THE HUMMELN STRUCTURE (SWEDEN) – IMPACT ORIGIN CONFIRMED AND ITS LINK TO THE L-CHONDRITE PARENT BODY BREAK-UP EVENT.

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Introduction: The Hummeln structure (57°22'N, 16°15'E) is located in the Småland province, in southern Sweden. It consists of an over 160 m deep and 1.2 km wide depression in the Precambrian crystalline basement, within Lake Hummeln. The origin of the circular depression has puzzled the geological community for nearly 200 years (see below).

Here we report on the analysis of crystalline breccia samples collected at the Hummeln structure, combining optical, scanning (SEM), and transmission electron microscopy (TEM), as well as universal stage (U-stage) investigations. Through the findings of unambiguous shock deformation features, we demonstrate, for the first time, that this structure is an impact crater. This result not only solves an almost 200-year old enigma, but also strengthens the hypothesis that the cratering rate was increased during the Middle Ordovician as a consequence of the L-chondrite parent body (LCPB) break-up event. It is also one of the oldest of the smallest impact craters confirmed on Earth, illustrating that such small craters that are usually expected to be quickly eroded can, under the right circumstances, survive for hundreds of millions of years.

Previous work: First described in 1826 by Hisinger [1], it was then considered to be due to explosive volcanism or related to tectonics [2]. Not until the 1960's, after a detailed mapping of the lake topography, an impact origin was proposed for the structure [3]. Although additional investigations, including the completion of a core-drilling campaign and geophysical investigations of the structure, gave further information in support of the impact hypothesis [4,5], no conclusive evidences for an impact origin (such as shock-deformation in minerals or traces of extraterrestrial matter) were presented. Nevertheless, the drill core (terminated before reaching the bottom of the crater), recovered from the eastern part of the structure, showed that the depression is partially filled with slumped Paleozoic rocks. These Paleozoic rocks occur as a sedimentary breccia and in parts even with overturned sequence. Detailed lithostratigraphic comparisons with preserved coeval sequences at the relatively nearby Baltic island of Öland, as well as acritarch, chitinizoan, and conodont biostratigraphy gave an age of formation of the sedimentary breccia to be roughly coeval with that of the Granby impact structure (located in south central Sweden), i.e., ~467 Ma [4,6,7].

Material and Methods: Twenty-one polished thin sections were prepared from two samples of crystalline breccias. The thin sections were investigated and searched for shock metamorphic features, first using the polarizing microscope, and then using SEM and TEM. All quartz grains displaying planar deformation features (PDFs; Fig. 1) were further investigated using the U-stage microscope.

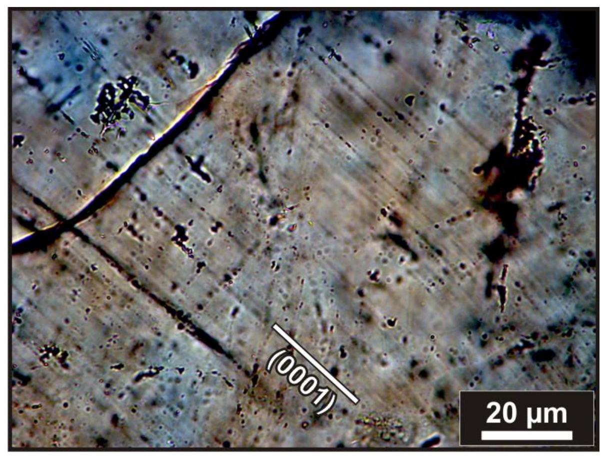

Fig. 1: Photomicrograph (crossed polars) of a quartz grain with one set of decorated PDFs oriented parallel to c(0001) orientation (Hummeln structure sample HUM13_01).

Results: Both investigated samples display angular fragments of foremost granitic composition, embedded in a finely crushed cemented matrix. At macroscopic scale, the clasts vary in size from ~0.5 to 20 cm (smaller clasts are visible under the optical microscope) and are mainly composed of quartz, microcline, and minor amounts of plagioclase and micas. Our optical microscope survey revealed that most of the quartz grains do not exhibit shock features. However, we were able to detect some quartz grains displaying shock metamorphic features in the form of PDFs (Fig. 1). These grains are either part of larger clasts or free grains in the matrix of the breccia samples. Quartz grains with up to three sets of PDFs were identified under the U-stage microscope. As seen under the optical microscope, and further documented using the SEM, the PDFs are decorated with vugs or tiny fluid inclusions (generally less than 2-3 μm in diameter). The TEM observations on a focused ion beam (FIB) foil, cut across a shocked quartz grain, allow us to confirm that the straight and parallel lamellae seen under the optical microscope are really PDFs (Fig. 2).

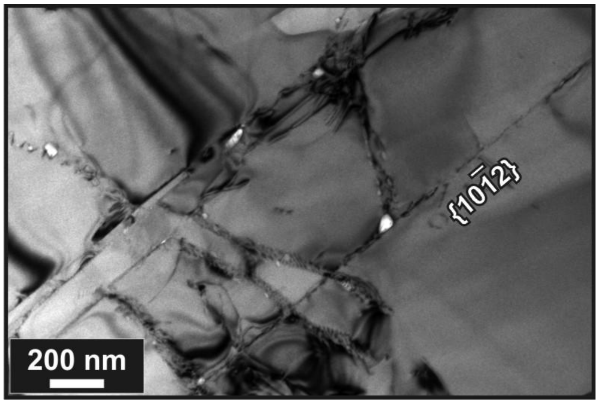

Fig. 2: Bright field transmission electron micrograph of a quartz grain from the Hummeln structure with one set of decorated PDFs oriented parallel to $\pi\{10\bar{1}2\}$ orientation.

At higher magnification, more lamellae, with apparent thicknesses of a few tens of nanometers, are visible. They are composed of dislocations and fluid inclusions or vugs, microstructures typical of annealed PDFs. Using the U-stage and TEM, we were able to characterize the PDFs in more details, especially their crystallographic orientations. The investigated PDFs are oriented parallel, notably to c(0001), $\pi\{10\bar{1}2\}$, $\xi\{11\bar{2}2\}$, and $m\{10\bar{1}0\}$ orientations. In addition, a few quartz grains with one set of planar fractures (PFs), oriented parallel to c(0001), were observed.

Discussion: Our investigations show that quartz grains with PDFs are present in rocks from the Hummeln structure. As these features are uniquely associated with shock metamorphism [8], we can conclude that the Hummeln structure is an hypervelocity impact crater. The observation that the PDFs are annealed and decorated indicates that the originally amorphous PDFs were altered, which is not surprising as it is typical for shocked quartz from ancient impact craters. The PDF orientations and the observed low number of PDF sets per grain indicate that the studied material experienced relatively low shock pressures.

The fact that the Hummeln structure has an age of ~467 Ma, coinciding with a relatively large number of other craters on the confined space of the present Baltoscandia [e.g., 6,9], strongly suggests that it results from the impact on Earth of a fragment from the LCPB. Thus, the confirmation of the Hummeln structure as being the remnants of an impact crater also strengthens the idea that the LCPB break-up event spawned large asteroidal fragments which have collided with Earth at a rate that was higher than the normal background flux [10]. Interestingly, the roughly coeval Granby impact structure (2 km in diameter) is located only ~150 km away from the Hummeln structure [7, 11], suggesting that the bombardment of Earth with projectiles in the hundred meter diameter range was severe after the LCPB break-up event, unless considering pure coincidence regarding the relatively close-by occurrence of these two impact craters.

Despite its relatively small size, only ~1.2 km in diameter, and its old age, the Hummeln structure is remarkably well preserved. This shows, contrary to the general assumption, that under specific conditions, i.e., a marine target environment with continued sedimentation, a small impact crater can survive more or less unaffected for hundreds of million years.

Conclusions: Our finding and characterization of (decorated) PDFs in quartz grains from the Hummeln structure provide definite evidence for its hypervelocity impact origin, closing an about 200 years old debate. The Hummeln structure can now be added to the list of the 186 (now 187!) confirmed meteorite impact craters on Earth, but also, and more importantly, to the growing list of Ordovician impact craters. Our work also further the hypothesis of intense bombardment with asteroids during the Ordovician (following the LCPB break-up event), but it also illustrates that likely many more impact craters were formed at that time on Earth and still need to be discovered/confirmed and/or better dated.

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