PROJECTILE PRESERVATION DURING OBLIQUE HYPERVELOCITY IMPACTS. R.T. Daly and P.H. Schultz, Department of Earth, Environmental and Planetary Sciences, Brown University, 324 Brook St., Providence, RI 02912. Email: terik_daly@brown.edu.

Introduction: NASA's Long-Duration Exposure Facility (LDEF) spent 69 months orbiting Earth. During that time, the spacecraft accumulated multitudes of micron- to submillimeter-sized craters. A significant fraction of these craters preserved residues of the projectile: ~30% contained projectile-rich glasses [1] and a few percent hosted intact projectile fragments [2].

In light of these findings, some studies used impact experiments to assess the conditions needed to preserve projectile residues [e.g., 1–6]. Of these, only [4] examined the role of impact angle. However, many studies using both experiments [7–10] and shock physics codes [11–13] have highlighted the dramatic effect that impact angle has on projectile fate.

In this contribution we report new experiments that explore how impact angle and other variables influence projectile preservation. These new experiments use projectiles up to 300 times larger than those used in [4]. This contribution emphasizes the physical state (quenched melts vs. fragments) and spatial distribution of the projectile component. We find that portions of the projectile survive impact and are preserved within craters across the entire range of conditions studied, including conditions relevant to the asteroid and Kuiper belts.

Methods: A suite of experiments at the NASA Ames Vertical Gun Range (AVGR) explored how impact variables affect projectile preservation. These variables included impact angle (15° to 90° wrt. horizontal), impact speed (1.5 to 6 km s^{-1}), target type (ETP copper and 6061-T6 aluminum), and projectile type (Pyrex, quartz, basalt, serpentine, and aluminum).

After impact, multiple techniques were used to identify surviving projectile fragments and characterize projectile-rich melts. These methods included optical and scanning electron microscopy, electron microprobe work, and reflectance spectroscopy.

Results: Craters formed by oblique impacts preserve projectile fragments and projectile-rich melts.

Impact speed effects: In these experiments, Pyrex projectiles impacted copper targets at 30°. Craters contain three facies: a white, fragmental facies, a dusty-looking, reddish-brown facies, and a red, vesicular, vitreous facies (Fig. 1).

SEM/EDS analyses reveal that the white, fragmental facies consists of unmelted projectile fragments. The extent of this facies shrinks as impact speed increases. However, this facies occurs on the uprange wall even at the highest impact speed (5.7 km s^{-1}). Hence, unmelted fragments of the projectile were preserved on the uprange wall for impacts at 30° across all speeds studied.

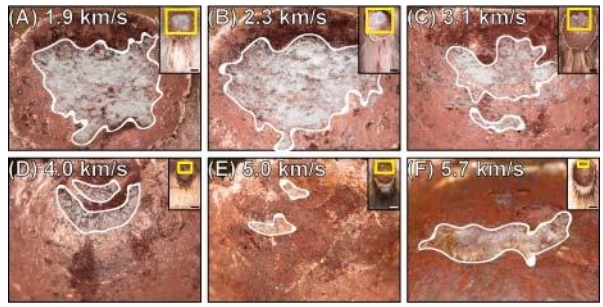

Figure 1. Effect of impact speed on projectile preservation. Areas outlined in white contain projectile fragments. Thumbnails at the upper right of each panel show the location of the field of view. Scale bars in the thumbnails are 1 cm long. Impact direction: from the top.

Impact angle effects: In these experiments, Pyrex spheres impacted copper targets at 5 km s^{-1}. The white, fragmental facies is observed on the uprange crater wall at 30° and 45°. Deposits of the red, vitreous facies occur at 15°, 30°, 45°, 60°, and 75°. The extent and distribution of these facies evolve with impact angle. A new facies of colorless to white vitreous material occurs at 75° and 90°. This facies is composed of copper-free glasses derived from the projectile (Fig. 2).

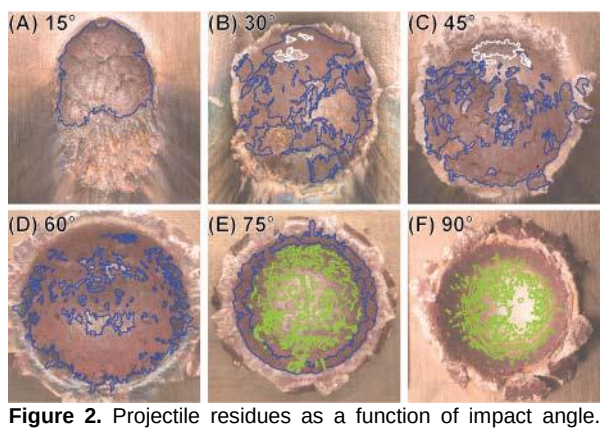

Figure 2. Projectile residues as a function of impact angle. White lines define areas with surviving projectile fragments. Blue lines mark areas covered with the red, vitreous facies. Green lines denote the extent of the white to colorless facies. Impact direction: from the top.

Projectile type effects: In these experiments, projectiles impacted copper targets at 30° and speeds between 4.3 and 5.1 km s^{-1}. Fragments of Pyrex, quartz, serpentine, and basalt projectiles were preserved on the uprange walls of all craters. For serpentine and basalt, VNIR reflectance spectra confirm that the projectile fragments are crystalline (Fig. 3). Projectile-rich melts drape the uprange wall, side walls, and crater floor.

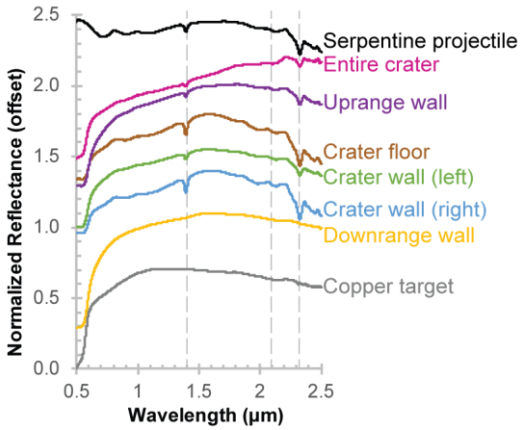

Figure 3. VNIR spectra from a crater formed by the 30° impact of serpentine into a copper target at 4.3 km s^{-1}. Many locations contain diagnostic serpentine absorption features at 1.4, 2.1, and 2.3 µm [13]. Hence, crystalline serpentine was preserved.

Target type effects: In these experiments, identical projectiles were launched at identical speeds and 30° into copper and aluminum targets. Projectiles are better preserved and residues are more widespread in copper than aluminum. Only two facies occur in aluminum targets, in contrast to the three seen in copper (Fig. 4).

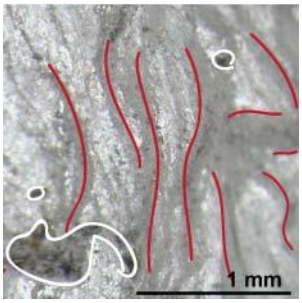

Figure 4. Optical micrograph showing a facies of web-like silicate stringers (marked by red lines) that drape the walls of a crater formed in aluminum. These stringers trap a second, darker facies (circled in white). This second facies is composed of projectile fragments and glass. This crater formed when basalt impacted an Al target at 30° and 3.1 km s^{-1}.

Discussion: Impact variables affect projectile survival and preservation in characteristic ways. Here we focus on impact angle and target type.

Impact angle: Changes in projectile preservation with impact angle reflect the competing effects of peak pressure, projectile momentum, and melting. As impact angle approaches horizontal, reduced peak pressures in the projectile increase the fraction of the projectile that survives unmelted. However, many of these surviving fragments are not preserved within the crater because of their residual downrange momentum [7]. Hence, the crater formed at 15° contains no intact fragments. The fragments preserved on the uprange wall at 30° and 45° are glued to the crater wall by rapidly-quenched melts. These melts are likely produced by shear heating along the projectile-target interface [15].

Target type effects: For all types of projectiles and all speeds studied, copper targets preserved projectiles more effectively than aluminum targets during 30° impacts. If impedance mismatch were the primary control on preservation, then the opposite would be expected because aluminum has a lower impedance. However, textures indicate that rapidly-quenched melts at the projectile-target interface provide the "glue" that preserves surviving projectile fragments. Aluminum targets do not preserve survivors as easily because, under identical conditions, impacts into aluminum generate less melt.

Implications: The uprange crater wall is the most likely place to preserve intact fragments of the projectile. Multiple factors enhance preservation on the uprange wall including: a weaker shock in the uprange direction [16]; reduced peak pressures in the back of the projectile [7,17]; uprange acceleration of the projectile after the shock reflects off its back surface; and melting along the projectile-target interface during penetration. Such factors occur at large scales as well as lab scales. Hence, enhanced projectile preservation on the uprange crater wall may occur during larger oblique impacts, if melts quench rapidly enough—consistent with recent shock-physics-code results [17,18].

These results suggest a new strategy for missions that rely on impact to collect samples. The Stardust mission is one example [19]. The proposed LIFE mission to Enceladus [20] is another. A strategy that capitalizes on preservation during oblique impacts may minimize the shock and thermal processing effects that have complicated analyses of the Stardust particles [21]. Devices designed to encounter particles at 30° (with respect to ram direction) may have a significant advantage over head-on capture. At 30°, peak pressures are reduced by a factor of four compared to vertical impacts and the uprange wall of the crater or pit will likely preserve intact fragments of the collected material (i.e., particles from Enceladus' plume). Although only a part of each impacting object would be preserved, the captured material would be minimally altered, thereby increasing the science return from such a mission.

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