NEW CONSTRAINTS ON THE DELIVERY OF IMPACTORS TO ICY BODIES: IMPLICATIONS FOR CERES. R. Terik Daly[1] and Peter H. Schultz[1], [1]Department of Earth, Environmental, and Planetary Sciences, Brown University (324 Brook St., Box 1846, Providence, RI 02912; ronald_daly@brown.edu).

Introduction: During collisions at impact speeds typical of the main asteroid belt [1], significant fractions of the impactor survive and remain on the target [2–5]. Most previous numerical [2, 3, 6–9] and experimental [4, 5] studies investigating impactor delivery have used silicate targets. However, many of the objects in the Solar System have icy surfaces or ice-rich near-surface layers. This includes Ceres, which may have an icy mantle beneath a porous silicate crust [10].

Preliminary work by [11] suggests differences in projectile delivery efficiency for silicate and icy targets. The goal of this work is to gain insight into the role of projectile delivery at Ceres by constraining how much of the impactor is retained in and near the crater during impacts into porous, ice-rich targets that provide possible analogs for the surface of Ceres. Unlike prior theoretical work [6], this study assesses impactor delivery at speeds between 4.5 and 5 km s^{-1}, conditions representative of impacts at Ceres. The findings of this study suggest that Ceres is heavily contaminated by the impactors that bombard it.

Methods: Experiments at the NASA Ames Vertical Gun Range (AVGR) constrain how efficiently the impactor is delivered during impacts into icy targets. The two-stage light gas gun at the AVGR launches projectiles at hypervelocity speeds into an impact chamber that accommodates a variety of targets over a range of impact angles [12], a variable which strongly affects impactor delivery [5,9]. Consistent with [5], this study emphasized the impactor retained inside the crater and within a few crater radii of the rim.

The use of both basalt and aluminum projectiles revealed the effects of projectile properties on impactor delivery. Experiments were done at 30, 45, 60, and 90° (with respect to horizontal) at 4.5 to 5 km s^{-1}. These are typical impacts speeds among bodies in the main belt, including Ceres [1]. Therefore, impact speed need not be scaled when extrapolating results from these experiments, although other factors (e.g., size, strain rate) should be considered for larger craters.

These experiments used two different targets. First, porous, snow-like ice provided an analog to the icy regolith surfaces of Kuiper Belt objects and icy satellites. Second, a layer of sieved perlite was place on top of the porous ice. Perlite-veneered targets revealed the effect of an under-dense silicate surface layer, which could strongly modify coupling of the impactor's energy and momentum to the target [13], thereby affecting impactor delivery. Such a layer may be present on ice-rich main belt asteroids [14] and Ceres [10, 15].

After each experiment, the portions of the target that mixed with the projectile were excavated and melted. The meltwater was sieved to recover projectile fragments. A second stage of sorting eliminated any contamination. Recovered projectile fragments were characterized using optical microscopy, as well as in polished section, to gain insight into how the projectile failed upon impact (e.g., shear, spall, catastrophic disruption) and the role of rapid quenching.

Findings: At vertical incidence, >70 wt. % of aluminum impactors is retained inside the crater or slightly beyond the rim during impacts into porous snow-like targets (Figure 1). Experiments at 45° for the same targets revealed a ~10% decrease in retention efficiency compared to the vertical case. Preliminary analysis comparing snow-like and perlite-veneered targets reveal that the presence of an underdense silicate veneer over an icy substrate biases the delivered projectile component toward fine-grained fragments (Figure 2).

Thin section and electron microprobe analyses of fragments of basalt projectiles reveal selective preservation of feldspar grains compared to a melt predominantly derived from mafic phases. The impact glass appears unaltered by aqueous processes. This indicates that rapid quench rates severely limit the time available for aqueous alteration of projectile relicts at the elevated temperatures associated with impact. Rapid quenching also limits the extent of melting in projectile pieces.

Implications for Ceres: The results of this study predict significant projectile contamination at Ceres. Not all impacts will contribute a projectile component, depending on, for example, impact angle [5, 9], but some impacts will deliver portions of the impactor to Ceres. This summer, the *Dawn* mission may find pockets of delivered material on crater floors and reveal signatures associated with different types of meteorite impactors. A projectile component is likely also distributed farther away from the crater [e.g., 5].

In experiments, projectile relics do not exhibit clear signs of aqueous alteration. While it is possible that alteration of primary impactor material might take place over longer timescales on Ceres, these results suggest that the impactor component, particularly in younger craters, may consist of nearly pristine impactor material that has not been extensively altered during delivery or since being deposited on Ceres.

The fact that water ice is not stable over much of the surface of Ceres [15] (depending on latitude) will affect the accumulation of a projectile component on Ceres through time. Impact-exposed ices (or excavated and mixed with projectile survivors) may sublimate rapidly on geological timescales depending on location [15]. As a result, a lag of projectile relics, accompanied by phases already present in the sublimating ice (e.g., silicates, carbonates, hydroxides) would accumulate on the surface of Ceres (See Figure 1). Although pieces of projectiles delivered to Ceres will be larger than those in experiments, they will still be fairly small (e.g., increasing projectile size by a factor of 10 only increases fragment size by ~1.8, assuming ¼ power scaling of strain rate). This sublimation process should result in a concentrated layer of projectile contamination on Ceres, in contrast with vertical mixing on Vesta [16].

These results also suggest it is possible that much of the porous silicate veneer (phyllosilicates, carbonates, brucite [17]) that covers the putative ice-rich mantle of Ceres (e.g., [10]) may represent impactor material delivered to Ceres, rather than the result of endogenic alteration (e.g., [17,18] or even the product of syn- and post-impact alteration (e.g., [19]).

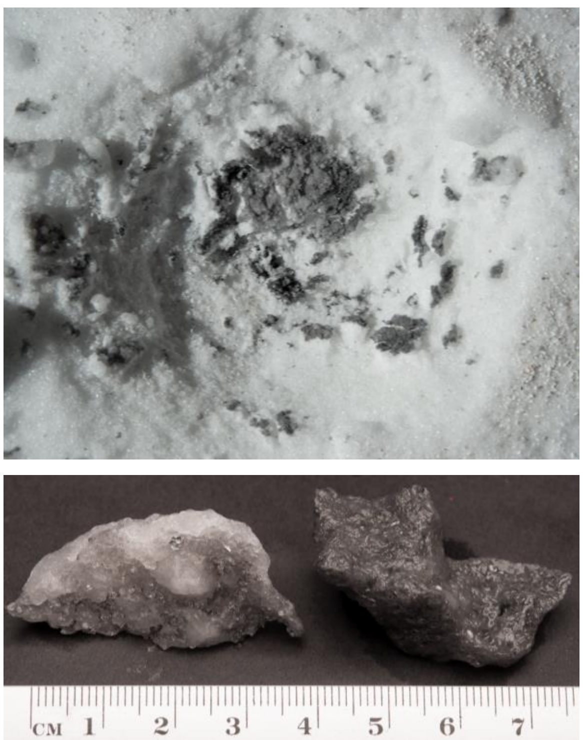

Figure 1. (A) The projectile component (distributed throughout the dark gray deposits) is largely retained on the crater floor during impacts at vertical incidence. As impact angle decreases (with respect to horizontal), the projectile component is increasingly distributed beyond the crater rim. (B) Pieces of the dark gray deposit shown in (A). They consist of ice that melted and rapidly re-froze, trapping the dispersed projectile relics. The finely dispersed projectile relics give these pieces their gray color. On Ceres, where exposed water ice is unstable for geologic timescales across much of the surface, the ice will sublimate away, leaving a lag of projectile relics on the surface.

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References: [1] O'Brien, D. P. and Sykes, M. V. (2011) *Sp. Sci. Rev.*, *163*, 41–61. [2] Svetsov, V. (2011) *Icarus*, *214*, 316–326. [3] Turrini, D. and Svetsov, V. (2014) *Life*, *4*, 4–34. [4] Schultz, P. H. and Gault, D. E. (1990) *GSA Sp. Pap*. *247*, 239–262. [5] Daly, R. T. and Schultz, P. H., (2014) *LPS 45*, Abstract #2070. [6] Pierazzo, E. and Chyba, C. F. (2002) *Icarus*, *157*, 120–127. [7] Bland, P. A. et al. (2008) *LPS 39*, Abstract #2045. [8] Ong, L. et al. (2010) *Icarus*, *207*, 578–589. [9] Bruck-Syal, M. and Schultz, P. H. (2014) *AGU Fall Mtg.*, Abstract #P51C-3960. [10] Castillo-Rogez, J. and McCord, T. M. (2010) *Icarus*, *205*, 443–459. [11] Daly, R. T. and Schultz, P. H. (2013) *LPS 44*, Abstract #2240. [12] Gault, D. E. and Wedekind, J. A. (1978) *Proc. 9th LPS*, 3843–3875. [13] Schultz, P. H. et al. (2005) *Sp. Sci. Rev.*, *117*, 207–239. [14] Schorghofer, N. (2008) *Astro. J.*, *682*, 697–705. [15] Fanale, F. P. and Salvail, J. R. (1989) *Icarus*, *82*, 97–110. [16] Jaumann, R., A. et al. (2014) *Icarus*, *240*, 3–19. [17] Milliken, R. E. and Rivkin, A. S. (2009) *Nat. Geo.*, *2*, 258 – 261. [18] Zolotov, M. (2009) *Icarus*, *204*, 183–193. [19] Zolotov, M. (2014) *Icarus*, 228, 13–26.

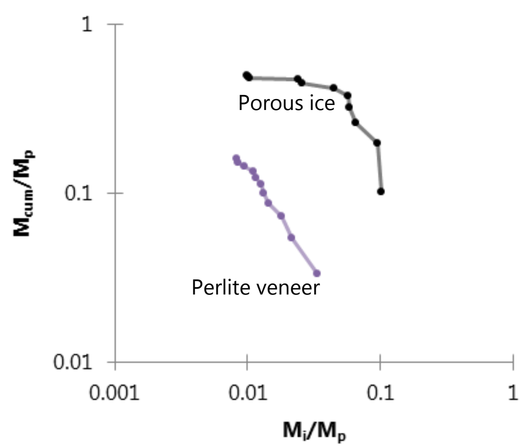

Figure 2. Mass frequency distributions of larger projectile fragments derived from the 45° impact of aluminum spheres into two different ice-rich targets at ~5 km s^{-1}. The difference in the two distributions indicates that impacts into the perlite veneered target produced a projectile component biased toward fine-grained fragments compared to the impact into the porous snow-like target. The *x*-axis is the mass of an individual projectile fragment, M_i, normalized to the projectile mass, M_p. The *y*-axis is the cumulative mass of all fragments ≥M_i normalized to the projectile mass.