GEOLOGIC STUDY OF UNUSUALLY DEEP SIMPLE CRATERS IN THE LUNAR SIMPLE-TO-COMPLEX TRANSITION.

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Introduction: Planetary simple craters have been modelled and observed to form with a depth/diameter (*d/D*) ratio of ~0.20 [1, 2] if the target has bulk properties such that it can be considered strengthless, homogenous, and not unusually porous. We analyzed the geology of 244 well-preserved lunar impact craters in the 15-20 km diameter range [3], which globally contains a mix of simple, transitional and complex crater forms. Of these craters, the 117 simple craters occur exclusively in the highlands. The *d/D*s of 110 of the lunar simple craters were observed to span a range of ~0.15 to 0.20. However, from both LOLA [4] gridded topography data and individual tracks, we observed that the remaining seven craters are unusually deep (their *d/D*s exceeded the total of 0.20 and their uncertainties). These craters occur around mare-highlands boundaries (Figure 1).

Based on the similar locations of the unusually deep craters, we propose two hypotheses for their formation:

Hypothesis 1 – Porous target. Because the regions around the mare-highlands boundaries are characterized with maximum porosity (17-20%, see red-orange regions in Figure 1) [5], a large amount of the impact energy was consumed in compacting the target material, and a permanent, deep cavity [6, 7, 8] was created during crater excavation. The deep transient cavity experienced minimal modification, and a final, deep simple crater was produced.

Hypothesis 2 – Mafic intrusions. Basaltic magma filled in cracks and voids in the highlands around the mare margins and enhanced the strength and cohesion of the lunar near-surface [9]. The increased strength stabilized the transient cavity and reduced the minor slumping that occurs with simple crater formation.

We have conducted a detailed examination of the geology of these unusually deep craters to constrain possible mechanisms for their formation.

Methods and Data: To understand if the large depths are a function of a target property, we selected six unusually deep craters and ten ordinarily deep craters, and evaluated the *d/D*s of smaller, well-preserved simple craters occurring within 100 km radius of each selected crater using Kaguya TC ortho and DTM data [10]. Next, using LOLA DEMs, we generated scatter plots of morphometric parameters such as *d/D*, rim height/crater diameter ratio (*h/D*), wall slope (θ) and floor diameter/crater diameter ratio (*f/D*) for all 117 craters and studied their trends to determine the differences between the profiles of the unusually deep and the ordinarily deep craters. Lastly, any visual signatures that could potentially explain the differences between the cavities of the two crater groups were assessed using LROC NAC [11] images, Kaguya Optical Maturity (OMAT) maps [12], LRO Diviner rock abundance maps [13], and Kaguya FeO wt% maps [12].

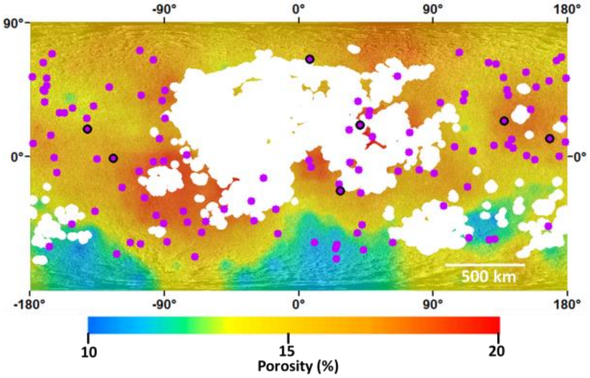

Figure 1. Mapped distribution of 15-20 km-sized simple craters (purple circles) on the lunar porosity map (reproduced from the data of [5]). The white patches represent the mare. The craters outlined in black are the unusually deep craters.

Results:

Depths of proximity craters. From the *d/D* statistics of the smaller craters surrounding the selected craters, we observed that in the 17-20% porosity regions, irrespective of unusually deep or ordinarily deep craters, 10-31% of the smaller craters are unusually deep. This percentage reduces to 2% in the 15-17% porosity regions and 0% in the lowest porosity terrains.

Trends in crater morphometry. After statistically testing for a pattern of depths of ordinarily deep craters with change in porosity, we noted that the frequency of the shallowest craters ($0.14 < d/D < 0.16$) declined with increase in porosity such that the highest porosity (17-20%) regions are devoid of these craters and are most abundant in the deepest crater population ($0.18 < d/D < 0.20$).

Figure 2 illustrates the cavity profiles of two normally deep and two unusually deep craters that represent the general morphometric trends. The rim heights of all craters are similar. Wall slope shows a slight increase with increase in crater depth, but the slopes of craters with *d/D* measuring ~0.20 are similar to that of the unusually deep craters. Floor diameter correlates weakly (correlation coefficient = -0.293) with decrease in depth and appears to be independent of wall slope.

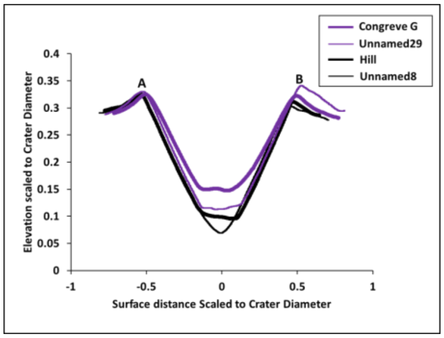

Figure 2. Profiles of two normally deep craters Congreve G (*d/D*~0.178±0.023; -0.89°N, 196.12°E) and Unnamed29 (*d/D*~0.192±0.022; -45.6°N, 207.7°E), and two unusually deep craters Hill (*d/D*~0.222±0.012; 20.91°N, 40.81°E) and Unnamed8 (*d/D*~0.248±0.015; 23.62°N, 137.65°E).

Visual examinations of crater cavities. Both younger (high albedo in NAC, high OMAT (red font in Figure 3(b)) and older (lower albedo in NAC, lower OMAT (white font in Figure 3(b)) granular flows can be seen on every crater's walls (Figure 3(a-b)). Diviner rock abundance maps show that debris of these flows is either composed of unconsolidated material (blue shade in Figure 3(c)) or cohesive material in the form of layering (green-red shade in Figure 3(c)). The FeO wt% maps show the unconsolidated anorthositic material (0-10 wt%) and the cohesive material sourced from mare basalts (11-22 wt%) [12] (Figure 3(d)).

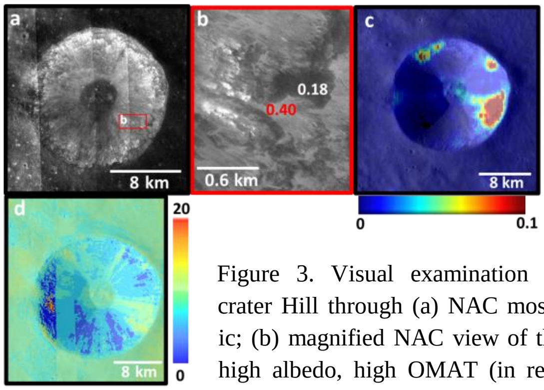

Figure 3. Visual examination of crater Hill through (a) NAC mosaic; (b) magnified NAC view of the high albedo, high OMAT (in red) granular flows and cavity wall (low OMAT in white); (c) Diviner rock abundance map that shows layering (in green-red); (d) Kaguya FeO wt% map displaying mafic lithologies (>10 wt%) associated with layering regions and the flows.

Discussion: If the larger-than-normal depths were attributable to less slumping because of a younger age of unusually deep craters, it is unlikely that the craters would be preferentially located around the mare margins. Also, the deep craters would have larger (and not similar) rim heights, and increasing floor size would correlate with (and not show independence from) a decrease in depth and wall slope [14].

Porous target. The occurrence of all seven unusually deep craters in high porosity regions, the decline in frequency of surrounding unusually deep simple craters with reduction in porosity, and the occurrence of the largest proportion of shallow craters in low-porosity terrains, suggests that porosity plays a major role in shaping the unusually deep craters. The overlapping rim heights indicate that the unusually deep craters excavated a similar volume of material as the standard simple craters. The increase of wall slope with crater depth but its independence from floor size also suggests that a modification in the typical cratering process, possibly compaction of porous material, yielded the large depths. However, only 7 of 61 craters in the high porosity regions are unusually deep, suggesting that high regional porosity alone is not sufficient to create an anomalously deep crater. Because the lunar porosity map has ~100-km resolution, it may be that porosity is locally heterogenous so that impact into only the highest-porosity "patches" results in an unusually deep crater. Also, compaction is thought to dominate crater volume for porosities only larger than ~35% [8]. Therefore, forming an unusually deep crater may require both a high-porosity target and an unusual impactor property such as a dense impactor [2], a high velocity impact [2] or a near-vertical impact [15].

Mafic intrusions. Beyond occurrence in the highlands, we saw no correlation between local interior composition with crater depth. Mafic lithologies, if any, exist in the form of layering on 3 unusually deep and 38 normally deep craters' walls, that appear to contribute to slumping in the form of granular flows. Also, granular flows can be seen in all 117 craters. Therefore, these observations do not provide any signature of resistance by the highlands target to wall collapse for the formation of the unusually deep craters.

References: [1] Pike R. J. (1977) *Impact and Explosion Cratering*, 489-509. [2] Melosh H. J. and Ivanov B. A. (1999) *Annual Review of Earth and Planetary Sciences*, *27*, 385-415. [3] Chandnani M. et al. (2017) *LPS XLVIII*, Abstract #2610. [4] Smith D. E. et al. (2011) *LPS XLII*, Abstract #2350. [5] Besserer J. et al. (2014) *Geophysical Research Letters*, *41*, 5771-5777. [6] Zel'dovich Y. B. and Raizer Y. P. (1966). [7] Love S. G. et al. (1993) *Icarus*, *105*, 216-224. [8] Housen K. R. and Holsapple K. A. (2003) *Icarus*, *163*, 102-119. [9] Gong S. et al. (2016) *JGR*, *121*, 854-870. [10] Haruyama J. et al. (2006) *36th COSPAR Scientific Assembly*. [11] Robinson M. S. et al. (2010) *European Planetary Science Congress*. [12] Lemelin M. et al. (2016) *LPS XLVII*, Abstract #2994. [13] Bandfield J. L. et al. (2011) *JGR*, 116. [14] Fassett C. I. and Thomson B. J. (2014) *JGR*, *119*, 2255-2271. [15] Pierazzo E. and Melosh H. J. (2000) *Icarus*, *145*, 252-261.