EXPERIMENTAL CRATERING IN SOLID ROCKS AND THE DIFFICULTIES OF STRENGTH SCALING. M. H. Poelchau[1], T. Hoerth[2], F. Schäfer[2] and T. Kenkmann[1]. [1]Universität Freiburg, Geologie, Freiburg, Germany. E-mail: michael.poelchau@geologie.uni-freiburg.de. [2]Fraunhofer Institute for High-Speed Dynamics, EMI, Freiburg, Germany.

Cratering experiments in solid rocks: Within the framework of the MEMIN and NEOShield research groups [1-4], a considerable amount of experimental impact craters have been generated in solid geological materials. The processes observed there should contribute to the understanding of terrestrial and planetary cratering, as well as asteroid deflection. An important aspect in these groups is the use of experimental data as a benchmark for numerical models. It is therefore vital that the experimental datasets themselves are well understood when applied to simulations.

Transient and final/spall crater volumes: A major issue that arises in strength-dominated experiments is the generation of large amounts of spall that significantly enhances crater volumes. Numerical models (iSALE) have not yet integrated spallation mechanisms into their code. Therefore, experimental transient crater dimensions are required as input for numerical simulations.

Transient craters have so far not been measured in-situ, but their dimensions can be constrained [4]. In this method, the maximum transient crater depth is limited by the scanned crater floor topography, and maximum crater width is constrained to the furthest extent of the ejecta cone on high-speed videos, thus yielding upper limits for the transient crater. Experimental transient craters are in good agreement with iSALE models [5]. Modeled transient crater volumes are at most 10-20% smaller.

Spall volumes can be calculated by subtracting transient crater volumes from final crater volumes, under the assumption that late, non-spall related removal of material is negligible. Spall contributes to between ~50-80% of the final crater volume in these experiments.

Unexpected results: Experimental crater volumes show variations in their scaled size, which have implications for the excavation and spallation mechanisms.

Spall volumes: As described in [4] and [6], experiments with varied projectile diameters yield increased amounts of spall for larger projectiles. [4] postulated that this is the result of weaker target material in larger-scale experiments due to either the Weibull effect, or due to a reduction of dynamic strength correlated with lower strain rates expected in larger impacts.

A reevaluation of large and small cratering experiments shows that spall plates are ejected from deeper scaled levels in large craters, as opposed to greater diameters. ([7] also observed higher depth-diameter ratios in larger craters.) This is in contradiction to analytical spallation models from [8], where a decrease in dynamic tensile strength leads to shallower spallation depths. Analysis of spallation in numerical models would certainly help to understand how spallation can be scaled.

Transient crater volumes: When scaled, transient crater volumes show none of the size effects seen in spallation, and thus behave according to strength scaling theory [9]. The failure mechanisms in the transient crater are apparently not influenced by Weibull and strain rate effects postulated for spallation.

To offer an explanation for this, a schematic profile of a sandstone crater (1 cm spherical steel projectile at 4.5 km/s) is shown in Fig. 1. The subsurface deformation zones are taken from [10]. Pervasive crushing of the sandstone should occur above the Hugoniot elastic limit (HEL; >~0.5 GPa), while localized shearing requires strong differential stresses (~0.5 GPa [10]). In Fig. 1, these deformation zones were roughly extrapolated up to the target surface and combined with the transient crater estimation of the experiment from [7]. This suggests that the majority of material in the transient crater was subjected to stresses above or near the HEL. Deformation above the HEL is suggested to be independent of strain rate effects in fracture-kinetics controlled strength (e.g. [11]), and would thus suggest why there are no measurable size effects in transient crater volumes.

Strength scaling of different geological materials: In light of this, the use of quasi-statically determined strength values for comparative scaling of different target materials seems unreasonable. Surprisingly, the use of quasi-static uniaxial compressive strength (UCS) values for scaling final craters in basalt, Taunus quartzite and Wasa quartzite yields adequate results, as these three non-porous materials plot together, while the location of craters in porous targets below the non-porous trend is interpreted as a dampening effect of the shock wave (Fig. 2). Perhaps these results are coincidental? On the other hand, craters in non-porous Carrara marble are ~3-4 times too small for their UCS values (Fig. 2; cf. [12]).

While the HEL may be the best representation of failure in the transient crater, its application to strength scaling of transient craters does not resolve the issues with Carrara marble targets (Fig. 2), and scaled transient craters volumes of Carrara marble remain below those of quartzite targets. This suggests that a single failure stress value in strength scaling does not sufficiently represent failure in the transient crater, and even less so in the final crater.

As a final note on strength scaling, in Güldemeister et al.'s numerical study on MEMIN craters [5], UCS values were used for the strength model. It was discovered that the size of modeled transient crater volumes was largely insensitive to a variation of the UCS value up to a factor of ~3. More detailed numerical modeling could certainly help "observationalists" and "experimentalist" better understand their data, and in this specific case, help determine how much relevance brittle failure of the target actually has for the cratering process.

Acknowledgements: MEMIN is funded by the DFG, FOR 887; NEOShield is funded by the European Commission, FP7/2007-2013.

References: [1] Harris A. W. et al. 2013. *Acta Astronautica* 90:80-84. [2] Hoerth T. et al. 2015 *Proc. Engin.* 103C:197-204. [3] Kenkmann T. et al. 2011. *M&PS* 46:890-902. [4] Poelchau M. H. et al. 2014 *Icarus* 242:211-224. [5] Güldemeister N. et al. 2015 *GSA Special Papers* 518 (in press). [6] Hoerth et al. 2015, this volume. [7] Poelchau M. H. et al. 2013 M&PS 48:8-22. [8] Melosh H. J. 1984 *Icarus* 59:234-260. [9] Holsapple K. A. 1993 *Annu. Rev. Earth Planet. Sci.* 21:333-73. [10] Buhl E. et al. 2014 *Tectonophysics* 634:171–181. [11] Grady D. E. 1998 *Mechanics of Materials* 29:181-203. [12] Poelchau M. H. et al. 2015 LSPC Abstract #2447. [13] Ahrens T. J. & Gregson V. G. 1964 *JGR* 69:4839-4874.

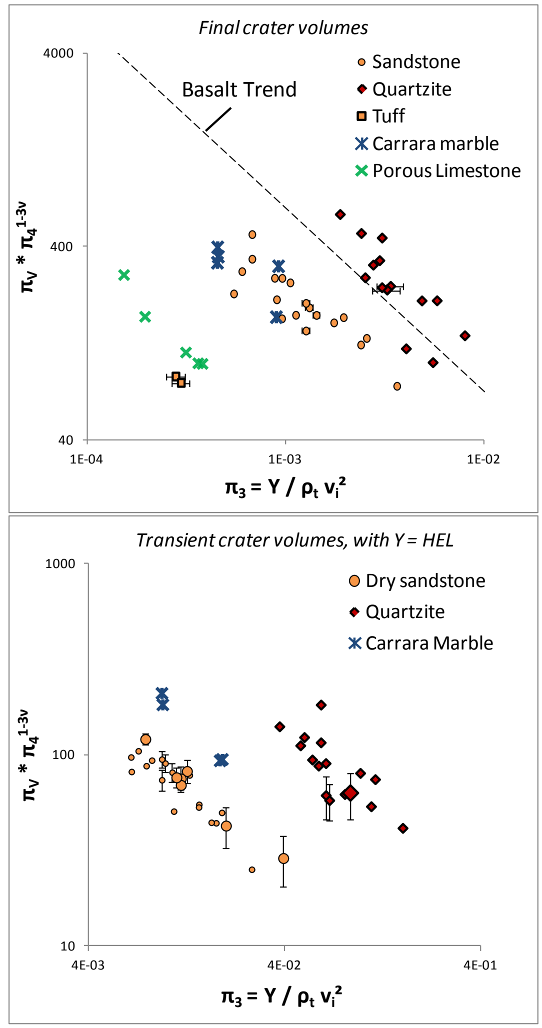

Fig. 2: Scaling of final craters (top), using quasi-static UCS values for *Y*, and scaling of transient craters (bottom) using the Hugoniot elastic limit (HEL values from [13]). Both plots are problematic, as discussed in the text.

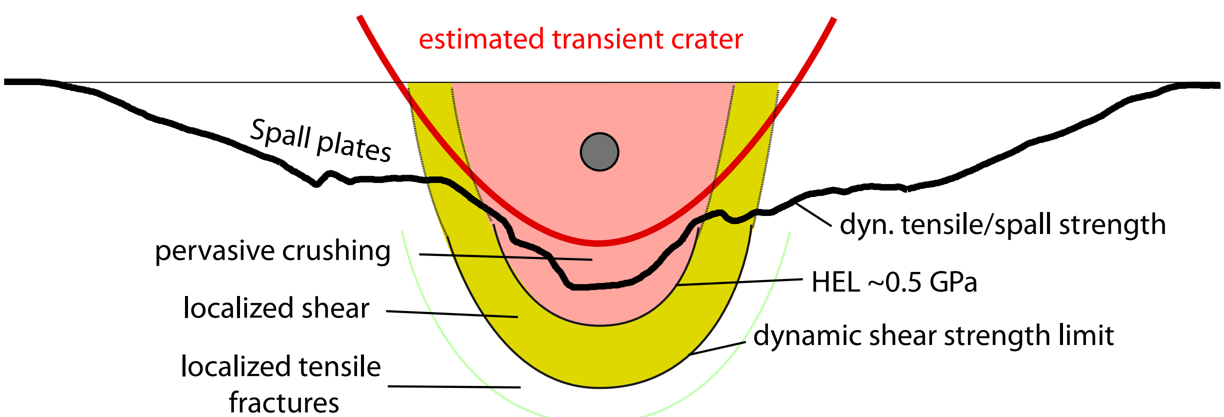

Fig. 1: Schematic overview of deformation in a sandstone target impacted by a 1 cm steel projectile (center) at 4.5 km/s. Subsurface damage was mapped in [10], final crater profile and transient crater are from [7]. Most of the transient crater is dominated by material damaged above the Hugoniot elastic limit, and thus may not show strain rate or Weibull effects seen for spallation.