TOPOGRAPHIC DEGRADATION BY IMPACT CRATERING ON AIRLESS BODIES IS DOMINATED BY DIFFUSIVE EROSION FROM DISTAL EJECTA. D. A. Minton[1], C. I. Fassett[2], M. Hirabayashi[3], B. A. Howl[1], James E. Richardson[4], [1]Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, West Lafayette, Indiana USA 47907 (daminton@purdue.edu), [2]Marshall Space Flight Center, NASA Marshall Space Flight Center, 320 Sparkman Drive NW, Huntsville, AL 35805, [3]Department of Aerospace Engineering, Auburn University, Auburn, Alabama USA 36849, [4]Planetary Science Institute, 299 E. Lasalle Ave, Apt. 303B, South Bend, IN 46617.

Introduction: We have developed a new model for diffusive erosion of airless bodies on which impact bombardment is the dominant surface evolution process. We use terrains in simple crater equilibrium to constrain an analytical model of the diffusive erosion process. Using LROC observations of the Apollo 15 landing site as well as a numerical Monte Carlo code called the Cratered Terrain Evolution Model, we set constraints on the cratering processes that determine the diffusive erosion rate of lunar topography.

Diffusive Equilibrium. Crater equilibrium occurs when there is a balance between the production and erasure of craters. The production population is the true number of craters that formed on a surface over a time period, t, which is the exposure time over which a particular surface is only modified by impacts.

The crater production function is typically characterized by a power law cumulative size-frequency distribution (CSFD) of the form:

$$n_{p,>r_c} = n_{p,1} r_c^{-\eta}, \tag{1}$$

where $n_{>r_c,p}$ is the cumulative number of produced craters per unit area over time t, $n_{p,1}$ is a coefficient that gives the cumulative number of craters larger than 1 m in radius, and η is the log slope of the production distribution. To keep notation simple, the crater radius r_c in equation (1) is assumed to have units of meters.

Once crater densities become high enough, they may no longer follow the production population CSFD given in equation (1). Instead, they follow the equilibrium CSFD. The equilibrium crater density as a function of crater size may also be characterized by a power law CSFD of the form:

$$N_{eq,>r_c} = N_{eq,1} r_c^{-\beta}, \tag{2}$$

where the coefficient $N_{eq,1}$ is the cumulative surface number density of craters in equilibrium with $r_c > 1$ m, and β is the log slope of the equilibrium line. For equilibrium terrains when $\eta > \beta$ (i.e. a steep-sloped production function), the primary mechanism by which old craters are degraded is not by having their rims overprinted by new craters, but by the diffusive erosion.

The studies of Ross [1] and Soderblom [2] modeled the erosion of the lunar surface using a classical diffusion framework. In classical diffusion, the random walk distance is assumed to be a fixed value. This assumption is problematic for modeling erosion by cratering, because the random walk distance is related to the size of craters doing the eroding, which is not a fixed value, but follows the production CSFD given by equation (1) .

As exposure age increases, the probability that largest crater that will affect a piece of terrain will also increase. This means that the mean square displacement of transported material will have a non-linear time dependence. This process causes a time-dependent displacement distance, which gives rise to anomalous diffusion, as opposed to classical diffusion [3, 4]. Anomalous diffusion has been used to model material transport on the lunar surface [3, 5], but has not been explored in detail as a mechanism for topographic evolution.

A Diffusion Model for Crater Count Equilibrium. We define a quantity called the degradation state, K. The degradation state is equivalent to κt, where κ is the diffusivity in classical diffusion. Each new crater contributes some amount of degradation to the old surface, which we call K_d. Each cratering event contributes some amount of downslope degradation within some finite region that we will call its *effect region*. This effect region could include the final crater rim, the proximal ejecta blanket, the distal ejecta and secondary craters, or a region effected by seismic shaking. To simplify our analysis we will assume that this degradation can be approximated as a uniform circular region of radius $f_e r_c$ over which the degradation within is given as K_d. We will call the function $K_d(r_c)$ the *degradation function*.

At some point a crater must become so degraded that it is no longer recognizable by a human. We can define a function $K_v(r_c)$, which describes the maximum degradation state that a crater can undergo before it becomes uncountable. We call this the *visibility function*.

Our degradation function will be defined using a generic power law function as:

$$K_d(r_c) = K_{d,1} r_c^{\psi}, \tag{3}$$

and our visibility function will be similarly be defined as:

$$K_v(r_c) = K_{v,1} r_c^{\gamma}. \tag{4}$$

Using the degradation and visibility functions, $K_d(r_c)$ and $K_v(r_c)$, we derive equations for the equilibrium crater CSFD for two regimes, which depend on the size of the effect-radius scale factor the case where f_e.

For the small effect-radius regime:

$$N_{eq,>r_c}\Big|_{f_e\sim 1} = \pi^{-1}\left[\frac{K_{v,1}}{K_{d,1}}\left(\frac{\psi-\eta+2}{\eta}\right)\right]^{\frac{\eta}{\psi+2}} r_c^{\gamma-\psi-2} \quad (5)$$

$$N_{eq,>r_c}\Big|_{f_e\gg 1} = f_e^{-2}(4\pi)^{\frac{\eta-2-\psi}{\psi}}\left[\frac{K_{v,1}}{K_{d,1}}\left(\frac{\psi-\eta+2}{\eta}\right)\right]^{\frac{\eta-2}{\psi}} r_c^{\gamma-\psi-2}. \quad (6)$$

Using CTEM to contrain the diffusive erosion. We tested a model similar to one developed by Soderblom [2] in which the majority of diffusive degradation caused by crater formation is due to direct excavation and preferential downslope ejecta deposition. Using this model we found that our predicted equilibrium line had crater number density nearly an order of magnitude higher than is observed. We used constraints on observations of proximal ejecta burial to constrain our degradation function to have a very large effect-region radius, with $f_e \gtrsim 50$.

Our major results suggest that crater equilibrium is controlled primarily by relatively small amounts of topographic degradation that are produced for a very large, spatially heterogeneous region with each impact crater. By relatively small, we mean that the quantity degradation at any point in the distal degradation effect-region is many orders of magnitude smaller than the amount of degradation caused by the direct excavation of the crater, its deposition in the proximal ejecta, and burial by proximal ejecta. However, because the distal degradation occurs over a vastly larger area than the proximal degradation, this relatively small amount of distal degradation dominates the topographic evolution of lunar surface features and is primarily responsible for setting the equilibrium size-frequency distribution. This implication is consistent with recent observations of rapid regolith overturn generated by distal secondaries from recent craters [6].

Conclusion: Our results show that the majority of each new crater's contribution to diffusive topographic degradation occurs over a spatially heterogeneous region much larger than that bounded by the crater's proximal ejecta blanket, possibly as much as $50\times$ larger than the final crater rim diameter. This is in contrast to previous studies that assumed that the majority of topographic degradation occurred by the direct excavation and preferential downslope deposition of proximal ejecta. We conclude that the dominant mechanism for topographic degradation on the Moon is related to energetic distal ejecta deposition, and it is this distal process that sets the empirical equilibrium cumulative size-frequency distribution for simple post-mare craters.

References: [1] Ross, H. P. (1968). J. Geophys. Res., *73*(4), 1343–1354. [2] Soderblom, L. A. (1970). J. Geophys. Res., *75*(14), 2655–2661. [3] Li, L., & Mustard, J. F. (2000). J. Geophys. Res., *105*(E8), 20431–20450. [4] Vlahos, L., Isliker, H., Kominis, Y., & Hizanidis, K. (2008). eprint arXiv:0805.0419. [5] Li, L., & Mustard, J. F. (2005). J. Geophys. Res., *110*(E11), E11002. [6] Speyerer, E. J., Povilaitis, R. Z., Robinson, M. S., Thomas, P. C., & Wagner, R. V. (2016). Nature, *538*(7624), 215–218.