ANALYTICAL AND NUMERICAL PREDICTIONS FOR REGOLITH PRODUCTION ON ASTEROIDS – E. Asphaug and M.C. Nolan, Lunar and Planetary Laboratory, University of Arizona, Tucson AZ 85721 USA

Competition among scaling laws, and the complexity of numerical models, has fostered much debate as to whether small asteroids have regolith [1,2]. Prior to the arrival of Galileo at Gaspra, many predicted a clean surface, while others foresaw a highly evolved regolith or even a rubble-pile. The images in fact show a substantial degree of regolith maturity, causing revisionist thinking in some circles. We use Gaspra as a test-case for hydrocode computations, in comparison with the ejecta velocity scaling law of Housen *et al.* [3], and show that both models predict a mature regolith on this small body and its kin.

1. Crater Ejecta Velocity Scaling

Housen *et al.* [3] arrive at the following equation for the volume of ejecta, V_e, exceeding a velocity v in a crater of radius R_C on a target with surface gravity g:

$$\frac{V_e}{R_C{}^3}=k_3\left(\frac{v}{\sqrt{gR_C}}\right)^{-e_v} \tag{1}$$

They find experimentally that e_V=1.23 for sand and 2.0 for basalt (compared to e_V=9/4 of Gault *et al.* [4]), and that k_3=0.32. We transform Eq.(1) into a relationship predicting how much ejecta from a given crater will escape a target of radius R_T: Let the crater be a hemisphere, such that $V_C={}^2/_3\pi R_C{}^3$, and let $v\rightarrow v_{esc}=\sqrt{2gR_T}$. The volume fraction of crater ejecta escaping (V_{esc}/V_c) reduces to a simple function of the scaled crater radius r =R_C/R_T, independent of the target gravity:

$$\frac{V_{esc}}{V_C}=\frac{3k_3}{2\pi}(r/2)^{e_v/2} \tag{2}$$

In the limit of $r\rightarrow0$, no ejecta escapes: small impacts are net producers of regolith. As r gets large, the outcome is sensitive to the choice of k_3. An upper limit of $k_3\leq{}^2/_3\pi$ results if ejecta fast enough to travel a distance R_C cannot remain in the crater. Using the laboratory value k_3=0.32, Eq.(2) predicts that craters up to half the target radius (r=0.5) will lose less than ~5% of their ejecta to space (whether the target is sand or rock), the remainder being bound to the asteroid.

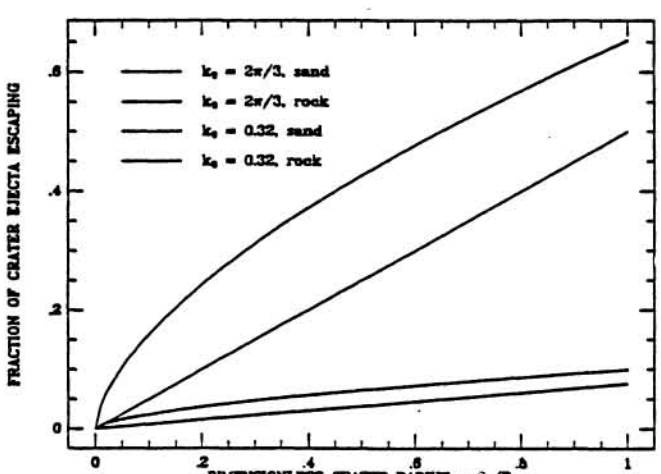

Figure 1. The analytical predictions of Eq.2, based on the ejecta velocity scaling relationship of Housen *et al.* [3], indicate that it is very difficult for target asteroids to lose regolith. Smaller impacts are more efficient regolith producers, in that a greater fraction of the crater ejecta remains bound to the asteroid. The lower curves (k_3 = 0.32) are based on fits to laboratory cratering measurements, while the upper curves (k_3 = $2\pi/3$) are theoretical upper limits, as described in the text.

About ~25% to 40% of the ejecta will escape from r=0.5 craters if we use the upper limit $k_3={}^2/_{3\pi}$ instead; since smaller craters will lose an even smaller fraction, the prediction for all craters is that most of their ejecta is bound, such that regolith will be prevalent on cratered bodies. This analysis will break down as $r \rightarrow 1$ since then gravity is not even approximately uniform throughout the crater bowl, and since boundary effects will make the cratering phenomenon far different from what one would expect in a half-space.

2. Hydrocode Results

We model Gaspra as basalt sphere with R_T = 6.4 km, v_{esc} = 7.9 m/s, g = 0.005 m/s^2, a mass M_T = 3x10^{15} kg and a central pressure P = 0.4 bar. The hydrocode SALE 2D [5] is run in axial symmetry with the Tillotson equation of state and the Grady-Kipp fragmentation rheology [6]. We create large craters (2 km, 4 km and 6 km in radius) by impact with projectiles of various sizes at 5.3 km/s. Crater diameters are determined from the flow field which evolves subsequent to the impact, although we do not account for subsequent crater modification. The ejecta fraction escaping, as predicted by the code, is greater than the upper-limit estimate of Eq.2, although only the largest craters eject more than they distribute as regolith. Because the code is run within the boundary conditions of a sphere, which does not allow for the free dissipation of impact energy, it is reasonable that these craters would eject more than their half-space equivalents. Virtually all crater ejecta escapes the largest crater (r=0.93); this impact also causes extensive fragmentation throughout the asteroid on a size scale of ~1km or less. The interesting conclusion is that in order to clean an asteroid of its regolith, you have to make a rubble pile.

Impacts into a 6.4 km Basalt Gaspra at 5.3 km/s

Crater Radius	2km	4km	6km
$r = R_C/R_T$	0.31	0.62	0.93
Projectile Radius (code)	76m	150m	284m
Ejecta Escaping ($^{code}/_{scaling}$, %)	30/15	65/32	99/68
Regolith Depth ($^{code}/_{scaling}$,m)	24/28	40/180	5/280
Transport Distance (code)	100m	500m	Escapes
Final State (code)	Intact	Rubble	Rubble

Table 1. Numerical and scaling-law outcomes for large crater formation on a spherical Gaspra-sized target. A greater fraction of the ejecta escapes in the hydrocode simulation than Eq.1 predicts for reasons described in the text. The regolith depth is computed assuming all ejecta not escaping from the crater blankets the final target uniformly. Peak surface velocities achieved away from the crater are used to estimate the typical transport distances; pre-existing craters of this dimension or smaller would be severely degraded. The hydrocode predicts that the 4km and 6km craters result in a rubble-pile asteroid with mean fragment sizes < 1km.

REFERENCES: [1] Housen, Wilkening, Chapman & Greenberg, *Icarus* **39**: 317-351 (1979). [2] Cintala, Head & Wilson, in *Asteroids*, U of A Press, (1979). [3] Housen, Schmidt & Holsapple, *J. Geophys. Res.* **88**: 2485-2499 (1983). [4] Gault, Shoemaker & Moore, *NASA Tech. Note D-1767* (1963). [5] Amsden, Ruppel & Hirt, *LASL Report LA-8095* (1980). [6] Asphaug, Ryan & Melosh, *LPSC XXI Abstracts* (1990).