A STATISTICAL STUDY OF SHOCKED QUARTZ GRAINS FROM THE SILJAN IMPACT STRUCTURE (SWEDEN) – HORIZONTAL VERSUS VERTICAL C-AXES. S. Holm[1], L. Ferrière[2] and C. Alwmark[1], [1]Department of Geology, Lund University, Sölvegatan 12, SE-223 62 Lund, Sweden (sanna.holm@geol.lu.se), [2]Natural History Museum, Burgring 7, A-1010 Vienna, Austria.

Introduction: Shock metamorphic effects in quartz is the most common diagnostic tool for recognizing impact structures on Earth. The study of shock metamorphism in a given structure/sample is frequently focused on the characterization of planar deformation features (PDFs) in quartz. They occur either as thin lamellae composed of amorphous silica or as multiple mechanical Brazil twin lamellae (for a review see [1]), both oriented along rational crystallographic planes of low Miller indices. The lamellae are planar, with narrow spacing between each one (2-10 µm), often occurring in multiple sets in the same quartz crystal (Fig. 1). It is well established that specific orientations of PDFs are formed at different shock pressures (e.g., [2]), implying that PDFs can be used to estimate the average shock pressure for a given sample. The standard technique used to determine the crystallographic orientations of PDFs consists of measuring poles perpendicular to planes of PDFs in quartz crystals with the Universal stage (U-stage; [3]) mounted on a polarizing microscope. This method is performed in four steps (see [4, 5] for details): (1) determination of the optic axis (c-axis) of the studied grain; (2) measurement of the poles of all visible PDFs within the considered grain; (3) plotting the c-axis and the poles of all PDFs on a Wulff stereonet; and (4) indexing of PDFs using a stereographic projection template (see [5] for an updated version) which displays the common, possible pole orientations of PDF planes. This also involves determination of the polar angle (angle between poles of PDFs and the c-axis). Note that step (1) is extremely important, because all PDF plane measurements will relate to the c-axis measurement for the indexing. For each c-axis (and PDF set), the azimuth (value between 0° and 360°) and the inclination (value between 0° and 90°), in either E or W direction, are measured. For the c-axis it is also necessary to note its attitude (horizontal or vertical), i.e., determining if the c-axis is closer to either a horizontal or a vertical plane projected from the thin section. This is important because there will be a major difference in calculating angles between the pole of the PDFs and the c-axis during plotting on the Wulff stereonet based on whether the c-axis is horizontal or vertical.

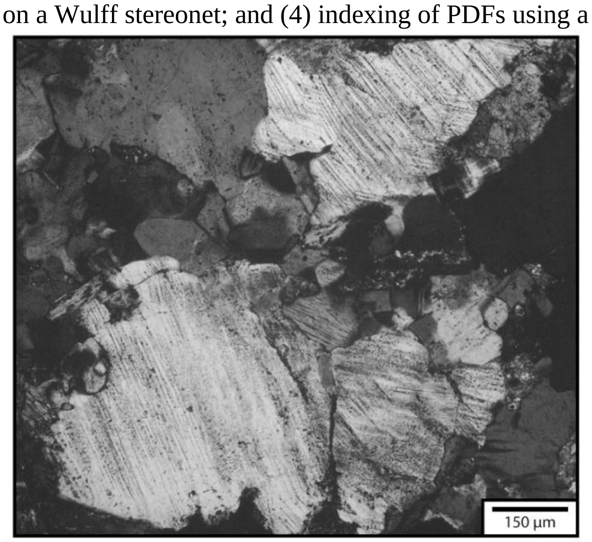

Fig. 1. Thin section photomicrograph of shocked bedrock from the Siljan impact structure with three quartz grains (in light color) displaying multiple sets of decorated PDFs parallel to $\{10\bar{1}3\}$-equivalent orientations (crossed polars).

Due to basic crystallography, and the limitations of the U-stage (i.e., U-stage tilting is restricted to approximately 50-55°, making it impossible to measure or even to detect PDFs with higher inclinations than ~55°), it is expected that quartz crystals with vertical c-axes should show a higher number of high-index PDF orientations (such as the $\{22\bar{4}1\}$, $\{21\bar{3}1\}$, $\{51\bar{6}1\}$ orientations), because of their higher angular relation to the c-axis. Thus, the observed/reported number of PDF sets per quartz grain is always a minimum number as one or more additional sets can occur but cannot be detected due to the limitations of the U-stage.

The aim of this study is to investigate, by using a large dataset of PDF measurements, if, as expected, high-index PDF orientations are more frequent in quartz crystals with vertical c-axes, and to also discuss implications for the interpretation of U-stage measurements and derived shock pressures.

Material and Methods: The studied material consists of 17 granite and granodiorite samples from different localities across the central part of the Siljan impact structure in Sweden (see [6] for a detailed description of the samples). Out of all investigated quartz grains in each of these samples, between 81-100% display PDFs. The samples have recorded shock pressures of between ~10 to 20 GPa [6]. A total of 2692 PDFs in 1020 quartz grains were investigated, with an average of 2.6 indexed PDF sets per grain.

PDFs in quartz were studied with a 5-axis Leitz U-stage following the technique described above (see also [3–5]). The indexing of the PDFs was done by hand, and polar angles between PDFs and the c-axis of the grains were also checked using the computer program Stereo32 to guarantee precise angular relations.

All percentage values represent absolute frequencies, as defined by [4, 5], meaning that reported percentages of PDF abundances in the samples are calculated as the number of symmetrically equivalent planes measured in *n* quartz grains, divided by the total number of measured PDF sets in *n* quartz grains.

Results and Discussion: Our measurements show that there is a correlation between the occurrence of "less abundant" PDFs (i.e., only few observations of specific orientations compared to the total amount of indexed PDFs), and the orientation of the c-axis of the host quartz grain (Fig. 2). More specifically, PDF sets with $\{10\bar{1}2\}$, $\{10\bar{1}1\}$, $\{10\bar{1}0\}$, $\{11\bar{2}2\}$, $\{11\bar{2}1\}$, $\{21\bar{3}1\}$, $\{51\bar{6}1\}$, $\{11\bar{2}0\}$, $\{22\bar{4}1\}$, $\{31\bar{4}1\}$ and $\{40\bar{4}1\}$ orientations are more frequently reported from quartz grains with vertical c-axes. On average, in our dataset, about 11% of all investigated quartz grains in a sample have vertical c-axes, with values that range from 0 to 28%. Furthermore, on average, the amount of indexed PDFs in "less abundant" PDF set orientations represents 6% of the total amount of indexed PDFs in the samples, with values ranging from 0 to 18%. Despite the fact that the average number of grains with vertical c-axes in a sample is about one out of ten grains, the average percentage of "less abundant" sets among all indexed PDFs in these grains is 14.5%. This proportion can be compared with an average of 5% of the "less abundant sets" among all indexed PDFs in grains with horizontal c-axes. This phenomenon is especially prominent if only samples that contain more than 5% "less abundant sets" among the total number of measured PDFs, are considered. The average is then 24% for grains with vertical c-axes, compared to 8% for grains with horizontal c-axes. Thus, it is clear that more high-index PDF orientations are visible, and thus measured, in grains with vertical c-axes. Most of these PDF orientations are in the "blind area" of possible inclinations that can be investigated with the U-stage if the quartz grain has a horizontal c-axis.

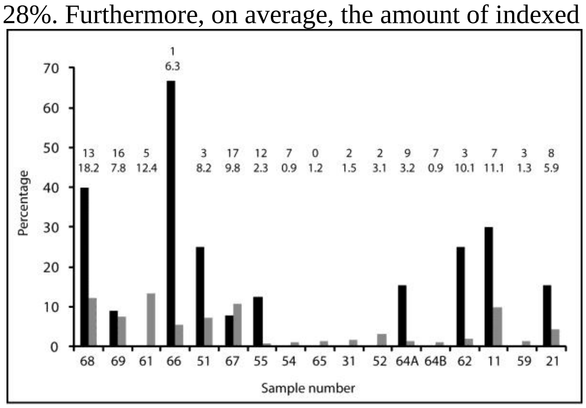

Fig. 2. Histogram showing the abundance (in percent) of indexed PDF sets oriented along orientations other than the (0001), $\{10\bar{1}4\}$ and $\{10\bar{1}3\}$ orientations in shocked quartz grains with vertical c-axes (black) and horizontal c-axes (grey). Samples (on the x-axis) are ordered according to their relative distance to the geographical center of the impact structure, with sample 68 being located the closest to the center. Numbers indicated on top of the columns represent the total number of grains with vertical c-axes in the sample (above), and the abundance (in percent; absolute frequency) of planes parallel to other orientations than the (0001), $\{10\bar{1}4\}$ and $\{10\bar{1}3\}$ orientations in the sample (below). Note that, interestingly, the recorded shock pressure (i.e., in this case higher for the samples from the left part of the histogram) do not seem to have a significant influence on the abundance of high-index PDF orientations.

Our investigation shows that if quartz grains that have vertical c-axes are ignored or "selectively not measured" (as might have been the case in the past for some U-stage operators, because PDFs in these grains are somewhat more complicated to index), the resulting data set of PDFs is to some extend affected, and, thus, the estimated shock pressure too.

Conclusion: On the basis of our results, in addition to the recommendations by [5] on the strict U-stage measurement procedure, we recommend that all possible grains with PDF sets, in a given sample, should be measured, i.e., including also grains with vertical c-axes. However it is clear that PDF sets that fall in the "blind area" (i.e., with inclinations higher than ~50-55° to the horizontal plane of the thin section) cannot be investigated. Thus, depending on the interest of the operator, a second thin section, cut perpendicular to the other one, should be prepared for investigation.

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References: [1] Grieve R.A.F. et al. (1996) *Meteoritics and Planet. Sci., 31*, 6–35. [2] Hörz F. (1968) In *Shock metamorphism of natural materials*, edited by French B.M. and Short N.M., pp. 243–253. [3] Emmons R.C. (1943) The Universal Stage (with five axes of rotation). *Geological Society of America Memoir* 8. 205 p. [4] Engelhardt W. von and Bertsch W. (1969) *Contrib. Mineral. Petrol., 20*, 203–234. [5] Ferrière L. et al. (2009) *Meteoritics and Planet. Sci., 44*, 925–940. [6] Holm S. et al. (2011) *Meteoritics and Planet. Sci., 46*, 1888–1909.