CRATERING MECHANISMS OF OBLIQUE IMPACTS IN TARGETS OF DIFFERENT STRENGTH – INSIGHTS FROM NUMERICAL MODELING.

D. Elbeshausen[1] , K. Wünnemann[1] and G. S. Collins[2], [1]Humboldt-Universität zu Berlin, Museum für Naturkunde, D-10099 Berlin, Germany (dirk.elbeshausen@museum.hu-berlin.de) [2]Impacts and Astromaterials Research Centre, Department of Earth Science and Engineering, Imperial College London, London SW7 2AZ, UK

Introduction: Meteorite impact is a fundamental process on all planetary surfaces. Most impacts occur at angles between 30° and 60° (measured from horizontal) [1]. However, most of our knowledge on crater formation is based on vertical impact scenarios. Therefore studying the physics of oblique impacts is of crucial importance. Experimental studies have shown that the impact angle affects crater properties such as depth, diameter, morphology [2,3]. However, most of these experiments are controlled by the strength or friction of the material. In previous modeling studies it was demonstrated that in the initial contact and compression stage of an impact (where the impactor penetrates the target) the strength of the generated shock wave is highly asymmetric in oblique impacts [4,5]. This suggests that the late stage crater formation and collapse is influenced by the impact angle as well. However, both observations and numerical calculations (Fig.1) show a circular morphology of most crater structures, regardless of impact angle.

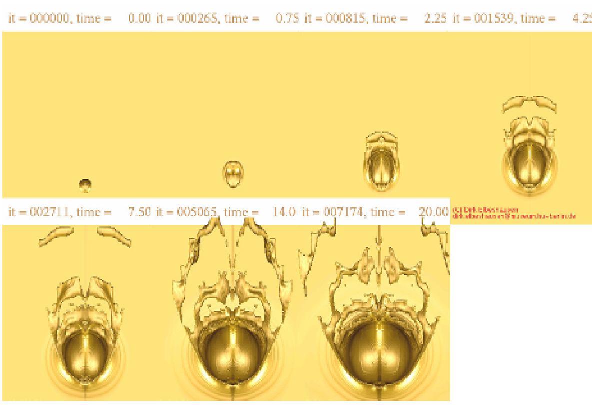

Fig. 1: *Steps of crater formation during an oblique impact (impactor size: 10km, velocity: 20km/s, impact angle: 45°). The initially formed oval crater shades off into a circular morphology.*

One of the most important tasks in analyzing existing impact structures is to link the size of a crater to the energy released during the crater formation. This is essential for estimating the environmental consequences of the impact. Since most of the required scaling laws are valid only for vertical impacts, investigating the influence of the impact angle is of crucial importance. Therefore, we are using our new hydrocode, iSALE-3D, to address following questions: Does a low impact angle change the main cratering mechanism from an energy-driven to an impulse driven scenario? How is the scaling of crater dimensions affected by the angle of impact? And how does strength influences this scaling?

Numerical Results: To answer these questions we performed some scaling analysis using the Pi-Group-Scaling [6]. Point source solutions [7] show a power law dependency between the gravity scaled source size $\pi_2 = 1.61 \cdot g \cdot L / v_i^2$ and the cratering efficiency $\pi_V = V\rho_t/m$ which looks as follows:

$$\pi_V = C_V \cdot \pi_2^{-\gamma}$$

g is gravity, L is the projectile diameter and v_i is the initial impact velocity, ρ_t is the density of the target, m the mass of the projectile and V the volume of the crater. C_V and γ are experimentally derived, material dependend scaling constants. The range of γ is limited between ¾ ("Energy-Scaling", the cratering efficiency is dependent on the impactor's energy only) and 3/7 ≅ 0.43 ("Momentum-Scaling", the crater formation is dependent on the impactor's momentum only) [8]. In our calculations we used Earth conditions (g=9.81 m/s^2) and chose a constant impact velocity of 20 km/s which corresponds approximately to the mean impact velocity on Earth of 17 km /s. In order to vary π_2 only the projectile diameter was changed. So far we only performed hydrodynamic calculations but also different strength models will be introduced. We calculated each scenario (π_2) for different impact angles in a range between 30° and 90°. Figure 2 shows the scaled maximum crater volume in a strengthless target as a function of π_2 for different impact angles. For vertical impacts, we obtained a scaling exponent of γ=0.66, which is in good agreement to experimental results of 0.65 (for water saturated sand) [8]. In the vertical case, γ is close to the energy-scaling limit, so impactor's momentum is less important than its energy. For lower impact angles (increasing obliquity) the scaling exponent does not change significantly (fig.3). Since the accuracy of the calculation dependending on the impact angle is not sufficiently known, the slight decrease of the exponent may be over-interpreted. However, even for low impacts (up to 30°) we found high exponents, which suggests that in a strengthless target the cratering efficiency of oblique impacts is also dominated by the impactor energy.

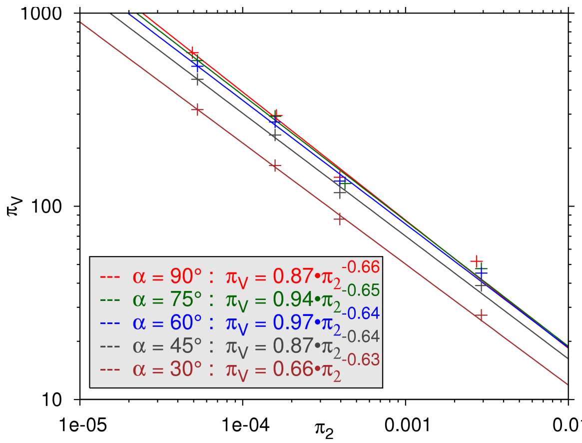

Fig. 2: *Scaling of oblique impact craters.*
The Pi-group-scaling (here: gravity scaled source size π_2 vs. cratering efficiency π_V) applied for multiple oblique impacts. A lower impact angle is resulting in lower crater volumes.

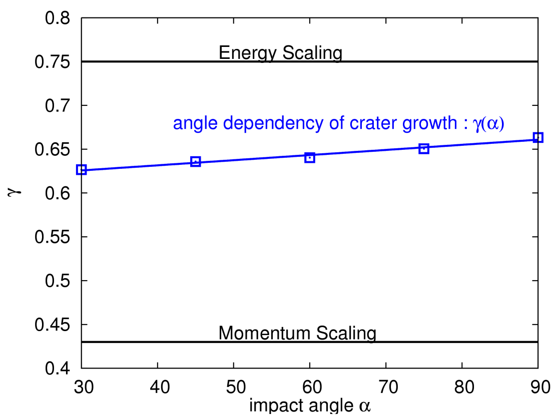

Fig. 3: *Scaling exponent depending on impact angle.*
Since the scaling exponent does not change significantly with the impact angle, also crater formation of oblique impacts (above 30°) is mainly dependend on the impactor's energy.

Conclusion and future studies: These are the first results of a detailed parameter study on crater formation for oblique impacts in the gravity dominated regime (crater size is controlled by gravity where strength plays only a minor role). We found that the main cratering mechanism is based on the impactor's energy. This does not change with increasing obliquity for impact angles in the range 30-90°.

This probably is no longer valid at very low (but also very unlikely) impact angles, which are close to the transition to ricocheting projectiles [3]. At very low angles to the horizontal we expect a rapid decrease of the scaling exponent γ towards the momentum scaling limit. This critical angle probably depends (amongst others) on the projectile size, its velocity and most likely on the strength of the target and projectile material. A numerical study concerning this question is intended.

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