IMPACTS ONTO SLOPES IN COARSE, RUBBLE-LIKE TARGETS. R.T. Daly[1], O.S. Barnouin[1], M.A. Sevalia[1], K. Hikosaka[2], D.A. Crawford[3], A.A. Knuth[1], [1]Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel MD, USA (terik.daly@jhuapl.edu). [2]Department of Earth and Planetary Physics, University of Tokyo. [3]Crawford Technical Services, Winona, MN, USA.

Introduction: Many impact craters on the Moon [e.g., 1], Mars [e.g., 2], and asteroids (e.g., Vesta [3], Lutetia [4], etc.) formed on slopes and have morphologic asymmetries attributed to topography. However, the effects of target slope on impact crater growth, scaling, and morphology remain poorly understood. A detailed understanding is a prerequisite for interpreting craters observed on slopes across the solar system.

Laboratory studies have investigated impacts on slopes [2,5–8]. However, most earlier studies convolved the effects of target slope with those of an oblique impact: the impact vector was kept constant with respect to gravity while varying the target surface slope. ([8] is an exception.) With this approach, changes in the target slope implicitly change impact angle. Because oblique impacts also affect crater formation and scaling [e.g., 9], it is essential to separate the effects of a sloped surface from the effects of impact angle.

Another factor may be at work on some asteroids. Many near-Earth asteroids visited by spacecraft, including Itokawa, Ryugu, and Bennu, have rubbly surfaces and steep slopes [10–12]. Coarse-grained targets may affect crater formation and scaling [e.g., 13,14]. Earlier studies [2,5–8] used relatively fine-grained targets. Here we focus on coarser-grained targets.

Methods: We carried out impact experiments at the NASA Ames Vertical Gun Range (AVGR) and the Johns Hopkins Applied Physics Laboratory Planetary Impact Lab (PIL) to investigate cratering on slopes in coarse-grained targets. The experiments used a target of 3-mm diameter alumina spheres (angle of repose = 28°; bulk density = 2.1 g cm^{-3}). Individual grains possess strength, but the bulk target is mostly cohesionless with shear strength following a Mohr-Coulomb criterion. Alumina spheres (AVGR, either 6.35- or 4.76-mm diameter) or 3D-printed polymer cylinders (APL, equivalent in volume to a 12.7 mm diameter sphere) served as projectiles. Impact velocities were 0.25–0.30 (PIL) and 1.58 to 5.28 km/s (AVGR). These velocities significantly exceed those in [2,5–8]. To separate the effects of impact angle from the effects of target slope, we performed normal-incidence impacts onto targets with surface slopes of 0, 15, and 28° wrt. horizontal. High-speed Phantom and Shimadzu cameras recorded the impacts.

The final craters were scanned using an Artec Eva 3D scanner to capture crater morphology. We extracted topographic profiles across each crater at eight azimuths and measured the rim-to-rim diameter and rim-to-floor depth relative to the pre-impact surface.

Results: High-speed imaging shows that early-time crater growth is relatively unaffected by the sloped surface, but later-time collapse on the 15° and 28° slopes is asymmetric in the slope dip direction. Ejection in the cross-slope direction is relatively unaffected. Enhanced collapse on the uphill side ultimately leads to a steeper wall on the downhill side in the final crater. Crater growth and collapse parallel to slope strike appear similar to that observed in flat targets.

The evolution of crater shape with slope angle is similar between the PIL and AVGR experiments, which indicates that impact velocity has a minimal effect on final crater planform. Craters formed on a 0° slope are axisymmetric, as expected, with a well-defined uniform rim (Fig. 1A). Craters formed on a 15° slope are elliptical, larger, and shallower than craters formed on flat surfaces (Fig. 1B), with the elongation parallel to the slope dip direction. Uphill crater rims are absent; downhill rims are broadened relative to the rims of craters formed on 0° slopes. The crater wall is much steeper on the downhill side than the uphill side, and the deepest part of the crater is offset downhill from the center of the planform. The widest part of the crater is offset downhill from the deepest point. Impacts onto 28° slopes triggered landslides that completely erased the transient crater and left no trace of the impact (Fig. 1C).

The craters formed on a 15° slope have up to a 25% larger rim-to-rim average diameter than those formed on a 0° slope at a similar impact velocity. This increase occurs as a result of rim expansion during the collapse phase, a process which is enhanced on sloped targets. The depth-to-diameter ratio, *d/D*, of craters formed at normal incidence on 0° slopes was 0.19 at the AVGR (1 experiment) and 0.19 $\pm$ 0.01 at the PIL (8 experiments). For craters formed at normal incidence on a 15° slope, the *d/D* was 0.14 $\pm$ 0.02 at the PIL (4 experiments) and 0.11 $\pm$ 0.01 at the AVGR (4 experiments).

Discussion: These results are broadly consistent with previous studies [2,5–8]. However, differences in rim morphology exist. For example, the craters formed on slopes in [2] reportedly had sharp upslope rims. This differs from the morphology observed here: craters formed on a 15° slope in the coarse target had no uphill raised rim. An inflection in the crater profile instead marks the uphill edge of the crater. Several factors could account for differences in rim morphologies, including that the experiments reported here isolated the effect of a sloped target from the effects of an oblique impact, difference in target grain sizes ([2] used quartz sand and glass beads whose sizes ranged from 0.15 to 0.8 mm, much smaller than the grains used here), differences in target strength properties, or differences in the grain size distribution of particles in the targets (monodisperse in this study vs. distributed in [2]). The coarser grain size and monodisperse nature of the target in this study may influence crater collapse because more work is required to move each particle over its neighbors.

Implications. Our preliminary investigation of impacts onto coarse-grained, sloping targets has yielded some similarities to earlier studies; the observed differences may stem from the coarse-grained nature of the targets used here, differences in target strength, or differences in target grain size distribution. The fact that craters formed on a sloping target have larger average rim-to-rim diameters than craters formed on a 0° slope has implications for cratering statistics on rubble-rich bodies. Cratering statistics studies often focus on crater diameter. The results of this study imply that the ages derived from crater counts on slope-rich areas of rubble-pile asteroids might yield artificially old ages due to the enlarged crater diameter which would, unless slope effects were accounted for, imply a larger projectile.

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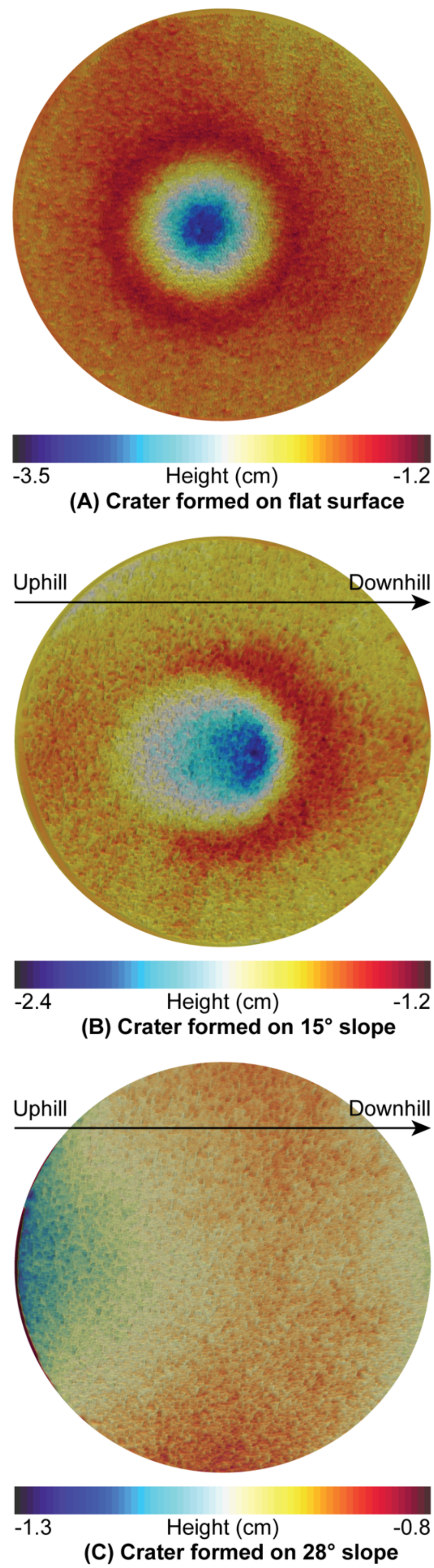

Fig. 1 (right). Craters formed in 3-mm alumina sphere targets on (A) a 0° slope, (B) a 15° slope, and (C) a 28° slope. Scans are colorized based on height relative to the pre-impact surface and are viewed from a perspective normal to the pre-impact surface. This emphasizes crater morphology, but masks the slope of the pre-impact surface. In (B) and (C), the slope dips down to the right. The uphill side of the target in Fig. 1C is depressed below the pre-impact surface because material moved downslope during the impact-triggered landslide. Note the difference in scale between the color bars. Each scan is ~40 cm across. The projectile trajectory was normal ($\pm$ 2°) to the target surface in all cases.