ANALYSIS OF CAUSES FOR MORPHOLOGICAL VARIATIONS IN LUNAR CRATERS WITHIN THE SIMPLE-COMPLEX TRANSITION.
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Introduction: The threshold diameter for the transition from simple to complex craters depends upon the gravity and the strength of the target material of the planetary body [1, 2]. On the Moon the transition diameter range occurs from 15 km to 20 km [3, 4, 5]. This diameter range corresponds to a factor of two variation in kinetic energy (nearly constant) [6]. Within the transition range craters of the same size may have different appearances which must be caused by differences in either target or impactor properties. We aim to address the following question: what causes morphological differences in impact craters of the same size? The investigation of the morphologies of impact craters in the simple-complex transition zone may provide an insight to the regional variations in crustal structure of the Moon (if target variations are involved in causing the morphological variations) and add to our current understanding of the complex cratering process.

Methods: We generated a database of 249 well-preserved craters with $15 < D < 20$ km using the most recent and complete lunar catalogs [7, 8]. We performed morphological characterization of each crater. We also formed groups of close proximity craters to look for differences in craters within the same geologic setting that might be caused by variation in impactor properties. For the close proximity analyses, we eliminated craters that overlap or are interconnected to each other or are elliptical in shape, to ensure that the analyses are performed on craters occurring on smooth surfaces and are not formed by highly oblique impact. We limited the maximum near-neighbour distance to be 150 km.

We used panchromatic image data from Lunar Reconnaissance Orbiter Camera Wide Angle Camera (LROC WAC) processed to 100 m per pixel and the 0.5 m resolution LROC Narrow Angle Camera (NAC) to observe the crater units. The Lunar Reconnaissance Orbiter Lunar Orbiter Laser Altimeter (LRO LOLA) (vertical accuracy of 1 m) along with the WAC Digital Terrain Model (vertical accuracy of 20 m) were used to analyze the topography of the craters.

Results:

Morphological characterization (Figure 1). Simple craters constitute 42% of the population. Five of the simple craters were observed to have depth/diameter (*d/D*) ratios above 0.20; these unusually deep craters are in the highlands located near the mare-highlands contact. Most of the craters in this size range (51%) have some slumped material within them, one of them having $d/D > 0.2$ and located on the mare near the mare-highlands boundary (351.4°N, -22.36°N). The majority of the remaining craters were observed to contain more complex features : the ones with slumped and terraced material (10 craters), central rise with slumping (2 craters), and central uplift in addition to slumping and terracing (2 craters). One floor-fractured crater and a concentric crater were also identified.

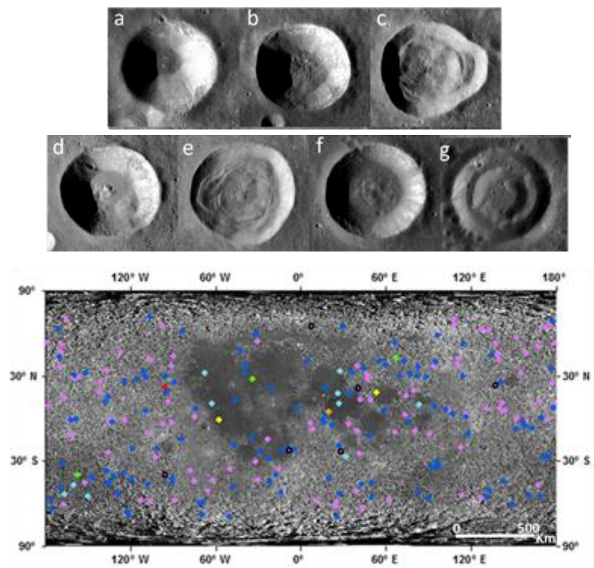

Figure 1. Top shows examples of morphologic types, and bottom shows global distribution of well-preserved lunar impact craters in the simple-complex transition zone. Violet circles refer to simple craters (a: 13.2N, 49.3E), dark blue represent craters with slumped material (b: 19.5N,40.4E), light blue circles indicate craters with both slumps and terraces(c: 10.7N, 26.7E), green circles correspond to craters with central uplift and slumped material (d: 27.6N, 325.7E), yellow circles refer to central uplift in addition to slumping and terracing (e: 0.9S, 302.5E), one orange circle denotes floor-fractured crater (f: 4.6N, 20E) and one red circle shows concentric crater (g: 22.1N, 264.1E). The LROC WAC mosaic is used for shading. Extra deep craters are outlined in black.

Mare vs Highland craters. The highlands were observed to contain simple craters and craters with slumped material, while the mare contained all of the craters with traditional complex crater morphologies. We also noticed that the complex craters on mare have layering on their walls and broader floors (average floor size being 4.3 km) than the ones on the highlands with 2.8 km mean floor diameter.

Close proximity craters. Out of 36 craters, we observed that craters in 4 pairs had the same morphology and rim-to-floor depth due to similar highland terrain which was smooth for simple (an example illustrated in Figure 2a) and little undulated for craters in the slumping category. For 2 pairs and 1 triplet, all of the craters were simple but differed in depth. For the triplet, we attributed this difference to slight difference in rim sharpness. Three triplets had craters differing in morphology in the simple and slumping category due to superposition of the crater with slumped material on a buried crater (Figure 2b). Two pairs had craters differing in morphology which we inferred to occur because the crater with slumped material occurs almost in the mare and has layering on its walls (Figure 2c and 2d). Values of some morphometric parameters for the craters in Figure 2 are given in Table 1. The rest of the groups comprised of a triplet in which craters bearing slumped material were located closer to a crater on its ejecta blanket than the simple crater, another triplet that had craters in the slumping category located adjacent to a larger and fresher crater and a pair in which the floor-fractured crater on mare is in the vicinity of volcanic rilles while the crater with slumped material was on the mare but right next to the mare-highlands contact.

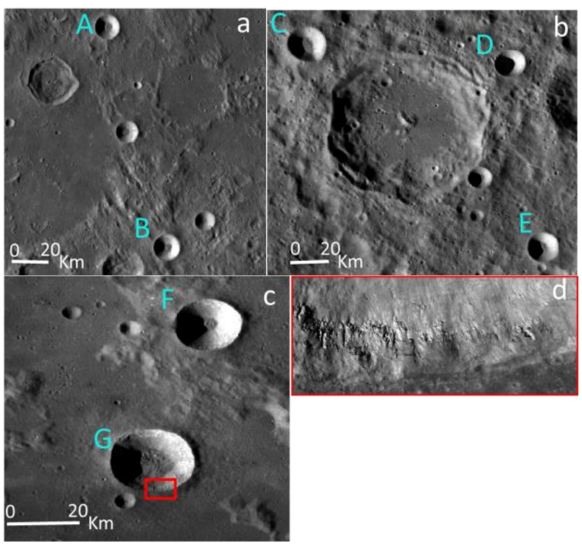

Figure 2. a) A pair of identical simple craters that were formed on smooth highland terrains. b) A triplet of craters in which the crater with slumped material is superposed on a buried crater. c) A pair of craters where one crater is almost in the mare with layering on its walls that is outlined in red and magnified in Figure 2d. The data from the global LROC WAC mosaic was used to represent the craters. North is up.

Table 1. Location and morphometric parameters of craters shown in Figure 2.

Crater	Longitude (°E)	Latitude (°N)	Diameter (km)	Morphology	Rim-to-floor depth (km)
A	6.9	-2.9	16	Simple	3.2
B	8.2	-7.4	17	Simple	3.3
C	134.77	44.88	19	Slumping	2.9
D	139.37	44.52	15	Simple	3
E	140.07	41.18	16.7	Simple	3
F	40.81	20.91	15.8	Simple	3.4
G	40.36	19.53	19.7	Slumping	3.5

Discussion: Regarding the unusually deep craters, we hypothesize that either higher than average porosity around the lithological contact [9] allowed larger than normal penetration or the intrusion of mare into the highlands made the target material more coherent and less prone to post-impact slumping. Layering within the mare may be able to explain the presence of only complex craters on mare, which may increase heterogeneity and cause instability in the transient cavities. The close proximity analyses reveal that simple craters may differ from their closest neighbours if the impact occurred on a relatively smoother terrain. Any heterogeneity caused by topography, lithology or layering can form complex craters.

Conclusion: The lunar impact craters in the simple-complex transition have varied morphologies that have helped us in going beyond the mare-highlands dichotomy. Although the highlands are older and more heterogeneous than the mare due to being battered by more number of impacts, there are regions on the highland surface that are relatively smooth that hold simple craters. The layering on the mare creates heterogeneity that may be dominating the coherence and driving weakening forces that destabilize transient cavities and form complex craters. Thus complex crater morphology was observed to rely heavily on heterogeneity in topography, layering or lithology, whether in the highlands or mare.

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