DIAPLECTIC QUARTZ GLASS AND SiO_2 MELT EXPERIMENTALLY GENERATED AT ONLY 5 GPa SHOCK PRESSURE: LABORATORY OBSERVATIONS VERSUS MESOSCALE MODELING.

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Introduction: The identification of impact craters formed in porous and wet sedimentary rocks, such as sandstone, on the basis of recognition of shock deformation features is a complex task. Most of the impacted target material is only weakly shocked, especially in the case of eroded remnants of impact structures or in small craters. There is a serious lack of diagnostic shock features, especially for the low shock-pressure range, which is addressed in this project focusing on shock deformation experimentally generated in sandstone in the low shock-pressure range from 2.5 to 17.5 GPa. We aim at establishing a shock classification scheme for porous, quartz-bearing rocks.

The *laboratory impact experiments* were accompanied by *meso-scale numerical modeling* in order to quantify processes beyond the optical and electron optical observational capabilities. The model enables a detailed description and quantification of thermo-dynamic parameters during single pore collapse. Both sub-projects are part of the "MEMIN" (Multidisciplinary Experimental and Modeling Impact crater research Network) research unit [1].

Methods: Seven *shock recovery experiments* [2] were conducted with cylinders (Ø 1.5 cm, length 2 cm) of dry Seeberger sandstone (layer 3; grain size: ~0.10 mm, porosity: ~25-30 vol.%, quartz-content: ~89 vol.%). The shock recovery experiments (Fig. 1) were carried out with a high explosive driven flyer plate set-up generating a plane shock wave propagating into the sandstone cylinder [3]. To avoid multiple reflections of the shock wave within the sample material and to reach the desired pressures of 2.5 to 17.5 GPa, the impedance method was used [3].

Numerical model [4]*:* To simulate shock wave propagation, the multi-material, multi-rheology hydrocode iSALE [5] coupled with the ANEOS for quartzite [6] and a virtual experimental set-up (Fig. 1b) similar to that used in the actual experiments was used. Meso-scale modeling investigates the effects at individual pore spaces to obtain a better understanding of shock wave propagation through a heterogeneous material and of the processes associated with shock-induced pore-space collapse. A quantification of localized pressure amplification due to pore collapse is performed.

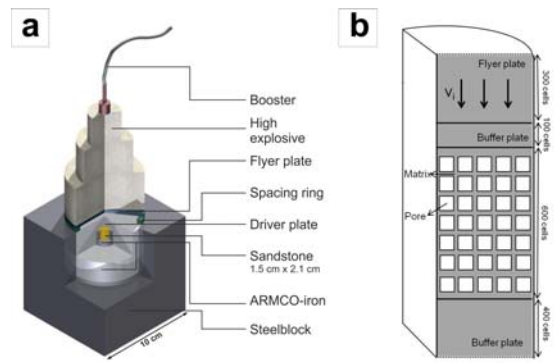

Fig. 1. (a) Experimental set-up for the shock recovery experiments. (b) Illustration of the meso-scale model set-up including the sample with a defined number of well resolved pores.

Results: Backscattered electron (BSE) SEM images demonstrate that pores are entirely closed even at an initial shock pressure of 2.5 GPa (Fig. 2a, 2b). In our samples shocked to 5 -17.5 GPa we observed whole quartz grains or parts of them that appear somewhat blurry under plane polarized light, remain black under crossed polarizers, and appear homogeneous and totally unfractured in SEM images (Fig. 2c). Furthermore, in BSE-SEM images, these SiO_2 areas appear darker than the adjacent crystalline quartz, corresponding to reduced density [7] due to amorphisation. These areas do not show any vesicles or flow structures and the particle shape is completely preserved. This indicates transformation of crystalline quartz to diaplectic quartz glass without true melting. Raman measurements confirm the presence of diaplectic quartz glass in these homogeneous-appearing areas, because the distinct and narrow Raman peak of unshocked crystalline quartz at 464 cm^{-1} wavelength is replaced by a broad band with two small peaks at ~ 454 cm^{-1} and ~ 490 cm^{-1}.

On the other hand, there are areas of SiO_2 glass showing vesicles and flow structures which clearly indicate proper melting. In the deeper part of the sample there are also up to 3 µm wide subplanar features filled with SiO_2 melt forming a widespread network of tiny and ramifying veins with fills that show distinct flow structures. In general, the glassy/molten areas are distributed heterogeneously; they rarely occur at 5 GPa but increase in frequency up to ~85% of the observed area at 17.5 GPa.

Surprisingly, a lot of grains show Raman spectra which clearly indicate crystal deformation characteristic for higher shock pressure than the nominal experimental ones, although they are not directly situated in an area of a pre-existing pore and therefore not affected by an increased pressure/temperature due to pore crushing.

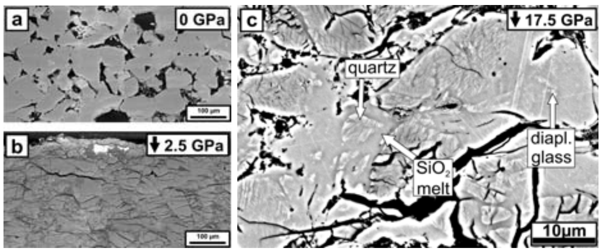

Fig. 2. Comparison of quartz in SEM-BSE images of (a) unshocked and (b) shocked (2.5 GPa) Seeberger sandstone. Note the total closure of pore space. (c) Formation of diaplectic quartz glass and SiO_2 melt (homogeneous zones without fractures) in the sandstone shocked to 17.5 GPa.

The meso-scale numerical models show crushing of pore space resulting in complete closure of pores as the immediate response to shock loading, already at low initial pressures (<6 GPa). Despite the overall decrease of shock pressure during shock wave propagation through a porous material, detailed analysis of the closure of single pores indicates localized amplification of shock pressure during pore collapse. When a pore has been completely closed, a secondary shock wave is generated that propagates outward from the original center of the pore. The secondary shock wave superposes the release wave and the initial shock wave, which results in pressure amplification in the material that originally surrounded the pore. Considering similar pressure ranges as used in the shock experiments, these amplifications can reach as much as 3-4 times the average shock pressure in the porous material (Fig. 3). The much higher pressures can be observed in the zone where the pore was initially located but pressure amplification also affects surrounding areas [6]. Note, the material, and thus the respective tracer, experienced a relative motion downward. Localized zones of pressure amplification after shock wave propagation through a representative sample with randomly distributed pores are shown in red in Fig. 3c.

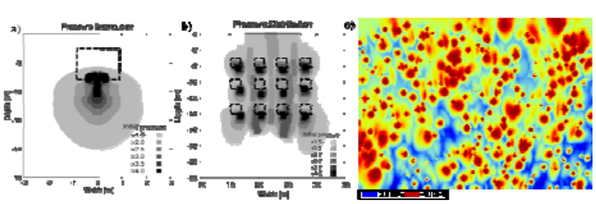

Fig. 3. Modeled peak pressure distribution for (a) a single pore and (b) a set of pores with an initial pressure of 6 GPa, and (c) for a more realistic sample with initially randomly distributed pore space. Pore space is completely closed.

Discussion: Shock compression of porous sandstone results in distinctly different effects than observed in non-porous rocks, especially at low shock pressures. The crushing mechanism is strongly dependent on porosity. In particular, the large contrast in shock impedance between quartz grains and pores leads to a distinct heterogeneous distribution of shock pressures and temperatures in the target until the pores are completely closed. This causes a heterogeneous distribution of shock effects (e.g., local occurrence of diaplectic quartz glass and SiO_2 melt) at the microscopic scale, as observed in shock experiments and nature, e.g. Meteor crater [8] or at BP and Oasis [9, and own observations]. The quantification of shock amplification due to pore space collapse using meso-scale modeling is in good agreement with observations on our shock experiments with dry sandstone at 2.5 to 17.5 GPa. Despite low shock pressures, the formation of diaplectic glass and SiO_2 melt was observed that usually occur only at about 30-35 GPa and >45 GPa in shocked quartz single crystals, respectively [3]. The meso-scale models showed that an amplification of pressure by a factor of 3-4 can occur in the vicinity of a pore - considering that a significant volume of material corresponding to at least 20% of the initial pore volume has experienced these strongly amplified pressure conditions [4]. However, it is still conceivable that smaller volumes are subjected to even higher pressures, which could explain the formation of SiO_2 melt already at 5 GPa. The localized pressure amplification may lead to much enhanced shock temperature that would facilitate the formation of melt and diaplectic glass, even at these relatively low nominal experimental pressures.

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