PROPAGATION OF IMPACT-INDUCED SHOCK WAVES IN HETEROGENOUS ROCKS USING MESOSCALE MODELING. N. Güldemeister[1], N. Durr[2], K. Wünnemann[1], Dirk Elbeshausen[1], Stefan Hiermaier[2], [1]Museum für Naturkunde, Leibniz-Institut an der Humboldt Universität zu Berlin, Invalidenstr. 43, 10115 Berlin, Germany (nicole.gueldemeister@mfn-berlin.de), [2]Fraunhofer Institute for High-Speed Dynamics, Ernst-Mach Institute (EMI), Freiburg, Germany

Introduction: The presence of porosity and volatiles in planetary crusts, asteroids and comets significantly affects crater formation and shock loading of material. How such heterogeneities on a meso-scale (empty or water-filled pores) are related to macroscopic observations such as shock-induced melt production [1,2], ejection of material [3], cratering efficiency [4,5,6], and final crater morphology [1,7] has often been discussed but is not well quantified. Porosity and material mixtures pose in particular a problem for numerical modeling of shock wave propagation in such heterogeneous materials.

In the framework of the "MEMIN" (**M**ultidisciplinary **E**xperimental and **M**odeling **I**mpact crater research **N**etwork) project, the effect of porosity in dry and water-saturated sandstone on, inter alia, shock wave loading is investigated. The performed impact experiments [8,9] were used to validate material models in hydrocode simulations. In the present work we conducted a series of numerical experiments of shock wave propagation in porous material. Porosity was either treated as a state variable that depends on pressure [10] or volumetric strain [5], so-called macro- or homogenized models, or individual pores were resolved directly by the model, so-called meso-scale models [e.g. 11,12,13].

Here we focus on (1) a detailed description and quantification of thermodynamic parameters in the vicinity of single pores, (2) the validation of the macro-scale porous compaction models [5,10] against meso-scale numerical experiments, (3) the determination of the relationship between strength and parameters that have been suggested to parameterize the crushing behavior of porous materials in macro-scale models [5], and (4) the investigation of the behavior of material mixtures, in particular water-saturated sandstone.

Methods: For our 2D and 3D numerical experiments we used the multi-material, multi-rheology hydrocode iSALE [5,14,15] and the ANEOS [16] for quartzite [17] to describe the thermodynamic behavior of the material. For the macroscopic description of porosity we employed the ε-α compaction model [5]. We generated planar shock waves of different pressure amplitudes (2-40 GPa) by impacting a cylindrical flyer-plate on a buffer plate at velocities between 500-4000 m/s. The shock wave propagates from the buffer plate into the sample containing porosities between 20-50 %. The porous sample was resolved in almost all experiments by 300 x 600 cells. In a separate study we found this resolution to be sufficient. We conducted a series of simulations examining the propagation of a planar shock wave through a sample containing (a) one single cubical pore (meso-scale, pore resolved by 120 cells per edge length), (b) a defined number of approximately 500 cubical pores (meso-scale, each pore is resolved by 8 cells per edge length), and finally (c) an infinite number of pores (macro-scale). In the last case porosity was treated as a state variable by using the ε-alpha compaction model [5]. In the meso-scale models (a,b) the pores were regularly distributed in the sample (Fig. 1). For the 2D models on a cylindrically symmetrical computational grid the pores represent rings with a rectangular cross-section. In the 3D runs pores are cubes. We also tested the effect of pore geometry by using spheres and a random distribution in 3D models but found the effect of geometry, distribution and dimensionality (2D vs. 3D) to be negligible if the number of pores is sufficiently high. However, for detailed studies of the collapse of a single pore, geometry may play an important role [11].

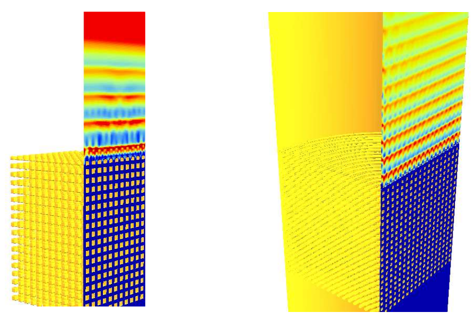

Fig. 1: Propagation of a planar shock wave through a porous sample in 3D (cubes) and 2D (rings).

The yield strength of the quartzite material surrounding the pores (matrix) was chosen between zero (hydrodynamic behavior) and 10 GPa. Finally we included pore-water in our study. Pressure, internal energy, density, shock (U) and particle (u_p) velocities were recorded during shock wave propagation in the sample. For the meso-scale models where localized pressure amplifications and reflections at pore boundaries cause heterogeneities across the shock front averaged shock wave parameters were determined. Additionally, we use tracer particles to record the peak shock pressures in the sample.

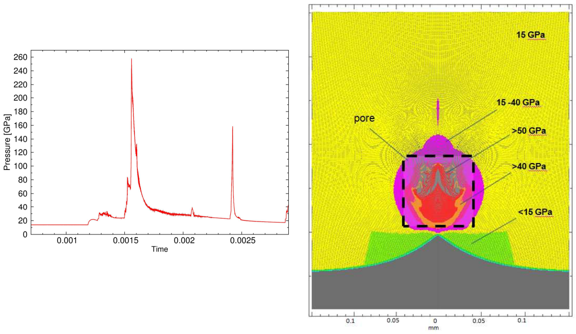

Fig. 2: Right: Peak pressure distribution after the collapse of a single pore. Left: Max. pressure as a function of time in the immediate vicinity of the pore. The initial shock pressure corresponds to 15 GPa.

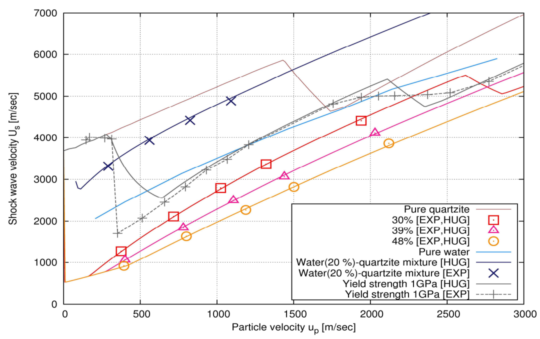

Fig. 3: Hugoniot curves in u_p-*U*-space. Note distinction between meso-scale models (EXP) and macroscopic porous compaction models (HUG), different yield strengths (0, 1GPa), porosities and water saturation.

Results: The high pressure during shock wave compression results in crushing of the porosity in the sample. The crushing of pore space is an effective mechanism for absorbing shock wave energy resulting in a faster attenuation of the pressure amplitude.

(1) Our detailed meso-scale models of the closure of a single pore shows that despite an overall decrease of the shock pressure localized amplification of shock pressure occur in the vicinity of the pore [compare 11] (Fig. 2). Depending on the initial shock pressure the pore is either closed by "shrinking" or "jetting" [18] whereas the latter causes stronger localized pressure amplification. The amplification of the shock pressure decreases with the number of pores due to interferences and reflections of the shock wave.

(2) Comparing meso-scale models with a large number of pores (~500) with the macroscopic porous compaction model led to a very good agreement for different porosities as can be seen in Fig. 3 showing hugoniot curves in the u_p–*U*-space. A similar good match was achieved when comparing other thermodynamic state parameters as pressure, density and internal energy.

(3) We also investigated the effect of crushing strength. Under hydrodynamic conditions the pores compact almost immediately at relatively small shock pressure. If we apply a constant yield strength $Y=1GPa$ to the matrix, the onset of plastic deformation and thus crushing of pores is shifted towards higher particle velocities (pressures) (Fig. 3). In the macroscopic ε-α compaction model the crushing of pore space starts if the volumetric strain exceeds the elastic threshold value ε_e. By adapting the macroscopic parameter we achieved a good agreement between macro- and mesosopic models; however, the transition from elastic to plastic regime is much smoother in the macro-scale model and deviates slightly from the meso-scale experiments.

(4) Meso-scale modeling of water-saturated pores shows that shock waves travel significantly faster and pores are only slightly compacted compared to empty pores (Fig. 3). Meso-scale models and hugoniot curves for water-quartzite mixtures are in good agreement derived by assuming a thermodynamic equilibrium between the water and the quartzite phase [7].

Discussion: We demonstrate that meso-scale modeling of pore collapse due to shock compression is an appropriate tool to develop and validate macroscopic models. Meso-scale models enable to determine the macroscopic parameters required to describe the crushing behavior in the ε-α model. The usage of an adapted ANEOS for a water-quartzite mixture [7] seemed to be a good approximation under the constraint that crushing of pore space is negligible. This assumption may not hold for very high shock pressures in the vicinity of the crater where water may escape and pores are fully crushed. Further work is required to develop an appropriate macro-scale model that can be used to simulate the MEMIN experiments.

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