HOW DEEP AND STEEP ARE SMALL LUNAR CRATERS ? NEW INSIGHTS FROM LROC NAC DEMS

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Introduction: Recent lunar missions (e.g. Lunar Reconnaissance Orbiter (LRO), Kaguya), carrying high resolution cameras (e.g. Lunar Reconnaissance Orbiter Camera (LROC) Narrow Angle Camera (NAC) [1], Selene Terrain Camera [2]) have acquired images that will lead to a deeper understanding of impact crater formation and degradation. Historical studies of lunar crater morphology exists for craters in the 10 km diameter (D) range [3, 4, 5, 6, 7], but is somewhat lacking for craters in the 1 km D range, and rare for crater D below 200 m. Morphology of small lunar craters (SLC; $D < 200m$) is critical to our understanding of the regolith because such craters are relatively rapidly degraded making their existence somewhat transient in a geologic time-scale. Accurate characterization of the topology of smaller craters will elucidate (and test our current models) impact cratering processes for simple lunar craters across the full range of lunar target materials. From an exploration point-of-view investigating the morphology of small craters is relevant as small craters are common and will be in the exploration path for a robotic and (or) human explorers. Understanding the average and full range of crater slopes and depths per diameter will also inform future engineering design decisions.

In this work, we present new results obtained by investigating the shapes of small lunar craters sampled globally. Specifically, we study the depth-to-diameter ($\frac{d}{D}$) values and the median wall slope of SLC. Unlike larger lunar craters ($D > 10km$), for which studies and crater catalogs exist [8], a comprehensive listing of such information is nonexistent for SLC. For this work, we derived a catalog of 4477 SLC [Fig. 3] manually selected from LROC NAC based digital elevation models (DEMs) [9]. Measurements of rim-to-rim diameter, rim-to-floor depth, crater rim area, crater volume and median wall slope (MWS) at 2 m/pixel were made from the DEM. Based on these observations and the DEM uncertainties, fundamental relationships correlated to impact cratering processes are investigated within the context of historical studies.

Methods: Data mining from the NAC DEMs is automated after craters are first identified manually from NAC ortho-photo image, the DEM and a derived slope map. The rim of the crater as well as the location of melt (if any) on the crater floor, was manually identified. Following this procedure, the measurements extracted automatically via image analysis algorithms. DEMs generated from NAC stereo images have resolutions as small as 2 m/px which allows the topographical investigation of SLC. However the footprint of a NAC stereo image is small (2.5 km wide) and hence the current NAC stereo-imaging coverage represents only a small part of the total lunar surface. However the geo-spatial sampling of the lunar surface by NAC stereo images is globally distributed (Figure 3). The smallest crater considered for this study is determined by the smallest raster deemed large enough for reliable automatic estimation of crater topographic descriptors. In this study we use a raster size of 10 px square for the crater diameter which translates to a minimum crater size 20 m, The upper limit of 200 m was chosen to limit this initial study and allow the project to come to completion in our lifetime.

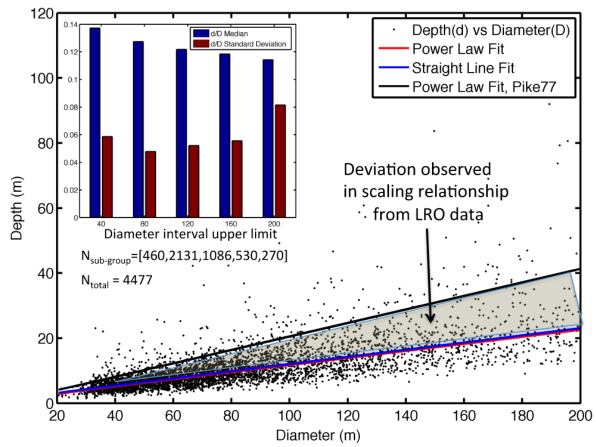

Figure 1: Depth vs Diameter from observed SLC. Fit to observations is shown as solid lines. Bar chart (inset) shows diameter range median and standard deviation values

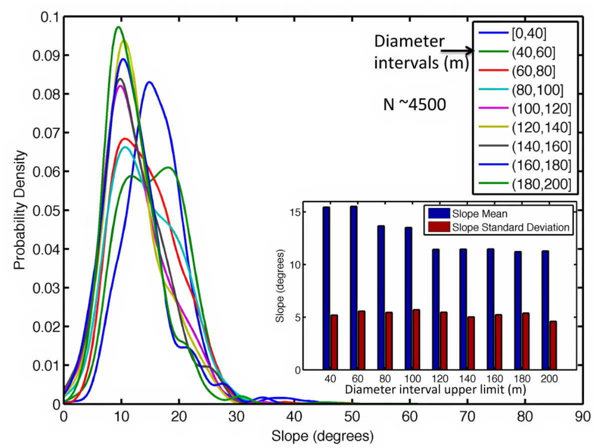

Figure 2: Wall slope statistics for SLC. Bar chart (inset) shows diameter range median and standard deviation values

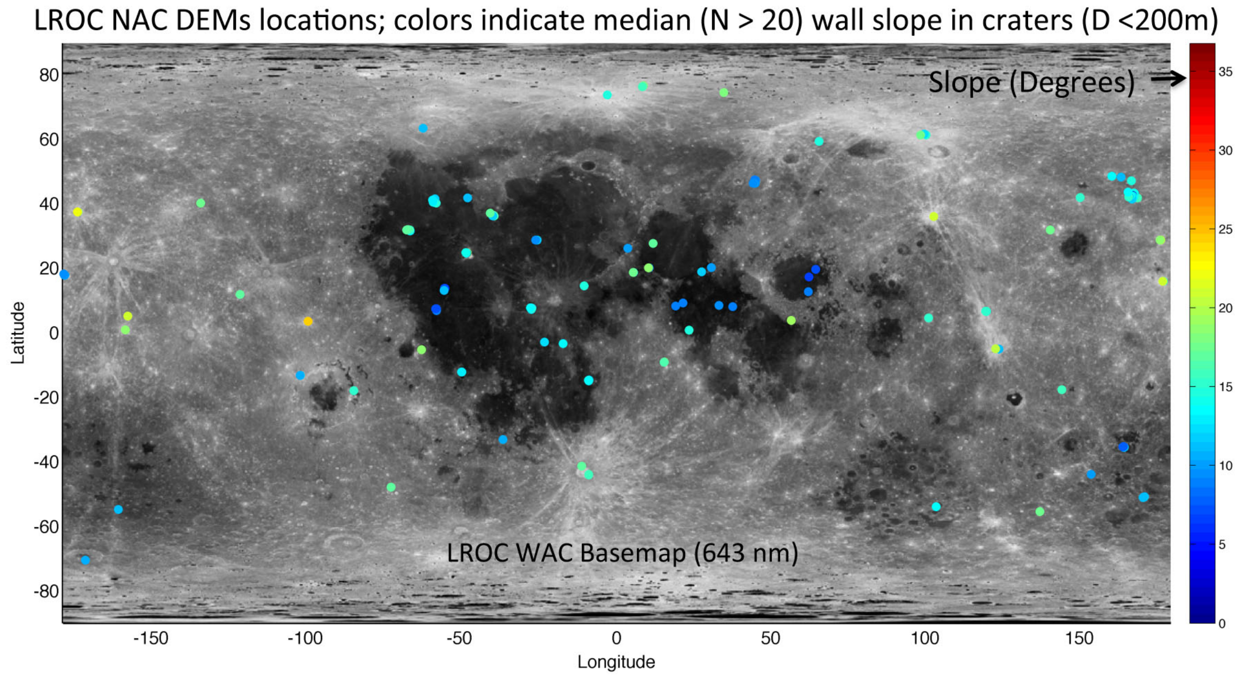

Figure 3: Global distribution of NAC DEMs used in this study. Some locations have multiple DEMs. The colorbar indicates the median wall slope

Results: The observed d vs D from SLC is well fit by both by a power law ($d = aD^b$; $R^2 = 0.98$) and a simple straight line ($d = mD + c$; $R^2 = 0.86$, Fig. 1). However, the variation trend indicated differs significantly from the power law of [4]. We note that in the previous studies [3, 10, 4] $D > 200m$ for most craters (in [3], $D < 200m$ for 25 craters out of 204, and these are not fit separately) so the fit to our range of D in that study is an extrapolation. SLC are found to be shallower than expected from [4], with median $\frac{d}{D}$ of 0.13 and not 0.2. With increase in D, the median $\frac{d}{D}$ decreases, likely due to a larger asymmetrical spread of depth. In general craters with $D < 100m$ appear to be a separate class, possibly due strength properties of the upper regolith relative to larger craters ($100m < D < 200m$).

Lower MWS are found with larger diameter craters (Fig. 2) investigated in this work. A MWS of $15°$ is observed for craters with $D < 100m$ and $11°$ for larger craters ($100m < D < 200m$). The peak slope in diameter bins decrease as diameter increases and MWS distribution among craters is also observed to change from a bimodal distribution to a more unimodal nature as diameter increases (Fig. 3). Globally, steeper wall slopes are observed in the highland regions rather than the mare. From the lunar exploration point-of-view, the distribution of MWS suggest that rover designs with stable locomotion performance up to $30°$ slope will be effective.

Conclusion: A new global dataset of small lunar craters is obtained from LROC NAC DEMs and analyzed to investigate fundamental morphological descriptors. In addition to filling the missing parts of scaling mechanism statistics, variation in the degradation rates for smaller craters is indicated by our results. The effect of data distribution non-uniformity (larger number of smaller craters) and comparative analysis of mare and highland craters is currently in progress and is expected to yield interesting results.

References: [1] M. Robinson, et al. (2010) *Space science reviews* 150(1):81. [2] J. Haruyama, et al. (2006) *Advances in Geosciences, Planetary Science* 3:101. [3] R. Pike (1974) *Geophysical Research Letters* 1(7):291. [4] R. Pike (1977) in *Impact and Explosion Cratering: Planetary and Terrestrial Implications* vol. 1 489–509. [5] R. Baldwin (1963) *[Chicago] University of Chicago Press [1963]* 1. [6] R. Baldwin (1965) *New York, McGraw-Hill [1965]* 1. [7] C. Elachi, et al. (1976) *Earth, Moon, and Planets* 15(1):119. [8] C. Wood, et al. (1978) in *Lunar and Planetary Science Conference Proceedings* vol. 9 3669–3689. [9] T. Tran, et al. (2010) in *Special joint symposium of ISPRS Technical Commission IV and AutoCarto* 15–19. [10] R. Pike (1976) *Earth, Moon, and Planets* 15(3):463.