UPRANGE PLUMES AND NATURE OF THE COMET 9P/TEMPEL 1. P. H. Schultz, Brown University, Department of Geological Sciences, 324 Brook Street, Providence, RI 02912-1846 (peter_schultz@brown.edu).

Introduction: The collision of the Deep Impact (DI) probe with Comet 9P/Tempel 1 in 2005 produced a rich record of data [e.g., 1]. The accompanying spacecraft, now re-commissioned as DIXI (heading for Comet Hartley), captured several intriguing phenomena. These included the delayed "flash," high-speed downrange plume, staged excavation, and high-angle plume that hid clear identification of the crater [2]. This contribution focuses on the early stages of excavation and necessary conditions for producing an early-stage the uprange plume.

Background: During the early stages of formation, the DI crater appeared to have ejecta emerging uprange, which requires lower thatn expected ejection angles [2,3]. Two explanations have been proposed. First, the probe made initial contact with a tilted surface facing the trajectory, thereby producing a conical curtain opened along the incoming trajectory [3]. Second, the DI collision penetrated deep into a highly porous surface, thereby producing an uprange-directed plume and delayed flash [2, 4]. The first hypothesis is reasonable (if not necessary) if it is assumed that the excavation resembles vertical impacts into loose particulates. Here, however, we focus on new laboratory experiments were designed to assess conditions that will produce the uprange plume.

Laboratory Experiments: A series of hypervelocity impact experiments were performed at the NASA Ames Vertical Gun Range. Projectiles were 0.635 cm aluminum and Prex spheres launched from 5.0 to 5.5 km/s at 30° from the horizontal. Targets included nominal no. 100-140 sand (density 1.7 g/cm^3), solid dry ice (0.016 g/cm^3), solid pumice block (0.2 g/cm^3), styrafoam (0.015 g/cm^3), perlite mixed with fine dolomite powder (45% $CaCO_3$ and 35% MgO; 0.74 g/cm^3), and a thin layer (1.2 cm) of finely sieved perlite (0.12 g/cm^3) over the perlite/dolomite mix. All impacts were done under vacuum conditions (<0.5 Torr), excepting the target of dry-ice, which required a small residual atmosphere (4 mm air). The goal of these experiments is to understand which specific conditions control the development of an uprange-directed plume. Prior experimental surveys [2] showed that a low-density target was necessary but a full range of densities had not been done.

The loose, fine sand target provided a nominal reference. The dry-ice block represented an easily volatized solid target of low density, whereas the solid pumice block removed the effect of volatiles. The styrafoam target represented an extreme case for a solid, low-density organic material. The perlite/dolomite mixture provided both low density and volatile rich target. Last, the layered target provided a refractory upper surface (two projectile diameters thick) over a slightly higher density volatile-bearing substrate. A thin (< 0.1mm) layer of powdered sugar was also added to this target.

The AVGR now has new imaging capabilities, which were used for this study. Two *Shimadzu HPV1* digital cameras captured the earliest stage processes from 125,000 frames per second (fps) to 10^6 fps. These cameras captured only the self-luminous components (gas emissions and thermal sources). Two *Phantom* V12 digital cameras (one color, one B&W) recorded the first few milliseconds at from different viewing positions (side and from a port 15° above the trajectory axis). Last, two time-synchronized color *Phantom* V10 cameras (above) provided the overall evolution in stereo (970fps).

Figure 1 illustrates selected time steps for sand, dry ice, perlite/dolomite, and the layered perlite/dolomite. Impact into the sand target initially generated produced strong thermal sources (rays) that rapidly decoupled from the excavation process. After the first 50 microseconds, an asymmetric ejecta curtain containing self-luminous ejecta rapidly evolved (Fig. 1a). The dry-ice target yielded a fast moving (~6 km/s) and expanding vapor cloud downrange [see 5]. The curtain expanded into a near vertical plume, flanked by arcuate (cooler) rays. Eventually, the plume disappeared since it was primarily composed of expanding vapor without significant thermal sources [Fig. 1b]. The evolution from the perlite/dolomite mix [Fig. 1c] initially resembled the plume emerging from the dry-ice block. As the downrange plume cooled, however, a distinct plume emerged from the transient crater 140 μs after impact. This is most likely the result of decompressed vapor made visible by aluminum-oxide emission bands, prominent in the visible [6]. This plume moved upward at 1.7 km/s while expanding but is only slightly inclined uprange.

The layered perlite mix target yielded two downrange plumes [Fig. 1d]: a faint leading front (resembling an eyebrow) moving downrange at ~ 7 km/s followed by the nominal self-luminous gas. This initial plume rapidly faded as it moved downrange. About 140 μs after impact, a new self-luminous (but fainter) reverse plume emerged at an angle very similar to the initial trajectory. The reverse plume is produced by expanding gas constrained by a penetration funnel, prior to complete coupling with the target. At later-times, this plume becomes more vertical as the crater cavity opens and grows.

Impacts into the low-density styrafoam and pumice block targets also generated an early-time reverse plume. The impact into the styrafoam target produced a black, non-luminous plume (condensed carbon) and emerged from a penetration tube reflecting the initial trajectory. The impact into to the pumice block resembled the perlite/dolomite mix with a higher angle reverse plume and fragmental ejecta.

Discussion: The generation of a reverse plume along the initial trajectory (at laboratory scales) appears to require a target with a density less than 0.3 g/cm^3. The surface layer of low-density refractory silicates (perlite) results in a delayed emergence of the reverse plume, after detachment of the downrange plume. As shown in Figure 1d, the uprange plume detaches from the surface and is replaced by a high-angle opaque curtain of optically thick ejecta (not shown here). This precedes the classic stages of crater excavation resulting in an asymmetric curtain composed of ballistic ejecta.

Such a description closely resembles the observed sequence for the first 60s for the DI crater [2]. From the perspective of Deep Impact observing spacecraft, a reverse plume would appear as a laterally expanding plume centered on the impact point. Between 3s and 60s, ejecta rays radiate back to the point of impact and obscure the growing crater. Meanwhile, a high-angle plume casts a long shadow. After 60s, the ejecta curtain emerges with a different set of rays emerges related to crater excavation.

The low-density surface layer in experiments results in a long penetration funnel that constrains a portion of the expanding vapor generated in front of the shock-decelerated impactor. Sufficiently small solids will be entrained initially but released once the gas density reduces as it escapes from the penetration funnel. As a result, this component becomes collimated back along the incoming trajectory. The delay in the intense DI flash is consistent with this deep initial penetration [2,4].

Conclusions: A layer of volatile-poor material (> two projectile diameters thick) seems required to produce the uprange reverse plume, consistent with other observations from the DI spacecraft [2,7]. The experiments also reveal a separate precursor plume from the dusting of sugar on the surface, consistent with earth-based telescopic observations [8]. The next step is to compare this evolution to computational code results and to set further constraints.

References: [1] A'Hearn M. F. *et al.* (2005) *Science, 310*, 258-264; [2] Schultz, P. H., *et al.*, (2007), *Icarus 190*, 295-333; [3] Richardson, J. E. *et al.* (2007), *Icarus*, *190*, pp. 357-390; [4] Ernst, C. M. and Schultz, P. H. (2007), *Icarus 190,* 284-294; [5] Schultz, P.H., (1996), *J. Geophys. Res. 101*, 21,117-21,136; [6] Sugita, S. *et al.* (1998), *J. Geophys. Res.*, *103,* 19,427-19,441; [7] Sunshine, J. M. *et al.* (2007), *Icarus 190*, 284-294; [8] Kadono et al. (2007), *ApJ Letts. 661*, L89–L92.

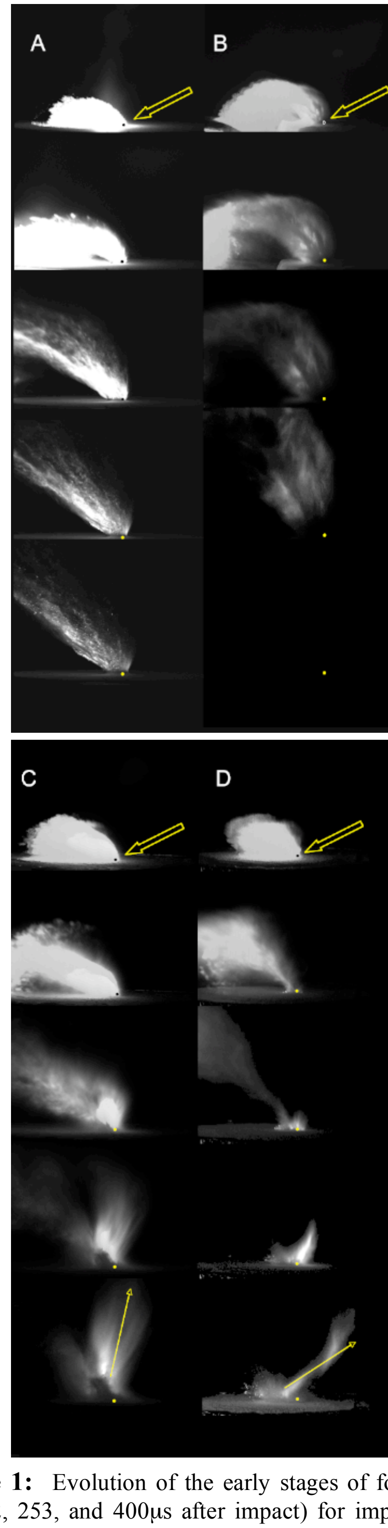

Figure 1: Evolution of the early stages of formation (40, 72, 142, 253, and 400μs after impact) for impacts into dry sand (A), dry ice (B), perlite/dolomite mixture (C), and target B covered by a layer of dry perlite dust (two projectiles thick).