IMPACTS INTO SANDSTONE: CRATER MORPHOLOGY, CRATER SCALING AND THE EFFECTS OF POROSITY. M. H. Poelchau[1], A. Dufresne[1], T. Kenkmann[1], and the MEMIN Team. [1]Instut für Geowissenschaften – Geologie, Universität Freiburg, Germany (michael.poelchau@geologie.uni-freiburg.de).

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. A table of all experiments is presented in [1], further details can be found in [2,3].

Target material: Triassic Seeberger sandstone of a specific stratigraphic layer ("layer 3", quarried in Thuringia, Germany) was chosen as a target material due to its high purity and quartz content. Small grain sizes of ~70 µm have the advantage of giving better scaling ratios to the projectile size. The porosity is 20-25%, uniaxial compressive strength (UCS) is 35-40 MPa. Note that for the prefeasibility tests the coarser-grained "layer 5" of Seeberger sandstone was used [3].

Cratering results: A qualitative assessment of crater morphology shows an outer, shallow-dipping area formed by spall fractures and transected by radial fractures. "Failed" or incipient spallation of fragments can lead to somewhat irregular crater shapes, which additionally appear to be influenced to a certain degree by target layering. In contrast, the inner section of the crater is characterized by a steeper pit or depression lined with lighter-colored, highly crushed rock (see also [3]). The craters thus resemble experimental impact craters formed in other geological materials reported in the literature [e.g., 4].

Crater depth and diameter were measured, and crater volume was determined non-intrusively using a 3D laser scanner. A few crater volumes were also cross-checked by filling the craters with 0.8-mm diameter glass beads and measuring the volume the beads used. The two methods showed less than 3% discrepancy. Weighing the targets before and after the experiment proved to be more inaccurate, possibly due to changing moisture levels in the sandstones in the lower pressure environment of the target chamber.

Discussion: Crater depth to diameter is presented in Fig. 1. Depth to diameter ratios range from 0.14 to 0.25. Craters formed by steel or meteoritic iron projectiles are deeper than the average craters formed in crystalline rocks with similar high-density projectiles [4,5], indicating that the sandstone's porosity results in greater penetration depth [e.g., 6]. The two sandstone craters formed by aluminum projectiles, on the other hand, are shallower. This most likely reflects a dependency of penetration depth on projectile density, although more data points are needed to consolidate this.

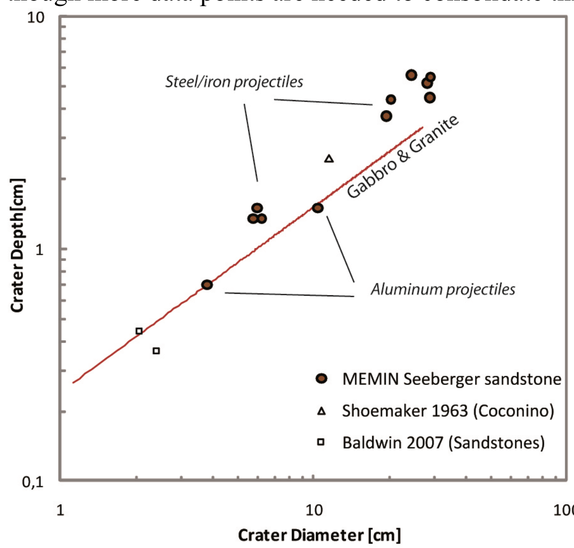

Fig. 1: Crater depth vs. diameter. Data indicates that porosity leads to deeper craters than non-porous rocks, although projectile densities need to be taken into account as an additional factor.

Fig. 2 displays the relationship of impact energy to crater volume. Volume is found to vary as a power of the kinetic energy of the projectile, and data values are in good agreement with the other 3 existing data points for dry sandstone craters in the literature [7, 8].

Interestingly, the sandstone data plot along the averaged slope for crystalline rocks [4, 5, 9-11]. Impact experiments at this scale lie within the strength regime of impact cratering, i.e., the UCS as a measure of strength of the target is considered the main constraining factor for crater growth. Average UCS values for crystalline rocks lie at 200-300 MPa, while sandstone UCS values are almost one order of magnitude lower at 35-40 MPa. The average slope for H_2O-ice [12-15] and additional data points for strongly cooled ice (81°K, [12]) have been added for further comparison. Ice has a UCS of ~7 MPa at 265°K (for strain rates of $\sim 10^{-3}$-10^{-4} [16]), while the UCS of "cold" ice (81°K) is about twice as large at ~14 MPa [12]. As can be seen in Fig. 2, craters in "warm" ice have roughly twice the volume of craters in "cold" ice for the same energy, implying that the decrease in UCS is the main factor for the increase in crater volume at a given impact energy.

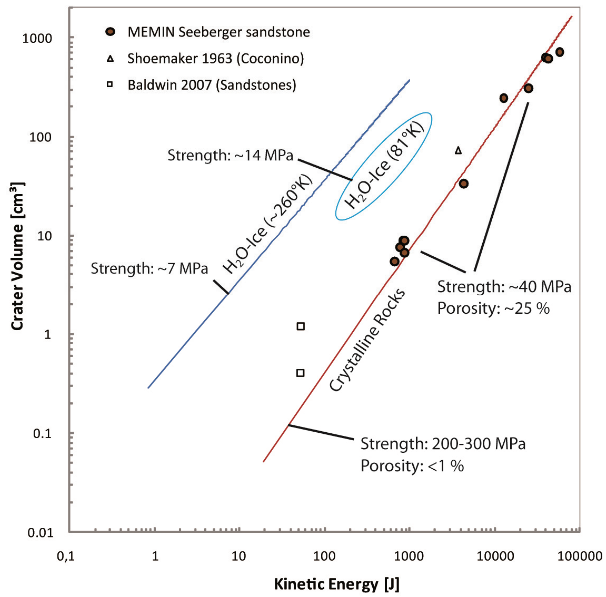

Fig. 2: Sandstones have the same crater volumes as crystalline rocks for a given impact energy, despite a much lower crushing strength, indicating how porosity reduces crater volume. In comparison "cold" ice with higher crushing strength leads to smaller volumes.

The fact that the sandstone craters are not larger than the equivalent, higher-strength crystalline rock craters indicates that another factor, in this case porosity, counteracts the effect of reduced strength. Numerical modeling results of the MEMIN impact experiments [e.g., 17] reveal how the shock wave is dampened by porosity and shock energy is spent closing pore space, leading to smaller craters.

Dimensionless scaling results are presented in Fig. 3. There, the cratering efficiency $\pi_V = m_t/m_p$ (m_t: excavated target mass; m_p: projectile mass) is plotted against the strength parameter $\pi_3 = Y/(\rho * v_p^2)$ (Y: target UCS, ρ: target density; v_p: projectile velocity). The diagram shows how non-porous materials with UCS values ranging over two orders of magnitude have the same average π_V when scaled to π_3. UCS is thus a principle factor controlling π_V, while most other material properties (e.g., phase changes to highly expansive water vapor in ice) appear negligible, based on the current published datasets of craters in brittle materials. 25% porosity, on the other hand, leads to an obvious reduction of π_V of up to nearly one order of magnitude.

Outlook: Spallation in brittle materials leads to a much large scatter in crater diameter and volume data than in high tensile strength materials like metals. First attempts have therefore been made to constrain the ratio of transient crater volume to spall volume [3]. This is done by fitting a parabola to the central depression of the crater and using ejection angles and ejecta imprints on witness plates as constraints. Preliminary results show that spallation makes up 50-90% of total crater volume. Transient crater volumes of sandstone data will be fitted and compared to craters in metals, while transient crater volumes of non-porous rocks will be estimated based on published crater profiles.

Furthermore, the effect of pore space saturation will be investigated. Results from two experiments [8, 3] already show that water saturation increases cratering efficiency. New data will be examined in detail.

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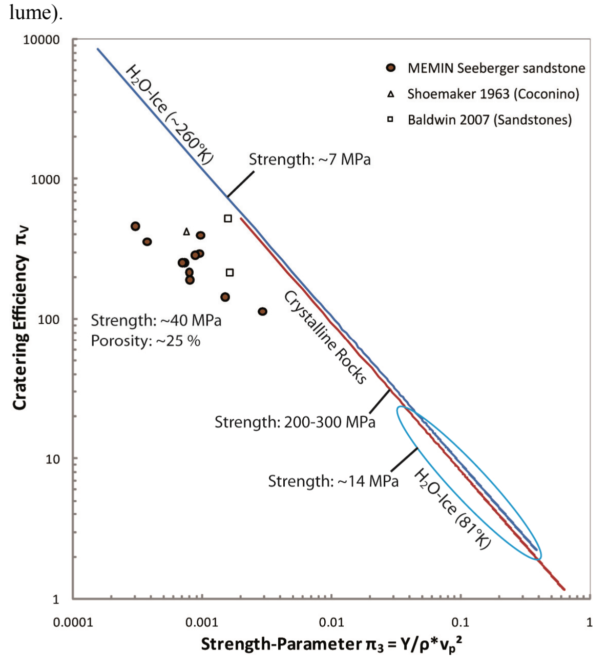

Fig. 3: When scaled to crushing strength, porosity greatly reduces cratering efficiency in brittle materials.