EVOLUTION OF CRATER DEPTH–DIAMETER POWER LAWS AS A PROXY FOR DEGRADATION.
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Introduction: We have used a diffusional sediment transport model to characterize crater degradation over a range of diameters with both simple and complex geometries. A power law relationship between crater depth and diameter has been previously established, but our model illuminates a more precise evolutionary trend of the depth-diameter power law as craters degrade. We have then applied this model to three equatorial Noachian-aged study areas with significant populations of both fresh and degraded craters. By comparing the depth-diameter power law relationships of craters in these study areas, we demonstrate that the exponent of the power law can be used as a proxy for degradation. This allows an independent estimate of the duration of sediment transport in degraded craters.

Landform evolution modeling of crater degradation: With the advent of topographic data for Mars over the past two decades [1], landform evolution modeling studies have shown that the morphology of the oldest Martian craters is likely to be explained by some combination of mass movement (creep, rain splash, impact bombardment, etc.) with fluvial, groundwater, or eolian processes acting on the surface [2-6]. We have used the MARSSIM landform evolution model [7] to simulate mass movement on the surface of Mars with a modified nonlinear diffusion equation (explained in detail in a separate contribution [8]). We sought to eliminate the complicating influences of additional transport mechanisms by focusing on mass movement only, which provides a robust upper limit on the time over which degradation could have occurred. The nonlinear diffusion model was applied to a representative subset of synthetic Martian craters, following a method first outlined by [2] and in subsequent studies by the same authors [3-6].

Synthetic crater geometry was either simple (D < 7 km) or complex (7 ≤ D < 100 km) based on definitions given by Garvin and colleagues [9-10]. Simple and complex craters have traditionally been distinguished by morphology [11], but they also follow distinct depth-diameter power laws. By plotting crater depth vs. diameter in log-log space, the exponent of the power law becomes the slope of a straight line. A linear least squares fit is performed on the simulation results for simple craters and then for complex craters at ten time increments to determine how the exponent of the power law evolved for each geometry (Figure 1a). The power law exponent is significantly higher for simple craters due to their greater relative depth, but the exponent is seen to increase for both simple and complex craters over the simulation run.

Application to Noachian-aged study areas: We now apply this hypothesis to Noachian-aged terrains on the surface of Mars, falling within three 15x15-degree study areas: Margaritifer Terra (5-20˚S, 0-15˚W), Arabia Terra (5-20˚N, 5-20˚E), and Terra

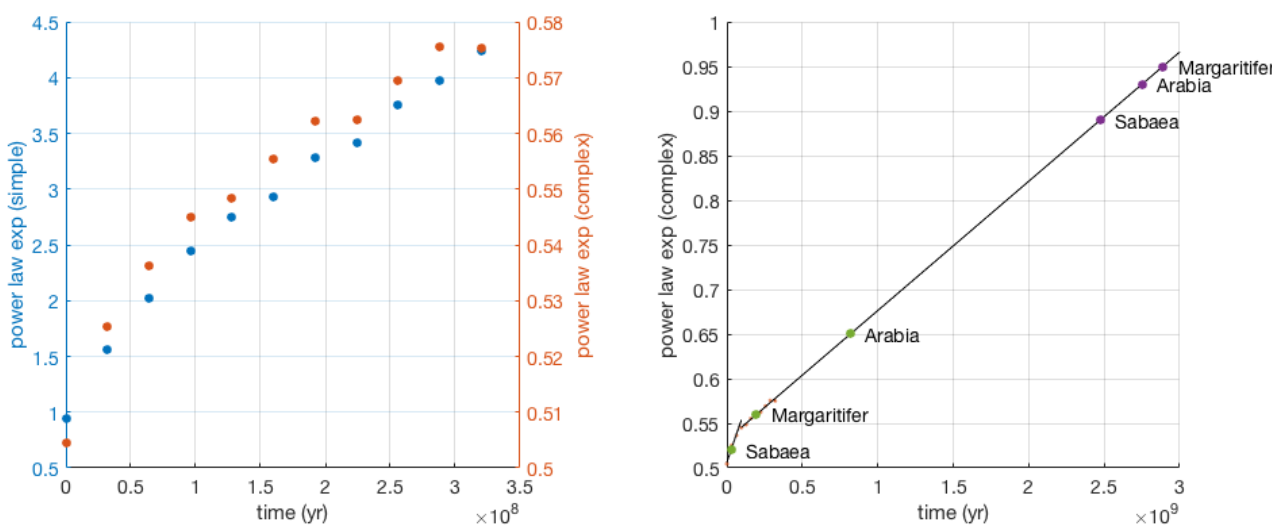

Figure 1. a) Evolution of depth-diameter power law exponents for synthetic craters with simple (blue) and complex (orange) geometries, plotted on different scales to show similar qualitative behavior. b) Extrapolation of part a) with data fit to three study areas for complex Class 3/4 (green) and Class 1/2 (purple) craters.

Sabaea (10-25˚S, 25-40˚E) [12]. We limit our sample to complex craters between 7-100 km in diameter. Crater depth and diameter measurements are derived from the Robbins crater database [13] using THEMIS-based diameter and MOLA-based depth. The depth-diameter power law is then plotted in log-log space for the three study areas (Figure 2).

There is a bimodal distribution in the power law exponent for craters in the three study areas and a corresponding bimodal distribution of degradation states. Degradation states are defined by relative depth (d/D) [13], which is distinct from the power law exponent, so the observed correlation is significant. We have gone a step further by removing craters with d/D greater than 1 standard deviation from the mean of Group 1 to account for very low d/D craters, which follow a separate power law from complex craters [10] but are not differentiated in the Robbins database [13]. In each case, the exponent of the power law is greater for degraded Class 1/2 craters than fresh Class 3/4 craters. This confirms our previous hypothesis that crater degradation leads to an increase in the depth-diameter power law exponent.

Data fitting and degradation ages: The study area data can be fit to our model in order to derive a degradation age, i.e. an estimate of the total duration of crater degradation, in a scenario where mass movement is the only driver. We approximate the behavior of the power law exponent vs. time in our model with two linear trends before and after 100 Myr. If the craters in the study areas were to follow the same evolutionary trend as the synthetic craters, their maximum degradation ages would range from $2.8x10^7$-$8.2x10^8$ years for Class 3/4 craters and $2.5x10^9$-$2.9x10^9$ years for Class 1/2 craters (Figure 1b).

Past studies of Martian crater morphology have suggested that crater degradation on Noachian-aged terrains was enhanced before the Noachian-Hesperian boundary [2,14-16] over a period of no more than 320 Myr [17]. This constraint has been used in support of a warm and wet early Mars climate scenario [18-20]. Our findings require that degradation occur ~10x faster for degraded Class 1/2 craters than would be feasible with only mass movement. However, our results are highly model-dependent; an increase by 10x of the diffusivity could make up the difference entirely and eliminate the need for other transport mechanisms.

Conclusions: The time evolution of the depth-diameter power law is an inherent property of crater degradation, which we have reproduced under simulated conditions and measured directly for craters on the surface of Mars. By fitting this crater geometry data to our model, we have set an upper bound on the duration of degradation for craters in Noachian-aged terrains. The ages we find suggest that additional mechanisms beyond mass movement would be necessary to account for the shorter degradation time predicted by past studies for the same Noachian-aged terrains [2,14-17]. We are currently analyzing these results in order to assess the climate conditions responsible for the observed degradation.

References: [1] Smith D.E. et al. (2001) *JGR* 106; [2] Craddock R.A. et al. (1997) *JGR* 102; [3] Forsberg-Taylor N.K. et al. (2004) *JGR* 109; [4] Howard A.D. (2007) *Geomorph.* 91; [5] Matsubara Y. et al. (2011) *JGR* 116; [6] Matsubara Y. et al. (2017) *LPSC* 48; [7] Howard A.D. (2009) MARSSIM Release 3.0, http://erode.evsc.virginia.edu; [8] Boatwright B.D., Head J.W. (2018) *LPSC* 49; [9] Garvin J.B. et al. (2000) *LPSC* 31; [10] Garvin J.B. et al. (2003) *6th Intl. Conf. on Mars*; [11] Pike R.J. (1980) *Icarus* 43; [12] Gaz. Plan. Nom., http://planetarynames.wr.usgs.gov; [13] Robbins S.J., Hynek B.M. (2012) *JGR* 117; [14] Craddock R.A., Maxwell T.A. (1990) *JGR* 95; [15] Craddock R.A., Maxwell T.A. (1993) *JGR* 98; [16] Hynek B.M., Phillips R.J. (2001) *Geology* 29; [17] Boatwright B.D., Head J.W. (2017) *4th Intl. Conf. on Early Mars*; [18] Craddock R.A., Howard A.D. (2002) *JGR* 107; [19] Craddock R.A. et al. (2013) *LPSC* 44; [20] Craddock R.A. et al. (2017) *4th Intl. Conf. on Early Mars*.

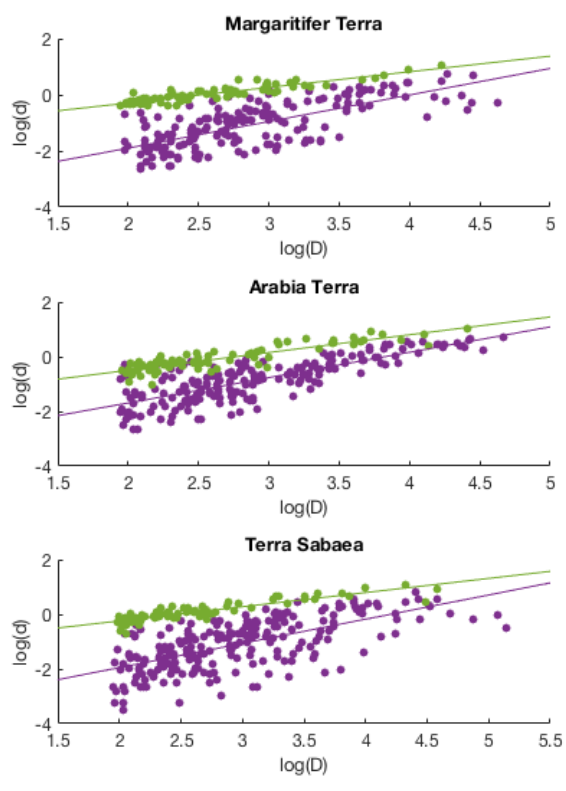

Figure 2. Log-log plots of the depth-diameter power law for complex Class 3/4 craters (green) and Class 1/2 craters (purple) in three Noachian-aged study areas. Power law exponents: Margaritifer Terra: 0.56 (3/4), 0.95 (1/2); Arabia Terra: 0.65 (3/4), 0.93 (1/2); Terra Sabaea: 0.52 (3/4), 0.89 (1/2).