HOW MUCH OF THE IMPACTOR (AND ITS WATER) ENDS UP IN VESTA'S REGOLITH?. R. Terik Daly[1] and Peter H. Schultz[1], [1]Department of Geological Sciences, Brown University, 324 Brook St. Box 1864, Providence, RI 02912 (ronald_daly@brown.edu; peter_schultz@brown.edu).

Introduction: Vesta bears the scars of 4.5 billion years of collisions [1]. The fact that Vesta is cratered is unsurprising, but the "dark material" associated with some of Vesta's craters was. Dark material is interpreted to be contamination from carbonaceous chondrites impacting Vesta [2–4]. Areas with dark material have elevated H concentrations [4]. This spatial link is thought to be due to OH-rich alteration minerals in carbonaceous chondrites. However, significant questions remain about how much of the water in an impacting carbonaceous chondrite actually remains in the projectile after impact.

Goals of this study: We seek to understand the *process* by which dark material is emplaced on Vesta. Vesta is perhaps the best example of projectile contamination observed to date, but the process by which projectiles contaminate their targets is fundamental.

Our focus is projectile material that survives in the solid state or as quenched melt. We address the following questions: How much of the projectile survives impact? How is the surviving material spatially distributed? What is the physical state of retained projectile material? What mixing processes occur between the target and projectile? And, how much of the water in a hydrous projectile survives impact and is incorporated into projectile-contaminated materials?

Parts of these questions have been addressed by earlier experiments [5–8] and numerical models (e.g., [9,10]). However, the mixing processes we investigate are not well resolved in current impact codes. Our experiments expand on those of previous studies, with particular attention to mixing processes and the physical state of surviving projectile material.

Experiments: We conducted hypervelocity impact experiments using the two-stage light gas gun at the NASA Ames Vertical Gun Range. Impact speeds ranged from 4 to 6 km s^{-1}; these are typical impact speeds in the asteroid belt [11]. Thus, our experiments are directly relevant to Vesta, although smaller in scale. Impact angles varied between 30° and 90°.

We used a powdered pumice target as an analog for airless body regoliths. We used four different projectile types: aluminum, basalt, Pyrex, and serpentine. Aluminum and basalt allow us to explore possible differences in the behavior of ductile, metallic and brittle, rocky materials (i.e., iron and stony meteorites). Serpentine projectiles were used to assess water retention.

Following each experiment, we recovered as many projectile relics and projectile contaminated materials as possible. Samples were recovered from the crater floor, sub-floor, rim, and near-rim. Samples were carefully cleaned to remove possible contaminants before being weighed and analyzed using optical and electron microscopy, the electron microprobe, and inductively-coupled plasma atomic emission spectroscopy.

Results: The samples we recovered from experiments into pumice targets are projectile-contaminated materials (PCM). That is, they are combinations of melted and brecciated relics of the projectile mixed with shock-compressed or melt-lithified portions of the target. In general, surviving projectile is retained in three ways: as melted blebs within glassy pumice melt, as clasts within such a melt, or as clasts within a shock-compacted portion of pumice. In experiments with Al projectiles, some PCM are nearly pure Al. In contrast, surviving material from basalt projectiles is finely dispersed in the melted portion of the PCM.

Survival rates. At ~4.75 km s^{-1}, the mean impact speed at Vesta [11], 20 to 75% of the projectile's mass survives as a solid or quenched melt incorporated into PCM. PCM remains within the crater floor, subfloor, rim, and near-rim. With increasingly oblique angles, a larger fraction of the retained PCM is located down-range (see Fig. 1).

Approximately 40 to 60 wt. % of PCM created by impact is found in fewer than 10 large pieces (see Fig. 2). The remaining mass is dispersed among numerous small pieces of PCM with small amounts of finely-dispersed projectile material.

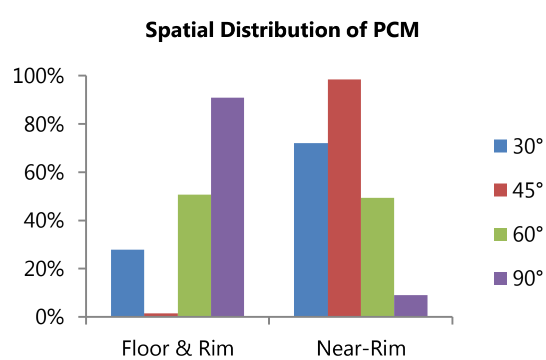

Figure 1. As impact angle (measured from horizontal) decreases, a larger mass fraction of PCM is found in the near rim (within two crater radii). At 60°, approximately equal amounts of retained PCM are located in the crater floor, subfloor, and rim as is in the near-rim region. (Impact conditions: basalt projectiles into a pumice target at speeds between 4.44 and 4.93 km s^{-1}.)

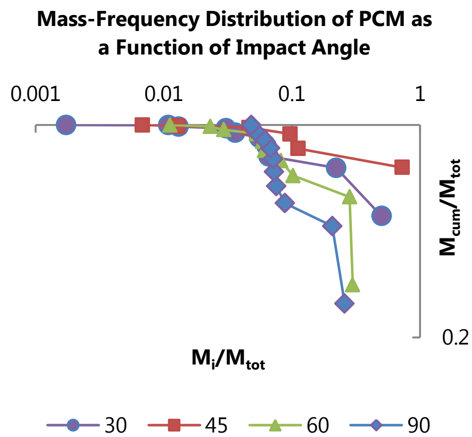

Figure 2. Mass distribution of PCM formed by impacts at 30°, 45°, 60°, and 90° from horizontal. The *x*-axis is the mass of an individual piece of PCM, M_i, normalized by the total mass of the 10 largest PCM pieces, M_{tot}. The *y*-axis is the *cumulative* mass of PCM, M_{cum}, normalized by M_{tot}. At all impact angles, three to four large pieces dominate the mass of PCM. However, the mass-frequency distribution changes with impact angle. (Impact conditions: same as Fig. 1.)

Projectile/target mixing ratios. The amount of projectile in samples of PCM from different regions of the crater (e.g., crater floor versus near-rim) is starkly different. The location of the most heavily contaminated PCM depends on impact angle. At vertical incidence, the most heavily contaminated PCM is in the crater floor. In contrast, at 45° the most contaminated pieces were collected the farthest downrange of the crater.

Implications: Carbonaceous chondrites are not the only impactors hitting Vesta, but they are the only impactors currently identified as contaminating the Vestan regolith (e.g., [2]). Given our results, other impactors (e.g., irons, etc.) should also contaminate the regolith. PCM from basaltic and Al projectiles have different mass-frequency distributions. So, the spatial pattern of contamination may vary with impactor type. Vertical regolith mixing through time (due to impacts) may complicate searches for projectile signatures.

Where are the signatures of other projectiles?. The howardites contain evidence for contamination by iron meteorites. Hewins [12] reported metal grains with meteoritic Ni-Co ratios in several howardites. His description of round masses of metal in Kapoeta melt matches what we observe in PCM from Al projectiles (Fig. 3). Kapoeta—a single howardite—records contamination from at least two different types of impactors: irons [12] and carbonaceous chondrites [13].

Beyond the Vesta problem. Experiments (e.g., [8]), models (e.g., [9]), geochemistry (e.g., [14]) and remote sensing data (e.g., [3]) tell a consistent story: parts of the impactor survive and may be retained by the target. The amount of retained projectile, its physical state, and projectile-target mixing depend on impact angle, velocity, impactor type, and target properties.

Impact velocity is a key variable. The low (4 to 6 km s^{-1}) impact velocities in the asteroid belt [11] lead to higher levels of projectile survival during asteroidal collisions than in collisions with the Moon or Mercury. However, extremely low (1 to 2 km s^{-1}) impacts are not required to preserve large amounts of the projectile.

The other large (Vesta-sized) objects in the main belt likely have regoliths littered with projectile material. Mars, with a mean impact speed of 10.6 km s^{-1} [15], should also be substantially contaminated by its impactors, unless reworked or buried.

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References: [1] Marchi, S. et al. (2012) *Science*, *336*, 690–694. [2] Reddy, V.R. et al. (2012) *Science*, *336*, 700–704. [3] McCord, T.M. et al. (2012) *Nature*, *491*, 83–86. [4] Prettyman, T.H. et al. (2012) *Science*, *338*, 242–246. [5] Daly, R.T. & Schultz, P.H. (2013) *LPS XXXXIV*, abs. #2240. [6] Stickle, A.M. & P.H. Schultz (2012) *LPS XXXXIII*, abs. #1269. [7] Schultz, P.H. & A.M. Stickle (2011) *LPS XXXXII*, abs. #2611. [8] Schultz, P.H. & D.E. Gault (1990), *GSA Spec. Pub.*, *247*, 239–261. [9] Pierazzo, E. & H.J. Melosh (2000), *Met. Planet. Sci.*, *35*, 117–829. [10] Svetsov, V. (2011) *Icarus*, *214*, 316–326. [11] O'Brien, D.P. and M.V. Sykes (2011) *Space Sci. Rev.*, *163*, 41–61. [12] Hewins, R.H. (1979) *Geo. Cosmo. Acta*, *43*, 1663–1673. [13] Zolensky, M.E. et al. (1996) *Met. & Planet. Sci*, *31*, 518–537. [14] Palme, H. et al. (1978) *Geo. Cosmo. Acta*, *42*, 313–323. [15] Le Feuvre, M. & Wieczorek, M.A. (2008) *Icarus*, *197*, 291–306.

Figure 3. When Al projectiles are launched into pumice at ~4.5 km s^{-1}, the melted, glassy surface of melt breccias contain blebs of melted and quenched Al. This observation is similar to the rounded masses of meteoritic metal in Kapoeta described by [12].