EFFECTS OF MEGAREGOLITH POROSITY STRUCTURE ON THE GRAVITY SIGNATURE OF LUNAR CRATERS: INSIGHTS FROM NUMERICAL SIMULATIONS.

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Introduction: The lunar crust experienced heavy bombardments since its formation, during which the upper crust was fractured and excavated. The lunar surface was thought to be covered by a layer of ejecta from larger-scale impacts, which is porous with a thickness down to several kilometers from surface [1]. The Gravity Recovery and Interior Laboratory (GRAIL) observations suggest that the porosity of this upper crust layer decreases with depth from the surface, with an average porosity of ~ 12% [2, 3].

The porosity of lunar crust greatly affects the gravity signatures of late-forming craters [4]. *Milbury et al.* [5] numerically simulated the effect of pre-impact porosity on the gravity signature for complex craters and showed that the crust porosity controls the crater gravity signature: the craters have negative residual Bouguer anomalies (RBAs) for the crust with porosity less than ~ 7%; porosity greater than ~7% produces positive anomalies. Here, the RBA is defined as the area-weighted mean Bouguer anomaly interior to the crater rim, subtracted by the mean Bouguer anomaly within a background annulus of width and inner radius equal to the crater radius.

Izquierdo et al. [6] analyzed the RBAs of smaller lunar craters with diameters (*D*) of 10-30 km from the GRAIL observations. They found that the RBAs of craters on lunar highlands statistically follow a two-slope linear relation with crater diameters, whose slope changes from positive to negative at *D* ~ 16 km. They proposed that this change is related to an abrupt porosity change of the lunar upper crust at a depth of ~ 3-5 km, which reveals the boundary between the layer of large-scale basin ejecta and the deeper less porous crust.

However, the exact relationship between the RBA and the crust porosity for small craters has not been well investigated. In this work, we conduct a series of impact simulations with varied pre-impact porosities and thicknesses for the top porous layer to produce craters with *D* between 5 km and 40 km. Our purpose is to systematically investigate the effects of the porous layer on the impact process and on the gravity signature for small impacts on the Moon.

Methodology: We use the shock physics code iSALE-2D to simulate the crater formation process. We use the ANEOS of granite and dunite [7, 8, 9] to represent the crust and impactor material, respectively. The strength and damage models [10, 11] are involved in our simulations. In addition, a porosity model [12] is considered for the top porous layer. All the simulations are assumed to be axisymmetric with a typical impact velocity of 15 km/s. To reproduce craters of ~5-40 km in diameter, the impactors are assigned to be 0.2, 0.5, 1.0, and 2.0 km in diameter.

In our simulations, we vary the thickness of the top porous layer from 0 to 8 km (i.e., 0, 3, 5, and 8 km) and the pre-impact porosity (ϕ) of this layer from 0 to 20% (i.e., 0, 5, 10, 15, and 20%). The underlying crust is assumed to be nonporous.

We then calculate the gravity anomalies and estimate the RBAs for the simulated craters, following [4]. The derived relationship between the RBAs and crater diameter from our simulations could be compared with that from the observations in [6].

Results and Discussions: An impact influences the target's porosity mainly through the compaction and expansion processes. Impacts dominated by compaction will result in positive RBAs, whereas impacts dominated by expansion will result in negative RBAs. Fig. 1 shows the Bouguer anomaly of a crater (*D* ~ 18 km) on a porous layer with a thickness of 5 km and an initial porosity of 15%. For such a porosity, the impact mainly compacts the porous crustal material near the crater center, and thus produces a positive RBA.

Fig. 2 shows the derived relationship between RBAs and crater diameters for our simulated craters with *D* ~ 4-38 km. For different thicknesses of the porous layer with an initial porosity of 15% (see Fig. 2a), the transition diameter for the *RBA-D* relationship to change from positive to negative varies. For the crust with none porous layer, the crater RBAs monotonously decrease with increasing crater diameter. This is because expansion dominates the cratering process in low-porosity regime. With the increase of the porous layer thickness, the compaction gradually dominates for small craters while the expansion still take control for large craters. Thus, the relationship between RBAs and crater diameter changes from positive to negative. For the case with a thick porous layer of 8 km, all of our tested impacts cannot excavate the porous layer. Therefore, compaction dominates for all craters, which only presents a positive relationship (see blue line in Fig. 2a). We note that the change of slope from positive to negative at *D* ~18 km for the porous layer of 3-5 km is well consistent with that derived from observations [6].

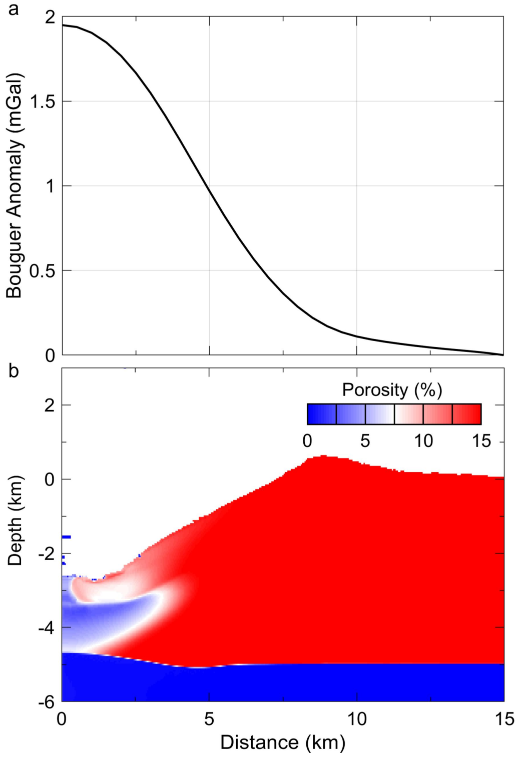

Figure 1. Crater profile and the corresponding Bouguer anomaly for a simulated crater with a top porous layer of 5 km and a pre-impact porosity of 15%. The crater shows a positive Bouguer anomaly.

The relationship between RBAs and crater diameter also depends on the initial porosity of the top porous layer. For a high initial porosity of 20% (purple line in Fig. 2b), craters with $D < 18$ km present a clear positive relationship while larger crater shows a negative one. The small impacts mainly compact the porous top layer materials; the larger impacts excavate the porous layer and penetrate to the underlying intact layer, the expansion of the lower layer gradually dominates. The diameter for the change of relationship reduces with decreasing pre-impact porosity. For a lower pre-impact porosity of 10%, the relationship changes from positive to negative at $D \sim 8.9$ km (see green line in Fig. 2b). A pre-impact porosity of 15-20% can be derived by comparing with observed transition at $D \sim 18$ km from observations [6].

Conclusions: We numerically simulate the crater formation and porosity evolution for craters with diameters of 5-40 km on the Moon, and investigate the effects of the pre-impact porosity and thickness of the top porous layer on the gravity signature of the craters. Our primary results show that the relationship between RBAs and crater diameter changes for different porosities and thicknesses of the porous layer. Comparison between simulation results and observations confirm the boundary between the layer of large-scale basin ejecta and the deeper less porous crust at 3-5 km from surface.

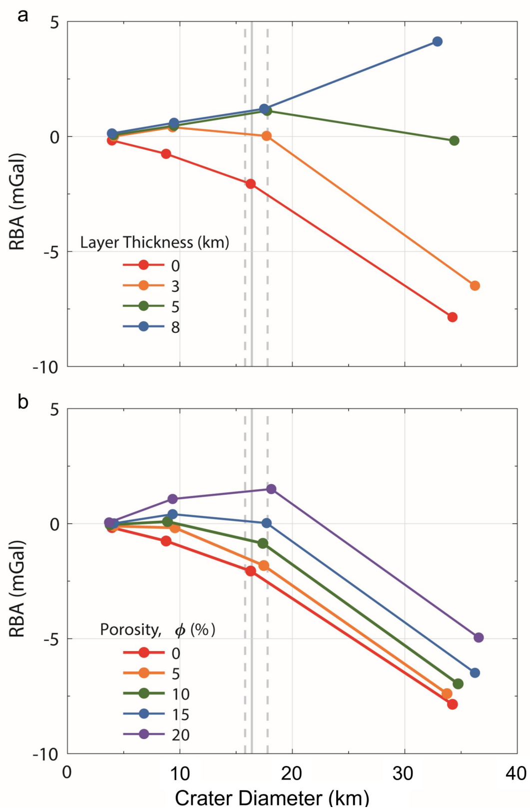

Figure 2. Relationship between RBAs and crater diameter for different porous layer thickness with a fixed porosity of 15% (a) and for different porosities with a fixed thickness of 3 km (b). The gray lines represent the changes of relationship from observations [6].

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