Large Impact Structures and the *GRAIL Bouguer Reduction Density*. Kenneth. F. Sprenke[1], Mark. W. Piersol[1], [1]Department of Geological Sciences, University of Idaho, Moscow, Idaho 83844. ksprenke@uidaho.edu.

Introduction: The bulk density of the lunar crust has been inferred based on the Bouguer reduction density found by minimizing the correlation between *GRAIL* gravity and the topography of the lunar highlands.. However, this inference cannot be made without taking into account density contrasts associated with the visible impact structures that shape, and are clearly correlated with, the topography of the Moon. It is reasonable to expect that the subsurface structures associated with the larger craters extend downward through the pre-impact megaregolith into lunar bedrock. This results in a negative density contrast between the deepest crater fill and the surrounding bedrock. We have found that the 2550 kg m^{-3} Bouguer reduction density found for the lunar highlands can be modeled by a bedrock bulk density of 2900 kg m^{-3} , a megaregolith bulk density of about 2400 kg/m3, and bedrock excavations about 1 km in amplitude beneath the larger currently visible craters.

GRAIL [1] resolved wavelengths as short as 26 km, a four-fold improvement on previous gravity models, making it useful for examining anomalies associated with surface topography. Not affected by deep sources, these short wavelength data offer an opportunity to directly determine the average bulk density of the rocks that form the surface topography. The correct reduction density is the one that minimizes the correlation between surface topography and the Bouguer anomaly. By this method, the reduction density of the lunar highlands is 2550 kg m^{-3} +/- 18 kg m^{-3} [2]. This value has been inferred to represent the bulk density of lunar crust [2]. This may or may not be correct because it does not take into account variations in the thickness of the lunar megaregolith associated with large impact structures. The detailed properties of the megaregolith including its thickness and distribution are essentially unknown [3, 4]. Knowledge both of the distribution of megaregolith thickness with surface elevation and its bulk density are required to get an unbiased estimate of bedrock density from the Bouguer reduction density. Below, we show that the Bouguer reduction density found by *GRAIL* can be modeled in terms of megaregolith thickness variations associated with the larger impact structures on the Moon.

Method: Over homogeneous crustal rock, the Bouguer anomaly is

$$g_{BA} = g - g_{BC} = \text{random noise} \qquad (1)$$

where g is the free air gravity (as processed from *GRAIL* observations onto a surface of constant elevation above the topography), and g_{BC} is the Bouguer correction for the surface topography using the Bouguer reduction density ρ_R found by minimizing the correlation between the Bouguer anomaly and topography.

However, if we consider the highlands to consist of megaregolith overlying bedrock, the Bouguer anomaly is equivalently represented as

$$g_{BA} = g - g_{BRC} - g_{MRC} = \text{random noise} \qquad (2)$$

where g_{BRC} is the correction for the bedrock thickness above the datum using a bedrock density ρ_{BR}, and g_{MRC} is the correction for the thickness of the overlying megaregolith of density ρ_{MR}.

Combining (1) and (2), we see that the Bouguer correction gets contributions from both the megaregolith and the bedrock components of the topography.

$$g_{BC} = g_{BRC} + g_{MRC} \qquad (3)$$

Or in terms of densities, we find the Bouguer reduction density is a weighted average of the densities of the two rock materials that compose the topographic response:

$$\rho_R = \rho_{MR}\, b + \rho_{BR}\, (1 - b) \qquad (4)$$

where b is a weighting factor as estimated below.

A simple linear regression model of megaregolith thickness t with surface elevation h would result in a linear relationship of the form

$$t = a + b\, h + \text{random noise} \qquad (5)$$

where a is the intercept and b is the slope, representing how megaregolith thickness changes with surface elevation. If b is zero, there is no correlation between regolith thickness and topography. This would occur if t is either evenly or randomly distributed on the topography. For the larger impact structures, we consider only the change in h and t as a result of the impact into megaregolith of unknown thickness. We find:

$$b = 1 - T_D / D_A \qquad (6)$$

where T_D is the thickness of the deposit filling any new sub-crater excavation in bedrock, and D_A is the apparent depth of the crater. Note that the actual thickness *t* of the megaregolith does not affect this relation. It is only the lateral density contrast between the bedrock and the fragmental megaregolith material occupying the bedrock excavation that is important. This creates a gravity effect that is correlated with h, thereby interfering with the correlation of gravity and surface topography.

If we assume the megaregolith is composed of materials fragmented by impacts into the highlands bedrock, then ρ_{MR} must be less than ρ_{BR} because of bulking. Fragmentation can increase the volume of a rock mass by as much as 80%. In terms of bulk density:

$$\rho_{MR} = \rho_{BR} / B_F \qquad (7)$$

where B_F is the bulking factor.

Using (7) in (4), and solving for bedrock density, we find (for $b \neq 1$):

$$\rho_{BR} = \frac{1}{(1-b)+b/B_F}\,\rho_R \qquad (8)$$

Thus the bedrock density of the lunar highlands can be related to the Bouguer reduction density provided that B_F and b are known. This relation is shown in Figure 1.

Our procedure to find an explanation for the *GRAIL* Bouguer reduction density in terms of impact structure is as follows. First we estimate the B_F and ρ_{BR} for the Moon. Then, we use (8) to find the factor b. Then we use b and an estimate of D_A for the larger complex craters in (6) to solve for a value of T_D that results in a ρ_R of 2550 kg m^{-3}.

Results: On Earth, bulking factors range from 1.1 for granular materials like sand to as high as 1.8 for hard rocks, with a median of about 1.38 for all materials [5]. Bulking factors directly measured on ejecta from nuclear test craters in the 1960s ranged from 1.1 to 1.6 [6]. Recent studies suggest that ρ_{MR} may be as low as 2400 kg/m3. [7,8]. This suggests a B_F of close to 1.2 on the Moon.

Plotting a point using a B_F of 1.2 on Figure 1, and using a ρ_{BR} of 2900 kg m^{-3} for lunar bedrock, we find that b is close to 0.7 for the larger craters on the lunar highlands. According to our model, using (6), this means that the bedrock excavations, at unknown depths below the larger craters, must have an amplitude equal to 30% of the apparent depth of the craters to explain the GRAIL Bouguer reduction density.

Large 50-200 km diameter complex craters on the Moon do not extend much deeper than 3400 m below the pre-impact datum [9]. So, we use a D_A of 3400 m in (6) along with our b of 0.7 to find that a T_D of close to 1 km is consistent with the GRAIL observed Bouguer reduction density.

Thus, we have found that the Bouguer reduction density of 2550 kg m^{-3} found by *GRAIL* can be modeled by a bedrock bulk density of 2900 kg m^{-3}, a megaregolith bulk density of about 2400 kg m^{-3}, and megaregolith-filled bedrock excavations of about 1 km in amplitude under the larger currently visible craters.

Discussion: What of the many ancient large lunar impacts with completely degraded craters? Provided they did not completely flatten the bedrock surface, they are irrelevant to our results because their gravity effects, though present, no longer correlate with topography.

The net megaregolith thickness does not affect our model. It could be as thin as about 4 km where seismic velocities increase from less than 3 km/s to as high as 6 km/s, suggesting a change from fragmental material to fractured, but coherent, crystalline bedrock, or it could be as deep as tens of kilometers where relatively undisturbed crystalline bedrock is present [10]. However, there is no way to tell from the simple correlation of GRAIL gravity with topography. Any use of the 2550 kg m-3 value for mean crustal density should be used only with extreme caution.

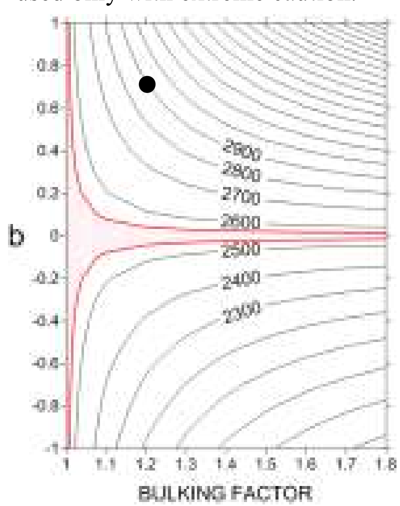

Figure 1. Lunar bedrock bulk density (kg m^{-3}) from *GRAIL* data as a function megaregolith bulking factor B_F and distribution of megaregolith thickness with topography b. [11].

References: [1] Zuber, M. et al. (2013) *Science* 339, 617. [2] Weiczorek, M. et al. (2013) *Science*, 339, 671. [3] McKay, D. et al. (1991) *LunarSourcebook*, Ch 7, 286. [4] Horz, F. et al.. (1991) *Lunar Sourcebook*, Ch 4, 93. [5] Ofoeghu, G., (2008), *NRC* Contract 02-07-006, 3.17. [6] Johnson, S. (1971), *NCG Tech Rpt* 21, 21.[7] Kiefer, W.S. et al.)2012) *GRL*, 39, L07201. [8] Han S.C et al., (2014) *GRL*, 41, 1882-1889., [9] Pike, R.J., (1977) *LPS VIII*, p. 3427-3436. [10] Head J.W. (1976) *LPS VII*, p 354-355. [11] Piersol and Sprenke (2014) *LPS 45th*, Abs. 1006.