## CRATER FORMATION IN PRE-EXISTING TARGET STRUCTURES: IMPLICATIONS FROM HYPER-VELOCITY IMPACTS INTO PARTICULATES.

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The influence of pre-existing target structures on the shape of craters have been observed at terrestrial craters, the most dramatic example being Meteor Crater. Such structures also influence the formation of craters on small bodies. For example, the formation of observed square craters on asteroid 433 Eros were probably affected by the nearby presence of pre-existing tectonic ridges, while on 25143 Itokawa the paucity of observed craters can be attributed in part to the presence of surface rubble. These surface blocks effectively armor a surface from small projectiles and hides craters.

This study compares and contrasts the results from impact experiments from 0.5-5.5km/s in a coarse grained target with those in a fine grained one to explore how a well-characterized target structure that are similar in size to the projectile changes the cratering process. Target porosity and Coulomb friction properties are kept constant by using spherical glass beads of differing size. Measurements of crater growth and ejecta speeds are analyzed using non-intrusive laser-based techniques, and compared to preliminary 2 and 3D numerical calculations using the hydrocode model CTH.

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## HYPERVELOCITY IMPACTS INTO DRY AND WET SANDSTONES.

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**Introduction:** Several hypervelocity impact experiments into dry and wet sandstones were conducted in the framework of the MEMIN program [1, 2] (Multidisciplinary Experimental and Modeling Impact Research Network). The MEMIN pilot study, conducted in the year 2006 [2], showed a considerable effect of pore water on crater size and ejecta behavior. This effect was studied again during a MEMIN test campaign using sandstones with different degrees of water saturation.

**Experiments:** The impact experiments were conducted at a two-stage light gas accelerator at the Fraunhofer Institute for High-Speed Dynamics in Freiburg, Germany. As target material porous Seeberger Sandstone was used which has a high purity (high amount of $SiO_2$) and a porosity of about 20%. Projectiles were manufactured at EMI out of steel D290-1 with diameters of 2.5 mm. To record the ejection process a high-speed camera with frame rates of 75 and 100 kfps was used. Ejecta catchers consisting of floral foam and vaseline [3] provided additional information about the shape of the ejecta cloud.

**Results:** High-speed recordings show a different ejecta behavior for the wet sandstone compared to the dry sandstone. Ejecta fragments are less fine grained and seem to be glued to larger fragments. The ejecta imprint shows a smaller opening angle and is stronger for the wet ejecta. Peak velocities at the ejecta front are higher if the impact is conducted into wet sandstone. Crater sizes are much larger in the wet sandstone compared to the dry sandstone. The higher velocities and the larger crater sizes are most likely due to vaporization of the water caused by impact induced increase of internal energy in the target material.

**Outlook:** The effect of pore water on crater geometry and ejecta behavior was recently studied on a larger scale in another test campaign at the X-Large Light Gas Gun at Fraunhofer EMI in Efringen-Kirchen in September 2011. In this campaign projectiles with diameters of 12 mm made of steel and iron meteorite were impacted into dry and wet 80 x 80 x 50 $cm^3$ sandstone targets at velocities of about 4.5 km/s.

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## CRATER MORPHOLOGIES AND THE TRANSIENT CRATER IN IMPACT EXPERIMENTS.

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Morphometric analyses of experimental impact craters into sandstone reveal that an outer, shallow-dipping area, two central depressions and a fragile, white-coloured centre are characteristic features of all experiments into dry targets. In experiments using pore space saturated targets, the craters are generally larger and have an overall flatter profile appearance; i.e. they have greater diameters and are shallower than craters in dry targets at comparable experimental conditions. The transition in depth/diameter ratios between dry and wet targets lies at a value of 0.19. Additionally, craters in wet targets display flat, terrace-like morphologies in the outer area with two distinct fracture surfaces: one steeply dipping towards the crater centre and the predominant surfaces oriented sub-parallel to the original target surface. This illustrates distinctly different behaviors of late spallation of the brittle target between dry and wet materials. Furthermore, low-density projectiles (aluminium versus steel or iron meteorite) produce crater morphologies similar to those in saturated targets.

It is evident that late stage spallation induces a certain degree of variability in crater shape and total crater volume with the mass-percent of late spall fragments correlating directly with the craters' depth/diameter ratios. For a sensible comparison to experiments into other target materials and for scaling to natural impact craters, a comparable feature that is independent of late-stage spallation is needed. During the early cratering process, a transient crater forms with a shape that is initially unaffected by spallation effects. First results indicate that this transient crater can be well described by quadratic parabola-fits to crater profiles. The results are compared to geometric markers using the following methods: (i) extrapolating parabola radii to ejecta imprints on catcher systems, (ii) comparing the parabola slope to ejecta curtain angles and tracking ejecta cone angles on high-speed video images, and (iii) comparing weight fractions of grain size analyses to calculated transient crater volumes.

## IMPACTS INTO SANDSTONE: POROSITY EFFECTS IN THE STRENGTH REGIME.

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**Introduction:** The MEMIN (Multidisciplinary Experimental and Modeling Impact Research Network) is currently focused on experimental impact cratering into sandstone. One of the main goals of these experiments is determining the role porosity has on the impact process and on the resulting crater morphology. So far, four sets of impact experiments have been performed at the two-stage light gas gun facilities of the Ernst-Mach-Institut, Freiburg, Germany. Aluminum, steel and iron meteorite projectiles were accelerated to velocities between 2.5-7.8 $kms^{-1}$, resulting in impact energies ranging from 0.7-58.4 kJ. Targets were dry Seeberger sandstone blocks with a grain size of ~70 µm, a porosity of 20-25%, and a uniaxial compressive strength (UCS) of 35-40 MPa [1-2].

**Cratering results and discussion of porosity effects:** All crater dimensions were measured with a 3D laser scanner. Crater depth to diameter ratios range from 0.14 to 0.25. Craters formed by steel or meteoritic iron projectiles are slightly deeper (0.20) than the average craters formed in crystalline rocks with similar high-density projectiles (0.18) [3-4], indicating that the sandstone's porosity results in slightly increased penetration depth. The sandstone craters formed by aluminum projectiles, on the other hand, are much shallower (0.15), and thus reflect a stronger dependency of penetration depth on projectile density than on porosity, at least for porosity values of ~25%.

The effect of porosity becomes more apparent when crater volumes of the sandstone and non-porous crystalline rocks [3-5] are compared. For the same impact energy and roughly similar impact conditions (projectile mass, density and speed) the same crater volumes result, in spite of a difference of target crushing strength of nearly one order of magnitude (UCS of crystalline rocks is assumed at 300 MPa). This is in agreement with numerical modeling results [6] that show a dampening of the shock wave through porosity. Thus, the amount of energy available to work against the target's strength to form a crater is reduced by the work required to close pore space. Although density effects of the projectile on crater volume should be expected, no major differences were detected.

The cratering efficiency (the ratio of excavated target mass to projectile mass) in sandstone is also greatly reduced compared to strength scaled cratering efficiency values of crystalline rocks [3-5] by almost one order of magnitude. Based on the limited number of data, it is currently difficult to determine the exact effects of porosity on strength-scaled size parameters beyond a general reduction of cratering efficiency. Impact experiments into more highly porous target rocks are planned to better quantify the effects porosity has on cratering in strength dominated regimes.

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## FACILITY FOR EXPERIMENTAL STUDIES OF WET TARGET IMPACTS AT CENTRO DE ASTROBIOLOGÍA, SPAIN.

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**Introduction:** Impact cratering is a fundamental geological process in the Solar System and may greatly influence the evolution of life by both extinction and creation of habitats. The crater geology may also reflect the target environment allowing paleoenvironmental reconstructions. At the Centro de Astrobiología, Spain, the new Facility for Experimental Impact Cratering (FEIC) complements observational data from natural impact craters and numerical 2-D simulations (iSALE) with the objective to understand how impact craters can reveal information on environments of importance for life (e.g., targets containing liquid water).

**Instrumentation:** Based on the main objective, the FEIC is especially designed to allow the studies of wet-target impacts. It has a box-shaped small test bed (1.2x1.2m) and a funnel-shaped, circular large test bed (7m in diameter) with the capacity also for half-space experiments. The shape and size of the large test bed decrease disturbance from reflected surface waves at wet target experiments. The projectile launcher for the small test bed is a modified 17.5mm caliber paintball gun, and for the large test bed it is a compressed gas (200bar, N2 or He) gun (CGG) with 20.5mm caliber of our own design. Both guns can fire at any angle, into various targets, and with various projectile compositions and, for the CGG, with various diameters (with sabots if needed). Projectile velocities are currently estimated by combining frame rate of the high-speed camera used to document the tests, and the projectile travel distance.

**First results:** For the paintball gun the average projectile velocity is about 50 m/s (5.7g, glass) and 100 m/s (3g, paintball), and for the CGG 341 m/s (20mm, 16.3g Al2O3, N2) and 468 m/s (20mm, 5.7g delrin, N2). The velocities are below those at crater-forming events on planetary surfaces and therefore preclude study of the effects of melting and vaporization of the target, which, however, generally involve a relatively small fraction of the crater volume. A primary advantage of FEIC is that its large scale allows for detailed study of the dynamics of cratering motions through the phase of crater growth and subsequent collapse, especially in wet targets. These observations provide valuable benchmark data for numerical simulations and for comparison with field data [1].

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## THE SHOCKWAVE-LABORATORY AT THE FREIBERG HIGH-PRESSURE RESEARCH CENTRE (FHP).

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In 2007 a new shockwave-laboratory, situated in the research underground mine “Reiche Zeche”, with the possibility to perform blasting experiments were commissioned. As a part of the Freiberg High-Pressure Research Centre (FHP) the main goals are the synthesis, analysis and testing of new high-pressure-phases, esp. hard materials.

Since midyear a new blasting chamber with additional options is accomplished. Therein up to 20 kg of high-explosive or even 50 kg of mining explosive can be detonate in one experiment. New features are equipment for measurement devices (manganin gauges and shortening pins), active ventilation, water cooling for the samples, installation for sample preheating and high-speed internet connection. Continuous work with several blasting per day are possible.

For the synthesis of new materials the flyer-plate method with sample recovery and active plane-wave-lens for reproducible results with up to 1 kg high-explosive is used. The flyer-plate is accelerated up to 3,5 km/s resulting in a pressure of 90 GPa in the steel container (target). Different sample geometry resulting in a wide range of sample pressure (up to 76 GPa) and sample temperature (up to several thousand Kelvin). The infrastructure from sample preparation, recover, characterization and simulation of structures is given by the FHP.

In the new blasting chamber experiments with cylindrical charges to gain 300 GPa sample pressure or even tenth gram of high-pressure sample per shot at medium pressure will be carried out. Technologies like explosive platting and explosive forming will be enhanced. The conduction of shockwave experiments from different fields of research, like geosciences, solid state physics and material science is highly recommended.

## EJECTA-ATMOSPHERE INTERACTION IN NATURE AND IN EXPERIMENTS.

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**Introduction:** Impact ejecta layers are rarely preserved on Earth because of quick erosion/sedimentation. However, existing global ejecta layers are much older than the oldest terrestrial craters [1] and, hence, contain important information about early history of our planet. Lunar sample return missions as well as remote sensing deal exclusively with ejecta [2].

**Ejecta in natural impacts.** Impact ejecta mass per unit area M depends on an ejection velocity U (M~U-5.6) and on impact event scale (M~ D3, where D is a projectile diameter). Interaction with the atmosphere becomes an important factor if this mass is comparable with the mass of the atmosphere (104 kg/m$^2$ on Earth). In all natural impact events near-crater ejecta (up to 2 crater radii) is deposited ballistically, while distal ejecta may be substantially redistributed by the atmosphere. For example, substantial part (if not all) of the global K-Pg ejecta have been transported by ejecta-debris gliding on the top of the atmosphere [3]. Similar effects have been observed during the Shoemaker-Levy 9 comet collision with Jupiter [4]. After smaller impacts high-velocity ejecta are not massive enough to disturb the atmosphere and, hence, are deposited within a few crater radii (e.g., Ries, Bosumtwi, Meteor).

**Ejecta in experiments.** Experimental projectiles are usually <1 cm in diameter, i.e. 100 times smaller than iron projectiles producing the smallest terrestrial craters (e.g., Kamil [5]) and 106 times smaller than the biggest recorded in the Earth's history impactors (e.g., the Chicxulub > 10 km in diameter [6]).

Early plume ejecta are typical for high-velocity vertical impacts and develop mainly within a hot wake behind the projectile. The total amount of these ejecta is negligible in comparison with ballistic ejecta. However, the highest shock compression and the highest temperature are reached within this plume.

**Ballistic ejecta.** As the ratio of ejecta mass to atmospheric mass is roughly proportional to a projectile size, correct scaling to terrestrial conditions requires 1/100 of atmospheric density to model ejecta from small craters and 10-6 (vacuum) to reproduce large impacts (the latter is highly questionable, as the atmospheric stratification is a crucial factor).

Late non-ballistic ejecta are the most puzzling feature in impact experiments [7]. We analyze possible mechanisms to produce this "tube" and to scale it to natural events.

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## NUMERICAL MODELING OF HYPERVELOCITY IMPACT CRATERING PROCESSES.

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**Introduction:** The main focus of the project is the development of a mechanical and thermodynamic model that describes the material behavior of dry and water saturated porous geo-materials during the formation of hypervelocity impact craters on different scale. We use two in-house developed hydrocodes iSALE (MfN) [e.g. 1] and SOPHIA (EMI) [2] as well as the commercial code AUTODYN to simulate the cratering process and shock wave propagation. The performed experiments in the MEMIN project [3] are used to validate the material models in our simulations.

**Results:** In the first part of the project we investigated the effect of porosity and water content on shock wave propagation in detail. We conducted mesoscale models resolving single pores and grains to investigate the complete crushing and deformation of dry and fluid-filled pores as a result of shock wave compression. Based on the results of the mesoscale models that may be understood as "numerical experiments" for the characterization of material behavior we developed "homogenized" material models describing shock wave compression on a macro scale. The so-called $\varepsilon$-$\alpha$ porosity compaction model [4] treats porosity as a state variable that varies as a function of volumetric strain. Meso- and macroscale models show a very good agreement in terms of hugoniot data, enhanced attenuation of shock waves in porous materials and increased heating due to the additional amount of plastic work [5]. Following an approach by [6] we implemented an equation of state using tabulated thermodynamic state data generated with ANEOS [e.g. 7] to treat a water-quartzite mixtured target material. In a next step we started to use the improved material models for porosity and material mixtures to carry out simulations of impacts into (1) nonporous, (2) porous, (3) water saturated, and (4) partially water saturated target materials. Besides an accurate treatment of the thermodynamic behavior constitutive models of material strength are crucial to reproduce the crater morphometry and morphology in the experiments. Whilst the formation of large craters seems to be primarily affected by shear failure, tensile strength plays an important role in the laboratory-scale cratering experiments. This becomes most apparent by the large spallation zone observed in the experiments.

**Outlook:** Further improvements of material modeling are still required to achieve a better match with the experiments. The next steps will be: (1) improving the thermodynamic model with regard to shock release in material-mixtures (compressed water in cells may expand rapidly during shock release which may significantly contribute to the cratering process); (2) implementation of a spallation and dilatancy model (quantification of the increase of pore space by fracturing and shearing); (3) detailed comparison of fracture patterns and recorded acoustic waves with experimental data to further refine the material models.

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## SHOCK RECOVERY EXPERIMENTS AT LOW SHOCK PRESSURE WITH DRY SEEBERGER SANDSTONE.

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**Introduction:** Within the Multidisciplinary Experimental and Modelling Impact research Network (MEMIN) this project investigates shock effects in quartz in the low shock pressure range from <5 to 15 GPa, and the influence of porosity on progressive shock metamorphism.

**Methods:** Shock experiments were carried out with cylinders of Seeberger sandstone (layer 5; diameter 1.5 cm, length 2.0 cm) with a grain size of 0.17-0.01 mm and a porosity of ~18 vol.% [1]. This sample material is identical to the material used in the MEMIN feasibility study. The shock recovery experiments at 5, 7.5, 10 and 12.5 GPa were carried out at the Ernst-Mach-Institute with a high-explosive driven flyer plate set-up generating a plane shock wave. The impedance method was used to avoid multiple reflections of the shock wave within the sample material. For shock pressure determination Hugoniot data for Coconino sandstone [2] were applied, as at present only incomplete Hugoniot data for Seeberger sandstone are available that indicate an error of ~1-2 GPa in shock pressure determination.

**Results:** At the microscopic scale the shocked Seeberger sandstone shows a near-complete closure of pore space. Locally, pores are filled with Al-Fe-rich, foamy melts after phyllosilicates (melt abundance increases with shock pressure). Some irregular intergranular fractures have been induced. Quartz grains of the unshocked sample show sharp and undulatory extinction under crossed polarizers, whereas the shocked samples display quartz grains with mainly undulatory extinction at 5 GPa and weak mosaicism at 7.5, 10, 12.5 GPa. All shocked samples show intense intragranular fracturing (irregular and subplanar), which significantly increases from 5 to 7.5 GPa. At even higher pressures to 12.5 GPa, fracturing remains at a more or less constant level. At 5 GPa quartz grains usually display only one set of roughly planar fractures, whereas at 7.5, 10 and 12.5 GPa two or more sets could be observed. The samples shocked at 10 and 12.5 GPa display locally isotropic areas in the optical microscope, which comprise diaplectic quartz glass in the center and deformed quartz in the rim based on Raman and SEM analysis. Our shock experiments have produced shock features as known from naturally shocked porous sandstone.

Additionally, the sandstone cylinders shocked at 10 and 12.5 GPa display curved shear zones starting at the contacts of the sample cylinder with the surrounding ARMCO iron trap. Cataclastic microbreccias occur within broader shear zones, whereas thin shear zones are filled with SiO2 melts. The shear zones are associated locally with quartz grains displaying subplanar microfeatures with strong similarity to planar deformation features (PDF).

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## LOW AND HIGH TEMPERATURE STUDY OF EXPERIMENTALLY AND NATURALLY SHOCKED PYRRHOTITE.

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A broad range of magnetic anomaly pattern can be measured above terrestrial impact craters [1]. Three main mechanisms are generally described for an impact-related change of the magnetization: the acquisition of a thermo remanent magnetization (TRM), a chemical remanent magnetization and a shock remanent magnetization (SRM). Naturally shocked pyrrhotite from the suevites of the Chesapeake Bay impact crater (CBIS) could provide new clues for a better understanding of the SRM acquisition process. These pyrrhotites contain a high amount of lattice defects, which prove a shock induced deformation. Pressures up to 35 GPa are reported [2] for the crater. The chemical composition of the shocked pyrrhotites significantly deviates from that of stoichiometric monoclinic pyrrhotite ($Fe_7S_8$). It can be characterized by a significant depletion in iron and has a chemical formula between $Fe_{0.808}S$ and $Fe_{0.811}S$, which is similar to the one of smythite, $Fe_7S_{11}$. Such stoichiometric deviation is also reflected in the magnetic behaviour. The typical transition at 30 K [3] is present but strongly reduced and broadened. Also, the Curie transition, usually at 593 K, is shifted up to temperatures between 623 and 638 K.

We conducted a series of shock experiments on natural pyrrhotite in order to find out if the features in the naturally shocked samples are all impact related. Therefore, we shocked samples from a natural pyrrhotite ore from the Cerro de Pasco mine, Peru at 3, 5, 8, 20 and 30 GPa using a high pressure gun and high explosive devices. In these experiments we found that the 30 K transition is only visible as a slight bending in the susceptibility curves. With increasing shock pressure this bending disappears continuously and is no longer visible at 8 GPa. A general shock induced feature seems to be a broadening of the transition temperatures. This is noticeable for the 30 K transition, but also for the Curie temperature. On the other hand, no significant deviation in the chemical composition occurs at pressures up to 30 GPa; all samples exhibit a chemical formula of $Fe_7S_8$. However, first observations made by transmissions electron microscope (TEM) indicate that pressures between 5 and 8 GPa cause a partial amorphization of the crystal lattice. Below 8 GPa, a strong mechanical distortion of the crystal lattice is visible. Further TEM studies will show if these observations will be able to explain the features of the naturally shocked pyrrhotites in the suevites of the CBIS.

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## CHEMICAL MODIFICATION OF METEORITIC PROJECTILE, TARGET MELTS AND SHOCKED QUARTZ IN CRATERING EXPERIMENTS.

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**Introduction:** The detection of meteoritic components in impact-derived rocks is of great diagnostic value for confirming an impact origin [1]. The processes of mixing projectile matter into target and impactite materials are far from being understood. We present results of hypervelocity cratering experiments using a natural sandstone target and iron meteorite matter as projectile.

Experiments have been performed at the two-stage acceleration facilities of the Fraunhofer Ernst-Mach-Institute (Freiburg, GER). Our results are based on experiment #3298 [2] using a Campo del Cielo meteorite sphere projectile (Ø 10 mm) accelerated to ~4.5 kms$^{-1}$ ($E_{kin}$ ~43 kJ) and as target a 50x50x50 cm block of Seeberger Sandstone. Ejecta material was captured with a catcher system [3] and analyzed by an electron microprobe.

**Results:** The ejecta fragments show metamorphic shock features (PDFs in Qtz, diaplectic glass, lechatelierite) and partial melting of the clay mineral-bearing sandstone matrix, which involves Qtz too. Droplets of projectile have only entered the sandstone melt.

Projectile residues occur as spheres, spheroids and partly to completely molten fragments in the ejecta. The residues are enriched in Ni and Co and depleted in Fe compared to the Campo del Cielo meteorite. The spheres vary in composition (Ni: 7.2 -17.3 wt.%, Co: 0.5-1.3 wt.%, Fe: 77.7-91.3 wt.%). Enrichment of Ni and Co versus Fe correlates negatively with the sphere-size.

Sandstone melt consists of $SiO_2$ (50.1-93.1 wt.%), $Al_2O_3$ (2.5-16.4 wt.%), FeO (5.4-32.3 wt.%), and NiO (0.01-0.33 wt.%). Components of this mixture are Qtz, clay-bearing sandstone matrix (with FeO=3.2 wt.%) and up to ~20% projectile matter. The Fe/Ni-ratio of the sandstone melt is below the projectile ratio.

Shocked quartz with PDFs, diaplectic glass and lechatelierite contain slightly FeO (<0.9 wt.%) and NiO (< 0.06 wt.%). The average FeO content of the high-shocked Qtz is 0.42 wt.%.

**Discussion:** Our analyses suggest inter-element fractionation between projectile and target in different impact stages. (A) After shock compression with formation of PDFs in Qtz, diaplectic glass or lechatelierite, and during early unloading, <1 % of projectile matter is added to the glass phases without detectable fractionation. (B) Later, when waste heat triggers melting of the sandstone, molten projectile is mixed with the sandstone melt and significant element fractionation occurs. Fe is selectively enriched in the silicate melt; Ni and Co are enriched over Fe in coexisting projectile spheres. Comparable processes have been reported in natural impactites [4-6]. The increase of fractionation with decreasing spheres-size shows that the fractionation of Fe, Ni, and Co occurs during solution of the metal spheres in the silicate melt due to differences in chemical reactivity [6].

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## CHEMICAL INTERACTION BETWEEN PROJECTILE TARGET MELTS IN CRATERING AND LASER MELTING EXPERIMENTS USING STEEL AND AL ALLOY PROJECTILES.

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**Introduction and experimental methods:** Chemical fractionation during projectile-target interaction can modify the ratios between elements used for identification of meteoritic material mixed into impactites and disturb or hamper chemical projectile identification in nature. We have performed experiments to better understand the control on the distribution of meteoritic elements (or their analogs) between projectile and target material during the extreme physico-chemical conditions of cratering. A Co-Cr-V-W-Mo-rich steel "D290-1" (exp. # 5126) and a Cr-Ni-Mg-Cu-bearing Al alloy "55X G28J1 Alu" (exp. # 5185) were used as projectiles and Seeberger Sandstone as target material. Both cratering experiments were performed with the "space" light gas gun at the Frauenhofer Ernst-Mach Institute (EMI) at Freiburg (see [1] for some experimental details). Ejecta fragments recovered from the ejecta catcher system [2] were studied. In addition melting experiments using a 3 kW welding laser of the TU Berlin were done to study partial melting of projectile and target materials and chemical mixing of melts under more idealized conditions. Mainly Co, Cr, Ni, V, Mo, and W ("tracer elements") are used because they are typical meteoritic elements and/or low in concentration in the sandstone target.

**Results:** Partial to locally complete melting of sandstone and projectiles and compositional mixing between these melts has been achieved in the cratering and laser experiments. The composition of the sandstone melts that interacted with projectile melt varies depending on a) primary chemical variation of partial melts, b) the degree of melt mixing, and c) the chemical behavior of the projectile tracer elements. The more lithophile elements Cr and V can be significantly enriched in the silicate target melts up to the projectile values of several wt.%. In case of the aluminum projectile Mg is significantly enriched in or even scavenged by the silicate melt in contact to the projectile material. The concentration of the siderophile elements Co, Ni, W, and Mo of the target silicates melts are rarely above the primary sandstone range and mostly below the microprobe detection limits.

**Conclusions:** The first results suggest that mixing of molten projectile matter into target melts depends mainly on the distribution coefficients of the tracer elements between the interacting melts. This results in strong fractionation between lithophile and siderophile tracer elements during target-projectile interaction. In order to study possible fractionation processes among siderophile elements during mixing between projectile and target melts very high concentration of siderophile elements in the projectile and probably high impact energies are needed to reach siderophile tracer element concentration in the silicate melt well above the microprobe detection limits. This could be achieved by using the XL light gas gun at EMI with D290-1 steel projectiles. Further hypervelocity experiments will also study the influence of target porosity and water content on the chemical mixing processes.

**References:** [1] Poelchau M. et al. (2011) LPS XLII, abs #1824. [2] Reiser F. et al. (2011) LPS XLII, abs. #1733.

## EJECTION BEHAVIOUR CHARACTERISTICS DURING VARIATION OF IMPACT ENERGY AND TARGET WATER SATURATION: ON THE UTILITY OF USING APPROPRIATE EJECTA-CATCHERS.

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High-velocity impact experiments with two-stage light gas guns on geologic materials are fundamental to understand the processes involved with natural impacts on earth, moon and in space. Parameter studies with adjustable factors like modifiable target material properties and impact energies are especially required to model natural impact processes most adequately. In such parameter studies, the application of appropriate ejecta collection devices plays an important role for proper analysis of the particular ejection processes. A custom ejecta-catcher system on the base of Vaseline and phenolic foam was developed with regard to space-resolved ejecta recovery and changing experimental parameters. On the base of this custom ejecta-catcher system and high-speed imaging of the ejection process, ejection dynamics have been studied for different impact velocities and different target water saturation. The study revealed significant differences in secondary crater size and shape depending on fragment comminution, ejection angle and ejection velocities.

The angular distribution of the ejecta imprint and secondary crater densities shows maxima within 75 to 68° and 59 to 45° from the primary target surface for dry experiments and 76 to 72° and 64 to 52° for experiments involving target water saturation, indicating a significant influence of pore water on the ejection dynamics. Higher impact velocities lead to higher ejection velocities and more efficient grain comminution. Characteristics of peak shock metamorphism are far more developed for higher impact velocities. The degree of target water saturation clearly shows a substantial effect on the ejection angles and velocities as well as on the fragmentation behaviour.

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## GEOPHYSICAL STUDIES OF IMPACT STRUCTURES.

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**Introduction:** Impact cratering is one of the most important, often the most important, process occurring on planetary surfaces. Understanding the detailed structural geology and impact mechanics requires understanding how the crust has responded to the impact. Mapping the surface geology provides information in two dimensions that can be extrapolated for short distances into the third dimension (depth). Geophysical techniques and drilling are required to understand details of the third dimension. Geophysical techniques include gravity, magnetics, radioactivity, electrical resistivity, seismic reflection and refraction, and ground penetrating radar. These techniques provide data of variable resolution and can have more or less model ambiguity, and can be either rapid or time intensive. Geophysical studies cannot prove a structure is of impact origin. However, they can provide supporting evidence or, in some cases, disprove an impact origin.

**Gravity:** Gravity data provide a map of the spatial and vertical variations of the rocks density. The technique it is ideal for constraining the diameter, volume of low-density rock (breccia, fill), extent of fracturing, and central uplift dimensions. The gravity signature of an impact structure depends upon whether it is a simple or complex crater.

**Magnetics:** The magnetic field over an impact maps the induced and remanent magnetization of the rocks. Thus, it maps the magnetic properties of the rock. The magnetic signature of an impact structure can be quite complex.

**Seismic Reflection and Refraction:** Seismic reflection profiling maps the structure of various layers as a function of depth; changes in the physical properties of the rocks (different sedimentary strata, crystalline basement, faults) act as reflectors which can be traced. Seismic refraction surveys map the velocity structure of the rocks; the velocity is a function of the physical properties of the rock (i.e., density).

**Examples:** The Chicxulub impact structure is completely buried and straddles the coast of the Yucatan Peninsula. Seismic, gravity and magnetic surveys have been instrumental in defining the dimensions and structure of the crater. Gravity studies illustrate the non unique character of some of the techniques. Gravity data have been used to estimate the diameter of the Chicxulub structure with results ranging from 180 to 300 km. An array of geophysical techniques have been used at the Chesapeake Bay, Lake Lappajarvi, Mjolnir, and Vredefort impacts to define the major structural elements.

**Summary:** Geophysical techniques are powerful tools for understanding the lateral and vertical crust structure of impact craters. While such techniques can necessarily prove a structure if of impact origin, they can be used to guide drilling activities and in some cases they can provide critical data that a structure is not of impact origin.

## EVALUATION OF HYPERVELOCITY IMPACT-INDUCED DAMAGE OF ROCKS USING ELASTIC WAVES.

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**Introduction:** During a hypervelocity impact, shown in the MEMIN-Project, the damaged area on the surface of the sandstone sample is highly visible. Against this, the damage inside the sample is not visible. To investigate of the damage zone inside the sandstone after the impact, we use non-destructive testing methods. For a detailed evaluation of the damage zone acoustic emissions (AE) emitted by the crack formation during impact are recorded. In addition ultrasound tomography is applied before and after the impact.

**Techniques and Measurements:** Acoustic emission techniques will in particular lead to a better understanding of the timely and spatial formation of the damage zone underneath crater structures in terms of the degree of fragmentation. It can be considered as a form of micro seismicity. With AE sensors attached to the surface the elastic waves released during the formation of cracks can be recorded and analyzed in respect to their origin (hypocenter determination) and to the fracture mechanical process responsible for cracking ([1];[2]). The sensors have to be arranged around the sandstone to get a good spatial coverage. During the last measuring campaign four sensors were placed in drilled holes opposite to the surface of the impact. Calculations by travel time differences indicate the localization of the events. The first event is the impact itself, followed by much smaller events (aftershocks), which accrue out of the displacement as a result of the impact.

A second method to determine the damage zone inside the sandstone is tomography based on a through-transmission ultra-sound technique. The aim was the evaluation of the whole impact area inside the sandstone underneath the crater interpreting transient waves being propagated by analyzing signal amplitude, frequency content, travel time and wave velocity. Using diffraction techniques additional information can be obtained using a velocity background model to calculate scatting hyperbolas for each grid point [3]. The results are compared with computer tomography measurements done at the Bundeswehr Research Institute for Materials, Fuels and Lubricants, WIWeB.

**Conclusions:** AE analysis techniques enable for the localization of the impact and will be used to determine the regions of subsequent cracking underneath the crater. However, these after-shocks are events with low amplitude and hard to identify in the recordings. Tomography methods are supposed to complement to acoustic emission results by giving additional information about the damage zone.

**References:** [1] Grosse C., Finck F., Kurz J., Reinhardt M.-W. 2004. J. of Constr. Build. Mat., 18,3: 203–213. [2] Grosse C. and Ohtsu M. 2008. Springer Publ. page 400pp, Basics and applications of emission testing in cevil engineering. [3] Bronstein M., Bronstein A., Zibulevsky M., Azhari H. 2002. IEEE Trans. On medical testing, 21/11, Reconstruction in diffraction ultrasound tomography using non-uniform FFT.

## MAPPING OF MICROSTRUCTURAL DEFORMATION IN EXPERIMENTAL IMPACT CRATERS FORMED IN SANDSTONE.

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**Introduction:** As part of the MEMIN project experimental hypervelocity impacts into porous sandstone were conducted at the Ernst-Mach-Institut (EMI), Germany [1]. In combination with real-time investigations of the ejection process and ultrasound signals, spatially resolved impact damaging of the target was systematically investigated with a scanning electron microscope (SEM). As first result four distinct subsurface zones can be discriminated by their deformation mechanisms.

**Methods:** A 2.5 mm sphere of high alloyed steel impacted into a 20 cm sandstone cube with a velocity of 4.8 km/s. Acceleration was achieved by a two stage light gas gun (Space Gun, EMI)[2,3]. The sandstone has a porosity of ca. 22% and a quartz content of 94 wt%. The sub-rounded quartz grains are cemented by quartz and clay mineral coatings. For investigations the impacted block was bisected parallel to the impact direction and thin sections were prepared directly underneath the crater floor. For a detailed mapping ca. 300 SEM photomicrographs (160x, BSE) were merged to a high resolution image of the crater subsurface.

**Results:** The formed crater has a diameter of 5.76 cm and a depth of 1.1 cm. Deformation gradually decreases with increasing distance from the crater floor. The outermost zone (>3.6 projectile diameters (⌀p) from the impact center) of apparent deformation is dominated by concussion fractures which are well known from natural impacts [4]. These intragranular fractures occur on grain-grain contacts and have a preferred radial orientation. Macroscopic radial fractures as described for cratering in basalt [5] were not detected. The second zone of deformation (2.9-3.6 ⌀p from the impact center) is characterized by localized compactional shear bands in which grain comminution along with shearing and compaction occurs. This zone has a hemispherical appearance beneath the crater floor with a thickness of ca. 2.2 mm. In the third zone (1.7-2.9 ⌀p from the impact center) the compaction and grain crushing is pervasive. Pore space is completely crushed and filled with small quartz fragments and clay mineral aggregations. This zone has a maximum thickness of 3.1 mm. The innermost zone (1.4-1.7 ⌀p from the impact center) of deformation in contact to the crater floor has a maximum thickness of 0.9 mm. In addition to the deformation described for zone three, tensional fractures occur sub-parallel to the crater floor. These fractures are up to 1.2 mm long and formed new pore space in the compacted host rock. Macroscopic spall fractures are traceable laterally at distances >5 ⌀p from the impact center

**Conclusion:** The sub-surface deformation in shocked porous sandstone can be differentiated into four different zones by the occurrence of different deformation types. A more detailed analysis of deformational modes is planned to give further insights into deformation mechanisms in porous targets during shock loading.

**References:** [1] Kenkmann T. et al.. 2011. MAPS in press. [2] Schäfer F. et al. 2006. ESA SP-612. [3] Poelchau M. H. 2011. Abstract #1824. 42th Lunar & Planetary Science Conference. [4] Kieffer S. W. 1971. J. Geophys. Res., 76, 5449-5473. [5] Polanskey C. A. and Ahrens T. J. 1990. Icarus, 87, 140-155.