LOCALIZED SHOCK-INDUCED MELTING OF SANDSTONE AT LOW IMPACT PRESSURES (<17.5 GPa): AN EXPERIMENTAL STUDY.

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Introduction: Intense shock pressures are highly localized phenomena during a meteorite impact, whereas low shock pressures affect a comparatively large fraction of the target material [1]. A series of shock recovery experiments (as part of the impact research group MEMIN) have been performed to investigate the shock deformation of sandstones in this low shock pressure regime, with peak pressures achieved between 2.5 and 17.5 GPa. The current presentation is focused on the formation of silica-rich and metallic melts during these experiments.

Experimental setup: The shock recovery experiments were carried out with a high-explosive setup generating a plane shock wave, and using the shock impedance method. A porous (porosity 23±1 vol.%,) sandstone that is composed of ~89 wt.% quartz (Qtz), ~10 wt.% phyllosilicate minerals (kaolinite - Kln, two types of illite - Ill, and muscovite - Ms), and traces of rutile, zircon, pyrite and iron oxides/hydroxides were cut into cylinders (15 mm diameter, 20 mm length) and experimentally shock-deformed. Chemical compositions of the produced melts were analyzed by field-emission EMPA, SEM, and TEM. TEM was also used for the search for possible quartz polymorphs (see companion abstract by [2])

Results: The sandstone shocked at 2.5 and 5 GPa is mainly characterized by pore closure, fracturing of Qtz and compression and deformation of phyllosilicate minerals; no melting was observed. Five different types of melts were generated in situ around pores and alongside of fractures in the sandstone samples shocked to higher pressures: (1) The first type of silicate melt is highly vesicular and occurs as small melt pockets (Fig. 1). In backscattered electron (BSE) images it is much darker than the surrounding quartz. It shows foamy and/or flow texture with schlieren. The average composition is dominated by Al_2O_3 and SiO_2, which favors Kln as precursor. The foamy texture indicates that the hydrous Kln lost its structural water as vapor during the shock process. This dark melt was formed in all shock experiments above 7.5 GPa, whereby the melt proportion increases with increasing shock pressure. (2) The second type of melts is identical in appearance to the first one but chemical compositions indicate that these melts were formed due to melting of two different types of Ill (i.e., a high K_2O, low FeO, and a high FeO, low K_2O variety) and/or Ms. The FeO content of this melt type is typically higher than the Kln-based melt and results in a comparatively lighter color in BSE images. Melting of Ill starts at 7.5 GPa, that of Ms not until 15 GPa (Fig. 2). The abundance of this melt type increases with increasing pressure, as well. At 15 and 17.5 GPa chemical mixing of all phyllosilicate-based melts with silica melt could be observed. (3) The third type of melt, which occurs at shock pressures above 7.5 GPa, has similar chemical compositions to types (1) and (2), except for higher FeO contents, and contains conspicuous iron melt droplets of 0.5-2 µm size. (4) The fourth type of melt represents iron injected from the ARMCO iron driver plate into fractures initiated at the surface of samples shocked to 10 GPa or higher (Fig. 3). (5) The fifth melt type of pure SiO_2 composition is located in short and narrow (5-30 µm length, <3 µm width) elongated bands within quartz grains (Fig. 4). The bands contain tiny crystals (<<0.5 µm) of the SiO_2 high-pressure polymorph stishovite (Stv), as determined by TEM [2]. This SiO_2 melt with Stv develops at pressures (p) between 7.5 and 15, most significantly at 12.5 GPa.

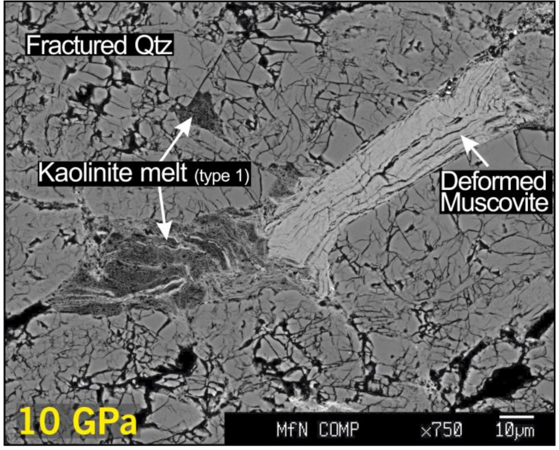

Fig. 1 BSE image of shocked sandstone. Melting of kaolinite; muscovite is only deformed (kink banded).

Discussion: The total combined amount of melt types 1-4 increases drastically with increasing shock pressure from 1.6 % at 7.5 GPa to ~14 % at 17.5 GPa. The amount of silicate melt depends on the type of phyllosilicate minerals that occur in the sandstone matrix. The higher the amount of water in these minerals (H_2O contents in the phyllosilicate minerals: Kln ~14 wt.%, Ill ~6-10 wt.%, Ms ~4 wt.%), the lower the shock pressure required to induce silicate melting. As the chemical composition of the produced silicate melts of types 1-3 is similar to that of the original minerals (except for the lost structural H_2O), we assume congruent melting of the phyllosilicates occurred. This is in distinct contrast to normal geological settings where melting of phyllosilicates is linked to thermal decomposition and dehydration (incongruent melting). The totals of EMPA analyses of melts are 99.5 ± 1wt.% - indicating that the silicate melts were completely dry. Previously, [3] and [4] observed incomplete melting of muscovite and biotite in experimentally shocked, non-porous gneisses p > 25-30 GPa, and complete melting at p > 70 GPa. Our study has demonstrated that Ms in the porous sandstone already melts at 15 GPa. Pore collapse of the sandstone during shock wave propagation leads to up to a four times amplification of the initial shock pressure, as recently shown by [5]; this explains the dramatic shift to lower P required for melting. Injection of metallic projectile melt into silicate target-derived melts, as described above, is also a common feature noted for several smaller craters (e.g., Wabar [6], Kamil [7], Meteor crater [8]) and known from previous MEMIN work [9]. During this process Fe of the metal melt is incorporated into the silicate target melts as FeO. In some cases the strong Fe enrichment induced a phase separation process of Si-rich and Fe-rich melts. This kind of liquid immiscibility is observable as emulsion textures in the mentioned impact melts, and was noted in this study, as well. Furthermore, the flow structure (Fig. 4) and the amorphous state [2] of the shear band indicate that shock and shearing within the impacted quartz produce a high temperature SiO_2 melt, from which the high-pressure phase Stv can nucleate. This observation supports the hypothesis for Stv formation by [10]. The author favored crystallization of Stv from SiO_2 melt during impact due to the fact that this process is much faster than a reconstructive solid-state transformation.

Conclusion: This study has demonstrated that phyllosilicates of shocked sandstone underwent congruent melting during the shock process. Chemical composition of the shock-induced melts can be used to identify the phyllosilicate precursor. Furthermore, we demonstrate that shock plus local shear heating at low pressures results in the formation of silica melt that nucleated stishovite.

References: [1] French B. (1996) LPI Co 954. [2] Langenhorst F. et al. (2015) *LPS XLVI,* Abstract, this volume. [3] Lambert P. and Lange M. A. (1984) *J. Non-Cryst. So., 67,* 521–542. [4] Lambert P. and Mackinnon I. D. R. (1984) *JGR Solid Earth 89, B685–B699*. [5] Kowitz A. et al. (2013) *EPSL* 384, 17–26. [6] Hamann C. et al. (2014) *GCA* 121, 291–310 [7] Fazio A. (2014) *MAPS, 49,* 2175–2200. [8] Hamann C. et al. (2014) *77th MetSoc*, #5222. [9] Ebert et al. (2014) *GCA 133*, 257-279. [10] Langenhorst F. (1994) *EPSL, 128*, 683–698.

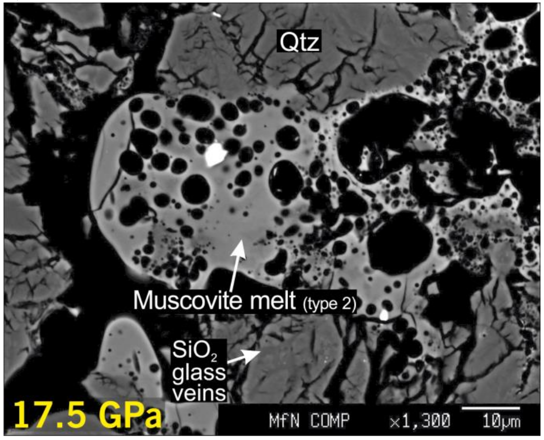

Fig. 2 BSE image of highly vesicular Ms melt.

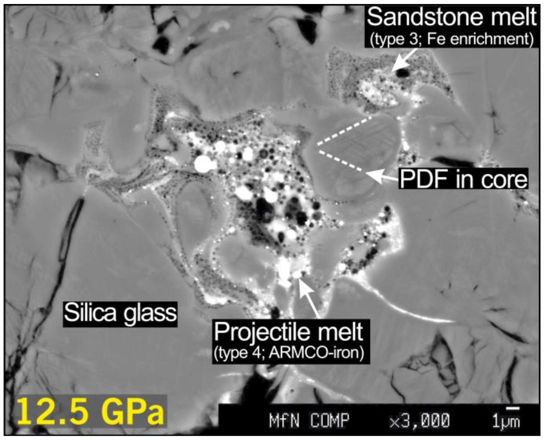

Fig. 3 Injected ARMCO iron melt droplets into silicate melt of shocked sandstone (BSE image).

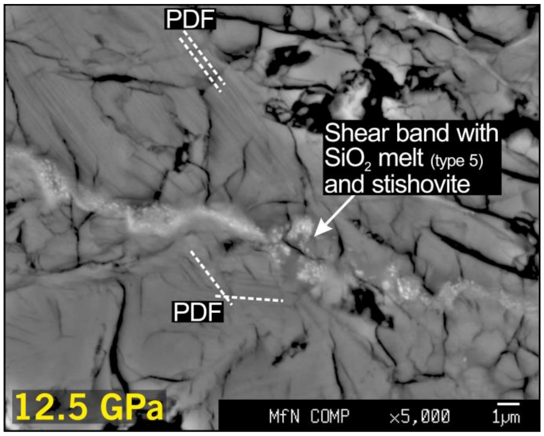

Fig. 4 Shear band within quartz consisting of pure SiO_2 melt and containing stishovite crystallites (light grey). Note the PDF in the vicinity of the shear band indicative of locally enhanced shock pressure.