SHATTER CONES AND ASSOCIATED SHOCK-INDUCED MICRODEFORMATIONS IN MINERALS – NEW INVESTIGATIONS AND IMPLICATIONS FOR THEIR FORMATION. L. Ferrière and G. R. Osinski, Department of Earth Sciences, University of Western Ontario, 1151 Richmond Street, London, ON, N6A 5B7, Canada (ludovic.ferriere@uwo.ca).

Introduction: Shatter cones are the only shock-deformation feature (i.e., diagnostic evidence of hypervelocity impact) that develop on a macro- to megascopic (i.e., hand specimen to outcrop) scale [e.g., 1]. However, despite being one of the most distinctive products of hypervelocity impact events, the shatter cone formation mechanism remains unclear. Different models for their formation exist in the literature [2-7], but none of them account for all of the current field observations of shatter cones [7,8]. In addition, it is notable that very few studies, combining observations of shatter cones from the outcrop to the microscopic scale, have been conducted [e.g., 9].

We report here on preliminary results of an ongoing study of shatter cones from several terrestrial impact structures, including the Charlevoix (“CS”), Haughton (“HS”), Keurusselkä (“KS”), Rochechouart (“RS”), Siljan (“SiS”), Sierra Madera (“SmS”), Steinheim (“StS”), and Sudbury (“SuS”) structures.

The challenge of this study is to combine observations on the occurrence, distribution, and characteristics of shatter cones at the scale of the impact structure with macroscopic observations (e.g., shatter cone morphology, etc.) and microscopic properties of (shocked) minerals (mainly quartz), to infer the course of events that result in the formation of shatter cones. The abundance and crystallographic orientations of planar deformation features (PDFs) in quartz grains, based on universal stage (U-stage) microscope examination [10], was studied to estimate the peak shock pressure recorded by the samples.

Results and discussion: Based on the compilation of an extensive literature database, we estimate that shatter cones have been reported for more than half of the currently 177 proven impact structures on Earth, in extremely different lithologies (from fine- to coarse-grained), with large variations of cone size (cm to m), but generally occurring *in-situ* only in the central part of the impact structure. In a few cases, such as at “HS”, “RS”, and “SmS”, shatter cones occur within clasts in crater-fill impact breccias and melt rocks, and also, at “HS”, within megablocks of the ballistic ejecta blanket. The shatter cones studied here are in various types of lithologies; in limestone, gneiss, and in metagreywacke at “CS”; principally in limestone and in sandstone at “HS”, in granodiorite and in orthogneiss at “KS”, in microgranite at “RS”, in granite at “SiS”, in limestone and in sandstone at “SmS”, in limestone at “StS”, and in quartzite, sandstone, metagreywacke, and in gabbro at “SuS”. Note that shatter cones are for the first time reported here in metagreywacke at “CS” and in gabbro at “SuS”.

In all the studied structures, shatter cones display reciprocal positive and negative curved, oblate, in some cases nearly flat, or conical surfaces, with striae that radiate outward from the cone apex and with subsidiary divergent striations ("horsetailing"; Fig. 1a). Shatter cones are generally found as composite groups, rarely as single specimens, of commonly partial to complete cones, mainly at “HS”, but also at “CS” and “StS”, and rarely at “SuS”, with very frequently opposite orientations at the centimeter to decimeter scale. Samples with apices pointing in opposite directions were mainly observed at “HS” (Fig. 1b).

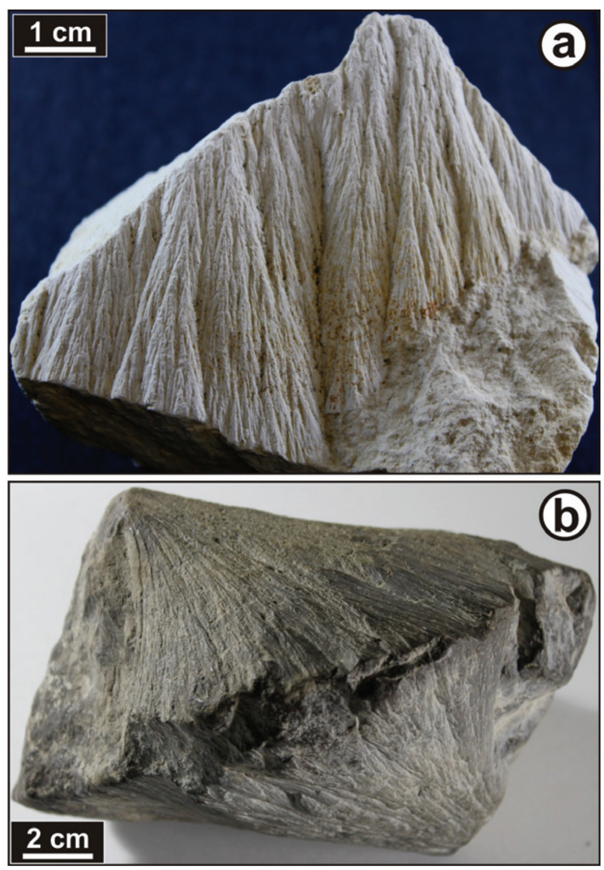

Fig. 1: Macrophotographs of shatter cones in limestone. a) Horsetailing shatter cone surfaces (“StS”). b) Two complete cones pointing in opposite directions. Clast from crater-fill impact breccia (“HS”).

Based on these observations it is obvious that the use of shatter cone apex orientation to determine the centre of an impact structure is likely to yield incorrect results. However, the study of the distribution of *in-situ* shatter cones can be used for the estimation of a minimum crater diameter.

It is also important to combine field observations with laboratory investigations. Our petrographic study confirm that a large number of micro-deformation features occur in shatter cones, including random penetrative fractures (in all samples), kink bands (mainly in micas at "CS", "RS", and "SuS", but also rarely in quartz and feldspar grains at "CS"), planar fractures (PFs) and PDFs in quartz grains in samples from "CS" (Fig. 2), "HS", "KS", "SiS", and rarely "RS". So-called "feather textures" were also noted in quartz grains from "CS" and "HS". Detailed U-stage investigations are in progress for quartz-bearing shatter cones from "CS", "HS", "RS", and "SiS", and are only fully completed for samples from "KS". In this case, we estimate that the investigated shatter cones have experienced peak shock pressures comprised between ~2 GPa to slightly less than 20 GPa for the more heavily shocked samples (results are reported in [11]).

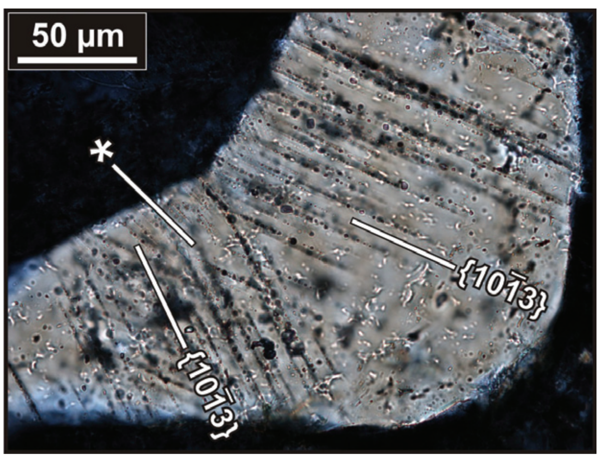

Fig. 2: Photomicrograph (in cross-polarized light) of a quartz grain, in a shatter cone from "CS", containing three decorated PDF sets; one set (*), with ω'{01$\bar{1}$3}-equivalent orientation, is hardly visible on this photomicrograph, but is evident under the U-stage.

No glassy patches or venners, as reported e.g., for shatter cones from Beaverhead [12], "SuS" [13], and Vredefort [7], were observed in any of the investigated samples. In addition, we were not able to confirm that, as currently recognized in the literature [e.g., 9,12], and based on qualitative investigations, PFs and/or PDFs occur in minerals only within 1–2 mm of the cone surfaces.

Furthermore, our petrographic and U-stage study shows that even from the same outcrop, shatter cone samples recorded significantly different peak shock pressures. This implys that at a certain distance from the crater center, where shatter cones form, at shock-pressures of ~2–20 GPa, the shock wave that propagates through the target rocks is highly scattered, refracted, and/or reflected.

Conclusions: Our study provides some important insights into the mechanism of shatter cone formation: (1) as previously suggested by some [7,8], our observations of shatter cones within crater-fill breccias, at "HS", "RS", and "SmS", indicate that they must form very early in the cratering process (i.e., prior to crater excavation); (2) the occurrence of shatter cones with complete cones and apices pointing in opposite directions reject the models by Sagy et al. [5,6]; (3) The record of shock pressures up to ~20 GPa also poses problems for the model of Baratoux and Melosh [4], as their proposed mechanism only operates "at pressures of 3–6 GPa". It is also, so far, not clear if shatter cone formation occurs during the post-shock phase of the compression stage of cratering and/or immediately thereafter during shock unloading, by decompression, as suggested by [7]. Thus, while we have begun to answer some questions, more arise and the mechanism for shatter cone formation remains elusive. Currently, none of the various proposed models can account for all of the observations of natural shatter cones.

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