THE EFFECT OF PRE-IMPACT POROSITY AND VERTICAL DENSITY GRADIENTS ON THE GRAVITY SIGNATURE OF LUNAR CRATERS AS SEEN BY GRAIL.

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Introduction and Background: As a result of NASA's dual Gravity Recovery And Interior Laboratory (GRAIL) spacecraft mission [1], we now know that the lunar crust is highly porous and that the porosity varies laterally [2] and vertically [3]. Porosity is related to the bulk density, and will therefore affect the gravity signature of craters.

Soderblom et al. [4] analyzed ~1200 complex craters located within the lunar highlands and calculated the Bouguer anomaly (BA) for each. Three trends emerged: 1) craters larger than diameters *D*~210 have a positive BA, 2) craters with *D* less than ~100 km have BAs that are both positive and negative that vary about the (near 0) mean by approximately +/- 25 mGal, and, 3) there is a small negative relation between *D* and BA for craters with *D* < 100 km.

Phillips et al. [5] showed that complex craters located in the South Pole-Aitken (SP-A) basin tend to have more negative BA values than those located in the highlands. Besserer et al. [3] noted that the low-density (porous) layer within SP-A is thinner than the rest of the farside.

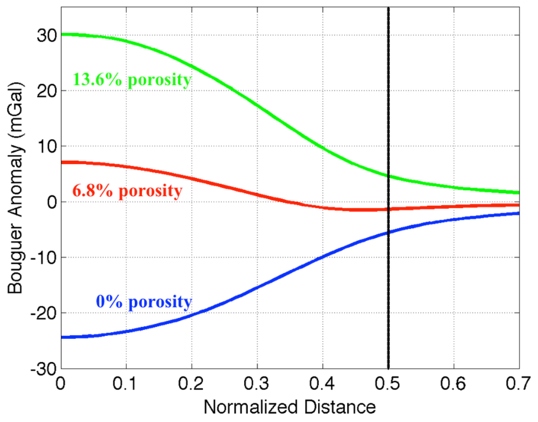

Figure 1. BA vs. distance from crater center divided by *D*, for a 3 km impactor. The thick black line is represents the crater rim.

Milbury et al. [6] showed that porosity influences the gravity signature of complex craters (most significantly) for *D* less than ~100 km (see Fig. 1), and mantle uplift dominates the gravity for *D* > 140 km (See Fig. 2). This study is motivated by the observation that if porosity generally decreases with depth, smaller impacts will affect portions of the crust with higher porosity more than relatively larger impacts.

We seek to address two issues by modeling vertical porosity/density gradients: 1) the observed negative relation between BA and *D* for *D* < 100 km, and 2) the observed difference between the gravity signature of SP-A and highland craters.

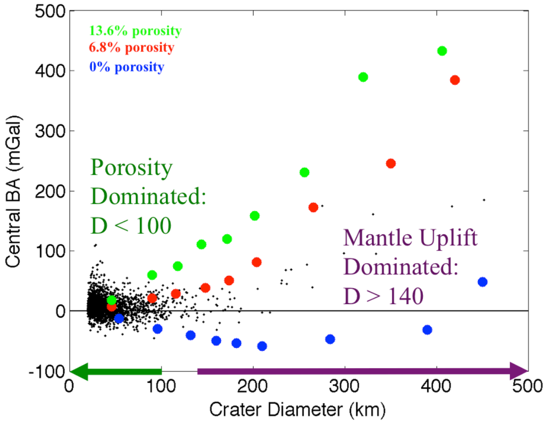

Figure 2. Central BA vs. *D*. The blue dots represent 0% initial porosity, the red dots are for 6.8% porosity, the green dots are 13.6% porosity, and the black stars represent the data from Soderblom et al. [4].

Methods and Modeling: Porosity is a measure of void space in a material, and dilatancy is the creation of pore space during shear deformation. In this study, we use the iSALE hydrocode, with improvements to model porosity [7], and dilatancy [8], to determine their effects on the gravity signature of impact craters. Milbury et al. [6] also modeled porosity and dilatancy, but for a crustal layer with uniform porosity. Here, we vary porosity with depth. We use the following relation from Besserer et al. [3] that relates bulk density (and therefore porosity) to depth:

$$\rho_z = \rho_0 + \Delta\rho\left(1 - z^{-z/d}\right)$$

where ρ_0 ρρis the surface density,ρ is the difference between the grain density (ρ_g) and the surface density, d is the e-folding depth, and z is depth. Besserer et al.

[3] found for the following values for the lunar highlands, which are used here: ρ_0=2223 kg/m^3, ρ_g=2917 kg/m^3, and values of 10 km and 30 km for *d* (which give mean porosities of 6.3% and 14.0%, respectively).

We approximate a 35 km thick crust with seven 5-km thick, constant-porosity layers and evaluate the porosity at the midpoint of each layer. We also performed simulations that have a top layer that is nonporous, analogous to the lunar maria. We performed simulations for impactors that are 3, 6, 8, 10, and 12 km in diameters.

We use the following model parameters in our simulations: an analytical equation of state (ANEOS) for granite in the crust and dunite for the mantle and impactor, a melt temperature of 1373 K, an impact velocity of 15 km/s, a surface gravity of 1.62 m/s^2, and a thermal gradient of 5 K/km. We use strength parameters of gabbroic anorthosite for the crust, and dunite for the mantle and impactor [9]. All of the computations assume axial symmetry so the impacts are necessarily vertical. The dilatancy model parameters used here were based on calibration of the dilatancy model with porosity/gravity data from terrestrial craters [8].

We calculate the *residual* and *central* BA associated with the simulations listed in Table 1 and compare them with results from Soderblom et al. [4]. The *residual* Bouguer anomaly is the area-weighted mean BA calculated interior to the crater rim less the mean BA within an annulus exterior to the crater rim, and the *central uplift* Bouguer anomaly is the area-weighted mean BA from the center to 0.2 rim radii less the area-weighted mean BA within an annulus that extends from 0.5 to 1.0 rim radii.

Results and Discussion: We find that the BA is significantly affected by varying the density/porosity as a function of depth. Fig. 3 shows that the uniform porosity simulations have a lower BA, for a given impactor *D*, as expected. It also shows that the BA increases with increasing porosity, similar to the uniform porosity simulations. Larger impacts will affect relatively larger portions of the crust, and therefore have lower porosity, so the amplitude of the BA will not increase with *D* as significantly as the uniform porosity simulations.

In the simulations where a nonporous surface layer is modeled (analogous to a mare layer), the amplitude of the BA is decreased, which is in agreement with previous results for a nonporous target [6]. This shows that the residual or central BA, are only useful for estimating general trends. In order to determine the porosity accurately for a specific crater, one must model crater formation in detail.

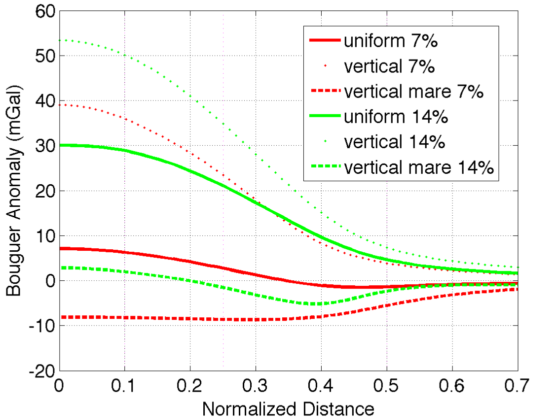

Figure 3. The same as in Fig. 1, but for simulations with uniform porosity, a vertical porosity gradient, and vertically varying porosity with a nonporous top layer.

These results are in agreement with the observation that SP-A has a lower density/porosity in general, but that the vertical gradient is also higher, and that craters within SP-A have BAs that are more negative than those within the highlands crust. If the lunar maria have a low porosity surface layer that is sitting on top of a more fractured and porous crust, then the expectation is that crater BAs would have different characteristics depending on which region of crust they are located within, which is what is observed [10].

Conclusions: We have demonstrated that the negative trend observed in the BA vs. *D* for *D*<100 km is likely explained by a vertical gradient in the density/porosity. This is especially important for small impacts, which are more affected by the porosity in upper part of the crust more than larger impacts are. This is in agreement with the observation that for small *D*, complex craters within SP-A, highlands, and maria, will all have different trends in the BA vs. *D* plot [10].

References: [1] Zuber M. T. et al. (2013) *Science*, 339, doi: 10.1126/science.1231507. [2] Wieczorek M. A. et al. (2013) *Science*, 339, 671. [3] Besserer J. et al. (2014) *GRL*, doi:10.1002/2014GL060240. [4] Soderblom J. M. et al. (2015), submitted. [5] Phillips R. J. et al. (2015), *LPSC XLVI*, abstr. #2897. [6] Milbury C. et al. (2015) *LPSC XLVI*, abstr. #1966. [7] Wünnemann K. et al. (2006), *Icarus*, *180*: 514-527. [8] Collins G. S. (2014), *JGR*, doi:10.1002/2014JE004708. [9] Potter R. W. K. et al. (2013), *JGR*, 118:963-979. [10] Bierson C. J. (2015), pers. comm..