Bulk Density of Lunar Highlands Bedrock from *GRAIL* Gravity. Mark. W. Piersol[1], Kenneth. F. Sprenke[1]
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Introduction: Gravity data from the *GRAIL* mission has revealed that the average Bouger reduction density for the topography of the lunar highlands is 2550 kg m−3. This result has been used to imply a bedrock (and crustal) bulk density of the same value. However, we claim that the bedrock density of the lunar highlands cannot be found from the Bouguer reduction density without taking into consideration the lunar megaregolith. We show that knowledge both of the distribution of megaregolith thickness with surface elevation and of the bulking factor of the lunar bedrock that forms the large scale ejecta of the megaregolith are required to get an unbiased estimate of bedrock bulk density from the Bouguer reduction density.

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, which might adequately represent the average bulk density of the terrain-forming material in the upper few kilometers of the highlands, has been presumed to represent the bulk density of lunar bedrock [2]. This may or may not be correct.

In the lunar highlands, beneath some 10-15 m of lunar soil (regolith) is the megaregolith, a complex zone that probably consists of large-scale (>1 m) ejecta and impact-fractured, brecciated bedrock (Figure 1). The detailed properties of the megaregolith including its thickness and distribution are essentially unknown [3]. The Bouguer reduction density found by *GRAIL* is an adequate estimate for bedrock bulk density only if one of the following unlikely assumptions is true: 1) the megaregolith has the same bulk density as the lunar bedrock; or 2) the megaregolith is either randomly or uniformly distributed on the highlands topography. Here, we investigate what this reduction density result actually reveals about the bulk density of lunar bedrock.

Method: Over homogeneous crustal rock, the Bouguer anomaly is

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

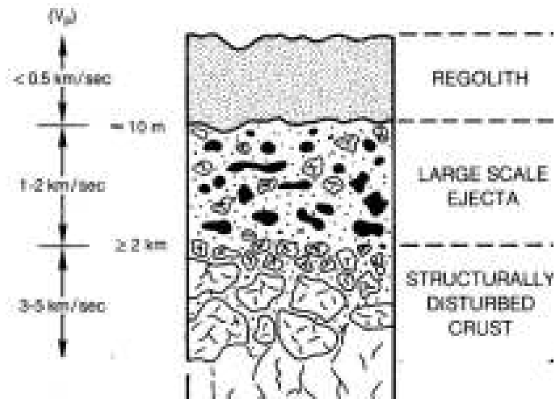

Fig. 1. The lunar megaregolith, lying between the regolith and bedrock, consists of ballistically transported coarse-grained, ejecta and melt sheets [4]..

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 homogeneous bedrock, the Bouguer anomaly is equivalently represented as

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

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}.

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

$$t = a + b\, h + \text{random noise} \quad (3)$$

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. In this case, the Bouguer reduction density provides an unbiased estimate of bedrock density. On the other hand, if b is non-zero, the estimate is biased.

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

$$g_{BC} = g_{BRC} + g_{MRC} \quad (4)$$

But, using the Bouguer slab formula

$$g_{BC} = 2\pi\,\gamma\,\rho_R\,h \quad (5)$$

and using the regression constants (3), we find, ignoring terms constant with respect to h::

$$g_{MRC} = 2\pi\,\gamma\,\rho_{MR}\,t = 2\pi\,\gamma\,\rho_{MR}\,b\,h \quad (6)$$

and

$$g_{BRC} = 2\pi\,\gamma\,\rho_{BR}\,(h - t) = 2\pi\,\gamma\,\rho_{BR}\,(1 - b)\,h \quad (7)$$

Substituting (5), (6), and (7) into (4), and dividing by $2\pi\,\gamma\,h$, we find the Bouguer reduction density is a weighted average of the densities of the two rock materials that compose the topography:

$$\rho_R = \rho_{MR}\,b + \rho_{BR}\,(1 - b) \quad (8)$$

Note that if the topography is all megaregolith, then b = 1; if the topography is all bedrock, then b = 0; if the megaregolith tends to concentrate in topographic basins, then b < 0.

If we assume the megaregolith is completely composed of ejecta from impacts into the highlands bedrock, then ρ_{MR} must be less than ρ_{BR} because of bulking. Excavation can increase the volume of a rock mass by as much as 80%. For a lunar impact crater, a bulking factor represents the volume of redeposited ejecta divided by the volume of the same bedrock material *in situ* prior to ejection. In terms of bulk density:

$$\rho_{MR} = \rho_{BR} / B_F \quad (9)$$

where B_F is the bulking factor. 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]..

Using (9) in (8), and solving for bedrock density, we find (for $b \neq 1$):

$$\rho_{BR} = \frac{1}{(1-b) + b/B_F}\,\rho_R \quad (10)$$

Thus the bedrock density of the lunar highlands can be found from the Bouguer reduction density provided that B_F and b are known.

Results: As predicted by equation (10), lunar bedrock bulk density depends not only on the Bouguer reduction density but also on both the distribution of megaregolith thickness with topography and the bulking factor of lunar bedrock (Figure 2). For example, if megaregolith thickness is positively correlated to topography, then the actual bulk density of the bedrock could be nearer to the 2800 kg m-3 to 2900 kg m-3 values used in most pre-*Grail* crustal models, particularly if the lunar bedrock has a bulking factor similar to rocks on Earth.

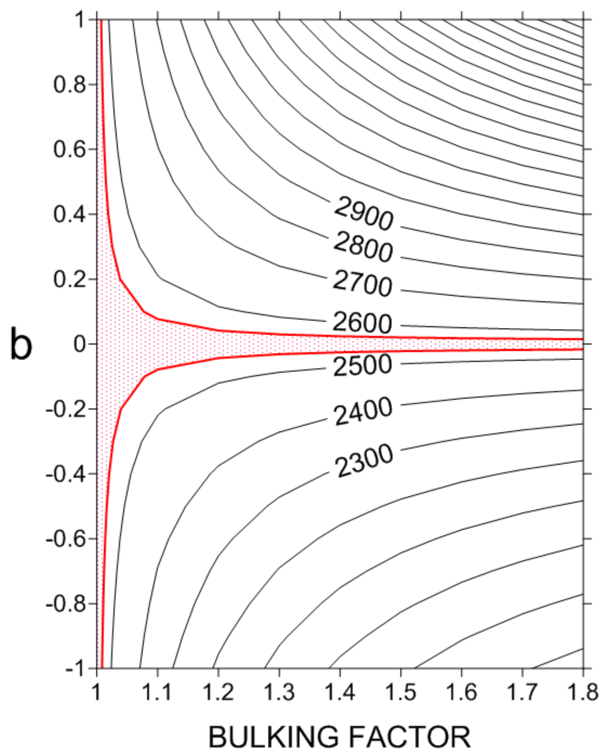

Figure 2. Lunar bedrock bulk density (kg m^{-3}) from *GRAIL* data as a function megaregolith bulking factor B_F and distribution of megaregolith thickness with topography b (See text). The Bouguer reduction density found by *GRAIL* (red area) is an unbiased estimate of bedrock bulk density only if $b \approx 0$ or $B_F \approx 1$.

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.