MODELING GRAVITY ANOMALIES AT MARTIAN SHIELD VOLCANOS: A REDUCED ESTIMATE OF ELASTIC LITHOSPHERE THICKNESS AT OLYMPUS MONS

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An important constraint on models of planetary structure and evolution is the heatflow or near-surface thermal gradient. This can be inferred indirectly from estimates of the thickness of a planet’s elastic lithosphere. Estimates of the elastic thickness at Olympus Mons on Mars have varied widely. Both gravity modeling [1] and observations of tectonic features [2,3] have been used to favor a lithosphere with a thickness of 140 km or more. On the other hand, the topography of a possible flexural moat and bulge surrounding Olympus Mons implies an elastic thickness of no more than 50 km [4]. Here, we use a new, high resolution gravity model to derive a new estimate of the elastic lithosphere thickness of 25 to 50 km.

We make use of the recently developed spherical harmonic degree 50 model for the gravity field of Mars, GMM-1 [5]. This model is a factor of 3 higher in resolution than the best previously available spherical harmonic model for Mars. The resolving block size is 213 km, allowing the large shield volcanos in Tharsis to be resolved for the first time.

We model lithospheric flexure using the model of Melosh [6], which uses axisymmetric, Gaussian shaped loads on an elastic plate over a fluid asthenosphere. The flat plate approximation in this model is acceptable given the relatively short wavelengths of interest here. The linearity of the flexure equation with respect to the applied load allows superposition of multiple loads to approximate more complex load geometries, although we use only a single Gaussian load in the results described here. The best overall fit to profiles of Olympus Mons topography extracted from the digital version of the USGS topography model [7] is for a Gaussian width parameter of 250 km. However, it is clear that there is also a somewhat broader component to the volcano topography, so we also present results for a Gaussian width of 350 km. The amplitude of the load was chosen so that the final (post-deflection) topography had a peak amplitude of 23 km, which represents the observed Olympus Mons topography relative to the regional elevation.

From the surface load and the associated deflection at the crust-mantle interface, we calculate free-air gravity profiles for a range of lithospheric thicknesses using elastic constants appropriate for basalt. Minimizing the crustal thickness maximizes the elastic thickness required to match the observed gravity anomaly; accordingly, we chose a reference crustal thickness of 25 km. The resulting gravity profiles are filtered to include only wavelengths included in GMM-1. Figure 1 shows the peak gravity amplitude as a function of elastic lithosphere thickness. The solid line is the results for the Gaussian width of 250 km and the dashed line is the results for the Gaussian width of 350 km. Olympus Mons has a peak gravity anomaly of 1200 mgal in GMM-1, although a portion of this is associated with the long-wavelength Tharsis bulge. Estimates based on profiles across Olympus Mons suggest that the peak anomaly relative to the Tharsis anomaly is 1100 mgal. Alternatively, a spectral filtering approach implies a peak free-air gravity anomaly of 1050 mgal when Tharsis is removed [8]. For a peak anomaly of 1050-1100 mgal, Figure 1 shows that the elastic thickness is in the range 25 to 35 km. The fit to the location and amplitude of the adjacent gravity minimum suggests a slightly larger elastic thickness. Overall, values between 25 and 50 km appear acceptable. A more precise estimate of lithospheric thickness may be possible once we consider multiple Gaussian loads. Elastic lithospheres of 75 to 150 km thickness predict gravity anomalies far in excess of that observed.

The GMM-1 model has an estimated uncertainty of about 50 mgal at low latitudes [5], and the correction for the effects of Tharsis on the reference baseline have a similar uncertainty. Uncertainties in the topography model are at present more significant, with formal error estimates of 1 km at low latitudes [7], although the actual uncertainties could well be larger [10]. These nominal errors in the gravity and topography have minimal effect on the estimated lithospheric thickness. Even if the actual topography is 20% smaller than we have assumed (equivalent to 4.5 km at the load center) or if the

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gravity anomaly is 20% larger than assumed (equivalent to 200 mGal at load center), the required lithospheric thickness would increase by only about 5 km. This suggests that our thickness estimate is relatively robust with respect to uncertainties in the input data sets.

Our estimated lithosphere thickness of 25 to 50 km for Olympus Mons is smaller than any prior estimate. Modeling of the tectonic features expected due to volcanic loading has also been used to constrain the elastic lithosphere thickness; the absence of circumferential graben around Olympus Mons was used to argue for a lithosphere with a minimum thickness of 150 km [2,3]. However, one might suppose that such graben actually did form and were later covered by lava flows, which would allow a much thinner lithosphere at Olympus Mons. Application of the same tectonic model to Arisia, Ascræus, and Pavonis Montes produced lithospheres of 18-26 km thickness [3], quite consistent with our estimate for Olympus Mons. A previous gravity study [1] used line-of-sight modeling of a single Viking 2 orbit to estimate a lithospheric thickness between 140 and 230 km. However, this model used the tectonic models [2,3] as a constraint on the allowed flexural stress and accordingly was restricted to a similar lower bound for the elastic thickness. If the stress constraint is relaxed for the reasons suggested above, the gravity data allow (indeed, require) a thinner lithosphere. The topography of a possible flexural moat and bulge around Olympus Mons sets an upper limit on the lithospheric thickness of 50 km [4], which is consistent with our results. The thermal gradient implied by a 150 km thick lithosphere is only 5 K/km [9]. In such a cold thermal environment, it would be difficult to understand how such a massive shield volcano could form. A thinner lithosphere implies a higher thermal gradient and easier magma production, providing additional qualitative support for the thin lithosphere model for Olympus Mons.

The technique applied in this study can also be applied to other large shield volcanos that are resolved by GMM-1, particularly Arisia, Ascræus, Elysium, and Pavonis Montes. We anticipate presenting results for these volcanos at the conference. Measurements by future Mars-orbiting spacecraft should allow further testing of our estimate for lithospheric thickness. High resolution altimetry [10] will permit the topography of a flexural moat and bulge to be used as a more quantitative constraint [4]. Doppler-tracking of a spacecraft in a low-altitude, circular, polar orbit will permit the gravity model to be extended to higher harmonic degrees [11], which is useful because flexure has its largest effects at short wavelengths. Improvements in both the gravity and topography data sets may also allow coherence techniques to be applied.


Figure 1. Maximum free-air gravity anomaly over Olympus Mons as a function of assumed elastic lithosphere thickness. The solid line is for a Gaussian load width of 250 km and the dashed line is for a Gaussian load width of 350 km.