GRAVITY EVIDENCE FOR EXTINCT MAGMA CHAMBER SYSTEMS ON MARS. Walter S. Kiefer, *Lunar and Planetary Institute, Houston TX 77058-1113, USA (kiefer@lpi.usra.edu, http://www.lpi.usra.edu/science/kiefer/, (281) 486-2110).*

The *Mars Global Surveyor* mission has vastly improved our knowledge of the topography and gravity of Mars [1,2,3], permitting detailed geophysical modeling of subsurface structures such as magma chamber systems for the first time. In this work, I describe gravity models for Syrtis Major [4], Tyrrhena Patera, and Hadriaca Patera as well as preliminary results for Amphitrites Patera. In each case, flexurally supported surface topography can not explain the observed gravity anomaly. High density, buried material is required at each volcano, most likely as dense cumulate minerals in extinct magma chamber systems. These results provide our first look at the magmatic plumbing of Mars.

Model

The gravity models are calculated for spherical harmonic degrees 2 through 50, corresponding to a half-wavelength spectral resolution of 213 km. This ensures that the signal-to-noise ratio remains high and thus that the observed gravity anomalies are robustly determined. The RMS uncertainty in the gravity models is 10-13 mGal [2], which is a small fraction of the observed peak amplitudes for the study regions. Flexural support of the surface topography is calculated using a spherical thin-elastic shell model [5] with elastic constants and a load density appropriate for basalt.

I model the subsurface structures as buried vertical cylinders. Bounds on the cylinder radius, R, are determined from the width of the gravity anomaly. The depth of the cylinder, D, and the density contrast between the cylinder and the surrounding crust, $\delta\rho$, are adjusted to fit the anomaly amplitude. Models with multiple cylinders sometimes improve the fit to the observations. The cylinders are assumed to be uncompensated to set a lower bound on the required density contrast between the cylinder and the surrounding crust. The density contrast inside the cylinder is tapered smoothly to zero at its outer edge to avoid problems with Gibbs phenomenon in the spherical harmonic expansion. The vertical integration over the cylinder's depth is performed numerically using a 1 km step size. The total model gravity anomaly is the sum of the contributions from the topographic and buried loads.

Some of the martian meteorites, such as Nakhla and Chassigny, are pyroxene or olivine cumulates and provide analogs for the material that may be present in the magma chambers. Densities of up to $3300\ kg\ m^{-3}$ (pyroxene dominated) or $3600\ kg\ m^{-3}$ (olivine dominated) are petrologically reasonable [6,7]. If the magma chamber is a network of intrusive material within a matrix of pre-existing crust, the net magma chamber density would be smaller than these values. Because D and $\delta\rho$ can not be separately determined, in this work I report minimum values of D based on the petrologically likely maximum values of $\delta\rho$.

Results

Syrtis Major: Syrtis Major has basaltic flow morphologies, a basal diameter of 1100 km, and is about 1 km high [8]. The topographic caldera is 150x250 km, elongated north-south, and is up to 2 km deeper than the rim. The gravity anomaly is 100 mGal at spherical harmonic degree 40 and 126 mGal at degree 50.

I have recently presented a gravity model for Syrtis Major [4] and showed that the gravity data requires the presence of a buried, high-density body. The spatial association between the caldera and the buried structure indicates that the subsurface structure is most likely due to dense cumulate minerals in an extinct magma chamber system. The Syrtis Major magma chamber is approximately 300 by 600 km across, broader than the topographic caldera but narrower than the overall volcanic edifice. Like the caldera, the magma chamber is elongated in the north-south direction. The minimum magma chamber thickness is 3.6 km (olivine dominated) to 5.8 km (pyroxene dominated). Assuming a 10% density change from melt to solid, solidification of the magma chamber can account for only a few hundred meters of caldera relief. Thus, most of the caldera's depth must be accounted for by removal of magma from the magma chamber and subsequent caldera collapse. The best fitting elastic lithosphere thickness is 10-15 km for a crust density of $\rho = 2800\ kg\ m^{-3}$.

Tyrrhena Patera: Tyrrhena Patera is 215 by 350 km across with a maximum relief of 1.3 km. The summit caldera complex is 41 by 55 km across [9]. Tyrrhena is primarily Hesperian in age, and based on its morphology is interpreted as forming primarily by pyroclastic flows [10].

Figure 1a shows the gravity anomaly across Tyrrhena. There is excellent agreement in shape and amplitude between models MGM1025 and MGS85F, which are based on the same Doppler tracking data but independent data processing and inversion. The anomaly is robustly determined, with a peak amplitude of 145 mGal at spherical harmonic degree 40 and 165 mGal at degree 50. Figure 2 shows an east-west profile through the Tyrrhena gravity anomaly. A model based on flexurally supported surface topography (lithosphere thickness 15 km, short dashed line) is a poor fit to the observations, so buried high density material is required in this region.

The long-dashed line is a model with both flexurally supported surface topography and a buried cylinder (108 East, 22.5 South, R=300 km). The cylinder radius is constrained to a value between 275 and 300 km by the width of the observed gravity anomaly. Assuming a maximum density contrast of $\delta\rho = 800\ kg\ m^{-3}$ (for an olivine-dominated magma chamber), the minimum thickness of the cylinder is 2.9 km. For a pyroxene-dominated magma chamber of $\delta\rho = 500\ kg\ m^{-3}$, the minimum cylinder thickness is 4.7 km. The buried structure is roughly twice the diameter of the surface volcanic edifice, and the total buried mass is roughly an order of magnitude larger than the mass of the volcanic edifice and its subsurface root. Tyrrhena is surrounded by more than 1 million square kilometers of Hesperian age lava plains [11]. Some of these plains are explicitly identified as flows associated with Tyrrhena (units Htf and AHtp of [12], unit HNre of [13]).

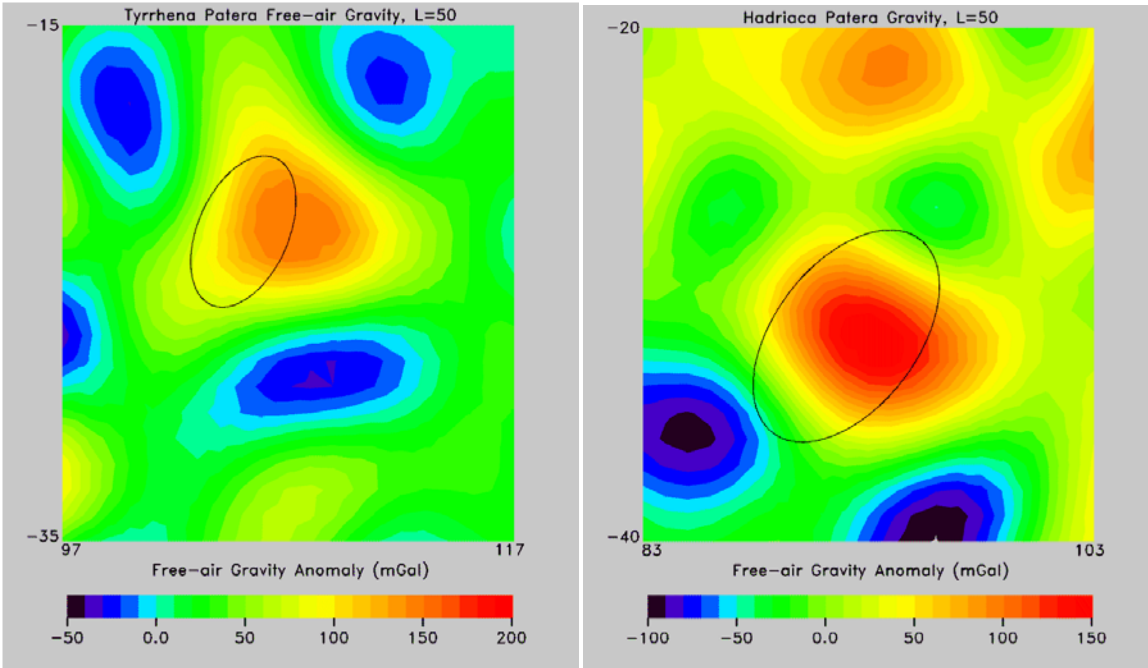

Figure 1: The spherical harmonic degree 50 free-air gravity anomaly at Tyrrhena Patera (left) and Hadriaca Patera (right). The ellipses shows the location of the volcanic edifices.

Much of the lava in these plains must have been processed through the magma chamber system imaged by the gravity anomaly.

Hadriaca Patera: Hadriaca Patera is 330 by 550 km across with a maximum relief of 1.1 km [9]. The summit caldera is nearly circular, with a diameter of 77 km. Hadriaca is primarily Hesperian in age, and based on its morphology is interpreted as forming primarily by pyroclastic flows [14].

Figure 1b shows the gravity anomaly across Hadriaca. The peak gravity anomaly at Hadriaca is 141 mGal at spherical harmonic degree 40 and 154 mGal at degree 50. A model using just flexurally supported surface topography is a poor fit to the observations over the volcano (Figure 3, 93 East, 33 South), so a buried high density load is required. The topographic high north of Hadriaca (Figure 3b, 20-25 South) is well fit by flexurally supported topography alone with an elastic lithosphere of 15 km.

An excellent fit to the data can be achieved using two buried cylinders in addition to the flexurally supported topography. Cylinder 1 (93.5 East, 32.5 South, R=250 km) has a minimum thickness of 4.7 km (olivine dominated) to 7.8 km (pyroxene dominated). Cylinder 2 (98.5 East, 32.5 South, R=150 km) is about 80% as thick as cylinder 1, assuming that the two cylinders have the same $\delta\rho$. As at Tyrrhena Patera, much of the lava plains surrounding Hadriaca Patera probably passed through the magma chamber system revealed by the gravity data. Assessing the volume and hence mass of these plains is difficult because Hadriaca is located on the topographic slope into the Hellas impact basin.

Amphitrites Patera: Amphitrites Patera and Peneus Patera are calderas that form a single volcanic complex on the southwest rim of the Hellas basin. Lava flow morphologies are obscured by aeolian mantling, but the caldera morphology resembles Syrtis Major [15]. Each caldera is 120-135 km across. The overall edifice is 600-700 km across, with a topographic relief of 0.5-1.5 km [9,15].

The gravity anomaly is 133 mGal at spherical harmonic degree 40 and 185 mGal at spherical harmonic degree 50, centered on the Amphitrite caldera at 61 East, 59 South. This anomaly is one of the largest known in the southern hemisphere of Mars [2]. Based on its large amplitude and the volcanic morphology, it seems likely that Amphitrites and Peneus are another example of a large, buried magma chamber. Detailed models of this anomaly are presently in development.

Implications

Magma chamber systems have now been observed at three volcanos on Mars, Syrtis Major, Tyrrhena Patera, and Hadriaca Patera. Amphitrites Patera is probably a fourth example. It is highly unlikely that errors in the gravity field determination would produce large gravity anomalies over each volcano. Similarly, it is also unlikely that high density material unrelated to the volcanos would occur beneath the each volcano by chance. Thus, the overall suite of results reported here greatly strengthens the case for buried magma chamber systems at each location.

The minimum magma chamber thicknesses inferred in

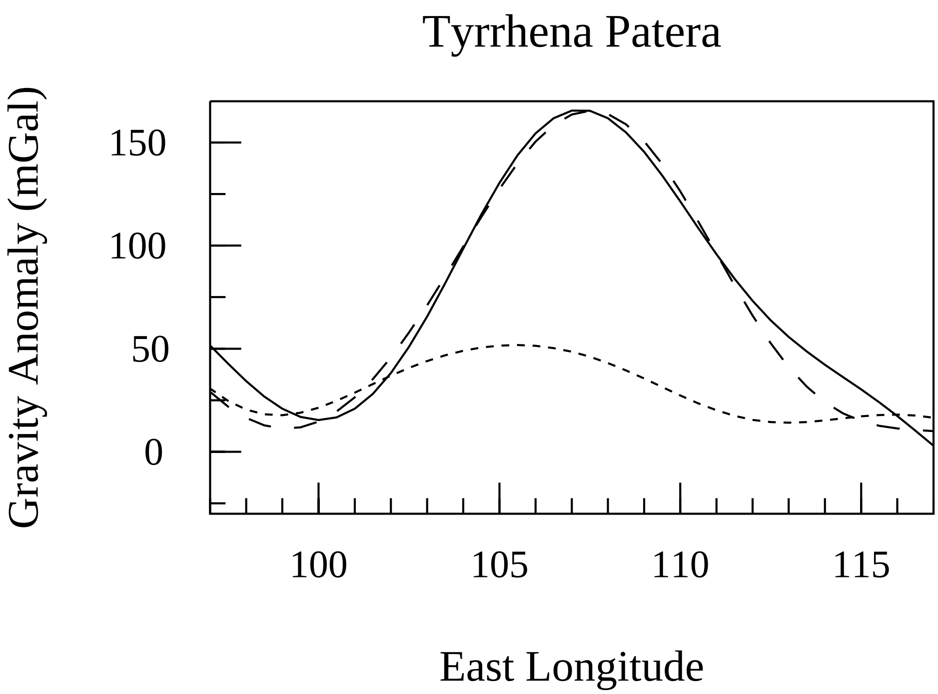

Figure 2: Gravity profiles across Tyrrhena Patera at 22.5 South Latitude. The solid line is the observed gravity anomaly (model MGM1025, spherical harmonic degrees 2-50), the short dashed line is a model based on flexurally supported topography, and the long dashed line is a model that includes both flexurally supported topography as well as the buried, high-density load.

this study range from 2.9 to 4.7 km for olivine-dominated systems and 4.7 to 7.8 km for pyroxene-dominated systems. Although olivine may contribute to these cumulate systems, it is unlikely that the required cumulate mass could be explained by olivine alone. Thus, the minimum chamber thicknesses are probably closer to the pyroxene-dominated thicknesses. However, considerably thicker chambers are permitted by the gravity data. Because of the large horizontal extent of the magma chambers and the likelihood that much of the lava in the surrounding plains flowed through these chambers, thicker chambers with correspondingly smaller values of $\delta\rho$ are likely. Because these structures formed as cumulates, probably over long periods of time, the entire thickness of the system did not need to be molten at any given time.

Terrestrial Analogs

A number of possible terrestrial analogs exist for these large-scale magmatic structures on Mars. Several large igneous provinces (the Deccan Traps, Kerguelen, the North Atlantic Volcanic Province, and Ontong Java) exceed $10^6 km^2$ in area and range from $6 \cdot 10^6$ to $7 \cdot 10^7 km^3$ in volume [16]. These are not primarily cumulate structures, although the small volume Skaergaard layered intrusive complex is a part of the North Atlantic Volcanic Province [17]. Seismic reflection and gravity data define a dense, subcrustal intrusive complex beneath Hawaii that is 200 km across and up to 6 km thick [18]. Gravity modeling of Iceland has recently been used to infer abnormally dense lower crust that is several hundred kilometers across [19].

Future Observations: Mars Reconnaissance Orbiter

The limiting factor in the spatial resolution of the martian gravity field is the spacecraft altitude. *Mars Global Surveyor* operated at a periapsis altitude of 370 km [2], whereas the *Mars Reconnaissance Orbiter* is currently planned to have a periapsis altitude of 250 km. This should permit roughly a 50% increase the gravity field resolution, with a geophysically interpretable resolution of about harmonic degree 80. This will permit tighter limits on the allowed cylinder radii in these models. In turn, this will also place tighter bounds on the required magma chamber thickness and density contrast, improving our overall knowledge of the magmatic plumbing system of Mars.

[1] Smith et al., JGR 106, 23,689-23,722, 2001. [2] Lemoine et al., JGR 106, 23,359-23,376, 2001. [3] Yuan et al., JGR 106, 23,377-23,401, 2001. [4] Kiefer, EPSL, submitted, 2003. [5] Turcotte et al., JGR 86, 3951-3959, 1981. [6] Consolmagno and Britt, MAPS 33, 1231-1241, 1998. [7] Britt and Consolmagno, MAPS, in press, 2003. [8] Schaber, JGR 87, 9852-9866, 1982. [9] Plescia, LPSC 33, abstract 1854, 2002. [10] Greeley and Crown, JGR 95, 7133-7149, 1990. [11] Greeley and Guest, USGS Map I-1802B, 1987. [12] Leonard and Tanaka, USGS Map I-2694, 2001. [13] Gregg et al., USGS Map I-2556, 1998. [14] Crown and Greeley, JGR 98, 3431-3451, 1993. [15] Plescia, LPSC 34, abstract 1478, 2003. [16] Coffin and Eldholm, Rev. Geophys. 32, 1-36, 1994. [17] Ernst and Buchanan, pp. 483-575 in Mantle Plumes: Their Identification Through Time, GSA Special Paper 352, 2001. [18] ten Brink and Brocher, JGR 92, 13,687-13,707, 1987. [19] Gudmundsson, EPSL 206, 427-440. 2003.

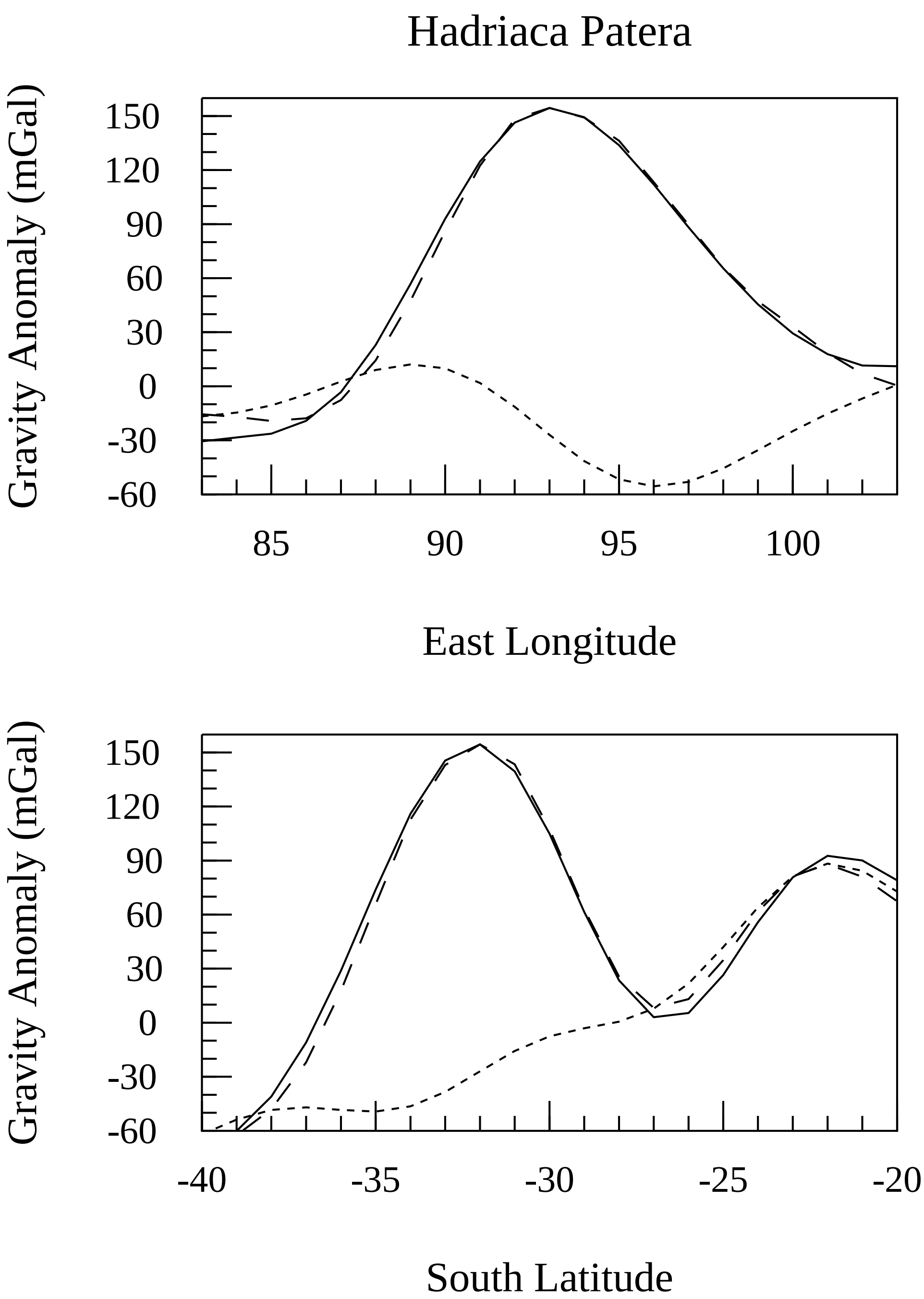

Figure 3: Gravity profiles across Hadriaca Patera. Top: East-West across 32 South latitude. Bottom: North-South across 93 East longitude. The solid lines are the observed gravity anomalies (model MGM1025, spherical harmonic degrees 2-50), the short dashed lines are models based on flexurally supported topography, and the long dashed lines are models that includes both flexurally supported topography as well as buried, high-density loads.