MODELING OF SURFACE AND SUBSURFACE LOADS ASSOCIATED WITH THE MAJOR MARTIAN VOLCANOES.

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Introduction: In the absence of in situ geophysical measurements, modeling the relationship between gravity and topography is one of the few methods that can be used to constrain the properties of a planet's crust and upper mantle. In this study, localized spectral admittances of the large Martian volcanoes are modeled by assuming that surface and subsurface loads are elastically supported by the lithosphere. The resulting gravity anomalies depend upon physical parameters such as the crustal and load densities and the thicknesses of the elastic lithosphere and crust. In order to increase the accuracy of this type of modeling, a new method for calculating gravity anomalies and lithospheric deflections when the load density differs from that of the crust has been developed.

As recent studies [12, 2] have highlighted the evidence for recent volcanic activity on Mars, the Martian mantle must be still dynamic, and variations in either temperature or composition are likely to play an important role in the planet's observed topography and gravity field. In addition of surface loads, we have therefore investigated the possible presence of subsurface loads acting on the lithosphere, either as dense intrusive materials in the crust or less dense materials in the mantle. This later possibility could be a result of temperature anomalies in a mantle plume and/or a depleted mantle composition.

We have generated surface and subsurface loading models by exhaustively sampling all possible values (within limits) of the load density, the crustal density, the elastic and the crustal thickness and the ratio of surface to subsurface loads. The observed and modeled admittance and coherence functions between gravity and topography were then compared as a function of these model parameters for the major Martian volcanoes.

Method: In previous studies, various approximations have been made in order to calculate quickly the lithospheric deflection and the predicted gravity field. However, some of the employed assumptions may not be entirely applicable to Mars as it is a small planet with extreme topographic variations. As an example, the use of the "masssheet" approximation when computing the gravity anomaly due to a large volcano on Mars can introduce an error of up to 500 mGals, corresponding to 25% of the signal [5]. Moreover, these previous studies have not been able to correctly model the case when the load density differs from that of the crust.

In order to improve the accuracy of the theoretical flexure and admittance models, we have here developed a new numerical method that calculates precisely both the load acting upon the lithosphere due to an arbitrary density distribution and the corresponding lithospheric deflection while remaining affordable from a computational point of view. First and foremost, we have developed a method for calculating the exact gravitational potential on any arbitrary interface within a planet. This method allows us to take into account all kinds of inhomogeneities (i.e., lateral density variations, variations of the depth of each interface). The technique is based on the propagation of a solution from a given height to the center of the planet, using the analytically calculated derivatives of U and g. Using this method, we can exactly compute the magnitude of surface and subsurface loads, which depend upon the potential at the surface, Moho, and internal density interfaces. Using the magnitude of this load, the flexure of the surface can be determined using standard thin shell elastic theory. However, as the flexure equation and gravity computations are coupled, this set of equations must be solved in an iterative manner.

The subsurface load is then parameterized to be proportional to the surface load by a factor f. We only consider two cases, which are determined by the sign of *f*: either the load is a positive density anomaly in the crust or a density deficit in the mantle (such as a plume or depleted mantle composition). By definition, the two loads are in phase, and the ratio f is defined by

$$f = \frac{\Delta\rho M}{\Delta_l h_l}, \qquad (1)$$

where M is the thickness of the anomaly, h_l is the thickness of the load of density Δ_l and $\Delta\rho$ is the subsurface density anomaly. If $f < 0$, a positive density perturbation is located exclusively in the crust and M is the thickness of the crust. In contrast, if $f > 0$, then a negative density perturbation is located in the mantle. For this case, the value of the subsurface load thickness was set to be M=250 km. Secondly, we calculate localized admittance and coherence functions using localizing windows that concentrate almost all of their energy (99%) with the region of

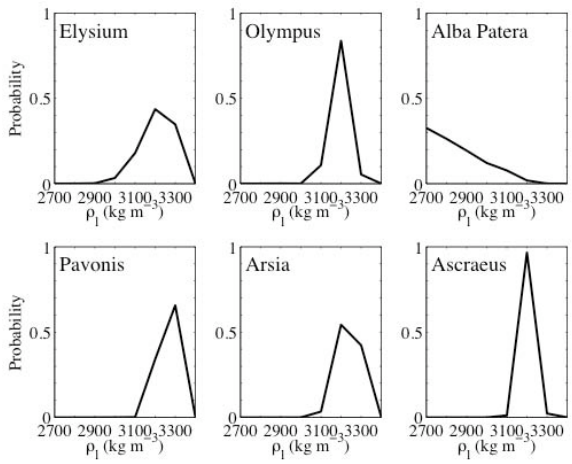

Figure 1: Marginal probability as a function of the load density

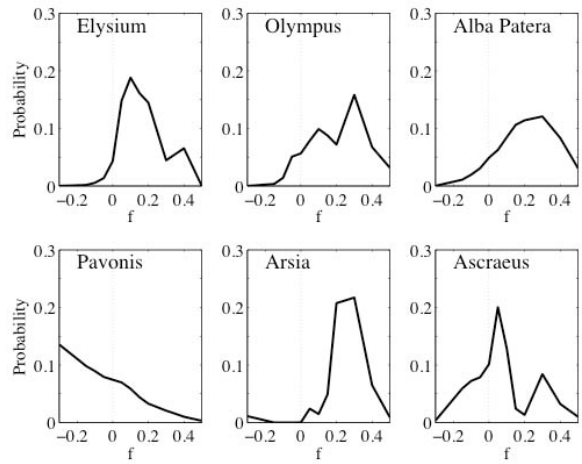

Figure 2: Marginal probability as a function of the surface to subsurface ratio

interest. Previous studies have employed suboptimal windows that only concentrate about 92% of their energy within the desired region.

Results: The main result we have obtained is the density of the volcanoes (see Figure 1). With the exception of Alba Patera, we have obtained a value of 3200±100 kg m^{-3} that is higher than what was previously published (i.e., 2900±100 kg m^{-3} [5, 7]) but is consistent with the corrected values of [6]. These high densities are in agreement with those of the Martian basaltic meteorites, which are believed to come either from the Tharsis or Elysium volcanic provinces [9, 3]. As the load density is relatively constant for all the volcanoes studied here, this suggests that similar magmatic process have operated at each of these regions. The lower density obtained for Alba Patera (less than 3100 kg m_3) might imply that its composition is less iron rich than the known Martian meteorites. Alternatively, given the low coherences for this volcano at high degrees, it is possible that uncorrelated subsurface loads might be important for this volcano, and that neglecting such a process could have biased our results there.

When subsurface loads are neglected, the elastic thickness is found to be moderately constrained for Elysium (56±20 km), Alba Patera (66±20 km), Olympus Mons (93±40 km) and Ascraeus (105±40 km). However, when subsurface loads are taken into account, the uncertainties thus obtained become extremely large, with the exception of Alba Patera where we obtain Te=73±30 km. The crustal density is only constrained beneath the Elysium rise (3270±150 kg m^{-3}). Given the similarity among the crustal density, load density and Martian meteorites, it is possible that the crustal composition of the Northern lowlands is similar to these meteorites. Estimates for the density of the Southern highlands crust are generally lower [10], and this seems to indicate that the northern hemisphere crust is more mafic in composition. Such a difference suggests the possibility that Pratt compensation may be partially responsible for the 3.1km center of mass/center of figure offset of the planet.

Finally, the investigation of possible subsurface loads shows evidence for dynamic processes acting under the volcanoes in this study. We found that all volcanoes are better modeled with the presence of less dense material in the upper mantle (when $f > 0$), which is either indicative of a mantle plume or a depleted mantle composition (see figure 2). The only exception is for Pavonis, where intrusive material in the crust gave the best results. An active plume beneath the major volcanoes is consistent with recent analyses of cratering statistics on Olympus Mons and the Elysium rise, which indicate that some lava flows erupted as late as 10-30 Myr [2], as well as with the radiometric age of the Shergottites which have crystallization ages of about 180 Myr [12].

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