IMPACT CRATERING PROCESSES ON SLOPES USING ANALOGUE EXPERIMENTS J. Aschauer[1], T. Kenkmann[1] and M. Rudolf[2], [1]Institute of Earth and Environmental Sciences, Albertstrasse 23-B, 79104 Freiburg, Germany; Jo.aschauer@posteo.de, [2]GFZ German Research Centre for Geosciences, Section Lithosphere Dynamics, Telegrafenberg, Potsdam D-14473, Germany

Introduction: The vast majority of impact craters is circular due to the impact and explosion analogy [1]. Although oblique impacts are prevalent occurrences, the crater shape remains circular for impact angles above 10–15° from the target surface [2]. Almost all craters with elliptical outlines are ascribed to very oblique impacts. Butterfly ejecta pattern are commonly associated with these very oblique impacts [3]. The effect of topography on crater formation is often ignored but could be an important factor in the production of asymmetric craters [4-6], in particular in high-relief regions. Nevertheless, there are a few observations of craters which have non-circular outlines and show an overall asymmetry for example on the Moon [4, 7] and the two main belt asteroids Lutetia [5] and Vesta [6] that was ascribed to topography.

Most of the craters formed on slopes have sharp uphill rims and smooth downhill rims, the downslope diameter is usually higher than the cross-slope diameter [4, 6]. Melt emplacement commonly occurs concordant with the dip direction of the slope plane [7]. Most of the findings on impact cratering processes on slopes have been gathered with remote sensing [6] and numerical modeling [5]. This study aims at a better understanding of impact cratering processes at inclined slopes by means of conducting a systematic parameter study utilizing analogue experiments.

Methods: The experimental set-up consists of a vertical spring driven air gun shooting at a plexiglass box (40 x 40 x 20 cm for half-space experiments) filled with the target material (Fig. 1). For quarter-space experiments which are used to determine the dimensions of the craters in cross section and to observe the crater flow field perpendicular to the target surface, the box is reduced to its half-size and the projectile enters the box right behind the front glass.

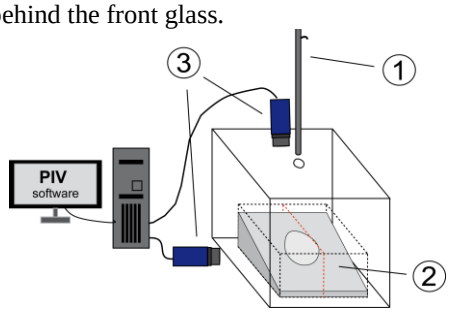

Fig. 1 Experimental set-up. A vertical air gun (1) shoots at the tilted target (2). Experiments are recorded by two cameras (3) from above and the side.

The cylindrically-shaped (6,35 x 10 mm) PVC projectiles have a mass of 0.416 g and a density of 1.355 g/cm^3. The projectile hits the target with a speed of 180.4 m/s and a kinetic energy of 6.7 J. We used two sorts of glass beads (150-250 µm and 420-840 µm grain size), and quartz sand (400-800 µm grain size) as target materials. The target materials have angles of rest (a_r) of 23.3° and 25.8° for the fine and coarse-grained glass beads, respectively, and 28.9° for the quartz sand.

In total 170 experiments on differently tilted target surfaces were conducted. The slope angle Θ was increased in 5 degree steps for each target material to a maximum of either 20 or 25 degrees. To test reproducibility, each experiment of the same slope angle was repeated 5 times. Two ImagerCMOS Cameras record the impact at 50 fps. They are imaging the impact experiments from either above or, in case of quarter space experiments, from the side perpendicular to the front glass and parallel to the strike of the slope.

In order to determine the aspect ratio of the final craters the rim-to-rim diameters have been measured both in cross-slope and downslope direction. Ejection angles have been measured just at the end of the excavation phase.

Results: The pre-impact surface morphology has a strong influence on the crater morphology. Impacts on flat surfaces lead to symmetric crater morphologies, impacts on tilted surfaces result in asymmetric craters. This holds true for even low slope angles of 5 degrees. Material from uphill slumps into the crater and fills it up (Fig 2c). The crater depth thus decreases with increasing slope angles. The crater floor, defined as the deepest point perpendicular to the slope plane, moves downhill. The rim-to-rim diameter parallel to the dip increases for increasing slope angles. This leads to an increasing aspect ratio of the craters for increasing slope angles (Fig. 3). The uphill rims are sharp whereas the downhill rims become smooth for high slope angles (Fig 2b).

The transient crater develops roughly symmetric perpendicular to the slope plane, resulting in higher ejection angles uphill than downhill (Fig. 4). This leads to increased ejecta deposition downhill of the crater compared to the uphill side.

Conclusion: The conducted parameter study confirms the results of impacts on slopes obtained by numerical simulations and remote sensing. Besides low

angle oblique impacts the effect of target topography should be kept in mind for the formation of asymmetric craters.

References: [1] Holsapple, K. A. (1980) *LPSC XI* 2379–2401. [2] Wulf, G. et al. (2012) *Icarus* 220, 194-204. [3] Herrick, R.R., Hessen, K.K. (2006) *M&PS* 41, 1483–1495. [4] Plescia, J.B. (2012) *MPSS 75*, 5318. [5] Elbeshausen D. et al. (2012) *LPSC XLIII*, 1903. [6] Krohn K. et al. (2014) *Planetary and Space Science 103*, 36–56. [7] Neish, C.D. et al. (2014) *Icarus 239*, 105-117.

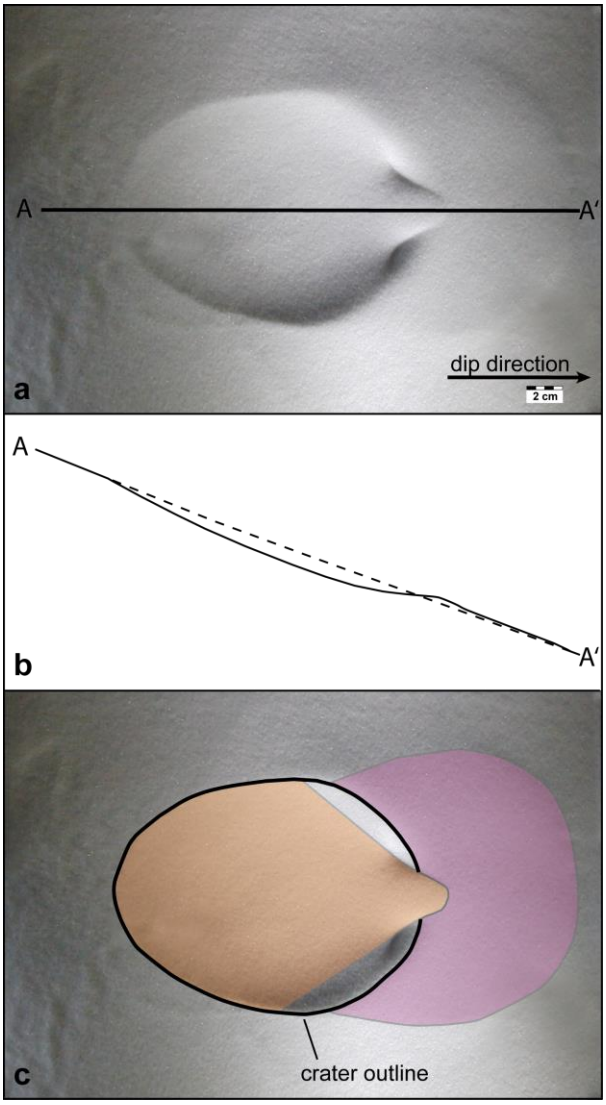

Fig. 2 Top view (a) and cross section (b) of a final crater in a glass bead target with 150-250 µm grain size. The slope is tilted to an angle of 20 degrees. This is only 3 degrees below the angle of rest of the target material. The slope is dipping to the right. The crater is elongated in dip direction. Target material from uphill slumped towards the center of the crater and overshot the downhill rim crest at the end of the modification stage. The crater has almost completely been filled up by this process. Residual mass-wasting material from uphill is mapped in orange in (c). The downhill rim is relatively smooth and low, the uphill rim in contrast is sharp and not elevated against the slope plane as visible in the cross section (b). The low rim height downhill results from the collapse of the downhill rim at the beginning of the modification stage. This mass wasting (purple in (c)) occurs due to the lack of an abutment in downhill direction.

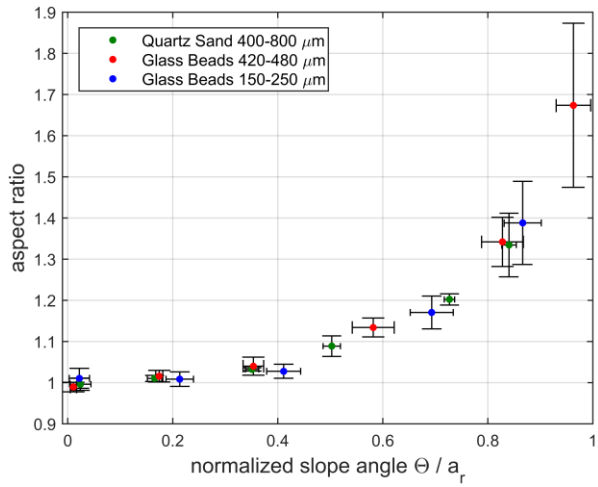

Fig. 3 Aspect ratios of the final craters plotted against the slope angle Θ divided by the angle of rest a_r of the target materials. The aspect ratio reflects the ratio of downslope diameter to cross-slope diameter. Aspect ratios increase non-linearly with increasing slope angle and reach values of ~1.7 with slope angles approaching the angle of rest.

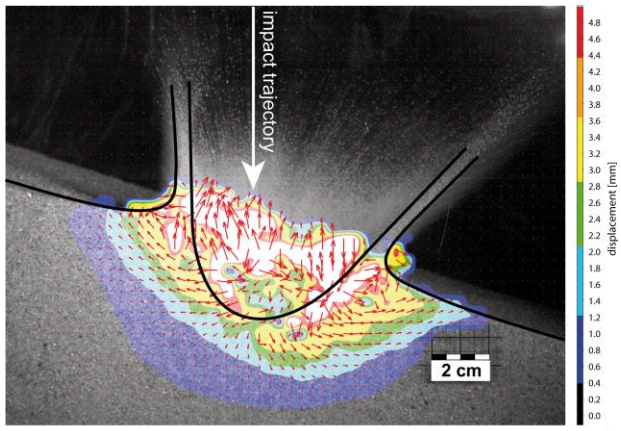

Fig. 4 Snapshot of a transient cavity 20 ms after the projectile hit the quartz-sand target which was tilted to an angle of 15 degrees in a quarter-space experiment. Subsurface particle displacement is illustrated with PIV software. The impact trajectory is vertical. The transient cavity develops perpendicular to the target surface resulting in a steeper ejection angle uphill than downhill.