THE EFFECT OF PRE-IMPACT POROSITY ON THE GRAVITY SIGNATURE OF LUNAR CRATERS.

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Introduction and Background: NASA's dual Gravity Recovery and Interior Laboratory (GRAIL) [1] spacecraft have globally mapped the lunar gravity field at unprecedented resolution; this has enabled the global study of small craters up to the largest basins. Results have shown that the lunar crust has a large range of porosities with an average value of 12% [2], and that there are vertical density gradients [3] within the crust.

Soderblom et al. [4] made a comprehensive analysis of the *residual* and *central uplift* Bouguer gravity anomalies associated with more than 5200 lunar craters. There were two main observations that are related to the work presented here: 1) craters less than ~150 km in diameter (*D*) have a *residual* Bouguer anomaly (BA) that is near zero on average (although a negative trend is observed), but have both positive and negative anomalies that vary by approximately ±25 mGal about the mean, and, 2) there is a transition at which the *central uplift* BA becomes positive and increases with *D*. Craters that are located in the maria and South Pole-Aitken (SPA) basin were excluded from the analysis because they tend to have more negative signatures than highlands craters.

These gravitational signatures contrast with the invariably negative gravity anomalies associated with terrestrial craters [5], and early analysis of four complex lunar craters [6]. We test the hypothesis that the observed difference in gravity signatures between lunar and terrestrial craters can be explained by differences in initial crustal porosity [4].

porosity	0%	6.8%	13.6%
$D_{impactor}$ (km)	D_{crater} (km)	D_{crater} (km)	D_{crater} (km)
3	52	46	46
6	98	88	86
8	130	118	112
10	160	146	138
12	178	174	163
14	215	206	198
18	282	264	258
24	388	350	340
30	450	424	410

Table 1. Table showing the size range of impactors and the resulting craters for each porosity that are modeled here.

Methodology and Modeling: Porosity is a measure of void space in a material, and dilatancy is the creation of pore space during shear deformation of rock material. In this study, we use the iSALE hydrocode to model porosity [7], and a new approach to include dilatancy [8], to determine their effects on the gravity signature of craters.

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 a 35 km thick crust, and dunite for the mantle and impactor [9]. See Table 1 for impactor and final crater diameters for each porosity. 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 uplift* 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 the background annulus, 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.

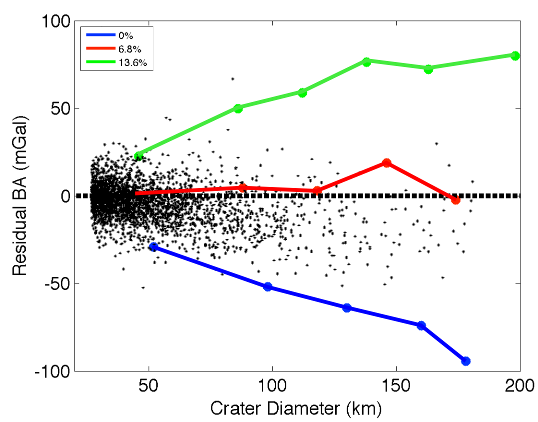

Figure 1. Plot of the modeling results (colored dots) for the *residual* Bouguer anomaly with data from [4] (black stars).

Results and Discussion: Figures 1 and 2 summarize the results of the simulations listed in Table 1 (colored dots) and show that they are in agreement with observations from GRAIL [4] (black stars). They show that magnitude of the Bouguer anomaly increases with increasing porosity. The plot of the *residual* Bouguer anomaly in Figure 1 shows that the porosity of the crust surrounding craters with *D*~50-200 km is likely to be less than the global average value of 12% reported by Wieczorek et al. [2]. However, this is an average value that includes the craters themselves and excludes the maria regions.

Figure 1 shows that smaller craters tend to have a more positive *residual* Bouguer anomaly than larger craters. This can be explained by vertical porosity gradients in the lunar crust [3], or if the amount of fracturing scales with crater diameter [4]. In general, porosity decreases with depth as lithostatic pressure increases, and smaller craters do not penetrate into the crust as deeply as larger ones do, so small craters will have a relatively larger magnitude *residual* BA for the same pre-impact target porosity. This can also explain the observed negative *residual* BA associated with craters formed in the lunar maria and SPA (and associated melt sheet) because they are typically less porous than the highlands crust.

These results show that a negative trend is predicted only for low porosities. Targets with nonzero porosities tend to have more positive *residual* Bouguer anomalies, and as the diameter of the crater increases, the amplitude decreases. However, there is a transition for large *D* where the *central uplift* BA becomes strongly positive (see Figure 2). This transition can be explained by a positive density anomaly associated with uplift of the mantle beneath large craters.

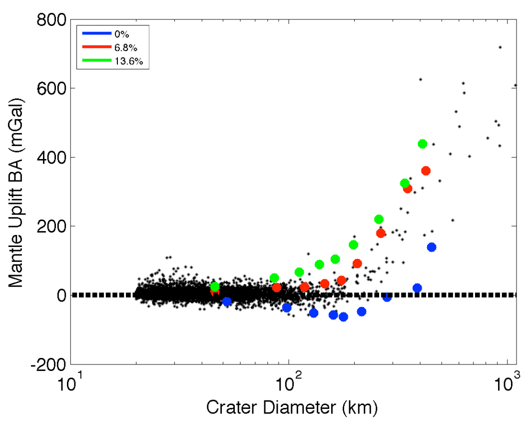

Figure 2. Plot of the modeling results for the *central uplift* BA (colored dots) with data from Soderblom et al. [4] (black stars).

Milbury et al. [10] calculated the BA for the simulations listed in Table 1, but due soley to mantle uplift. Figure 3 plots the *central uplift* BA for the simulations listed in Table 1 due to mantle uplift alone. This plot shows that mantle uplift can explain the observed transition from a zero to a positive BA. It also shows that the ±25 mgal scatter of BA anomalies is not due to mantle uplift; the source of that variation is likely pre-impact porosity, as explained above. This transition occurs at crater diameters of ~150-200 km, near the complex crater to peak-ring basin morphological transition.

Conclusions: The variable initial porosity of the lunar crust can explain why craters on the Moon exhibit both positive and negative Bouguer anomalies. The gravity signatures of craters on the Earth and Moon are qualitatively different, probably because of the high porosity of lunar crust [2] compared to terrestrial crust. The observed downward slope in the data (see Figure 1) is consistent with vertical porosity gradients and will be investigated in future work. Gravity anomalies due to mantle uplift reproduce the observed transition from zero to a positive *central uplift* Bouguer anomaly, which coincides with the morphological transition from complex craters to peak-ring basins.

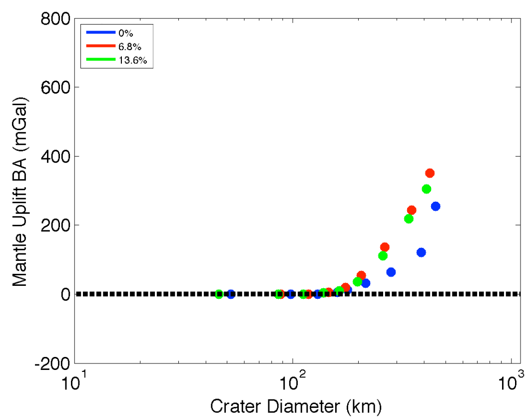

Figure 3. Plot of the *central uplift* Bouguer gravity anomalies due to mantle uplift alone [10]. The transition from zero to positive Bouguer anomaly occurs at crater diameters between ~150-200 km, which coincides with the complex crater to peak-ring basin morphological transition.

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. (2014), Abstract #1777, *45th LPSC.* [5] Pilkington and Grieve (1992) *Rev. Geophys*., 30, 2, 161-181. [6] Dvorak J. and Phillips R. (1977) *GRL 4,* 9.. [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] Milbury et al. (2014) *46th DPS*, abstract #205.06.