SCALING METEORITE IMPACT CRATER DIMENSIONS IN COHESIVE ROCK BY NUMERICAL MODELING AND LABORATORY EXPERIMENTS.

K. Wünnemann[1], N. Güldemeister[1], and M. H. Poelchau[2], [1]Museum für Naturkunde, Leibniz Institute for Evolution and Biodiversity Science, D-10115 Berlin, Germany (kai.wuennemann@mfn-berlin.de), [2]Institut für Geo- und Umweltnaturwissenschaften, Universität Freiburg, D-79104 Freiburg, Germany.

Introduction: The precise dating of planetary surfaces with crater size-frequency distributions depends on a comprehensive understanding of the relationship between crater size and the impactor's velocity and mass, and how this relationship is affected by the properties of the projectile and the target, such as density, strength, porosity, and gravity. Recent imaging missions e.g. of the Moon resolve increasingly smaller craters, allowing for a more precise determination of relatively young surfaces ages. However, our understanding of the effect of material properties on the impact energy-crater size relationship for small craters, in particular at the transition of strength to gravity dominated cratering, is incomplete. We present a combined experimental and numerical modeling approach to further refine existing scaling laws relating the impactor and target properties with the resulting crater size. The so-called "Pi-group" scaling [e.g. 1, 2] is the most successful approach to relate results from small-scale laboratory experiments with the dimensions of natural craters. The vast majority of laboratory experiments were carried out either in the gravity-dominated cratering regime using granular materials [e.g. 1, 3] or in the strength regime using cohesive rocks [4, 5]. To bridge the gap across the transitional regime, where both gravity and strength control crater size, we used numerical models calibrated against cratering experiments.

Methods: For the present study we used a twofold approach consisting of laboratory cratering experiments in cohesive rocks and a suite of numerical models of crater formation that were both carried out in the framework of the MEMIN (Multidisciplinary Experimental and Modeling Impact research Network) program: http://www.memin.de.

Experiments: The laboratory impact cratering experiments were carried out at the Fraunhofer Ernst-Mach-Institute (EMI) in Freiburg, Germany, using quartzite and sandstone as targets. 2.5, 10 and 12 mm spherical projectiles composed either of steel or iron meteorite with densities of δ=8.1 and 7.8 g cm^{-3}, respectively, were accelerated to velocities between U=2500 to 5500 m s^{-1}. The sandstone has a porosity of 23%. The density of the quartzite is ρ=2.65 g cm^{-3} and the density of the porous sandstone is ρ=2.05 g cm^{-3}. The uniaxial compressive strength (UCS) of the target material was measured under quasi static conditions to

be Y_{UCS}=292 MPa for the quartzite target and Y_{UCS}=67 MPa for the sandstone [4, 6]. The size of the final craters is significantly enlarged due to spallation. The size of the transient crater, which we consider throughout this work, was estimated (see [4] for details) assuming a parabolic shape of the transient crater. The depth is given by the depth of the final crater, and high-speed videos of the ejecta curtain enable an estimation of the maximum width of the parabola. [4] assume a volumetric error of <10% for this method.

Numerical Modeling: We used the iSALE-2D shock physics code [7, 8, 9] to perform a suite of numerical simulations. For the present study adequate treatment of the mechanical resistance against deformation (strength), dynamic fracturing (damage), and the effect of porosity are of particular importance and were considered by material models described in [8, 9]. As a specific material characterization under dynamic conditions to determine material parameters to feed into the models is lacking we estimated the cohesion Y_0 from the UCS measurements (Y_{UCS}) assuming a coefficient of friction of 0.8 and 0.67 for intact and damaged material, respectively. The crushing strength and other parameters for the porosity compaction model were taken from detailed meso-scale modeling validated against experimental observations [10]. To carry out numerical impact experiments in the strength regime we varied the impact velocities from U=2000 to 20000 m s^{-1} to cover a range of the dimensionless parameter $\pi_3 = Y_0/(\rho U^2)$ over three orders of magnitude (~10^{-3} to ~10^{-5}). For the gravity scaling we varied only the impactor diameter L from 0.012 m to 300,000 m corresponding to gravity-scaled size values $(\pi_2 = gL/U^2)$ over a range of eight orders of magnitude (~10^{-9} to ~10^{-1}).

Results: First we compared the results from cratering experiments with the numerical models in the strength regime in Fig. 1 where the strength-scaled size π_3 is plotted versus the scaled crater volume π_V. We found a reasonably good agreement between models and experiments for the nonporous quartzite and the porous sandstone target. The π_V values for quartzite are generally larger than for the sandstone targets for small π_3 values. The difference almost disappears for large π_3 values. Assuming that the deviation of the two trend lines results from the presence of pore space in sandstone in contrast to the nonporous quartzite we con-

clude that porosity generally causes a decrease in cratering efficiency, shifting the scaling curve towards lower π_V values. According to [2] we fitted a power-law to the modeling and experimental data and determined the exponent μ, the so-called velocity exponent of the coupling parameter [2]. In both, models and experiments, crater size decreases somewhat more rapidly with increasing π_3 for the nonporous quartzite than in the porous sandstone target $(\mu_q=0.55>\mu_s=0.48)$.
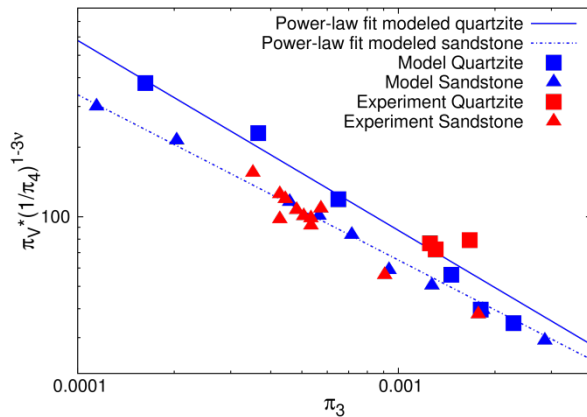
Figure 1: *Strength-scaled size π_3 versus scaled crater volume π_V. The factor $(1/\pi_4)^{1-3v}$ was used to normalize the effects of the density ratio of projectile and target $\pi_4=\rho/\delta$, with $v=0.4$ [11].*

Second, we used the same parameters for the material models calibrated against the experiments in the strength regime (see Fig. 1) and extended the projectile size range to realistic dimensions. As gravity now becomes important Fig. 2 shows the gravity-scaled size π_2 versus scaled crater diameter π_D. The strength and gravity regime can be clearly separated: If strength dominates, the crater size π_D is independent of π_2 and the data plot along a horizontal line (π_D =constant). In contrast to Fig. 1 craters in porous material (sandstone) lie above the craters in nonporous quartzite, because the difference in strength between the two lithologies is no longer factored in. For larger π_2 values the data (only available from modeling) plot as a straight line in the double logarithmic diagram and are independent of π_3. The scaled crater size in porous material (sandstone) is now smaller than in the nonporous target (quartzite), which confirms the observations using strength scaling on a π_3-π_V-plot, namely, that porosity decreases cratering efficiency. In order to fit a scaling line (power-law) to the data across the transition from gravity to strength scaling we used the equation suggested by [2] where π_D=f(π_2,π_3,π_4). In order to obtain a reasonable fit to the experimental and modeling data in the strength regime in Fig. 2 we had to choose a value for Y in π_3 that is significantly smaller than Y_{UCS} or Y_0.

This is presumably a consequence of dynamic fracturing and weakening of material during crater formation. We define an effective strength with $Y_{eff}<Y_0<Y_{UCS}$. We find Y_{eff}=4.62 kPa for quartzite and Y_{eff}=3.23 kPa for sandstone, which is several orders of magnitude smaller than the measured UCS values and the estimated cohesion values for intact rocks (Y_0=96.9 MPa for quartzite and Y_0=22.75 MPa for sandstone) but larger than the estimated cohesion for damaged material which we assume to be 0. For the exponent we found μ=0.49±0.05 for quartzite and μ=0.55±0.01 for sandstone. We interpret these inconsistencies with the values determined in the strength regime as a measure of the accuracy of the method we suggested.
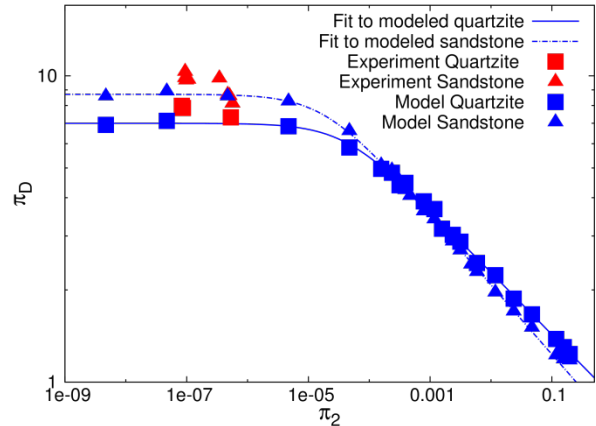
Figure 2: *Gravity-scaled size π_2 versus scaled crater diameter π_D.*

Conclusion: A long-lasting matter of debate has been the meaning of the strength parameter Y in Pi-group-scaling. In this study we demonstrate that for crater size scaling at natural crater dimensions the often used UCS value or the cohesion for Y in the scaling equations does not yield accurate results. It is important to consider dynamic weakening as a result of the accumulation of damage in rocks. The effective strength is approximately 5 orders of magnitude smaller than the quasi-static measurements.

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