REVISION OF EXISTING SHOCK CLASSIFICATIONS FOR QUARTZOSE ROCKS USING LOW SHOCK PRESSURE RECOVERY EXPERIMENTS (2.5-20 GPa) AND MESOSCALE MODELS.

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Introduction: The classification of shocked rocks is based on a progressive sequence of unequivocal effects of shock metamorphism observed in nature and (with the exception of the formation of high-pressure phases) also in shock experiments [1]. For quartzose rocks with different porosities two different classification schemes are in use: (1) for quartzo-feldspathic rocks without or very low porosity, and (2) for porous sandstone [1]. Whereas (1) is calibrated on shock experiments with single crystals of quartz and feldspar, (2) uses observations on naturally shocked Coconino sandstone (porosity Φ ~24 vol.%), and the differences between the Hugoniot curves of Coconino sandstone and single-crystal quartz for calibration [1-4]. There is a serious lack of diagnostic shock features for quartz in the low shock-pressure range. Nevertheless, most of the impacted target material is only weakly shocked, especially in the case of eroded remnants of impact structures or in small craters. In this project we investigate shock deformation experimentally generated in dry and water-saturated porous sandstone, and for comparison in dense quartzite, at pressures between 2.5 and 20 GPa - aiming at improving the existing shock classification schemes. The *laboratory impact experiments* were accompanied by *meso-scale numerical modeling* in order to quantify processes beyond optical and electron-optical observational capabilities. These studies are part of the "MEMIN" (Multidisciplinary Experimental and Modeling Impact crater research Network) research unit [5].

Methods: *Shock recovery experiments* [6-7] were conducted in the pressure range from 2.5 to 20 GPa with nearly completely water-saturated and dry Seeberger sandstone (layer 3 [L3]: porosity Φ:~25-30 vol.%), dry Seeberger sandstone (layer 5 [L5]: Φ:~17 vol.%), and for comparison with a dense quartzite (Φ: <1 vol.%). The experiments were carried out with a high-explosive driven flyer plate set-up generating a plane shock wave propagating into the sample [8]. To avoid multiple reflections of the shock wave within the sample material and to reach the desired pressures of 2.5 to 20 GPa, the impedance method was used [8]. For analysis (optical microscopy, SEM, EPMA and Raman spectroscopy) doubly polished thin sections were prepared - perpendicular to the bedding of targets and the propagation direction of the shock wave.

Numerical models: To simulate shock-wave propagation, the multi-material, multi-rheology hydrocode iSALE [9] coupled with the ANEOS for quartzite [10] and a virtual experimental set-up similar to that used in the actual experiments was used. A quantification of shock-pressure amplification due to pore collapse was simulated [11].

Results: Both the experiments and the numerical models show for both dry sandstones crushing of pore space resulting in complete closure of pores as the immediate response to shock loading, already at low initial pressures (2.5 GPa and <6 GPa).

Regarding fracture formation (all kinds of micro-fractures, mainly irregular), both dry sandstones behave similar; and the water-saturated sandstone behaves like the quartzite (Fig. 1). In dry sandstones the total number of fractures is higher at comparatively lower shock pressures and their saturation level is reached at relatively lower pressures – compared to the water-saturated sandstone. After saturation is reached, the number of fractures decreases distinctly. In contrast, the dense quartzite does not reach such a point of saturation until 17.5 GPa (experimental limit).

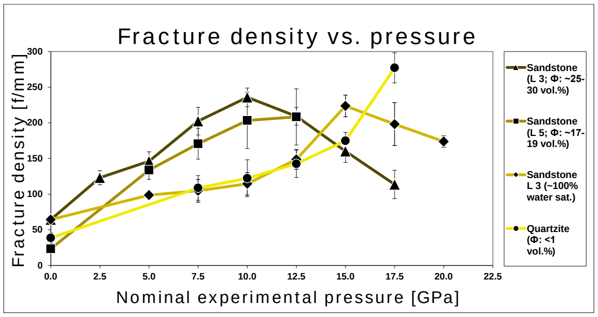

Fig. 1. Fracture density results for the four experimental series.

Planar deformation features (PDF) in quartz could not be observed in the quartzite up to 17.5 GPa (experimental limit), in the dry sandstone samples (L3 and L5) up to 12.5 GPa, and in the water-saturated sandstone up to 20 GPa (experimental limit).

Diaplectic quartz glass/SiO_2 melt (undifferentiated) were identified by BSE-SEM image analysis, whereby molten or glassy areas appear darker than the adjacent crystalline quartz, corresponding to their reduced density [12] due to amorphisation. In the most porous target (L3), glass/melt formation starts already at 5 GPa (Fig. 2) but increases distinctly to over 20 vol.% between 12.5 and 15 GPa, and reaches ~80 vol.% at 17.5 GPa. The less porous sandstone (L5) shows onset of glass/melt formation at comparatively higher pressure, and a comparatively lower amount (2.6 vol.% at 12.5 GPa) is produced than in L3. In general, the glassy/molten areas are distributed heterogeneously; they rarely occur at low pressures, preferentially in zones of preexisting pores, but increase distinctly in frequency and extent at higher pressures. The water-saturated sandstone displays at 20 GPa little glass/melt development attaining merely ~1 vol.%. The dense quartzite does not show any glass/melt formation up to 17.5 GPa (exp. limit).

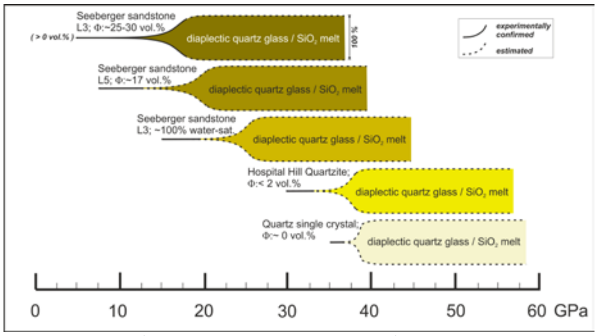

Fig. 2. Onset of diaplectic glass/SiO_2 melt formation based on our four experimental series (brown shades), data for quartzite [13], and for quartz single crystals [8]. Please note the different slopes (left).

The *meso-scale numerical models* show - despite the overall decrease of shock pressure during shock wave propagation through the porous material - localized amplification of shock pressure during pore collapse [7, 11]. 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. The much higher pressures can be observed in the zone where a pore was initially located but pressure amplification also affects surrounding areas [7]. The quantification of shock amplification due to pore-space collapse as determined by modeling is in good agreement with observations from our shock experiments with dry sandstone L3 [7]. Further studies (L5, wet L3 and quartzite) are in progress.

Discussion: The experiments clearly show that the shock compression of porous sandstone results in a distinctly different sequence of shock deformation as seen for non-porous rocks, especially at low shock pressures. Therefore, as already applied in the past [1], different shock classification schemes are necessary.

(1) For *non-porous quartzose-feldspathic rocks* the classification scheme of [1] is well suitable. Nevertheless, our experiments with quartzite and data of [13] show two problematic ranges for pressure calibration. The onset of PDF formation in polycrystalline rocks seems to be higher than in quartz single crystals, and occurs at 17.5-20 GPa. The formation of diaplectic quartz glass starts, in comparison to single quartz crystals, already at lower pressures (~30 GPa) and is complete at ~35 GPa.

(2) For *porous quartzose rocks* the following sequence of shock features is observed: i. crushing of pores; ii. intense fracturing of quartz grains (lacking PDF); and iii. increasing formation of diaplectic glass/SiO_2 melt replacing fracturing. Based on the existing shock classification scheme of [1-4] the experimentally shocked samples of L3 and L5 belong to shock stages 1b (L3 up to 12.5 GPa) and 2-4 (L3 above 12.5 GPa). The formation of diaplectic glass/SiO_2 melt together with SiO_2 high-pressure phases (normally not observed in experiments due to the short pressure pulse duration) is in porous samples a continuous exponential process that could only problematic classified into shock stages. Therefore, the existing shock classification scheme for porous quartzose rocks [1] needs to be revised for shock stages 2 to 5 that avoid for practicability also the given garbled amounts of diaplectic glass, SiO_2 high-pressure phases and melt (in wt.%) based on X-ray studies [2]. We propose for shock stage 2 a minimum amount of 2 vol.% diaplectic glass, SiO_2 melt or high-pressure phases, which should be easily detected in thin section. Shock stages 3 and 4 should be recognized by minimum amounts of 20 and 80 vol.% diaplectic glass, SiO_2 melt or high-pressure phases, respectively. The highest shock stage 5 should be characterized by a completely pumiceous texture of vesicular leachatelierite in accordance with [1-4]. The calibration of these shock stages will depend on the individual porosity of the target before shock loading.

(3) For *water-saturated quartzose rocks* in the pressure range up to 20 GPa (experimental limit) a cataclastic texture (microbreccia) may be typical. This microbreccia does not show formation of PDF up to 20 GPa but a maximum of diaplectic glass/SiO_2 melt formation of ~1 vol.% at 20 GPa.

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