POROSITY REDUCTION IN THE SUB-SURFACE OF EXPERIMENTALLY PRODUCED IMPACT CRATERS IN SANDSTONE.

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Introduction: Most hypervelocity impacts on earth and planetary bodies occur on porous rock material like sedimentary rocks or regolith. However, the role of pore space in impact events is not yet fully understood. To address this problem, impact cratering experiments in porous materials have been performed in loose porous materials like quartz sand [1-3] or glass beads [4], and solid porous materials like sandstone [5-7], or sintered glass beads [8]. Most of these studies investigate the ejecta characteristics and crater morphology. In contrast, only few studies about impact induced subsurface processes in porous target materials exist [9-11]. To better understand the role of target porosity and pore space saturation during crater formation, the research unit MEMIN (Multidisciplinary Experimental and Modeling Impact Research Network) was founded in 2009 and is funded by the German Research Foundation. A key research topic of MEMIN is to study impact cratering in experiments into dry and water-saturated sandstone blocks that serve as analogues for natural impacts into porous targets [11].

Experiments and Results: All experiments were performed at the two-stage acceleration facilities of the Fraunhofer Ernst-Mach-Institute (EMI) in Freiburg, Germany [6],[12]. As target material a quartz-rich sandstone (Seeberger Sandstein) was chosen for its small grain size (~70 µm) and its high porosity (23 ±1%). In the following we analyze two cratering experiments performed on sandstone cubes of 20 cm side length that were horizontally impacted by 2.5 mm steel spheres. One of the blocks was dry, the other was water saturated (~90 %). At impact velocities of 4.8 and 5.3 km/s for the dry and wet experiment, crater cavities show mean diameters of 5.76 cm and 10.16 cm and depths of 11.0 and 14.3 mm, respectively (Table 1). The resulting depth-to-diameter ratios are 0.19 for the dry and 0.14 for the wet target experiment.

For sub-surface investigations, craters were impregnated with epoxy and subsequently cut into two halves. After macroscopic documentation of both halves, thin sections were prepared along a cross-section directly beneath the crater center. The thin sections were analyzed by means of a Zeiss Leo 1525 field emission scanning electron microscope (FE-SEM) in backscattered electron (BSE) mode (20 kV, 16 mm working distance). BSE micrographs (160x) were merged to produce larger photomosaics for structural mapping (Fig. 1). This analysis revealed different modes of deformation with increasing distance from the crater floor.

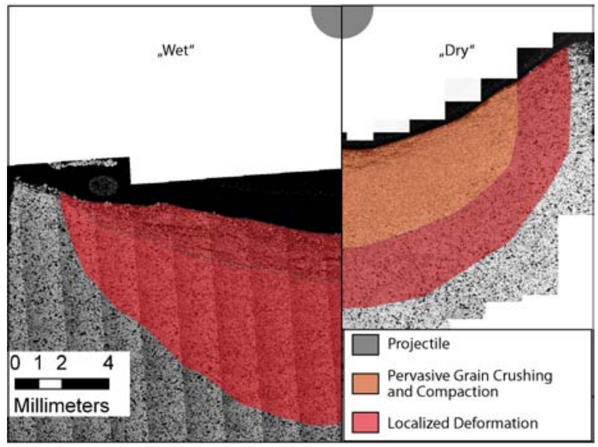

Fig. 1: Sub-surface map of BSE micrographs for the wet (left) and the dry (right) experiment. The scale is the same for wet (left) and dry (right) figures. The size of the projectile is illustrated in gray. As spatial reference the impact point source (center of the projectile) was used.

For the dry experiment a zone of pervasive grain crushing and compaction was revealed directly beneath the crater floor (Fig. 1a). This zone is surrounded by a zone of localized deformation where compaction bands and compactional shear bands are widespread. Here grain crushing and compaction are limited to small, distinct domains, whereas the surrounding host rock is hardly damaged. Further away the impact deformation is restricted to grain boundary cracking and intragranular fractures in quartz grains (i.e. concussion fractures, see [13]).

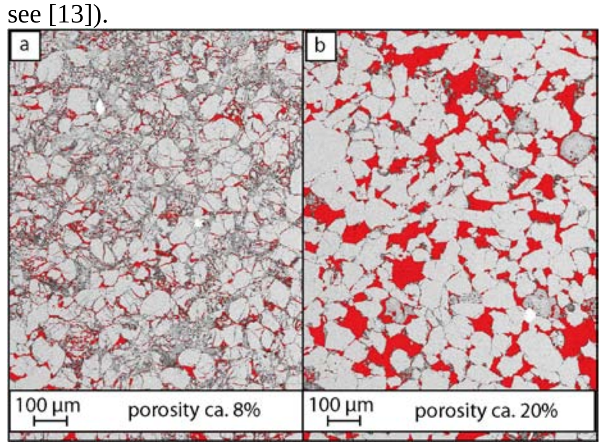

Fig. 2: Porosity (red) for dry compacted (a) and pristine (b) sandstone. Distance to impact point source for **a** ca. 7.9 mm and for **b** 14.1 mm.

Table 1: Overview of Described Experiments

Shot Nr.	Block Nr.	Water Saturation	Projectile Mass [g]	Velocity [km/s]	Kinetic Energy [J]	Crater Diameter [mm]	Crater Depth [mm]	Crater Volume [cm³]
5126	A6	Dry	0.0671	4.8	773	57.6	11.0	7.6
5181	A11	~90%	0.0670	5.3	941	101.6	14.3	31.1

The zone of localized damage and the spatial appearance of concussion fractures are very similar for the wet and the dry samples, although the extent of localized deformation is much larger for the wet target experiment. In contrast, no zone of pervasive grain crushing and compaction was found in the wet sample (Fig. 1). To quantify damaged-induced changes in target porosity with respect to the calculated impact point source (for calculation see [14]), quantitative image analysis software (ImageJ) was used on the basis of BSE micrographs (1.1 * 1.6 mm). The results shown in Fig. 3 were measured along series of images in direct elongation of the impact axes. Pore space resolution in 2D was 0.295 µm².

The highest porosities of ca. 40% in the dry experiment and ca. 57% in the wet experiment were measured in direct proximity to the crater floor (Fig. 3). The increased porosity is related to open tensional fractures, oriented sub-parallel to the crater floor (Fig. 1a+b). With increasing depth, the porosity is quickly reduced in both experiments. In the dry experiment, a zone of reduced porosity is developed with a minimum value of ~8% between 1.5 and 5 mm (0.026 and 0.087 crater diameter) located beneath the crater floor. At greater depths the porosity approaches the initial porosity. In the wet experiment, no zone of substantial compaction has been recognized below the tensile fractures. The porosity is unaffected below 2 mm (0.0197 crater diameter) beneath the crater floor. Pore space compaction is much stronger for the dry experiment (Fig. 2).

Discussion: We suggest that the presence of pore fluid reduced the pore collapse below the crater. Presumably the pore fluid reduced the shock impedance mismatch between grains and interstitial pores. It thus reduces and redistributes the stresses at grain-grain boundaries, which cause intragranular fracturation. This result is in good agreement with shock recovery experiments on dry and water saturated sandstone, [15]. However, as the wet target crater is much larger than the dry one, comminuted material may have been excavated, possibly driven by expanding steam. Indeed, for the wet target craters a larger fraction of pulverized quartz grains was recovered from the ejecta.

Outlook: Several experiments with 50% pore space saturation and especially larger scale experiments with centimeter sized projectiles have recently been conducted at Fraunhofer EMI. Preparation and investigation of these experiments are now in progress. We assume that the upcoming results are suitable to obtain further constraints for sub-surface processes in impact events and especially the role of pore fluids.

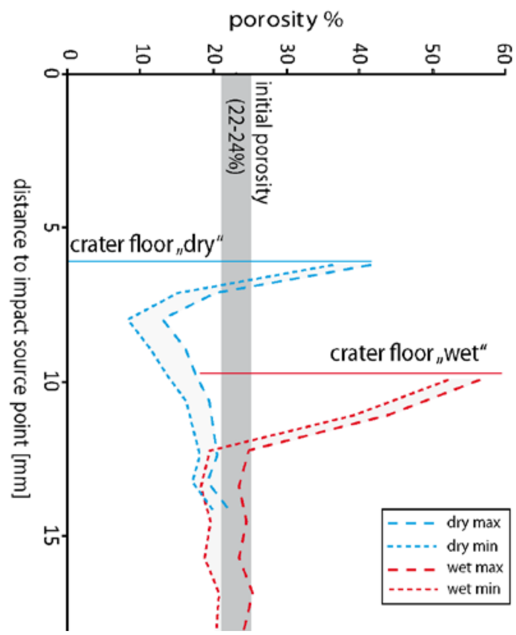

Fig. 3: Porosity variation within the dry (blue) and the wet (red) target. Porosity is plotted against the distance to the impact point source.

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References: [1] Stöffler D. et al. (1975) *J. Geophys. Res.* 80 (29) [2] Cintala M. J. et al. (1999) *MAPS* 34 (4) [3] Hermalyn B. and Schultz P. H. (2011) *Icarus* 216 (1) [4] Barnouin-Jha O. S. et al. (2007) *Icarus* 188 (2) [5] Shoemaker E. M. et al. (1963) *American Journal of Science* 261 (7) [6] Schäfer F. et al. (2006) *ESA* SP-612. [7] Baldwin E. C. et al. (2007) *MAPS* 42 (11) [8] Love S. G. et al. (1993) *Icarus* 105 (1) [9] Ahrens T. J. and Rubin A. M. (1993) *J. Geophys. Res* 98 (E1) [10] Xia K. and Ahrens T. J. (2001) *Geophys. Res. Lett.* 28 (18) [11] Kenkmann T. et al. (2011) *MAPS* 46 (6) [12] Poelchau M. H. (2011) *LPS XLII*, Abstract #1824 [13] Kieffer S. W. (1971) *J. Geophys. Res.* 76 (23) [14] Melosh H. J. (1989) *Oxford University Press* p.245 [15] Hiltl M. et al. (2000) *AIP Conference Proceedings* vol. 505