# INTERPRETATIONS OF GRAVITY ANOMALIES AT OLYMPUS MONS, MARS: INTRUSIONS, IMPACT BASINS, AND TROUGHS.

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**Summary.** New high-resolution gravity and topography data from the Mars Global Surveyor (MGS) mission allow a re-examination of compensation and subsurface structure models in the vicinity of Olympus Mons.

**Introduction.** Olympus Mons is a shield volcano of enormous height ($>$ 20 km) and lateral extent (600-800 km), located northwest of the Tharsis rise. A scarp with height up to 10 km defines the base of the edifice. Lobes of material with blocky to lineated morphology surround the edifice [1-2]. Such deposits, known as the Olympus Mons aureole deposits (hereinafter abbreviated as OMAD), are of greatest extent to the north and west of the edifice.

The free-air gravity field near Olympus Mons [3] exhibits a large anomaly centered over the Olympus Mons edifice (Figure 1a). However, a lower-magnitude positive anomaly extends outward from the edifice toward the north, partially covering several of the OMAD lobes. The existence of a positive gravity anomaly associated with the northern OMAD was first discussed by [4], who attributed it to a dense intrusive body at depth. Under this hypothesis, the intrusive body was the source of the OMAD, emplaced as pyroclastic flows. We use the gravity and topography data to constrain the dimensions of such a body. However, we also consider an alternative hypothesis, inspired by several observations about the nature of Martian northern-hemisphere crust. First, Olympus Mons is located near the boundary between the northern hemisphere (nearly constant-thickness crust) and southern hemisphere (generally thickening toward the south pole) crustal provinces [5]. Second, Mars Orbiter Laser Altimeter (MOLA) topography data from MGS have revealed a large population of partially buried impact craters and basins in the northern plains of Mars [6], indicating an ancient age for northern hemisphere basement units. If Olympus Mons was constructed on such basement, ancient impact basins adjacent to the edifice may have been filled and buried by volcanic flows or mass movements derived from the flanks [e.g., 7, 8]. Large ancient basins are likely to be compensated by an Airy isostatic mechanism (as observed elsewhere on Mars [9]). If such a basin is filled and covered by volcanic materials during a later time when thick elastic lithosphere conditions prevailed [e.g., 9], the basin becomes overcompensated, yielding a roughly circular positive Bouguer anomaly like that seen near the OMAD (see below).

**Method.** We use harmonic expansions of Martian shape (radius from center of mass [10]), topography (referenced to an equipotential surface [10]) and gravity [3] fields to degree ($l$) and order ($m$) 60 (the limit of adequate gravity resolution). The importance of the distinction between shape and topography is discussed in [9]. We calculate the Bouguer gravity anomaly $\Delta g_b$ in the following manner. First, we calculate the gravity signal $\Delta g_s$ produced by the observed shape (for an assumed density $\rho_l$ = 2900 kg/m$^3$), using a finite-amplitude formulation [11]. We then subtract $\Delta g_s$ from the observed free-air gravity $\Delta g_{fao}$ to obtain the Bouguer anomaly $\Delta g_{bo}$. We model the response of the lithosphere to topographic loads via a thin spherical-shell flexure formulation [9, 12], obtaining a model Bouguer gravity anomaly ($\Delta g_{bm}$). The residual Bouguer anomaly $\Delta g_{br}$ (equal to $\Delta g_{bo}$ - $\Delta g_{bm}$) can be mapped to topographic relief on a subsurface density interface, using a downward-continuation filter [11]. To account for the presence of a buried basin, we expand the topography of a hole with radius $r_0$ and depth $h_0$ into spherical harmonics $h_{ilm}$ up to degree and order 60. We treat $h_{ilm}$ as the initial surface relief, which is compensated by initial relief on the crust mantle boundary of magnitude $-\rho_c/(\rho_m - \rho_c)h_{ilm}$. These interfaces are subsequently deformed by the load of the observed topography, accounting for filling of the basin by material with load density $\rho_l$. We calculate a suite of models, varying $r_0$ and $h_0$ to determine the dimensions of the compensated basin that best reduces the residual Bouguer anomaly in the vicinity of the OMAD.

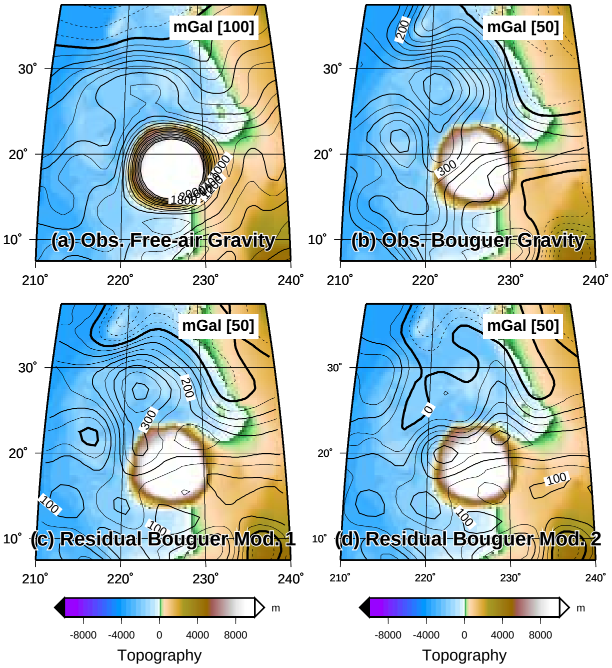

Fig. 1. Contours of gravity (harmonic expansion to degree and order 60; contour intervals given in white box in upper right), over color image of topography (1x1 degree grid; color scale bar in meters given at bottom). (a) Contours of Free-air gravity. Contours were cut off at 2000 mGal, the maximum anomaly over Olympus mons is 4052 mGal. (b) Contours of Bouguer gravity, for surface density of 2900 kg/m$^3$. (c) Contours of residual Bouguer gravity, for flexure model with $T_e$ = 200 km. (d) As in (c), for model with initial topography containing a buried, fully compensated basin ($r_0$ = 300 km and $h_0$ = 3.5 km, centered at 27.5 °N 222 °E).

**Results.** The Bouguer anomaly for the Olympus Mons region is shown in Figure 1b. In contrast with the free-air gravity (Figure 1a), the highest-magnitude feature in the Bouguer gravity is a roughly circular high ($>$ 500 mGal) centered northwest of the Olympus Mons edifice between two OMAD lobes (slightly northwest of the highest free-air OMAD-related anomaly). A flexure model with elastic lithosphere thickness $T_e$ = 200 km [9] yields a peak residual Bouguer anomaly $\Delta g_{br} >$ 400 mGal, again centered near the boundary of two OMAD lobes (Figure 1c). This anomaly corresponds to peak uplift $u_a$ = 18 km on an interface with density contrast $\Delta\rho$ = 500 kg/m$^3$, centered at depth $d_i$ = 50 km. For shallower $d_i$, $u_{max}$ decreases. The minimum value of $u_a$ is constrained by the lack of evidence for exposures of dense intrusive volcanic material at the surface of the northern OMAD, yielding the condition $u_{min} - d_i = t$, where $t$ is the topography at the location of peak uplift. The resulting $u_{min}$ is about 10 km. For flexure models that include the effects of a subsurface compensated basin (again, with $T_e$ = 200 km), we attempt to minimize $\Delta g_{br}$ in the vicinity of the OMAD anomaly. The best fit is for a basin with $r_0$ = 300 km (600 km diameter) and $h_0$ = 3.5 km (Figure 1d).

**Discussion.** The gravity and topography data from MGS place new constraints on subsurface structures in the vicinity of Olympus Mons. A gravity high northwest of the Olympus Mons edifice has been cited as evidence for a dense magmatic body at depth [4]. MGS gravity data reveal that such a body must be at least 10 km thick and have a large density contrast with the crust (lowering $\Delta\rho$ will increase the required thickness). While an association of thick intrusive bodies and large volcanic edifices is plausible, no other anomalies of magnitudes similar to that in the OMAD are seen near any other large Martian edifice or volcanic province. Such a model therefore requires a structure apparently unique on Mars. While the OMAD deposits themselves are often considered to comprise a unique structure, we note that there is no apparent correlation between the $\Delta g_{bo}$ and $\Delta g_{br}$ anomalies and visible OMAD structures, as might be expected if the source of these anomalies fed volcanic eruptions that produced the lobes.

Interpretation of the OMAD gravity anomaly as the signal of a buried, compensated impact basin is appealing for several reasons. The OMAD signal is readily accounted for by a basin of dimensions consistent with the observed depth-diameter relations of Martian craters and basins [13]. Basins with similar diameters have been detected in the northern plains basement [6], yielding a Noachian age for that unit. Thus, under the presumption that Olympus Mons formed at least partially on basement material belonging to the northern crustal province [5], the presence of a basin of the required size is likely; no unique event is required. Furthermore, Acheron Fossae, a fractured feature with a half-annular topographic profile located to the north of Olympus Mons and OMAD, is of Noachian age, implying a similar age for the basement terrain underlying the northern OMAD. For plausible values of $T_e$ [9], Acheron Fossae lies on the flexural arch produced by the load of the Olympus Mons edifice. The resulting uplift likely allowed Acheron Fossae to escape burial by OMAD materials and flows from Olympus Mons and Alba Patera. In contrast, the proposed basin lies within the flexural moat of Olympus Mons, subjecting it to burial [e.g., 8].

As noted above, no other volcanic regions exhibit residual Bouguer anomalies comparable in magnitude to that seen in the northern OMAD (Figures 1c,d). However, comparable anomalies are evident to the southwest of Olympus Mons, associated with northwest-trending valleys whose formation was recently attributed to catastrophic floods originating in central Tharsis (the northwestern slope valleys, or NSVs, of [14]). These valleys exhibit gravity anomalies that roughly follow the linear valley trends: free-air gravity lows but Bouguer gravity highs, the latter implying subsurface compensation. A similar linear residual Bouguer high extends from northern Tharsis westward though the Olympus Mons region (roughly along the 20°N parallel in Figures 1b-d). We propose an analogy to the buried basin hypothesis presented above: the linear Bouguer anomaly beneath Olympus Mons may reflect the presence of an at least partially compensated trough, subsequently buried during an era characterized by high $T_e$. The NSVs [14] may be the remaining surface manifestation of troughs analogous to the proposed sub-Olympus trough (although the former are less well-buried than the latter). If the NSV troughs and the sub-Olympus trough originated at the same time, the latter must be no younger than the Late Noachian-Early Hesperian age attributed to the carving of the valleys [14]. However, the NSV troughs may be still older features that exerted tectonic control on subsequent flooding events [e.g., 14].

**References.** [1] R. M. Lopes *et al., JGR, 87*, 9917, 1982; [2] P. W. Francis and G. Wadge *JGR, 88*, 9333, 1983; [3] F. G. Lemoine *et al., JGR, 106,* 23,359, 2001; [4] E. C. Morris, *JGR, 87*, 1164, 1982; [5] M. T. Zuber *et al., Science, 287*, 1788, 2000; [6] H. V. Frey *et al., GRL*, in press, 2001; [7] P. J. McGovern and S. C. Solomon, *JGR, 98*, 23,553, 1993; [8] P. J. McGovern and S. C. Solomon, *JGR, 102*, 16,303, 1997; [9] P. J. McGovern *et al., JGR*, submitted, 2002; [10] D. E. Smith *et al., JGR, 106,* 23,689, 2001; [11] M. A. Wieczorek and R. J. Phillips, *JGR, 103*, 1715, 1998; [12] D. L. Turcotte *et al., JGR, 86*, 3951, 1981; [13] R. J. Pike, *Icarus, 43*, 1, 1980; [14] J. M. Dohm *et al., GRL, 27*, 3559, 2000.