EFFECT OF PROJECTILE DENSITY AND IMPACT ANGLE ON EJECTA THICKNESS DECAY RELATIONS. D. Goldberg[1], P. H. Schultz[1], and B. Hermalyn[2], [1]Department Geological Sciences, Box 1846, Brown University, peter_schultz@brown.edu; [2]NASA Astrobiology Institute/Institute for Astronomy, University of Hawaii, Honolulu, HI.

Introduction: General analytical approximations describe an inverse power law for ejecta thinning with distance that requires a volumetric dependence [1]. This general relation also follows from similarity arguments [2] and has been extensively applied (e.g., [3,4]). The assumed volumetric dependence was initially justified by the assumption that any power law with an exponent less than 3 would not converge, i.e., result in ejecta beyond the rim exceeding the crater volume [1]. A more rigorous approach has now become the standard [5]. Rather than a strictly cubic relation for excavation, the power law dependence is about -2.6. Our experiments re-tested this relationship for different density projectiles, following the classic studies by [6]. This approach avoids the regions adjacent to the structurally uplifted rim, where the simple analytical relation should not hold without adjustments. Our new experiments were designed to assess whether crater excavation is characterized by volumetric (proportional) or cylindrical (non-proportional) growth for different impact variables (angles and impactor densities).

Experimental Approach: The experiments were conducted at the NASA Ames Vertical Gun Range (AVGR). Spherical projectiles (mostly 0.635cm in diameter) of different densities (aluminum, titanium, nylon, Pyrex, hollow aluminum) were launched at ~5km/s into a 59cm diameter bucket of loose, dry No. 20 - 30 sand with a bulk density of 1.7g/cc. Impact angles were 30°, 45°, 60°, and 90° (from the horizontal) for aluminum projectiles. Honeycomb sheets were positioned around the target bucket to capture the ejecta particles. The deep honeycomb cells prevented bounce out (as confirmed by high-speed imaging). Sand grains collected from each cell were weighed (and in some cases, counted by hand for validation). Data from individual cells at the same radius from the crater were combined in order to increase statistical significance.

Cloth sheets draped over the chamber wall suppressed contributions from high-velocity ejecta bouncing off the wall. High-speed imaging (and separate experiments that blocking contributions by the direct arrival) allowed assessment of potential contributions of secondary ejecta off the boundary wall. These results indicate that cells within about 20cm of the wall should be eliminated from further analysis. In addition, we eliminated contributions along the bucket edge where ejecta retain their lateral momentum, as previously noted [7].

The thinning of ejecta thickness (t) with distance (r) scaled to the crater radius (R) can be described by a simple power law: $t/R \sim (r/R)^{-\lambda}$ where the exponent λ has a value around 2.6 [5]. Ballistic ejecta reaching between about 2 and 10 crater radii (as in this study) correspond to late stages (75%) of excavation, based on the ejecta-velocity-growth dependence [7,8]. As a result, the correct power-law dependence reflecting the excavation process should not simply use r/R but depend on the scaled range from the launch position close to the crater rim, (r-R), which becomes: $t/R \sim [(r/R)-1]^{-\lambda'}$. This relation describes the ballistically delivered incremental ejecta thickness (mass/area) from the launch position near the crater rim; hence, it corresponds to the mode of crater excavation (volumetric or cylindrical). For greater accuracy, we alos have incorporated the measured ejecta-velocity-growth dependence f(x)/R, where f(x) represents the position of ejection for the ballistic velocity necessary to reach the given cell. We find, however, that this correction has little effect on the ejecta-decay exponent referred when to the rim for the distances examined.

Results: For vertical impacts (aluminum), we find that the exponent λ (i.e., r/R dependence) matches previous results with a value of 2.6. When partially corrected for the actual launch position within the crater [e.g., (r/R) - 1], the exponent λ' reduces to ~ 2.0 (Figure 1). The λ' exponent also depends on projectile density: aluminum (2.78g/cc), nylon (2.00g/cc), and hollow aluminum (1.72g/cc). Pyrex (2.22g/cc) projectile data, however, depart from this trend with a higher exponent (λ' = 2.43). Near-rim ejecta thickness for the titanium projectile is significantly less (factor of 2) than the thickness from an aluminum projectile near the rim but merges farther downrange. As a result, the ejecta-decay curve exhibits a pronounced two-component line: steeper near the rim (2.4R-3.6R: λ' = 2.20), shallower far from the rim (3.6R-6R: λ' = 1.18).

Oblique impacts require additional binning in order to increase the statistical significance. Figure 2 not only reveals the expected reduction in ejecta thicknesses around the crater but also different values for λ'. Even an impact angle of 60° affects ejecta thickness downrange. The power-law exponents again exhibit values near (or below) 2.0, except for a 30° impact where the exponent downrange is much steeper. The latter pattern reflects volumetric growth downrange at late stages but more cylindrical growth orthogonal to the trajectory.

These observations indicate that crater excavation for experiments using particulate sand do not grow volumetrically (proportionally with crater depth increasing with crater radius). Instead, craters grow cylindrically, i.e., expanding laterally after achieving a maximum depth. Non-proportional growth also can be observed in ¼-space experiments [9] and hydrocode models [10]. After the crater reaches its maximum depth, the lateral shock detaches and proceeds outward. Low density projectiles (nylon, hollow aluminum) transfer their energy and momentum closer to the surface, which results in shallower growth. This interpretation is consistent with the experiment using a titanium projectile, which continued to penetrate after shock detachment. Pyrex projectiles, however, disrupt catastrophically at impact; consequently, they couple more efficiently, thereby contributing to a value of λ' higher than that for aluminum, in spite of their similar density. These results are consistent with launch depth of ejecta based on the evolution of ejection angles [11].

Implications: Implicit assumptions of volumetric excavation [1] results in an overestimate of ejecta thicknesses at a given scaled range from the impact. *Ad hoc* reduction in transient crater volume by half compensates for this effect but does not fully incorporate a physical model for the coupling process. Moreover, referring ejecta thickness decay to the scaled crater center (r/R), rather than the position of launch (r/R-1), does not correspond to the excavation process, especially at mid-range distances (between 4R and 8R).

References: [1] McGetchin, T. R. et al. (1973), *EPSL 20*, 226–236; [2] Post, R. (1974), Tech. Rep. AFWL-TR-74-51; [3] Melosh, H. J. and Ivanov, B. A. (1999), *Annu. Rev. Earth Planet. Sci. 1999. 27:385–415*; [4] Fassett, C. L. *et al.*, *GRL 38*, L17201, doi:10.1029/2011GL048502; [5] Housen *et al*. (1983), *J. Geophys. Res*. *88*, 2485-2499; [6] Stöffler, D., et al. (1975) *J. Geophys. Res. 80*, 4062–4077; [7] Hermalyn, B. and Schultz, P. H. (2010), *Icarus 209*, 866-870; [8] Hermalyn, B. and Schultz, P. H. (2011), *Icarus 216*, 269–279; [9] Schultz, P. H. et al. (2013), *LPSC45*, this volume; [10] Schultz, P. H. *et al*. (1981), *Proc. Lunar Planet. Sci. 12A*, pp. 181-195; [11] Hermalyn, B. *et al.* (2012), *Icarus 218*, 654-665.

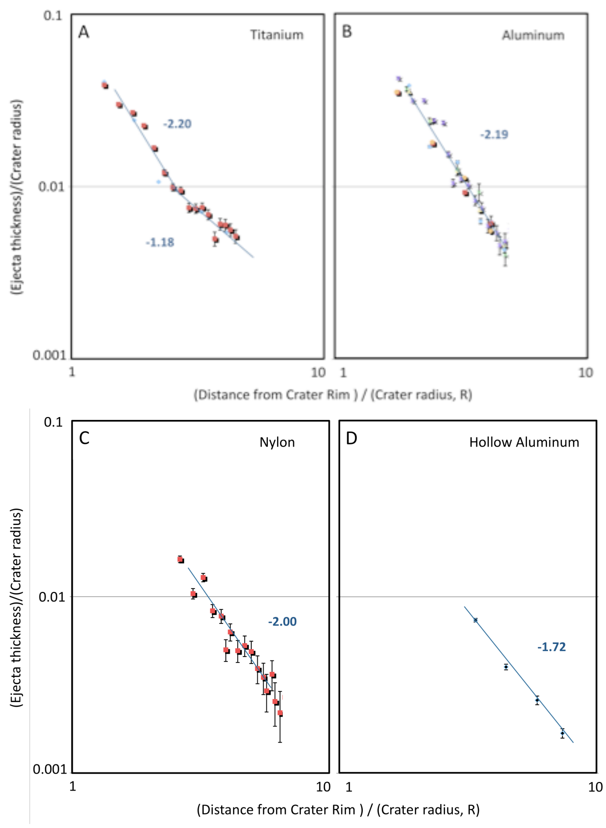

Figure 1. Comparison of ejecta thickness decay curves as a function of distance from the crater rim (approximate launch position) for vertical impacts with projectiles of different densities: titanium (A), aluminum (B), Nylon (C), and hollow aluminum (D). Scaled distance from the rim is equivalent to (r/R-1).

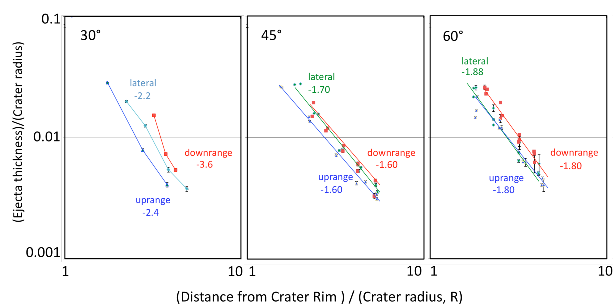

Figure 2: Ejecta thickness decay curves for different-angle impacts (aluminum projectiles) referred to the crater rim, equivalent to (r/R-1).