THREE-DIMENSIONAL NUMERICAL MODELING OF OBLIQUE IMPACT PROCESSES: SCALING OF CRATERING EFFICIENCY. D. Elbeshausen[1] , K. Wünnemann[1], and G. S. Collins[2], [1] [2]Humboldt-Universität zu Berlin, Museum für Naturkunde, D-10099 Berlin, Germany [2]Impacts and Astromaterials Research Centre, Department of Earth Science and Engineering, Imperial College London, London SW7 2AZ, UK
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Introduction: Meteorite impacts are a fundamental process on all planetary surfaces. However, most of our knowledge on crater formation is based on vertical impact scenarios. Since no projectile strikes the target vertically [1], the study of the physics of oblique impacts is of crucial importance. From experimental studies it is known that impact angle affects crater properties such as depth, diameter, eillipticity, morphology [2,3]. However, the overall morphology of crater structures remains circular and it is unclear whether minor deviations from this shape are due to the angle of impact or a result of pre-impact target inhomogenities. It also remains uncertain whether scaling relations based on laboratory experiments also hold for large impact craters.

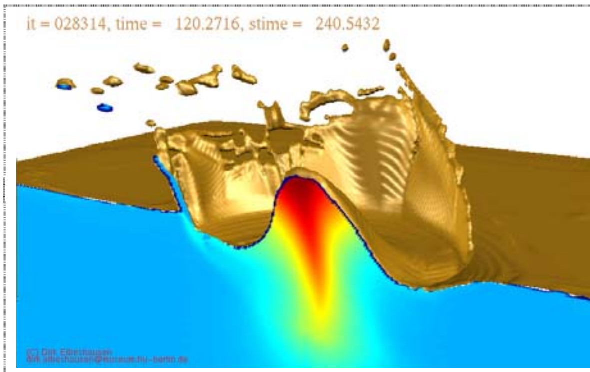

Fig.1: *Snapshot of an impact simulation with 30° impact angle (impact direction from top-right to bottom left). Front face shows temperature.*

Numerical modeling is an important tool for understanding large-scale crater formation. Most previous numerical modeling studies of oblique impacts have focussed on the early stage (contact- and compression stage, early excavation stage), e.g [4,5]. Very few models of the entire formation process have been done, e.g. [6,7]. This is mainly due to the high computation costs of 3D numerical models. Here we present iSALE-3D, a 3D-hydrocode, which follows the idea of SALE-3D [9] and iSALE-2D [8] using an ICEd-ALE technique [10]. We have implemented important advances to the original SALE-3D including the advection of material boundaries (free-surface) using a fast, modified Marching Cubes algorithm [11], and model parallelization. In this paper we use iSALE-3D to quantify the effect of impact angle on transient crater size and growth.

Scaling of vertical impacts: To verify that iSALE-3D correctly predicts the effects of vertical impact, we performed several vertical impacts over a range in gravity scaled source size, $\pi_2 = 1.61 \cdot g \cdot L/v_i^2$, where g is gravity, L is projectile diameter, and v_i is the initial impact velocity, by varying the quotient L/v_i^2 and holding g constant to 9.81 m/s^2. Figure 2 shows the scaled transient crater diameter ($\pi_D = D(\rho_t/m)^{1/3}$, where ρ_t is the density of the target, m the mass of the projectile and D the diameter of the crater) as a function of π_2. Our results are in good agreement with previous studies, both numerical and experimental (see Tab. 1). We found that in the vertical impact case the transient crater volume is nearly identical to the maximum crater volume.

Tab.1: *Comparison of different numerical and experimental derived scaling coefficients.*

	C_D	β
This work	1.53	-0.22
Wünnemann and Ivanov (2003) [13]	1.3	-0.20
O'Keefe and Ahrens (1999) [14]	0.96	-0.22
Experimental results for competent rock after Schmidt and Housen [12]	1.6	-0.22

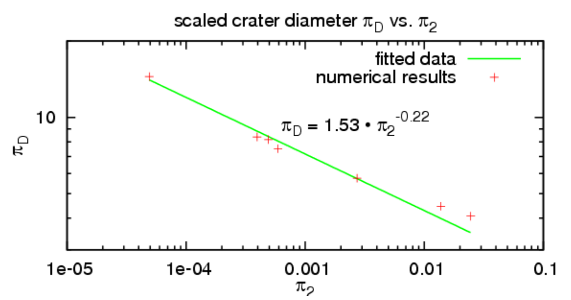

Fig. 2: *Scaled crater diameter π_D vs. gravity scaled size π_2.*

Oblique impacts: To investigate the influence of an oblique impact trajectory on crater formation, we conducted a suite of different model runs for various π_2-values with impact angles between 30° and 90°. In all runs the projectile and the target were composed of granite and we used the Tillotson equation of state [15] to compute the thermodynamic state of the material. We neglected material strength and assumed inviscid material behaviour during crater formation

Our results show that the growth of the crater diameter for angles of 60 degree and higher is nearly identical to the vertical impact case. For smaller angles, the diameter growth is much slower (Fig. 3). Both transient cavity volume and maximum crater depth increase with the impact angle in a sinusoidal manner. To describe the volume growth with the impact angle, we compared our results with a scaling law proposed by Chapman and McKinnon [16]: $V_{tr} = C_V\ (\rho_P/\rho_T)\ V_P\ \pi_2^{0.65}\ sin(\alpha)^{\gamma}$ (where V_P is the projectile volume, ρ_P and ρ_T are the densities of projectile and target). Our results (C_V = 0.32 and γ=0.7) are similar to those by Chapman and McKinnon (with C_V = 0.28 and γ=1.3) (Fig. 4); however the scaling parameters γ is much smaller for our results. The higher volume ratios we obtained may be due to different reasons. We have to note that we used the maximum crater volume which may differ from the transient cavity volume. Also the missing strength in our calculations can explain the consistently higher crater volume ratios. A more detailed scaling law considering a π_2-dependency will be presented later.

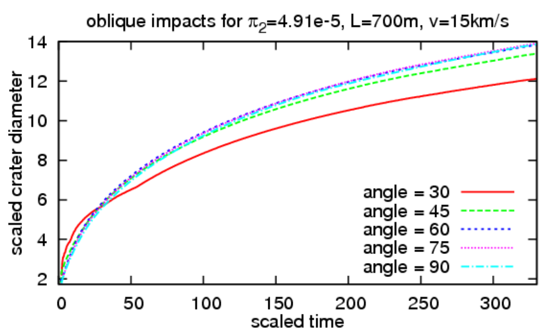

Fig. 3: *Development of maximum crater diameter for various impact angles. Crater diameter of 30° impact is growing much slower than those of 45° and above.*

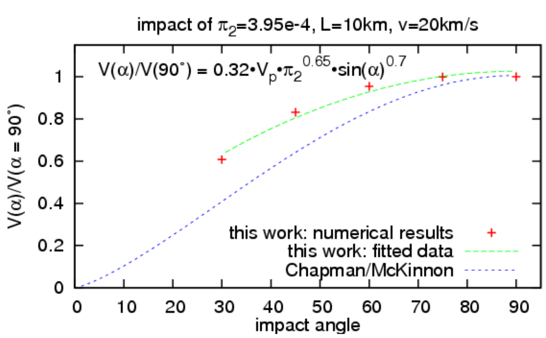

Fig.4: *Maximum crater volume (scaled with the one of 90°) vs. impact angle.*

Although in case of an oblique impact the transient crater is circular (except those with an angle beneath 10°) [17], there is an elliptical crater shape in the first stage of impact. The lower the angle of impact the higher the maximum ellipticy that is reached during crater generation. For a 30° impact, this maximum value occurs much later than for 45° and higher angles. For small impact angles it takes much longer before theinitially elliptical crater evolves into a circular shaped structure.

Conclusion and future studies: These are the first results from a detailed parameter study of crater formation for oblique impacts. Our primary goal is to demonstrate by numerical modeling the effect of impact angle and direction on structural characteristics of real impact craters. The focus of our future work will be the investigation of the shape of the central uplift (Fig. 1) and the crater rim particulary in uprange direction (see Fig. 1,5). Therefore it will be necessary the incorporate a strength model into the code in a similar manner as already present in the 2D version of iSALE [18].

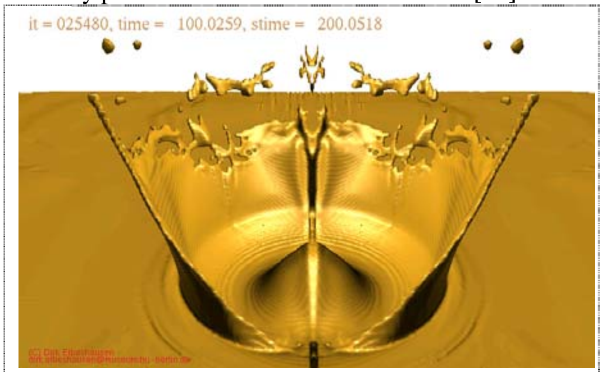

Fig 5: *View into the generating crater from impact direction (impact angle: 30°). The crater rim is higher downrange and reaches its minimum height uprange.*

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