Experimental impact cratering in sandstone: the effect of pore fluids

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Abstract.

Planetary surfaces are subjected to meteorite bombardment and crater formation. Rocks forming these surfaces are often porous and contain fluids. To understand the role of both parameters on impact cratering, we conducted laboratory experiments with dry and wet sandstone blocks impacted by centimeter-sized steel spheres. We utilized a powerful two-stage light gas gun to achieve impact velocities of up to 5.4 km/s. Cratering efficiency, ejection velocities, and spall volume are enhanced if the pore space of the sandstone is filled with water. In addition, the crater morphologies differ substantially in both experiments. We report on the effects of pore water on the excavation flow field and the degree of target damage. We suggest that vaporization of water upon pressure release significantly contributes to the impact process.

Keywords: experimental impact cratering, sandstone, meteorite impact crater, shock metamorphism, damage

1. Introduction

Hypervelocity collision of solid bodies has been and still is a fundamental geologic process throughout the solar system as documented by the heavily cratered surfaces of almost all planets, moons, asteroids, and comets with solid crust [1]. Among the 176 terrestrial impact craters discovered so far (http://www.unb.ca/passc /ImpactDatabase/; Earth impact database, 2009), 69 were formed in sedimentary rocks, and 54 in mixed targets with a sedimentary cover resting on a crystalline basement. Thus sediments and sedimentary rocks are by far the most frequent target material for impact cratering on the Earth’s surface. Aeolian and fluvial sediments are also widespread on Mars. On other planetary bodies like the Moon, regolith and regolith breccias are among the most frequent surface rocks. All these surface rocks are porous. The pore space may contain fluids, ice, or volatiles, depending on the atmospheric conditions of the planetary body. NASA’s recent LCROSS (Lunar Crater Observation

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and Sensing Satellite) impact experiment may indicate that even the Moon, which was over decades regarded as absolutely dry, contains interstitial water ice near the south pole. Pore space and pore space fluids affect magnitude and absorption of shock waves and significantly influence cratering processes [1, 2]. Love et al. [3] showed that it requires much more energy to produce craters of the same size in porous targets than in non-porous targets. Understanding the effects of porosity and fluids on cratering is crucial for accurately predicting crater sizes and the extent of impact damaging [3-4]. This knowledge is particularly important when correlating size-frequency distributions of impact craters with ages of planetary surfaces. Furthermore, impact craters can be used as tools to decipher environmental conditions of planetary surfaces if the effects of porosity and fluids among other parameters are well known. For instance, results of the collision experiment of the NASA Deep Impact mission with comet 9P Tempel 1, [e.g., 5-6] required a thorough analysis of impacts into porous targets. Our reconnaissance study aims at quantification of the effect of pore water on the cratering process of sandstone. We present results of two impact experiments on sandstone and discuss the progressive deformation of sandstone with increasing distance to the point of impact. The meso-scale experiments narrow the dimensional gap between experimental and natural craters. The presented experiments were conducted as a pilot study [7-9] in the framework of the recently established Multidisciplinary Experimental and Modeling Impact Research Network (MEMIN), a research unit funded by the German Research Foundation.

Nomenclature

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<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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<tr>
<td>d</td>
<td>distance from crater center</td>
<td>[m]</td>
</tr>
<tr>
<td>p</td>
<td>equivalent depth of burial of point source explosion</td>
<td>[m]</td>
</tr>
<tr>
<td>f</td>
<td>fractures per grain</td>
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<tr>
<td>φ</td>
<td>coefficient of internal friction</td>
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2. Techniques applied

2.1 Experimental set-up

The experiments were conducted with a two-stage light gas gun at Fraunhofer Institut für Kurzzeitdynamik, Ernst-Mach-Institut (EMI) in Efringen-Kirchen, Germany (Fig. 1). The configuration consists of a 22 m long pump tube with 150 mm diameter, in combination with a 12 m long launch tube of 50 mm diameter. We used CrMo steel spheres (AlSi 4130 German Industry Standard material number DIN 1.7218) of 1 cm diameter and 4.1 g mass as projectiles with a tensile strength of 800
N/mm². These spheres were encapsulated in cylindrical Lexan sabots of 113 g that got aerodynamically separated from the projectile in the blast tank. Before the projectile entered the target chamber, the projectile passed laser barriers 1.5 m and 6 m behind the launch tube that allowed to determine the flight velocity. The steel projectiles were launched against blocks of sandstone (1.0 x 1.0 x 0.5 m) enclosed in a steel frame. For technical reasons the blocks were positioned vertically to simulate a vertical impact on flat-lying sediments. Fiber boards were placed 55 cm above the target surface to reveal the imprint of the ejecta cone. A high speed framing camera has been integrated to capture shadowgraph images of the impact process. The shutter time was 180 ns. The camera was placed perpendicular to the shot direction, in the plane of the front target surface. Camera and flash were electrically triggered by a foil mounted to the target surface by the impacting projectile during the first tens of nanoseconds of the penetration phase. The ambient pressure in the target chamber was 500 mbar.

2.2 Target characterization

The sandstone target blocks were cut out of the so-called Seeberger Sandstein, (Fig. 2). Seeberger Sandstein (Seeberg near Gotha, Germany), quarried by TRACO company, is a well-sorted, cream sandstone of upper Triassic age (Rhätian, 215 Mio. a) that was deposited within the Thuringian basin as a fluvial sediment. The bed chosen for the target blocks (bank 5) is an arenitic sandstone with a mean grain size of 0.17 +/- 0.01 mm. The rock is relatively pure in composition (about 97 wt.% SiO₂) (Table 1), and shows a centimeter-spaced layering (Fig. 2a) with a porosity varying between 12 and 20 vol.% (Figs. 2c-d). Quartz grains are sub-rounded and often contain thin coatings of iron oxides and clay minerals. Accessory minerals are feldspar, mica, zircon, and hematite. Strength and elastic modulus are 62.4±2.8 MPa and 14.8±1.4 GPa for the dry, and 47.0±3.7 MPa and 12.1±1.0 GPa for a water-saturated sandstone measured perpendicular to the bedding planes.
2.3 Geochemical, petrological, and petrophysical analysis

Whole rock geochemical analysis was carried out by X-ray fluorescence spectroscopy (XRF) on glass tablets. Geochemical spot measurements of single grains and fragments were performed with a scanning electron microscopy (SEM) equipped with an X-ray energy-dispersive analytical system. Rock texture and impact-induced damage were studied with a polarizing microscope in transmitted light using polished thin sections and the SEM in backscattered electron mode (BSE). Applying the Archimedes method we measured density and porosity; the latter was in addition determined with an image analysis package on digitized thin sections. Degree of water saturation was determined by weighing the sample blocks prior and after watering. Strength and elastic moduli were determined with a servohydraulic loading frame.

2.4 Morphometrical analysis

For a quantitative analysis of crater shape and volume silicone molds were prepared from the craters after mapping and collecting loose fragments. These molds were used for producing negative and positive gypsum replicas of the crater cavity that served as base for the three-dimensional digital scanning of the cavity surfaces. The data set of each crater consisted of ~400 x 400 coordinate points with altitude information. Data processing, volumetric measurements and calculation of digital elevation models (DEM) were done with different software packages. Profiles across the crater center were examined every 10°. A major difference between our experimental craters and impact crater on planetary surfaces is that on laboratory scale craters are significantly enlarged by spallation. In natural cratering events the spallation zone lies within the extent of the transient crater that is formed as result of shock wave compression and subsequent release. The transient crater can be approximated by a parabola and represents the maximum extent of the cavity that is formed as a result of the shock-wave-induced excavation flow. It may be reached at different points in time for the maximum depth and the maximum diameter of the crater. Therefore the transient crater is a more virtual construct that may never exist in the course of crater excavation. In natural impact events the transient crater is much bigger (10-20 times the size of the projectile) relative to the size of the projectile than in laboratory experiments. That this transient crater reaches beyond the spallation zone is mainly due to the fact that the size of natural impact craters is limited by gravity while in our experiments crater growth is halted by the resistance of the material against plastic deformation (strength). In order to make our experimental craters comparable to natural craters we have to find the size of the “real crater” which we define here as the extent of the crater without spallation zone.

To account for this crater enlargement by spallation the size of the real crater was derived by fitting a parabola to the basal part of the crater cavity in various 2D profiles and extending this parabola to the surface of the target block. The crater paraboloid was further constrained by the ejection cone angles recorded with the high-speed camera and the imprint of the ejecta on the ejecta catcher. The fitted parabolas represent the best possible approximation to the transient crater that can be derived from the final crater morphology.
Fig. 2. Seeberger sandstone. A. Photograph of sandstone, Bank 5, target material for the experiments quarried near Gotha, Germany. Variation in grain size, porosity, and iron content cause the articulate layering (bedding plane) on the centimeter-scale. Bended tracks in the lower left are marks of the cutting. B. Optical micrograph of the sandstone imaged under linear polarized light. C. SEM-BSE micrograph, and. D. SEM-BSE micrographs with pore space in blue as basis for porosity determination via image analysis.

2.5 Sampling

We sampled excavated material and loose fragments attached to the crater floor. For sampling the sub-surface crater, the sandstone blocks were sawed perpendicular to the target surface in such a way that one of the cut surfaces runs through the crater center. Bore holes of 15 mm diameter and about 12 cm length were drilled from the cut surface into the block parallel to the target surface. Four profiles were drilled to obtain samples from various distances and depth below the crater floor surface. Each profile consists of 8 bore holes. Reference samples were taken from un-deformed sandstone.
Fig. 3. Cratering experiments with Seeberger sandstone. A-D. Experiment 2808: dry target. E-H. Experiment 2809: wet target. A, E. Plane view photographs of craters. B, F. Depth isoline maps. C, G. Digital elevation models (DEM) in perspective view D, H. Crater profiles extracted from the DEMs including the "real crater" paraboloids and the extended spall zones. The intersection of the paraboloid and the surface concurs with the most radially origin of the ejecta as documented by the high-speed imaging. Same scale for all figures.
3. Results of the cratering experiments

3.1 Impact experiments

Two experiments were carried out with a different water content of the target sandstone.

- In experiment 2808 a 1 cm steel sphere was launched against a room-dry sandstone block with an impact velocity of 5338 m/s. The achieved impact energy was 58.4 kJ.
- In experiment 2809 the impact speed was slightly lower (5269 m/s; the difference in velocity of about 1.3 % is a measure for the reproducibility of the projectile performance in the gun) and the impact energy was 56.9 kJ. The sandstone target block was watered in a basin for 4 months prior the experiments. We calculated that ~44 % of the totally available pore space (17 vol. %) was filled with water during experiment 2809 (Table 1). The 3D-distribution of the water in the sandstone block, however, is not known.

3.2 Crater morphometry

The resulting craters had diameters of 24.3 and 28.7 cm, and depths of 5.6 and 4.5 cm, for the dry (2808) and wet (2809) experiments, respectively (Fig. 3; Table 1). The crater in exp. 2808 has the shape of an inverted spherical cone (Figs. 3c, d) whereas, that one in exp. 2809 is much broader with a flat floor (Figs. 3g, h). The depth/diameter ratios are 0.23 (exp. 2808) and 0.16 (exp. 2809). Both craters were significantly enlarged by spallation. Volumetric analysis of the craters based on the digital elevation models resulted in 715 (exp. 2808) and 1099 cm³ (exp. 2809), including the spall zone. The diameters of the craters deduced from the intersection of the paraboloids with the pre-impact surface of the sandstone targets (“real crater” excluding spall zones) are 8.2 (exp. 2808) and 11.3 cm (exp. 2809), and the crater volumes are 149 (exp. 2808) and 223 cm³ (exp. 2809) (Figs. 3d, h). Hence, the volume of the real craters produced by ejection, amount to only ~21 % of the entire crater volume, and ~79 % were excavated by spallation in both shots. The cratering efficiency $\pi_v$ - ratio of the displaced mass of target material to the projectile mass - is 419 and 593 for the dry and wet target, respectively. If the spallation-induced crater volume is subtracted, cratering efficiencies $\pi_v$ for both shots are 80 and 130 for the dry and wet target, respectively.

3.3 Macroscopic damage of the target

The surface of the deepest part of the crater was covered by fine-grained quartz fragments embedded in whitish pulverized quartz in both experiments. The area of pulverization has a diameter of about 3 cm. The main fracture zones of the craters’ subsurface were mapped in plane view and cross sections (Fig. 4). Most fractures trend concentrically and dip at shallow angle towards the center, and extend sideways as tension cracks in both experiments (Figs. 4 c, d). Bedding planes are preferential sites for strain localization. These fracture zones in combination with steep radial fractures delineate spall plates. The volume of spallation is 566 cm³ and 876 cm³ in the dry and wet target crater. Fractures beneath the crater center extend for 3-4 cm and branch into subsidiary fractures. We did not detect macroscopic displacements and off-sets.
3.4 Damage of the target at the microscopic scale

Fig. 4. Fractures in the crater floor observed in plane view (A, C) and in cross section (B, D) for the two experiments. Same scale for all figures.
Fig. 5. SEM micrographs of the sandstone targets from various depth beneath the crater. Crater center is to the left of each image. Width of all photographs is 1.7 mm, except for G (850 µm) and I (425 µm). A – E exp. 2808 (dry target), and F-J exp. 2809 (wet target). The thin sections were cut perpendicular to the target surface, pore space is black. The fracture density decreases with increasing distance from the calculated point source of impact $p$. The depth of $p$ beneath the target surface is calculated by $p = L (\rho_p/\rho_t)^{1/2}$ with $L$ being projectile diameter, $\rho_p$ projectile density, and $\rho_t$ target density. 

- F Trans-granular fractures (black) trend radial with respect to the crater center.
- Tension along grain boundaries may be a result of wave interaction from free surfaces.
- G. Trans-granular fractures emanate from grain-to-grain point contacts.
- H. Localized grain crushing led to the formation of shear or compaction bands.
- I. Mobilization of swellable clay (medium grey) due to the presence of water in exp. 2809.
- J. Pore space reduction and grain crushing in samples from the crater floor.
The intensity of sandstone deformation beneath the craters is subdivided into three categories: (1) weakly to un-deformed sandstone (type 1, Figs. 5a-c) with intact porosity and absence of shock indicators occurs ubiquitously underneath both craters. Fractures, in particular trans-granular cracks, often emanate from grain-to-grain contacts. Tension of cracks may develop during radial flow and growth of the crater (Fig. 5f). Radial profiles beneath the crater show that the fracture densities decrease with distance from the impact center with a power of $-1.7$ (dry exp. 2808) and $-2.2$ (wet exp. 2809) (Fig. 6). (2) A few centimeters beneath the crater floor, grain crushing and pore space collapse are present and localized in millimeter wide zones (type 2, Fig. 5h). It is not clear yet whether these are formed as compaction bands, compactional shear bands, or as shear bands. These zones are particularly affected by later extension. (3) The surfaces of both crater cavities were decorated with pulverized grains and grain aggregates that also form a fraction of the recovered fine-grained ejecta. These aggregates show intensive grain size reduction by fracturing and closure of the pore space to a wide extent (type 3, Figs. 5e, j). Single grains often appear chopped along sub-parallel fractures (Fig. 5i, lower left). Very rare shock-deformed quartz grains with thin amorphous lamellae (planar deformation features, PDFs [10]) indicate local pressure plateaus of 10-35 GPa.

![Fig. 6.](image) The average number of fractures per grain decreases with increasing distance from the crater center and may obey a power law. Large error bars indicate that intensity of shock deformation is heterogeneous with increasing distance from the crater center.

### 3.5 Ejecta flow characteristics

Ejection velocity and cone development were analyzed by using sixteen high-speed shadowgraph images taken during a period of 1.2 ms after the initial contact of the projectile with the target for both experiments. The analysis is straightforward as any influence of gravity on the early ejection process is negligible: no deflection effects were detected in the shadowgraphs and in the catcher imprints. The ejecta velocities were determined from the projection of the expanding cone fragments in a plane perpendicular to the target surface (Figs. 7a-b).
Highest ejection velocities were measured in the central ejecta plume (fireball) above the crater. The ejecta developed a cone that got affected by ring winds (vortexes) due to ambient air pressure of 500 mbar in the target chamber (Fig. 7d). In the basal part a tube formed perpendicular to the target surface. Above this tube is a zone of turbulence with a characteristic kink in the cone profile. The upper part of the cone is symmetric and particularly well defined for the wet exp. 2809: there the envelope of the cone forms a straight line inclined ~60° to the target surface (Fig. 7c). In the dry exp. 2808 this angle decreased with time (Figs. 7a-c). Although ejected fragments of the sandstone did not get trapped
in the fiber boards, they produced very remarkable imprints (Fig. 8). In case of the dry exp. 2808, the ejecta imprint is diffuse in accordance to the shadowgraph images. The strongest imprint occurs around the center whereas the outer and later part of the ejecta cone yielded concentric schlieren and festoons within an outer diameter of 79 cm (Fig. 8a). In case of the wet exp. 2809, the ejecta produced a distinct ~17-cm-thick ring with an outer diameter of ~76 cm (Fig. 8b). Apart from this ring, ejecta also hit the catcher in the inner part. On average, the velocities of the ejecta are higher in the wet exp. 2809 than in the dry exp. 2808, in particular during the initial stages of the ejection process.

3.6 Numerical simulation of crater formation

Modeling the experiments was aiming at verification of the hydrocode iSALE [11, 18, 19] that has been widely used to model the formation of large-scale impact craters on planetary surfaces [e.g. 19, 22]. The code has been previously tested against laboratory experiments in sand and aluminum targets and other hydrocodes such as CTH or AUTODYN [23]. In particular a newly developed porosity model [11] that enables the computation of the closure of pore space as a result of shock wave compression was tested against the experiments. The new strain-based porosity compaction model was incorporated in the iSALE hydrocode [11] to study the effect of porosity on crater growth and enhanced shock heating [24]. We used the Tillotson equation of state to compute pressure and temperature as a function of internal energy and density. To account for the resistance of rocks against shear failure we utilized a rock rheology model described in detail at [12]. The model allows for the computation of dynamic
shear and tensile failure for intact (the pristine stage of material before deformation) and damaged rocks (where the material has accumulated a maximum degree of damage). Fully damaged rocks are assumed to behave similar to a granular material. Shear strength $Y$ is than a linear function of pressure $P$ according to a Drucker-Prager yield envelope $Y = Y_0 + \phi P$, where $Y_0$ is the cohesive strength at zero pressure that is usually assumed to be zero, and $\phi$ is the coefficient of internal friction. The strength of intact rocks is also strongly pressure-dependent and we assume a nonlinear relation between shear strength and pressure following e.g. [25]. The pressure dependence of shear strength for intact and damaged material is particularly important for modeling plastic failure on a large scale where the lithostatic pressure plays an important role. The behavior of rocks on large scale is dominated by shear failure, rather than tensile failure. As our primary purpose is to gain a better understanding of crater formation on planetary surfaces we tried as a first attempt to apply our well-established material and strength model to the given experiments. Since the material properties such as the coefficient of internal friction for the intact and damaged state, and the Hugoniot elastic limit were unknown (except the measured shear strength under static conditions on a small sample which is approximately $\sim$50-60 MPa) we varied the shear strength to match the experimental crater.

A comparison between the modeled crater and the different profiles through the experimental craters is shown in Fig. 9. A good agreement with numerical models could only be achieved by using much weaker cohesive strength for intact sandstone of 5 MPa than previously measured in static experiments ($\sim$50-60 MPa). However, yield strength increases significantly during shock compression (for damaged material $Y = Y_0 + \phi P$, where $\phi = 0.67$, and $Y_0 = 0$) and may be effectively an order of magnitude larger depending on the amplitude of the shock pressure. Another argument for the required weaker shear strength in the models could be the well-known strength decrease of rocks with increasing volume (Weibull law, 1951). In our experiments the deformed rock volume is much larger than that of quasi-static loading tests under zero confining pressure. Moreover, we did not consider tensile failure in our model which may also contribute to substantial weakening of the material. Additionally, the lack of tensile failure in our model does not allow for simulating the enlargement of the crater by spallation.

Fig. 9 shows on the right hand side where porosity was completely crushed (blue area) and where it remained intact (red). Note that completely crushed material falls out of the crater at the end of the experiment while in the models gravity is directed downwards and material stays inside the cavity. The left hand side in Fig. 9 shows the amount of total plastic deformation. Some deformation reaches down to approximately 5 cm below the crater floor, which is in agreement with the microscopic damage observations described in section 3.5 and shown in Fig. 6.

Fractures and flaws are indicated by high plastic deformation (shear localization) and are radially aligned around the crater. Note that we did not consider any anisotropy in the target; however, this was most likely not the case for the sandstone blocks used in the experiments where some layering was observed that may have been affected the direction and propagation of flaws as shown in Fig. 4.
4. Discussion

4.1 The effect of pore water on the cratering process

The experiments demonstrate a strong influence of pore fluids on the cratering process in sandstone. The effect of pore water is two fold: (i) It lowers the yield strength of the rock (Table 1), and (ii) it reduces the shock impedance mismatch on the grain scale between grains and interstitial pores, thereby preventing dissipation of shock wave energy into heat, and reducing the degree of shock wave attenuation with distance. We found cratering being ~50% more effective if the pore space is filled with interstitial water. The volumes of the “real” craters (excluding the spall zones) roughly correlate with the volume of cataclastically deformed sandstone (type 3 deformation) in which most of the grain-to-grain contacts are crushed and cohesion is strongly reduced. The zone of pervasive cataclastic deformation with pore space collapse and successive compaction reaches deeper in the dry experiment because pore space collapse is not impeded by the presence of a fluid. This is in agreement with experimental results by [3] but in conflict to [4] who observed deeper craters in water saturated targets. This discrepancy is probably related to the impact energy which are three orders of magnitude lower in [4] in comparison to the experiments in this study. The cratering efficiency is less in the dry experiment, as more energy is consumed by compaction of the sandstone leading to a stronger attenuation of the shock wave. As a consequence the crater cavity paraboloid is tighter and the ejection steeper than in the experiment with a wet sandstone. Pore water also seems to control the size of the
spall zone surrounding the “real” crater as pore fluids reduce the effective mean stress and favor tensile failure in the wet target experiment.

The higher ejection velocities measured in the wet target experiment indicate that vaporization of water upon pressure release may have served as an additional driving mechanism for ejecta acceleration. If peak pressures are below 5 GPa, water remains liquid upon pressure release; at pressures in excess of ~10 GPa, partial vaporization occurs, producing a liquid-vapor mixture, and at pressures ~70 GPa, water is completely vaporized on pressure release [14]. Under atmospheric pressure water expands by a factor of 1700 with respect to its initial volume when it starts to boil. The interaction of the hot target volume near the point of impact with surrounding water may have caused additional liquid/vapor transition of water and could be a possible source for explosions that

Table 1. Characteristics of projectile, target, and the experimental craters *(parabola = “real” crater; LOI= Loss on ignition)

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<th>Exp. 2809 wet sandstone</th>
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superimposed the ejecta plume (fuel-coolant interactions) [15]. The fact that in particular the hot ejecta plume expands at high speeds supports the importance of this mechanism. The very different ejecta imprints in exp. 2808 and exp. 2809 needs further explanation. The regular cone imprint of the wet exp. 2809 indicates that the ejecta trajectories follow the z-model approach [16].

4.2 Relevance for natural impact events

The experiments were performed to better understand impact craters on Earth and other planetary bodies in porous materials. The craters obtained are strength-dominated craters which means crater growth is limited by strength rather than gravity. Straightforward scaling is therefore restricted to other strength-dominated, i.e., small simple craters with a diameter on the order of a few hundred meters. The extrapolation by three orders of magnitude (20 cm diameter of experimental crater vs. 200 m real crater size) would imply a grain size of 10-20 cm (instead of ~170 µm in the experiments) which are characteristic for conglomerates, a geologically still reasonable material. The ratio of projectile diameter \( L \) to grain size in the experiments is ~60, in stark contrast to previous studies [4]. It follows that the pressure pulse duration is sufficiently long to simultaneously compress many neighboring grains. This circumstance yields a shock damage in the experiments similar to nature and allows a direct comparison. A caveat of the experiments is the negligible lithostatic pressure that increases along the target surface rather than perpendicular to it due to the upright position of the blocks. This could result in overemphasis of tensile rather than shear failure in unexpected orientations in our experiments (e.g. Fig. 6f).
Laboratory-produced craters can decipher crater formation of real impact craters if dimensional analysis (Pi-group scaling) is applied, e.g. [17] (Fig. 10). Crater efficiency $\pi_v$ - the ratio of the displaced mass of target material and the projectile mass - is a function of $\frac{1}{2}gL/U^2$, also denoted as $\pi_2$, if gravity controls the cratering process. It is a function of $Y/pU^2$, also denoted as $\pi_3$, if strength governs the cratering process. The power law relationships between $\pi_v$, or alternatively $\pi_0$ (Fig. 10), and $\pi_2$, $\pi_3$ do not account for porosity and pore water so far. The experiments contribute to further constrain dimensionless scaling parameters for porous and water-saturated targets.

5. Conclusions

Understanding the role of porosity and volatiles in natural impact events requires laboratory experiments. We used the newly designed powerful two-stage light gas gun of EMI to shoot centimeter-sized steel projectiles at ~5300 ms$^{-1}$ against dry and wet porous sandstone targets under fully controlled conditions. The impact yielded decimeter sized craters that enabled detailed spatial analyses of rock damaging. We found that (i) crater efficiency, (ii) ejection velocities, and (iii) spall volume are enhanced if pore water is present. In addition, the crater morphologies are remarkably different. We suggest that in addition to strength weakening the presence of fluids, vaporization of water upon pressure release provides an additional explosive potential that superimposes the impact-induced flow field.

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References


