DEVELOPMENT OF FRACTURES, MELT AND LOCAL SHOCK EFFECTS ON SHOCK RECOVERY EXPERIMENTS AT LOW SHOCK PRESSURES WITH DRY SEEBERGER SANDSTONE. A. Kowitz[1], R. T. Schmitt[1], W. U. Reimold[1], and U. Hornemann[2], [1]Museum für Naturkunde, Leibniz Institute at Humboldt University Berlin, Invalidenstrasse 43, 10115 Berlin, Germany, e-mail: astrid.kowitz@mfn-berlin.de, [2]Ernst-Mach-Institut, Am Klingelberg 1, 79588 Efringen-Kirchen, Germany.

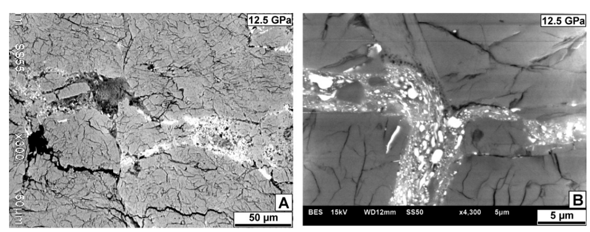
Introduction: Within the MEMIN (**M**ultidisciplinary **E**xperimental and **M**odelling **I**mpact Research **N**etwork) program this sub-project investigates shock effects in experimentally shocked quartz at low shock pressure (2.5 - 17.5 GPa) where diagnostic shock features and calibration data are lacking at the moment. Also, the influence of porosity on progressive shock metamorphism is investigated.

Experiments: Shock recovery experiments were carried out with cylinders (Ø 1.5 cm, length 2 cm) of dry Seeberger sandstone (layer 5) with a grain size of 0.17-0.01 mm and a porosity of ~18 vol.%. The sandstone mainly consists of quartz (96 vol.%) and phyllosilicate minerals (12 vol.%). Accessory minerals are altered ilmenite, biotite, sphene, rutile, limonite, zircon, and pyrite. This sample material is identical to that used in the MEMIN feasibility study [1]. The shock recovery experiments were carried out at the Ernst-Mach-Institute in Freiburg with a high-explosive driven flyer plate set-up generating a plane shock wave [2]. To avoid multiple reflections of the shock wave within the sample material and to reach the desired pressures of 5, 7.5, 10 and 12.5 GPa the impedance method [2] was used. At this time only incomplete Hugoniot data for Seeberger sandstone are available, so that Hugoniot data for Coconino sandstone [3] were applied instead. This suggests an error of ~1-2 GPa in shock pressure determination. Estimations of the shock wave travel time [2] indicate that the shock wave does not reach the bottom of the sandstone cylinder. In contrast, the microscopic observations show that the entire sandstone cylinders are shock deformed.

Results: At the microscopic scale the shocked Seeberger sandstone shows a near-complete closure of pore space at all pressures (5, 7.5, 10, 12.5 GPa). Quartz grains of the unshocked sample show sharp and rarely undulatory extinction, whereas the shocked samples display quartz grains with mainly undulatory extinction at 5 GPa and weak mosaicism at 7.5, 10 and 12.5 GPa. At low pressure (5 GPa) quartz grains usually display only one set of roughly subplanar fractures, which are orientated at ~0°, ~30° or ~45° in relation to the shock front. At pressures of 7.5, 10 and 12.5 GPa additional quartz grains with two or more sets of subplanar fractures could be observed. Within these grains the larger fractures are orientated at ~45° and the shorter ones at ~10° to the shock front. The spacing of the subplanar fractures shows a great variability from <10 to 60 µm.

More detailed SEM studies have shown obliteration of original grain boundaries and intense intragranular fracturing (irregular as well as subplanar) in all shocked samples. On the one hand, there are two generations of microfractures where the first and shorter one is orientated at ~45° and the second, larger one is oriented at ~80° to the shock front and displaces the first one. On the other hand, there are a lot of short, irregular, vermicular fractures, which form a complex fracture network and, e.g., have also been described by [4] in experimentally shocked Hospital Hill Quartzite at 8 GPa. The total fracture density of the quartz grains increases from, on average, 134/mm at 5 GPa, 171/mm at 7.5 GPa, to 203/mm at 10 GPa and 208/mm at 12.5 GPa and remains a at ± constant level at pressures of 10 GPa and above.

Microprobe and SEM images show that residual pores and fractures are filled with variably dark or light (SEM-BSE) Al-Fe-Mg-rich, vesicular melt, which is most likely generated by melting of phyllosilicates. The relatively lighter melt contains more Fe-particles probably derived from melting of ilmenite, limonite or pyrite. Both kinds of melt typically show flow textures (Fig. 1A). Also melt with large Fe-particles (from molten ilmenite, limonite or pyrite, Fig. 1B) and from molten ARMCO iron of the impedance cylinder that was injected into fractures (Fig. 1C) have been observed in the 10 and 12.5 GPa samples. The amount of the entire melt increases from ~1.6 vol.% at 5 GPa over ~2.4 vol.% at 7.5 GPa to ~4.8 vol.% at 10 GPa and 12.5 GPa.



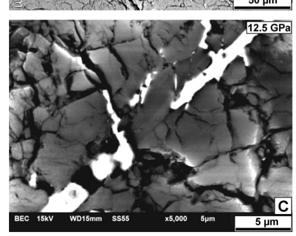


Fig. 1. SEM images (BSE) of Seeberger sandstone shocked at 12.5 GPa: **A.** Dark and light vesicular melt mainly based on phyllosilicates. **B.** Al-Fe-Mg-rich melt with large Fe-particles. **C.** Injections of molten ARMCO iron into fractures.

The samples shocked at 10 and 12.5 GPa display isotropic areas at the upper surface of the sandstone cylinder, which are only locally visible in the optical microscope (Fig. 2A). In SEM images these areas appear homogeneous without fractures (Fig. 2B), and are composed of SiO_2. Raman analysis (Fig. 2A, 2C) indicates in these zones a transition from diaplectic quartz glass at the surface of the sample cylinder to deformed crystalline quartz with increasing distance from the surface.

Additionally, the sandstone cylinders shocked at 7.5, 10 and 12.5 GPa display large, slightly curved intergranular fractures starting at the upper edges of the sample cylinder with the surrounding ARMCO iron trap, spreading diagonally through the sample and converging in the center of the sample. They show displacement of material and are therefore interpreted as shear zones. Within these shear zones cataclastic microbreccia, SiO_2 melt with flow texture (Fig. 2D) and diaplectic quartz glass occur. Sets of subplanar, slightly curved microfractures (spacing ~1-2 µm, Fig. 2E) with strong similarity to planar deformation features (PDF) in quartz grains are also associated with these large shear zones and appear sporadically at the starting points of the shear zones near to the upper edge of the sandstone cylinder.

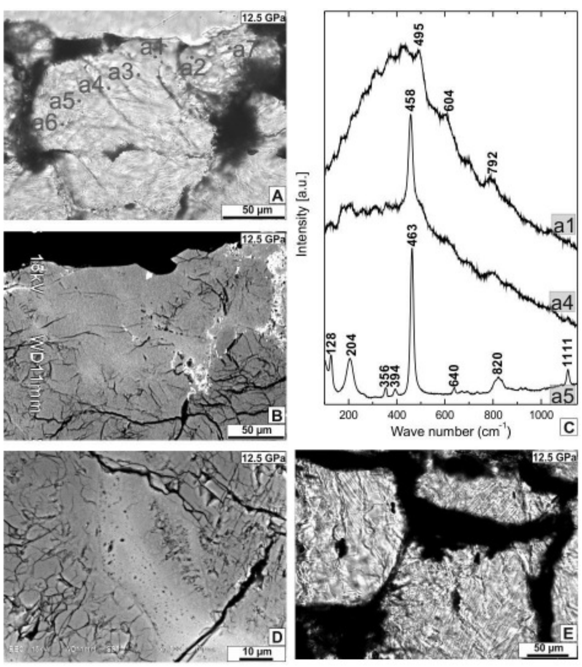


Fig. 2. Local shock features in the Seebeger sandstone shocked at 12.5 GPa. **A.** Transition of diaplectic glass to quartz in a single grain (plane polarized light) with points of Raman measurements (C). **B.** SEM image (BSE) of the identical area (A) with diaplectic quartz-glass (homogeneous zone without fractures) at the upper sample surface. **C.** Raman spectra of crystalline quartz (a5), shocked quartz (a4) and diaplectic quartz glass (a1) demonstrating the transition from diaplectic quartz glass to crystalline quartz with increasing distance from the upper sample surface. **D.** SEM image (BSE) of SiO_2 melt with flow texture containing elongated vesicles and cataclastic microbreccia along a large shear zone. **E.** Subplanar microfeatures with strong similarities to PDF at the starting point of a large shear zone near to the upper edge of the sandstone cylinder (plane polarized light).

Discussion: These shock experiments with dry Seeberger sandstone have produced shock features in quartz (e.g., closure of pore space, subplanar fractures) as known from naturally shocked porous sandstone and shock experiments with quartz single crystals and quarzites at low shock pressures, e.g., [2, 4-6]. Based on the shock classification system for porous sandstone [5-7], the experimentally shocked samples belong to shock stages 1b (5 GPa) and 2 (7.5, 10, 12.5 GPa). For these shock stages average shock pressures of ~3 - ~5.5 GPa and ~5.5 – 13 GPa, respectively, were estimated by [5-7] based on shocked Coconino sandstone and the differences between the Hugoniot curves of Coconino sandstone and single-crystal quartz. The shock experiment at 5 GPa shows a near-complete closure of pore space, which is the basic criteria for shock stage 1b [5-7], and confirms therefore the pressure calibration at this point. Nevertheless, the common occurrence of PDF and up to 10 vol.% of quartz glass, and small amounts of high-pressure phases, observed in shock stage 2 samples of Coconino sandstone [5, 6] could not be observed in these shock experiments at 7.5, 10 and 12.5 GPa. The formation of PDF, diaplectic quartz glass and SiO_2 melt in these experiments is a local effect associated with shear zones or the contact to ARMCO iron of the container material. This discrepancy between the shock experiments and the naturally shocked Coconino sandstone samples might be a general effect due to the differences in pressure pulse duration and post-shock temperature between experiment and nature. Nevertheless, a recalibration of the shock classification system for porous sandstone might be necessary based on supplementary shock experiments with sandstone.

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