WHAT IS THE ROLE OF ALPHA-QUARTZ IN IMPACT SHOCK METAMORPHISM? ANGLES BETWEEN POLE ORIENTATIONS OF PLANAR DEFORMATION FEATURES AS A PROXY FOR THE SHOCK-INDUCED TEMPERATURE CHANGE.

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Introduction: Planar deformation features (PDFs) are sets of parallel planes of amorphous material, less than 2 µm thick and spaced 2-10 µm apart, which form in minerals due to shock metamorphism [e.g., 1]. PDFs are predominantly developed along specific crystallographic orientations, and there are generally multiple sets per grain (for a recent discussion of PDFs in quartz, see [2]). PDFs are important in impact studies for three main reasons: (a) they are diagnostic features for confirming impact structures, (b) they enable to provide maximum pressure information for the impactites (for discussion and further references see [3]), and (c) under some conditions they can provide information on the pre-impact temperature of the target rocks [e.g., 4].

Most publications are based on analysis of PDFs (polar angles and Miller-Bravais indices) that reveal information on shock wave barometry and/or thermometry. Very few studies use the full crystallographic information that can be derived from universal-stage (U-stage) measurements (e.g., [4,5]). The reason is mainly that the manual method of indexing PDFs is very time-consuming. Using our new web-based application [6], indexing of PDFs can be easily and efficiently done.

Here we present preliminary results of a study on the variation of combinations of PDF orientations in quartz grains. The combinations of PDF orientations are defined as "all angles between all PDFs indexed within the same grain and in relation to the c-axis of the crystal". The original hypothesis – that PDF orientations within the studied samples reflect the symmetry of α-quartz – is not supported by the data. On the contrary, it appears as if some quartz grains were of β-quartz type when the PDFs formed.

Method: PDFs have been measured in three samples using U-stage and indexed using the indexing program of [6]. Angular relations of indexed PDFs (using "min-max" option and error value of 5°) of each grain were plotted separately [2]. Plotted PDFs are oriented only according to the c-axis and other PDFs from the same grain – not according to a-axes. Because of that, only combinations of angular relations between PDFs can be analyzed. Here, due to space limitation, we present only data for grains with two indexed PDFs (excluding basal PDFs).

Samples. The samples used here have been previously studied by Ferrière et al. [2]. They are from three different impact structures and represent distinct lithologies: AUS is a sandstone from Gosses Bluff (Australia, ~22 km, 142.5 Ma), BOS is a meta-greywacke from Bosumtwi (Ghana, 10.5 km, 1.07 Ma), and M8 is a biotite-gneiss from Manson (USA, ~35 km, 73.8 Ma) [2]. A total of 74, 65, and 71 grains were measured in AUS, BOS, and M8, respectively, with 44, 50, and 64 of those containing at least two indexed PDFs (after excluding basal PDFs).

Results: The most common combinations of PDF orientations are presented in Table 1. Combinations of PDF orientations A, B, and C represent the cases when two PDFs parallel to the $\{10\bar{1}4\}$, $\{10\bar{1}3\}$, or $\{10\bar{1}2\}$ orientation are located 60°, 120°, or 180° from each other, respectively. In all three analyzed samples, the most common combination is B, where pole orientations of PDFs are located 120° from each other. The frequency of the combination B in the three samples is very similar, representing between 45% and 54% of the total number of grains in which two PDFs were indexed. In each analyzed dataset, more than half of all grains with combination B consist of a pair of PDFs with the $\{10\bar{1}3\}$ orientation, the rest consisting of $\{10\bar{1}4\}$&$\{10\bar{1}3\}$ orientations; there are also single occurrences of $\{10\bar{1}4\}$&$\{10\bar{1}4\}$, $\{10\bar{1}2\}$&$\{10\bar{1}2\}$, and $\{10\bar{1}3\}$&$\{10\bar{1}2\}$ pairs.

The second most frequent combination of PDFs is the A, where pole orientations of PDFs are located 60° from each other. In the AUS and M8 samples, ~15-19% of grains have such a combination of PDF orientations, but only 7% in the case of the BOS sample. The most common pairs of PDF types are $\{10\bar{1}3\}$&$\{10\bar{1}3\}$ and $\{10\bar{1}3\}$&$\{10\bar{1}4\}$ orientations (equally frequent).

The most striking difference between the investigated samples concerns the frequency of the combination C in the BOS sample, where it represents 31% of the total, whereas this combination is absent in the other two samples. In almost all cases combination C consists of pairs of PDFs with $\{10\bar{1}3\}$&$\{10\bar{1}2\}$ orientations.

A few other combinations of PDF orientations occur only once or twice within the datasets.

Discussion: Alpha-quartz belongs to 32-point group symmetry, while β-quartz has a 622-point group symmetry. Because of this property, α- and β-quartz should have distinct combinations of PDF orientations; those present in α-quartz can exist also in β-quartz, but the combinations of PDF orientations characteristic in β-quartz cannot occur in α-quartz. Such a difference in PDF combinations between α- and β-quartz was observed by Langenhorst and Deutsch [4] in experimentally produced PDFs (for single quartz crystals shocked at 25 GPa, at 20°C and 630°C). However, no such observation was made in the case of natural PDFs up to now.

The pole orientations of PDFs presented here show that within a single sample, the observed combinations are characteristic of both types of quartz. This observation holds for all three samples that were investigated.

The most frequent combination of PDFs orientations in all three samples (i.e., B), consisting of a pair of PDFs with $\{10\bar{1}3\}$ orientation, is in agreement with rules for α- and β-quartz as stated in [4]. For pairs of PDFs with the same Miller-Bravais indices (e.g., $\{10\bar{1}3\}$&$\{10\bar{1}3\}$) located 120° from each other (i.e., combination B), both pole orientations of PDFs are from the same rhombohedron. Similarly, this reasoning applies for combination C, as it consists almost exclusively of pairs of PDFs parallel to $\{10\bar{1}3\}$&$\{10\bar{1}2\}$ orientations; these form in both types of quartz.

On the other hand, the combination A, where the pair consists of PDFs with $\{10\bar{1}3\}$&$\{10\bar{1}3\}$ orientations located 60° from each other, can be only formed in β-quartz. This is due to the β-quartz having a higher symmetry than α-quartz, where poles to PDFs oriented parallel to $\{10\bar{1}3\}$ are located every 60° degrees (and not 120° as for α-quartz). In order to produce PDFs with this specific combination of PDFs orientations, it is necessary for those grains to be within the β-quartz stability field (above 574°C for atmospheric pressure and above 1381°C at ~3.5 GPa) [7]. Additionally, if the combination B consists of PDFs with different Miller-Bravais indices (e.g., $\{10\bar{1}4\}$&$\{10\bar{1}3\}$ or $\{10\bar{1}3\}$&$\{10\bar{1}2\}$ orientations), it can form only in β-quartz. This combination is present in all three samples.

The most puzzling difference observed between our samples is the proportion of the combination C, accounting for 25% of all PDFs in the BOS sample, and its total absence in the two other samples. PDFs parallel to the $\{10\bar{1}2\}$ orientation are almost absent in sample AUS and M8 (accounts for ~1% of all PDFs) and are very numerous in BOS (~20%). In 6 out of 7 observed cases the combination C consists in pairs of PDFs with $\{10\bar{1}3\}$&$\{10\bar{1}2\}$ orientations. The explanation of this phenomenon is not yet clear, but could be related to: a) differences in petrographic characteristics of the samples; b) differences in peak shock pressures experienced by the samples; and/or c) differences in shock wave propagation direction relative to the c-axis.

Conclusions: 1) Different samples can have different characteristic combinations of PDF orientations. 2) Quartz grains in many cases reveal a higher symmetry than what is expected for α-quartz. Among our samples, the one from the smallest crater (i.e., BOS) reveals the smallest number of grains with PDF combinations characteristic for β-quartz. 3) If there are two PDFs present in a grain, parallel to the $\{10\bar{1}3\}$&$\{10\bar{1}2\}$ orientations, in most cases they will be located at 180° (azimuthal degrees) from each other.

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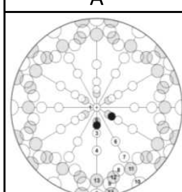
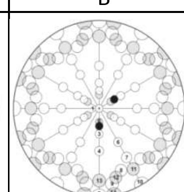
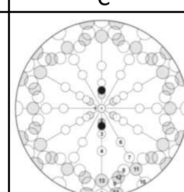
References: [1] Stöffler D. and Langenhorst F. (1994) *Meteoritics & Planet. Sci.*, 29, 155–181. [2] Ferrière L. et al. (2009) *Meteoritics & Planet. Sci.*, 44, 925–940. [3] French B.M. and Koeberl C. (2010) *Earth Sci. Rev.*, 98, 123–170. [4] Langenhorst F. and Deutsch A. (1994) *Earth Planet. Sci. Lett.*, 125, 407–420. [5] Walzebuck J.P. and Engelhardt W. (1979) *Contrib. Mineral. Petrol.*, 70, 267–271. [6] Losiak A. et al. (2011) *LPSC XLII* (this volume). [7] Shen A.H. et al. (1993) *Am. Mineral.*, 78, 694–698.

Table 1. Number and percentages of grains with specific combinations of PDF orientations in studied samples. Only data for grains with two PDFs were indexed (excluding basal PDFs) and are presented here. Percentages relate to the total number of grains with two indexed PDFs.

Sample	Total no of grains	No of grains with 2 or more indexed PDFs		A	B	C	Other
							With 2 indexed PDFs (excluding basal)
AUS	74	44	No & % of grains with specific combination of PDF orientations	5	14	0	7
				19%	54%	0%	27%
BOS	65	50		2	14	7	5
				7%	50%	25%	18%
M8	71	64		3	9	0	8
				15%	45%	0%	40%