EXPERIMENTAL IMPACT CRATERING INTO SANDSTONE: A MEMIN-PROGRESS REPORT. M. H. Poelchau[1], A. Deutsch[2], T. Kenkmann[1], T. Hoerth[3], F. Schäfer[3], K. Thoma[3] and the MEMIN Team*. [1]Institut für Geowissenschaften, Universität Freiburg, D79104 Freiburg, Germany, [2]Institut für Planetologie, Universität Münster, [3]Fraunhofer Ernst-Mach-Institut, Freiburg, (michael.poelchau@geologie.uni-freiburg.de)

Introduction: The MEMIN-Project (Multidisciplinary Experimental and Modeling Impact Research Network) was founded in 2009 as a delocalized DFG research unit. It focuses on impact cratering experiments into geological materials to comprehensively understand details of the cratering process through in-situ measurements, extensive post-impact analysis and numerical modeling [1,2].

Four sets of experiments have been performed so far at the two-stage acceleration facilities of the Fraunhofer Ernst-Mach-Institute (EMI) in Freiburg, Germany. Each campaign was set up to focus on different aspects of impact cratering into sandstone, including studies on reproducibility and target heterogeneity, velocity and energy scaling, and pore space saturation. The innovative aspects of these experiments are diverse instrumentation, including high-speed framing cameras, ultrasound sensors and ejecta catchment devices, combined with detailed numerical modeling based on experimental observations. An overview of experiments is given in Table 1. Details of these experiments are given below and in several other LPSC abstracts referenced here.

Cratering experiments: An initial pilot study was carried out with the EMI's XLLGG ("extra large" light gas gun) to study the effects of pore water on cratering. A dry sandstone and a sandstone saturated with water to ~40% were impacted with 1 cm steel spheres at 5.3 km/s. Pore water was found to influence both ejecta behavior and crater size and shape. Results are published in [1-3]. The success of the pilot study resulted in the foundation of the MEMIN research unit.

The first set of MEMIN experiments took place at the EMI's SLGG ("space" light gas gun) with the goal of studying the reproducibility of the impacts and effects of target layering on the cratering process. For this, 20 cm cubes of dry Seeberger sandstone (lithological details are given in [4]) were equipped on 5 surfaces with ultrasound sensor systems to record pressure waves and fragmentation processes in the target during and directly after the cratering process [5]. High speed cameras were employed to observe and quantify the ejection process, filming at up to $5*10^5$ frames per second [6]. Ejecta catchment assemblies were placed adjacent to the target surface, with a small entrance hole for the projectile. The most efficient materials for debris catchment turned out to be degassed Vaseline and phenolic floral foam [7].

2.5 mm D290-1 steel spheres were chosen as projectiles due to the high content in trace elements, in order to trace target-projectile mixing and fractionation processes [8]. Four shots were made at ~5 km/s under 100 mbar target chamber pressure. For the fourth shot, the target was rotated by 90° so that the projectile impacted parallel to the sandstone layering instead of perpendicular to it. This constellation led to a reduction of the crater diameter and ejected mass of ~20%.

The next set of experiments at the XLLGG was configured as a velocity study with the same basic setup and instrumentation. 1 cm meteoritic iron spheres (Campo del Cielo meteorite) were accelerated to 2.5, 3.5 and 4.6 km/s. Target chamber pressure was 300 mbar. Due to the higher impact energy, 50 cm Seeberger sandstone cubes were used as targets, and had an additional "bull's eye" layer on the center of the target surface consisting of three rings of paint spiked with diagnostic trace element ratios for a better reconstruction of excavation and ejection paths. Resulting crater diameters and volumes are shown to scale as a power law with impact energy [4].

The most recent set of experiments was carried out at the SLLG. 20 cm Seeberger sandstone cubes were saturated with water to ~90% and ~50% for a more detailed study on the effects of pore saturation. Setup and instrumentation were the same as in the first SLGG campaign, once again with a trace element paint layer on the target surface. Results confirm the initial findings of the pilot study, showing that the degree of saturation directly effects crater size and shape, and also the ejecta formation and behavior [4,7]. Two additional shots were made into dry 20 cm Seeberger sandstone cubes using a 5 and 2.5 mm sphere made of a high Ni-Cr aluminum alloy (55X G28J1). Impact velocities of 7.0 and 7.8 km/s, respectively, were achieved in order to broaden the range of impact energy and peak impact pressure (Table 1). Target chamber pressure for these shots was reduced to 1 mbar.

Cratering results: Evaluation of high speed videos gives first insights into the excavation and ejection processes [6]. Quantitative values for ejection speed

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and crater diameter growth have been produced, while a qualitative assessment of the ejecta shows that the ejecta cone is followed by a tube-like stream of debris. The cause of this stream is currently being investigated.

The two stages of ejection are reflected in the imprints of the ejecta catchment assemblies [7]. An outer ring of fine, high-speed material and an inner area of more mixed debris with cm sized spall fragments occur in all experiments. Imprints of the outer ring are more clearly defined and penetrate the catchment assemblies more deeply for higher impact energies, although this effect is greatly increased for saturated targets. Preliminary evaluation of fragment size-frequency distribution suggests stronger comminution for higher impact energies in dry targets.

Melt particles and remnants of the projectile were collected from the ejecta [8]. Microanalysis of these particles shows two phases of chemical and physical mixing at projectile-target interfaces, and selective inter-element fractionation effects. Also, sets of PDFs have been documented for the first time in laboratory cratering experiments.

Morphological evaluation of the impact craters with digital scanning methods reveals that crater volume is related to the impact energy by a power law for the sandstone, while cratering efficiency is reduced by open pore space in comparison to non-porous rocks [4]. Water saturation of the pore space, on the other hand, leads to an increase in crater volume and cratering efficiency for the same impact energy [1].

Further results: The results of the pilot study and numerical models are in good agreement [1]. Currently, meso-scale and macroscopic numerical models of porous materials are being validated [9] for a better understanding of the influence of porosity and pore space saturation on shock wave behavior.

Parallel to the cratering experiments, shock recovery experiments on Seeberger sandstone were carried out to investigate shock effects in the low shock pressure range <5 to 15 GPa and the influence of porosity and water saturation on progressive shock metamorphism [10].

Outlook: Further impact experiments, including experiments using lithologies of different porosity are planned. Future studies will also focus on the material parameters of the sandstone, including micro- and mesoscale impact effects, e.g., comminution and fracture generation. The results will be used to validate numerical modeling, which in turn is expected to deepen insights into the cratering process, allowing scaling into geologically relevant dimensions.

Acknowledgments: The MEMIN research unit FOR 887 is funded by the German Research Foundation DFG.

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Table 1: Overview of MEMIN impact cratering experiments

	Shot Nr.	Block Nr.	Target dimensions [cm]	Water saturation	Projectile Material	m_p [g]	v_p [km/s]	KE [J]	P [GPa]	V_c [cm³]
pilot study	2808	-	100x100x50		AlSl 4130 Steel	4,10	5,3	58413	70	715,4
XLLGG	2809	-	100x100x50	~44%	AlSl 4130 Steel	4,10	5,3	56913	-	1098,7
velocity	3296	D2	50x50x50		Iron Meteorite	4,10	4,4	39688	52	629,2
study	3298	D3	50x50x50		Iron Meteorite	4,12	4,6	42627	55	612,1
XLLGG	3299	D4	50x50x50		Iron Meteorite	4,14	3,5	25113	37	309,3
	3300	D5	50x50x50		Iron Meteorite	4,12	2,5	12813	22	242,9
reproduci-	5124	A3	20x20x20		D290-1 Steel	0,0670	5,0	838	63	8,8
bility	5125	A5	20x20x20		D290-1 Steel	0,0672	5,1	874	65	8,9
study	5126	A6	20x20x20		D290-1 Steel	0,0671	4,8	773	59	7,6
SLGG	5128	A8	20x20x20		D290-1 Steel	0,0672	5,1	874	65	6,7
pore	5181	A11	20x20x20	~90%	D290-1 Steel	0,0670	5,3	941	-	
saturation	5182	A13	20x20x20	~50%	D290-1 Steel	0,0667	5,3	919	-	
& velocity	5183	A12	20x20x20	~90%	D290-1 Steel	0,0676	5,3	932	-	
study	5185	A15	20x20x20		55X G28J1 Alu	0,1792	7,0	4353	70	33,4
SLGG	5186	A16	20x20x20		55X G28J1 Alu	0,0224	7,8	673	83	5,4

m_p: projectile mass; v_p: projectile velocity; KE: kinetic energy; P: peak impact pressure estimates for planar impact approximation, Coconino sandstone and steel coefficients were used; V_c: crater volume; XLLGG: “extra large” light gas gun; SLGG “space” light gas gun