to surface heat flows of 26 to 82 mW m^{-2}. These heat flows are consistent with other estimates for the Noachian period and fall within the range calculated by thermal evolution models, which predict heat flow of 60 mW m^{-2} between 4.5 and 3.5 Gyr if dehydration stiffening of the mantle rheology is taken into account [6].

Likely carriers of the remanent magnetization in the Martian crust are pyrrhotite, magnetite, and hematite, which have Curie temperatures of 600, 850 and 950 K, respectively. Given the heat flows determined above, the Curie temperatures for these minerals are exceeded at depths of 9-29, 15-48 and 17-56 km, respectively. As the magnetic spectrum of Mars indicates that the magnetized crustal layer has a thickness of 47.8 ± 8.4 km [7], pyrrhotite is an unlikely carrier of the Martian crustal magnetization.

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