REGOLITH GENERATION, RETENTION, AND MOVEMENT ON ASTEROID SURFACES: EARLY MODELING RESULTS. J. E. Richardson[1]. [1]Dept. of Earth & Atmospheric Sciences, Civil Engineering Bldg., Rm. 2267, 550 Stadium Mall Dr., Purdue University, West Lafayette, IN 47907, email: *richardson@purdue.edu*.

Introduction: Impacts and impact cratering are the primary geologic processes affecting asteroid shape, internal structure, and surface morphology [1], while impact fragmentation and crater excavation act as the source of nearly all regolith on these small, airless bodies [2]. Immediately following the formation (via some much larger impact) of a regolithless, monolithic or fractured-monolith rocky asteroid, numerous small impacts will begin weakening its outermost surface layers. These small impacts will initially produce little regolith since the surface begins at some high strength (relative to the asteroid's gravity) and most of the impact ejecta that is produced escapes at high speed (relative to the asteroid's escape velocity). However, these small impacts do produce new fractures in the asteroid's outermost surface layer and thus weaken the surface with regard to subsequent impacts. Thus, as the number of impacts accumulate, the surface is gradually weakened to deeper and deeper depths. Small impactors will begin to encounter very little target strength, and as such will begin producing significant amounts of retained ejecta (regolith). As the asteroid's fracture structure grows in extent and depth, the relative size of impactor which encounters little to no target strength will also increase, as does the corresponding degree of retained ejecta (regolith) production [3].

I hypothesize that the above processes will produce an asteroid regolith which exists in a state of quasi-equilibrium, having both a production term and a loss term. Regolith loss occurs with each new impact event, wherein a small amount of relatively high-speed ejecta will be generated which leaves the asteroid. Regolith production occurs when impact fracturing and crater excavation turn former `bedrock' into small fragments which form the crater's surrounding ejecta blanket. On the one hand, small impacts, which are the most numerous, tend not to excavate below the asteroid's existing regolith layer (once formed), instead overturning it in a process called impact 'gardening' [4], and as such small impacts act as the primary source of regolith loss to space. On the other hand, less numerous large impacts tend to penetrate below the existing regolith layer, and this serves as the primary source of new regolith as these impacts produce much more retained ejecta than is lost to space. Additionally, as each new impact occurs, the resultant seismic vibrations propagate throughout the asteroid body and cause the gradual migration of regolith toward topographic lows and slowly degrades areas of high topographic relief, such as crater rims [5]. The result is a regolith layer which is in a constant state of slow production, loss, and migration over the asteroid's surface.

Modeling Approach: Previously, modeling the above process has been hampered by the lack of an adequate model describing impact ejecta production and deposition behavior in the extremely low-gravity, asteroid surface environment. While ejecta production in strengthless target materials was well understood [6], the addition of even small amounts of target strength in this setting significantly curtails impact ejecta production, making such gravity-dominated cratering models overly optimistic with regard to asteroid regoliths. Fortunately, the Deep Impact experiment at Comet Tempel 1 led to the development of an updated, scaling-relationship based, predictive model of an individual impact's excavation flow properties [7]. This revised model permits the computation of crater excavation flow properties even in the strength-dominated, low-gravity environments of asteroidal and cometary surfaces.

Taking this model development a step further, I have built upon my Excavation Flow Properties Model (EFPM) and other recent advances in our understanding of the geologic processes involved in crater production, ejecta production, and crater erasure to construct a highly-detailed, three-dimensional, Cratered Terrain Evolution Model (CTEM) [8], which will be utilized in this study in an iterative, forward-modeling mode to investigate the generation, retention, and migration of regolith within the very low-gravity, impact-dominated environment of a rocky asteroid surface, for asteroids ranging in size from a few hundred meters to tens of kilometers in diameter (covering the size-range of the spacecraft-imaged S-type asteroids to date).

In its current configuration, the CTEM has two methods for covering a matrix element with regolith, and two methods for removing that regolith. In the first instance, regolith can be deposited by either impact ejecta emplacement (ballistic sedimentation), or by the downslope motion of regolith from upslope of the pixel in question. In the second instance, regolith can be removed by the process of crater excavation, or by the downslope motion of regolith to regions downslope of the pixel in question. Note that upturned crater rims (uplifted rock beneath the crater's ejecta blanket) are not considered to be regolith in the model, although they can act as a source region for regolith, since this rock has been uplifted, broken, and is severely weakened compared to the surrounding country rock. Therefore, to be considered as `regolith' in this model, material must be transported, either ballistically or via downslope movement.

Preliminary Results: Fig. 1 shows the result of a preliminary, proof-of-concept CTEM model run, depicting the first $10^{7.5}$ yrs of regolith development, distribution, and migration on the surface of an Eros-sized body exposed to a Main Asteroid Belt (MAB) impactor flux. In this environment, impact-induced seismic shaking acts to move regolith downslope and degrade small craters rapidly, as described in [5]. Black `rings' in the regolith map mark the position of eroding crater rims, which act as source regions for new regolith.

Moving to the vertical scale, Fig. 2 plots mean regolith depth as a function of time in an Eros-sized body, preliminary simulation which was permitted to run out to a MAB bombardment time of 10^{10} yrs. The left half of the figure shows mean regolith depth as a function of bombardment time plotted in linear fashion, while the right half of the figure shows the same, plotted in log-log fashion. Note that the linear plot displays the quasi-equilibrium behavior described in the Introduction, where regolith depth tends to stabilize or even drop slightly in between large impact events, but can experience large step changes upward when very large impact events occur. Regolith depth finally stabilizes in the 20-40 meter range, consistent with the observations of 433 Eros [9]. The log-log plot on the right provides a means for estimating regolith generation and overturn rates, in that on decimeter scales, the regolith is generated on timescales of 10^7 yrs; on meter scales, the regolith is generated on timescales of 10^8 yrs; while on decameter scales, the regolith is generated on timescales of 10^9 yrs. As discussed in the Introduction, large step-changes in regolith depth are generally created by the largest cratering events permissible on the body without disrupting it.

References: [1] Sullivan, R. J. et al. (2002), *Asteroids III*, 331–350. [2] Scheeres, D. J. et al. (2002), *Asteroids III*, 527-544. [3] Sullivan, R. J. et al. (1996), *Icarus 120*, 119–139. [4] Oberbeck, V. R. et al. (1973), *Icarus 19*, 87-107. [5] Richardson, J. E. et al. (2005), *Icarus 179*, 325-349. [6] Housen, K. R. et al. (1983), *J. Geophys. Res 88(17)*, 2485–2499. [7] Richardson, J. E. et al. (2007), *Icarus, 190*, 357-390. [8] Richardson, J. E. et al. (2009), *Icarus, 204*, 697-712. [9] Robinson, M. S. et al. (2002), *Met. and Pl. Sci 37*, 1651-1684.

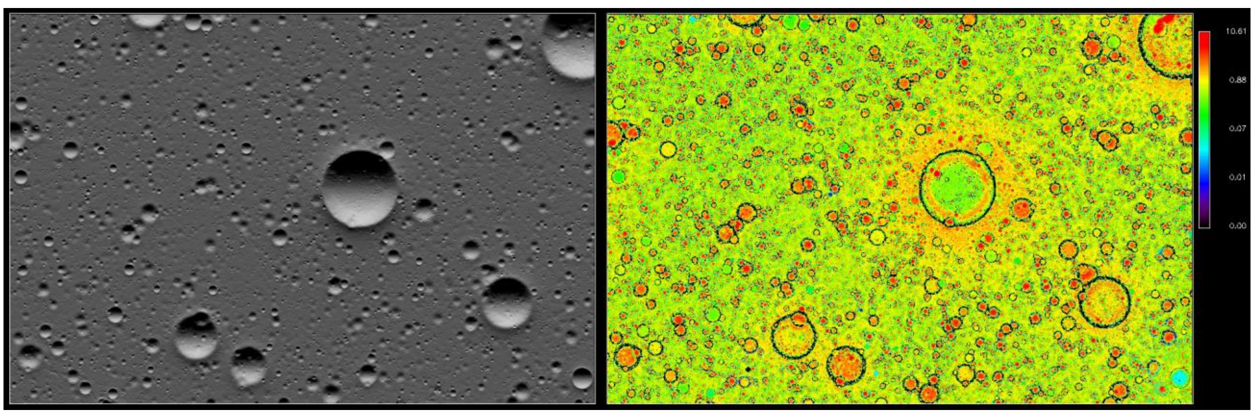

Fig. 1: a 3D model of an asteroid surface, showing surface relief (left) and log-stretched regolith depth (right).

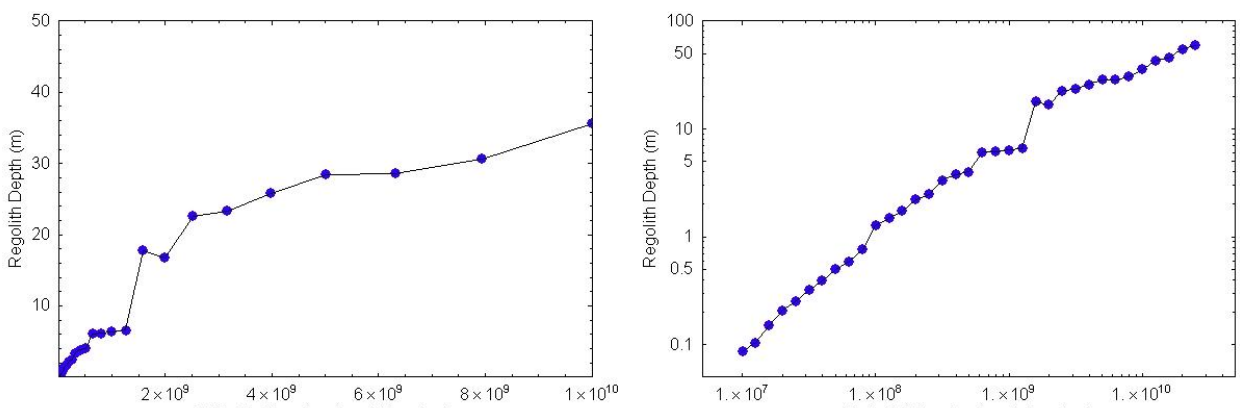

Fig. 2: Eros-modeled regolith growth as function of time, plotted in linear (left) and log-log (right) fashion.