MELT FORMATION ON SHATTER CONE SURFACES RECOVERED FROM THE MEMIN HYPERVELOCITY IMPACT EXPERIMENTS IN SANDSTONE.

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Introduction: Shatter cones are widely considered as an "index fossil of astroblemes" [1] and their presence is diagnostic for the discovery and verification of impact craters [2, 3]. They are the only macroscopic feature considered as evidence for shock metamorphism and can unambiguously be identified in the field based on their distinct morphology; namely their conical and curved fracture surfaces, with superimposed striae, and the hierarchical bifurcation. However, the precise formation mechanism of shatter cones is spotlighted in recent discussions and still not fully understood. Most authors align the formation of shatter cones with the passage of the shock front or the release from shock loading (e.g. [4-7]). Several reports of melt films on shatter cone surfaces might further impede our understanding of shatter cone formation [8, 9], and may allow to constrain pressure-temperature-time conditions during or immediately after shatter cone formation. **The aim** of this study is to narrow closer the latter parameters, by investigating silicate melt films formed on shatter cones produced under controlled impact conditions. These cratering experiments were performed in the context of the Multidisciplinary Experimental and Modeling Impact Research Network (MEMIN).

Materials and Methods: A series of hypervelocity impact experiments was performed using two-stage light-gas guns at the Fraunhofer Ernst-Mach Institute for High-Speed Dynamics in Freiburg. We thoroughly examined the MEMIN hypervelocity cratering experiments by handpicking of the ejecta and soft stimulated fracturation of the crater subsurface in the search for slightly curved or conical and striated fracture surfaces. A detailed 3D model and a morphometric analysis of each potential shatter cone fragment was carried out with white-light interferometry (WLI). The thin melt films on the fracture surfaces of the recovered fragments, were analysed in detail with scanning electron microscopy (SEM) data, performed with a Zeiss Leo 1525 field-emission SEM at the ALU Freiburg and a JEOL JSM-6610LV SEM at the MfN Berlin.

Results: So far we recovered 23 mm-sized fragments from the ejecta of the hypervelocity experiments, with conical to hyperboloid geometries and fine striae diverging from an apex point. Those fragments, fulfilling the morphological criteria of shatter cones, were found in experiments with 20 to 80 cm sized target cubes of sandstone, quartzite and limestone impacted with 2.5 to 12 mm sized aluminum, steel and iron meteorite projectiles and impact velocities ranging from 4.6 to 7.8 km/s. So far in experiments with impact velocities below 4.6 km/s no shatter cones have been found. In this study, we present shatter cone fragments recovered from experiments with a 5 mm aluminum projectile shot onto dry sandstone at 4.59 km/s, and a 12 mm Campo del Cielo iron meteorite shot onto water-saturated sandstone at 4.95 km/s.

Surface Characteristics and melt textures: The 3D scans with µm-accuracy display morphologies coherent with shatter cones from terrestrial impact craters which were analysed as well (e.g. Steinheim, Germany; Siljan, Sweden; Rochechouart, France; and Haughton, Canada). In addition, the striated fracture surfaces of the experimental shatter cone fragments from the sandstone experiments are typically covered with a 1 to 10 µm thin film of melt-textured material; very different from the fractured and crushed sandstone underneath. The fragments revealed a variety of melt textures: (i) a very vesicle-rich film of melt splats and splashes, a (ii) "frothy", reticulate film with melt smears and fibers, which alternates with (iii) smooth, almost polished surfaces marked by very fine melt striations. We also observed scattered microspherules firmly attached to the surface or trapped in vesicles.

Melt composition: The three melts described above differ markedly in composition. The SiO_2-rich melt is not a pure quartz melt, as indicated by the presence of, on average, ~2 wt.% Al_2O_3 and TiO_2. Compared to the bulk sandstone prior to impact, it is slightly enriched in Ti, which is likely caused by additional melting of, and mixing with, accessory rutile. The vesicle-rich, TiO_2-Al_2O_3-rich melt is primarily a mixture of phyllosilicates and accessory rutile, which must have incorporated limited amounts of the SiO_2-rich melt and/or a pure quartz melt (lechatelierite). The frothy, reticulate melt closely mimics the composition of phyllosilicate minerals present in the target. However, compared to the phyllosilicates prior to impact, this melt is also slightly enriched in Ti, closely following a mixing trend with rutile. Hence, limited mixing with either a pure rutile and/or the TiO_2-Al_2O_3-rich melt is indicated.

Discussion: Melting and mixing of quartz, phyllosilicates, and rutile requires high post-shock temperatures in excess of 1842 °C (melting point of rutile at ambient pressure), localized in the narrow µm-thick melt film along the shatter cone surface as proposed by [8] and [10]. We think the fine striae to be shear-attributed and probably experienced frictional heating; whereas the vesicular melt films we observed probably formed at strain releasing steps, advocating for an additional extensional component in the process of shatter cone formation. Due to the formation of melt films formed along the shatter cone surface by a combination of frictional heating and shock, locally inducing fast decompression and post-shock temperatures in excess of ~1850 °C, respectively, we suggest shatter cones to be mixed mode I/II fractures.

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