NEW LABORATORY AND FIELD STUDIES ON SHATTER CONES.

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Introduction: Shatter cones (SC) were first described in 1905 from the Steinheim impact basin, southern Germany [1]. Generally, SC are considered to be characterized by a conical morphology, although this may actually vary between curvilinear surfaces and strictly conical geometries. They display striations that originate and diverge from an apex or an apical area. SC invariably show a positive and negative imprint of their morphologic features. Striations and whole SC never crosscut one another; however, both can originate from each other [2]. For the inexperienced observer it might be challenging to distinguish SC from other geological features resembling them [3]. Natural exhibits from a few mm to 12 m in size have been observed [2], and mm sized SC have been generated in experiments [4].

SC represent the only known meso- to macroscopic recognition criterion for meteorite impact structures [5]. The processes involved in their formation are not entirely understood; however, all current hypotheses agree that they form when a shock wave encounters a heterogeneity and is scattered, reflected, and/or refracted [6]. It is, however, not yet understood how the shock wave interacts whith heterogeneities, or upon what the variations in size and orientation of SC depend. The shock waves required to form SC are of a magnitude only occurring during meteorite impacts or upon brisant man-made explosions [7]. It has been estimated that SC formation requires shock pressures between 2 and 30 [5], possibly up to 45 GPa. Melt and minor displacements of less than 0.25 mm have been observed on SC surfaces, and on related multiplistriated joint surfaces [8].

Investigations of orientation, distribution, and shock micro-deformation of shatter cones were undertaken with micro-Computed Tomography and polarizing microscopy in the laboratory, and in the field at the Keurusselkä impact structure (Finland).

Methods and Results: For the first time *Micro-Computed Tomography (µCT)* investigations of SC have been conducted on a sandstone sample from the Serra da Cangalha (SdC) impact structure (Brazil) [9]. This specimen contained differently oriented SC, and the analytics were done to examine the inherent microfracture pattern in a SC. The sample from SdC is 65x16x15 mm in size. The sample from the Haughton impact structure (Canada) displaying a very well developed SC in dolostone was investigated. Both samples were scanned with a Phoenix X-ray Nanotem at the MfN in Berlin. Three-dimensional volumes with a Voxel (the 3D equivalent of a 2D Pixel) size of 13 µm were obtained for the SdC specimen. The sandstone sample was then cut into 47 thin sections oriented parallel to the three axes (x, y and z) of an arbitrary orthogonal coordinate system and investigated with polarizing light microscopy to gain a better understanding of the shock micro-deformation. The results of both techniques were compared. Additional scans of a quarzitic SC sample from the Vredefort impact structure (South Africa) and a SC in gneiss from the Santa Fe impact structure (USA, courtesy of Elmar Buchner, Neu-Ulm) were undertaken at the LMU in Munich. High resolution scans were gained on several mm sized splits.

Even though 3D volumes with high resolution were obtained by µCT scanning, the scans are lacking optimum contrast and were interspersed with artefacts. The scans from the second scanning campaign at the LMU showed the same problems as encountered during the first attempts at MfN. The quality of the scans was insufficient for the investigation of microfracture patterns.

In contrast, we were able to study the microfracture pattern in thin section and also to observe (shock) micro-deformation features in the form of planar deformation features (PDF), planar fractures (PF), and feather features (FF) [10], along with recurring sets of subplanar to curviplanar fractures. These occurences allowed us to narrow down the timing of the formation of SC with respect to the shock wave passage.

Feather Features are defined as a combination of a PF and narrow (2 to 10 µm) spaced microfractures that initially were described to branch off only to one side of the PF [10]. Whether they are a diagnostic feature for shock deformation is still under discussion; however, they have never been reported from tectonically deformed specimens to date. Here, several types of previously undescribed FF were identified. FF as described by [10] are common in the sample. Additionally, FF with microfractures emanating from a curved and from a curviplanar fracture were observed. A FF, showing lamellae emanating from both sides of the PF, was also found for the first time here. FF and PDF that are displaced by a SC fracture surface were observed. Additionally, FF show microfractures that are seemingly not attached to the PF they originate from and others that are bifurcating were also detected. The formation mechanisms for FF are still investigated. Apart from shearing being obviously involved; bifurcation processes may play a role.

Timing of SC formation: Our new observations pertaining to the timing of the formation of shock micro-deformation within SC involve: SC form post- or syngenetic with PF, FF, and subplanar fractures. They also form before or simultaneously with PDF. PDF form prior to FF microfractures because the latter may overprint PDF. According to these observations, the earliest possible timing for SC formation is at the late compressional stage of shock wave passage.

The Keurusselkä Impact Structure is situated in south-central Finland within the Central Finland Granitoid Complex that formed during the Fennoscandian orogeny approximately 1880 Ma ago [11]. A possible age of the impact was postulated by [12, 13] at about 1140 Ma. Country rocks at Keurusselkä include meta-granites/-granodiorites and amphibolitic gneisses. Due to extensive erosion the crater topography is not preserved. The impact structure was discovered by [14] through SC findings and later confirmed by [15] through the observation of microscopic shock features. Though the structure's size was estimated at 30 km by [14], no definite extent of the Keurusselkä impact structure has been given to date.

Prominent joints occur pervasively in the basement rocks both within and outside the Keurusselkä impact structure. The average spacings within the alleged extent of the impact structure range from cm to dm and are closest near the alleged center. Joint orientation trends show no variation between inside and outside of the alleged confines of the structure. It is, thus, probable that the impact reactivated preexisting joint systems.

SC within the Keurusselkä impact structure are extremely well exposed, especially at shore line locations in the central part of the structure. At such locations, sections of joint surfaces are commonly striated. Considerably more open forms occur rather than conical structures. Joint sets of different orientations combine to form semiconical or even fully conical features (as confirmed by polygonal apical cross sections). Similar observations were made by [8] at the Vredefort structure. SC orientations were measured together with orientations of their corresponding joints. Results include the observation that SC orientations follow those of single joints or fall on the intersection between two joint orientations. These observations suggest that the genesis of joints and SC are closely linked. A possible SC has been observed at Palojärvi situated about 20 km from the structure's center. Should SC really be present at this distance from the proposed craters center, the Keurusselkä impact structure would be much larger than previously thought.

Micropetrographic Analysis: Samples of country rocks and SC were studied in thin section. Shock deformation features, such as PDF, were observed only in SC samples from Jylhänniemi in the centralmost part of the structure. Up to 2 sets of PDF were observed in a single grain. The most widespread crystallographic orientation is $\{10\bar{1}3\}$ with 43% frequency of measured orientations. This result is in line with analysis made by [15]. PDF are observed in SC, but not in country rock. Their preferred occurrence in SC indicates higher shock pressures being present at their genesis location than in the rest of the basement. This could be caused by interference of several shock waves, which might be caused by a scattering of the impact shock wave in SC, as is suggested by [7].

Some samples are cut by fractures coming off SC surfaces. The fractures show widths between 20 and 50 µm and strong dilation (several 100 µm) at the SC surface. The fractures also show displacement of up to 100 µm and are filled with a aphanitic material of dark-brown color. The fracture fill was analysed as an assemblage of two clay mineral phases, which might be the result of alteration – possibly of an original - SC formation related – melt phase.

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