WHAT ACCELERATES THE DEGRADATION OF SMALL LUNAR CRATERS? UNEXPECTED, CONTRASTING RATES OBSERVED AT APOLLO 16 AND 17 REGIONS
P. Mahanti[1], M.S.Robinson[1], T.J.Thompson[1], C.H. van der Bogert[2] [1]Lunar Reconnaissance Orbiter Camera, School of Earth and Space Exploration, Arizona State University, Tempe,AZ,USA (pmahanti@asu.edu);[2]Institut für Planetologie, Münster, Germany.

Introduction: For most surfaces on the Moon smaller crater populations are in equilibrium, that is the craters disappear at the same rate as new ones are formed [1, 2]. Cataloging the degree of erosion suffered by each crater in a small lunar crater (SLC ; 35 m $< D <$ 250 m) population, within a geological unit, gives insight to the processes that control degradation over time and the rate of degradation. Analysis of crater density describes the retention of craters at a target but does not elucidate the effects progressive degradation. Here we use high resolution (2 to 5 m pixel scales) Lunar Reconnaissance Orbiter Camera Narrow Angle Camera stereo derived topography to investigate crater shapes within a crater population (depth over diameter, or $\frac{d}{D}$) and infer degradation rates and processes.

In this work, we compare the time-dependent degradation state of SLCs by analyzing the population density vs $\frac{d}{D}$ for the Cayley formation (Apollo 16) a highland region and mare plains exhibiting dark mantle deposits in the Taurus Littrow Valley (Apollo 17) with methods similar to a study based on craters in mare regions [3]. The flat local topography for our two study regions (Fig. 1) ensures that terrain steepness has minimal effect on the slow impact-induced degradation process.

Methods: Craters were identified manually from NAC ortho-photo mosaics, the digital terrain model (DTM) and a derived slope map [4]. We characterized 1471 craters in the Cayley formation region and 1372 craters in Taurus Littrow. Most craters were smaller than 100 m (median $D <$ 75 m). Depth and diameter measurement for each crater was extracted automatically [5] from NAC DTMs and cumulative distribution functions (CDF) of $\frac{d}{D}$ was obtained. Degradation rates are estimated as a product of crater production rate and inverse of $\frac{\partial N}{\partial (d/D)}$ [3], where N is modeled from the CDF and [6] is a function of $\frac{d}{D}$ and is the number of craters with $\frac{d}{D}$ greater than a given value. The crater production rate for the size range investigated is obtained from previous work and was found to vary between 10^{-10} to 10^{-8} (cumulative number; per square km per year) [7]. Our estimated degradation rates originating from the change in crater shape with time are directly proportional to the true absolute physical degradation rate.

Results and Discussions: A crater production rate of 10^{-9} yields degradation rates (measured as change in $\frac{d}{D}$ value per unit time) varying from 0.65 x 10^{-6} per year (when $\frac{d}{D}$ = 0.17) to 0.04 x 10^{-6} per year (when $\frac{d}{D}$ = 0.1) for the Apollo 16 Cayley region. In contrast, corresponding rates for Apollo 17 mare plains were 2.95 x 10^{-6} per year and 0.05 x 10^{-6} per year. Degradation rates at the Apollo 17 mare plains was higher compared to the Cayley plains, implying faster transition from fresh to degraded craters. Degradation slows over time such that the difference in degradation rates also decreases as craters mature (rate for Apollo 17 is about 5 times that for Apollo 16 at $\frac{d}{D}$ = 0.17 and at $\frac{d}{D}$ = 0.1, the rates are same (Fig. 2)).

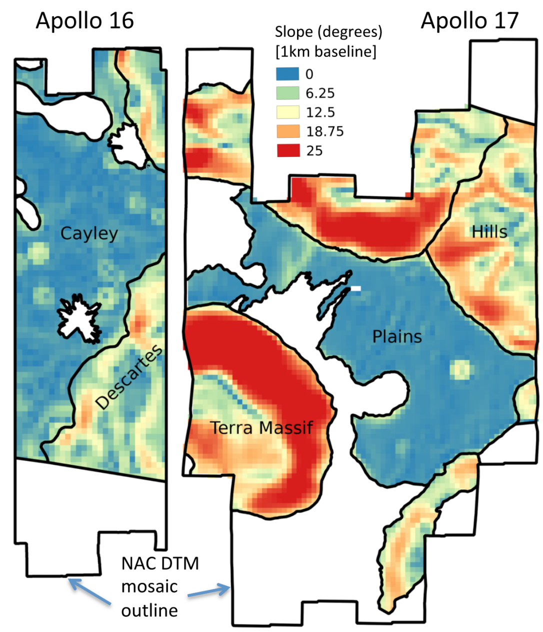

Figure 1: Local slope at Apollo 16 and 17 sites

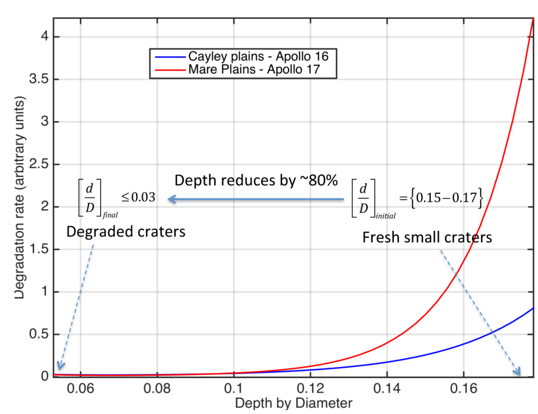

Figure 2: Degradation rates for Cayley and Taurus Littrow derived based on the CDF of $\frac{d}{D}$. Small craters leave the population when depths are less than 20% of initial depth.

The result obtained is counter-intuitive since degradation rates in the highlands (deeper regolith) are expected to be faster compared to mare regions for smaller craters [8]. Degradation rates for larger craters (800 m−5 km) were found to be 10x slower in the maria in a recent work [9]. At crater sizes investigated here, the degradation process differs in some significant manner from that of larger craters.

Small crater lifetime is affected by factors (Fig.3) other than the average production and impact-based degradation rates - the dynamics of the formation obliteration equilibrium can change within an equilibrium population, and SLCs can degrade faster (or slower) than the average equilibrium rate based on local conditions [10]. Degradation is accelerated at less-cohesive /weaker targets and targets can be intrinsically weak due to the material property or layering. Effusive and (or) explosive volcanism can add discontinuous strength boundaries in the target layers that accelerate or slow the pace of degradation. Seismic and impact events can weaken existing targets, either instantly or progressively.

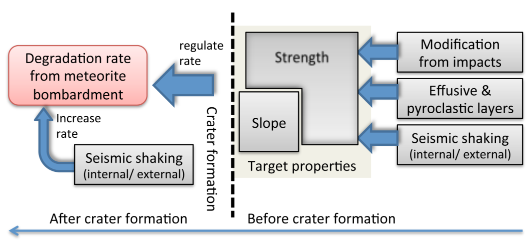

Figure 3: Factors affecting degradation rate in small craters

Faster degradation of fresh SLCs at the Apollo 17 site could be attributed to various causes. Shaking from the impact of Tycho secondaries [11] may have accelerated the degradation while possibly obliterating other SLCs. Another possibility is seismic shaking from movement along the Lee-Lincoln scarp [12, 13]; both in terms of weakening the mare materials and also directly accelerating degradation in then-existing craters.

Recent work suggests an upper limit of 400 My for the time in which small crater ($D \leq 50$ m) depths are reduced by 99% [9]. However, SLCs are typically unrecognizable when their d/D drops below 0.03 (80% reduction (Figure 2)). Since the time spent at every successive degradation step increases exponentially (the rate decreases exponentially), we estimate that SLCs become unrecognizable in less than 25% of the suggested upper limit (100 My). Since post-Tycho craters could have formed and matured to the current population, role of Tycho secondary impacts in accelerating the degradation of the crater population is questionable. Further, plotting $\frac{d}{D}$ values corresponding to crater location do not indicate a change in maturity with distance from either the general location of Lee-Lincoln scarp or the central cluster of Tycho secondaries (Fig. 4). Thus, we propose the hypothesis that the unconsolidated nature of the target with multiple strength boundaries (basalt at base followed by effusive and pyroclastic layers) at various depths) causes SLCs to degrade rapidly at Taurus Littrow, leading to a deficiency in SLC counts[14, 15, 16, 17]. The Cayley plains are thick and unconsolidated but perhaps lack the presence of strength boundaries leading to stabler crater walls.

Conclusion: We characterize SLC degradation and estimate the faster degradation rates (about 5x for fresh craters) at the Taurus Littrow due to the weaker, non-cohesive, multi-layered nature of the target (in comparison to the Cayley formation) that speeds the degradation process. Similar local accelerated degradation can change the size-range of craters in equilibrium which needs to be considered when deriving absolute model ages from CSFDs.

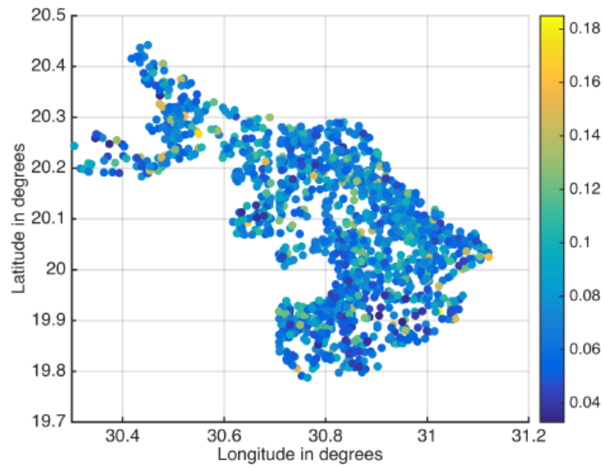

Figure 4: Spatial variation of $\frac{d}{D}$ at the Apollo 17 mare plains.

References: [1] L. A. Soderblom (1970) *Journal of Geophysical Research* 75(14):2655. [2] E. M. Shoemaker (1965) in *The Nature of the Lunar Surface* vol. 1 23. [3] A. Basilevsky, et al. (2014) *Planetary and Space Science* 92:77. [4] M. Henriksen, et al. Submitted to Icarus,2015. [5] P. Mahanti, et al. (2014) in *LPSC Proceedings* vol. 45 1584. [6] P. Mahanti, et al. (2015) in *LPSC Proceedings* vol. 46 1615. [7] M. Le Feuvre, et al. (2011) *Icarus* 214(1):1. [8] M. Robinson, et al. (2002) *Meteoritics and Planetary Science* 37:1651. [9] C. Fassett, et al. (2014) in *LPSC Proceedings* vol. 45 1429. [10] P. Schultz, et al. (1977) in *LPSC Proceedings* vol. 8 3539–3564. [11] B. K. Lucchitta (1977) *Icarus* 30(1):80. [12] C. van derBogert, et al. (2012) in *LPSC Proceedings* vol. 43 1847. [13] T. R. Watters, et al. (2015) *Geology* 43(10):851. [14] B. Lucchitta, et al. (1975) in *LPSC Proceedings* vol. 6 2427–2441. [15] L. Gaddis, et al. (2011) in *LPSC Proceedings* vol. 42 2584. [16] E. Wolfe, et al. (1975) in *LPSC Proceedings* vol. 6 2463–2482. [17] I. M. van derBogert C.H. Gaddis L, Hiesinger H., et al. (2016) in *LPSC Proceedings* vol. 47.