GEOLOGY OF UNUSUALLY DEEP LUNAR CRATERS IN THE SIMPLE-COMPLEX TRANSITION.

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Introduction: Simple craters typically form with a depth/diameter (*d/D*) ratio ranging from 1/5 to 1/7 [1,2]. While examining the geology of well-preserved lunar craters in the simple-complex transition size range of 15-20 km [3], we identified 22 unusually deep simple craters ($d/D > 0.20$ and more than a standard deviation from the mean *d/D*). Figure 1 shows that ~80% of the deep craters are located in close proximity to a mare-highlands contact that generally coincides with a region of high porosity. We consider two hypotheses for the formation of the craters: compaction-dominated cratering [4] due to significantly high porosity around the mare margins [5], or stabilization (i.e., less slumping) of deep transient cavities due to the intrusion of the more coherent basaltic lava flows into the fractured highlands. Here we present additional observations to try to test these hypotheses.

Methods: We evaluated *d/D* ratios of smaller well-preserved simple craters in the vicinity of ten of our deep craters from both high porosity and low/average porosity terrains. We also measured *d/D* for small craters around four $15 < D < 20$ km normal-depth craters from the low/average porosity regions. We performed the measurements for craters within a radius of 100 km of the main crater using Kaguya TC data [6]. We also generated topographic profiles of the 14 deep craters using LOLA data in order to examine interior crater shape. A crater formed in a porous target has steeper walls and flatter floors than the one formed on a more consolidated substrate. Furthermore, we checked for boulder abundance in and around the craters and layering on the walls using LRO Diviner [7] maps and LROC NAC [8] images for an indication of any common or distinct terrain attribute.

Results: Based on our preliminary geologic investigation of the unusually deep craters, we classify the crater terrains into three categories:

Unusually deep craters around mare-highlands contact. The high porosity (20%) terrains (red dots in Figure 1) overlap with the mare-highlands boundaries. Porosity was not derived for some regions along these boundaries because in those terrains it was cumbersome to separate the mare from highland composition for porosity calculation. However, the porosity along all edges of the mare exceeds the value elsewhere on the Moon due to fracturing by impact-generated shock waves and contribution of impact basin ejecta [5]. For the 6 deep craters belonging to this category, we noticed that > 50% of the surrounding simple craters are unusually deep. These craters are characterized with steeper slopes and flatter floors than the ordinarily deep craters from the remaining classes. Also, the interiors of these craters are abundant in boulders (green spots in the first image of Figure 2(a)). The walls exhibit layering (green-red areas in the Diviner overlay and NAC inset of Figure 2(a)).

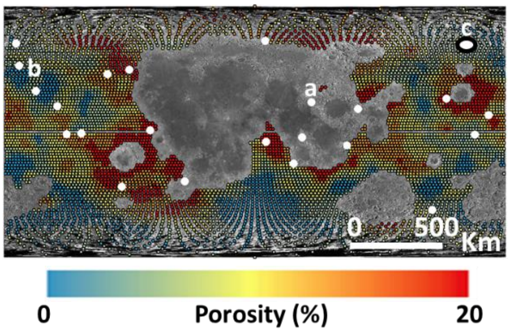

Figure 1. Lunar porosity map generated from GRAIL data [5], superposed on the global LROC WAC mosaic. The white circles without outlines correspond to the unusually deep simple craters within the simple-complex transition. The white circle marked as ‘c’ and outlined in black towards the NE is an ordinarily deep crater. The geology of the terrains bearing craters a, b and c is shown in Figure 2.

Unusually deep craters in highland region distant from mare. These terrains overlap with low to average porosity values (3-10%) as is evident from Figure 1. The number of unusually deep simple craters surrounding the few selected craters located in this type of target rises gradually from none to > 80% with increase in porosity (or decrease in distance to the mare). However, the topographic profiles of the deep craters show steep walls with slight layering, flat floors and high boulder abundance inside and on the crater walls as observed for the deep craters located near the mare margins. Figure 2(b) illustrates such a crater. It is not surrounded by similarly deep craters but is characterized with similar geology as the one in Figure 2(a).

Ordinary simple craters in low/average porosity terrains. The 3 craters with $d/D \leq 0.20$ that occur on low or average porosity surfaces are in areas where < 20% of the surrounding smaller well-preserved simple craters are unusually deep. Their walls appear to be slightly more shallow and lack layering (no red spots observed in the first image of Figure 2(c)).The crater floors are smaller as compared to the above two classes. The boulder count (absence of green, yellow or red spots) is minimal.

Discussion: The occurrence of similarly deep craters around the unusually deep craters within the simple-complex transition suggests that target properties may play a major role in the formation of these craters.

The location of majority of the deep craters around the mare-highlands contact, the steep walls, flatter floors, and boulder abundance indicate that the origin may be associated with impact cratering into highly porous targets where most of the impact energy is used in compacting the target. This results in carrot-shaped craters and low ejection velocities due to which the majority of the ejecta boulders fall back inside the crater [4]. The experiments on compaction-dominated cratering involved minimum 35% porosity. The GRAIL gravity-determined porosity map only shows a maximum value of 20%. However, it was generated by averaging the values over large areas and tens of kms of depths, so the local porosity could be higher.

The rise in the number of unusually deep craters surrounding the craters from the second class with decrease in distance to the mare margins, the steep walls, flat floors and boulder abundance also hints at the possibility of compaction dominated cratering on surfaces that are characterized with significantly high local porosity amidst low/average regional porosity.

The ordinarily deep craters are characterized by a parabolic cavity that may have formed in the gravity regime. The scarcity of surrounding unusually deep craters and lack of/smaller-sized boulders suggests that the cratering process was different from the one that formed the deep craters.

The contribution of the layering observed on the walls of the deep craters is not well understood. If the layering refers to mare basalts or a coherent rock layer that can prevent the collapse of transient cavity to sustain the large depths, the second hypothesis suggesting strength-dominated cratering can be considered as well.

Conclusion: The preliminary geologic analyses of around half of the unusually deep lunar craters in comparison to few ordinary simple craters within the simple-complex transition have strengthened the possibility of compaction-dominated cratering. However, we are currently studying the geology of the remaining craters to confirm the robustness of this result. Additionally, for all 22 craters, we will perform more detailed morphometric analyses to decipher the crater shape and thus the formation mechanism. Identification of lithology associated with the layering would be valuable for discerning its influence on the cratering process.

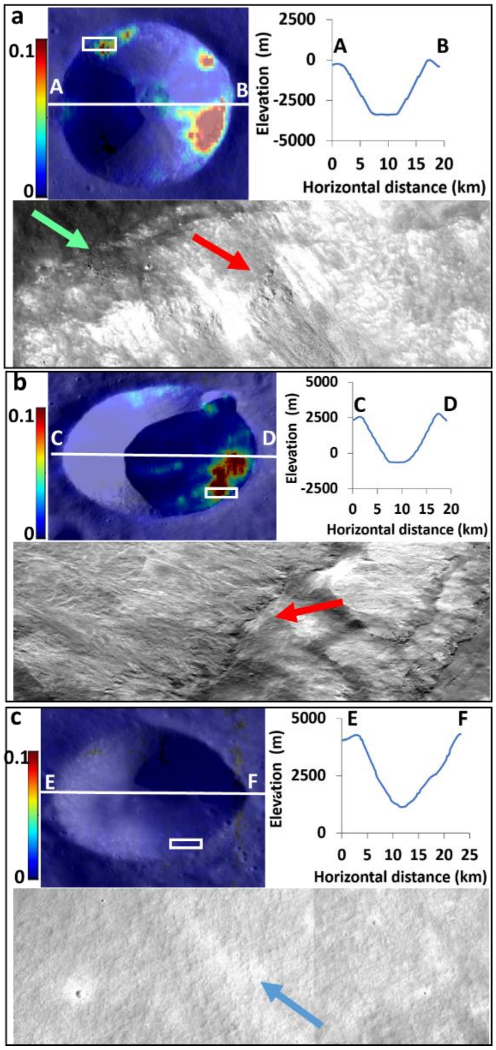

Figure 2. Diviner rock abundance maps superposed on WAC mosaic, topographic profiles along the transects shown in the Diviner overlay and NAC insets showing layering (red arrows), boulders (green arrows) and smaller rock fragments (blue arrow), for a) Hill crater (20.9°N,40.8°E; D=16 km, *d/D*=0.21; NAC: M1131572797RC), b) Unnamed crater (47.2°N,191.1°E; D=16 km; *d/D*=0.21; NAC: M1102301746RC) and c) Unnamed crater (38.6°S,234.9°E; D=19 km; *d/D*=0.21; NAC pair: M102974471). The white boxes on the Diviner overlays refer to the NAC insets. Their locations are displayed as white circles in Figure 1.

References: [1] Melosh H. J. and Ivanov B. A. (1990) *Annu. Rev. Earth Planet. Sci*, *27*, 385-415. [2] Osinski G. R. and Pierazzo E. (2012) 32-75. [3] Chandnani M. et al. (2017) *LPS XLVIII*, Abstract #2610 [4] Housen K. R. & Holsapple K. A. (2003) *Icarus*, *163*, 102-119. [5] Wieczorek M. A. et al. (2012) *Science*, 1231530. [6] Haruyama J. et al. (2014) *LPS XLV*, Abstract #1304. [7] Bandfield J. L. et al. (2011) *JGR*, *116*. [8] Robinson et al. (2010) *EPSC*, *1*, 457.