# Specific combinations of planar deformation feature orientations in shocked quartz grains from the Bosumtwi impact crater as a signature of β-quartz

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## WHAT DO WE KNOW?

Impact cratering is one of the most important geological processes in the Solar System. The recognition of importance of meteorite impacts in the terrestrial geological record has increased with the rapidly rising number of confirmed impact structures [1]. Nowadays more than 180 of them are known on Earth *(Figure 1)*.

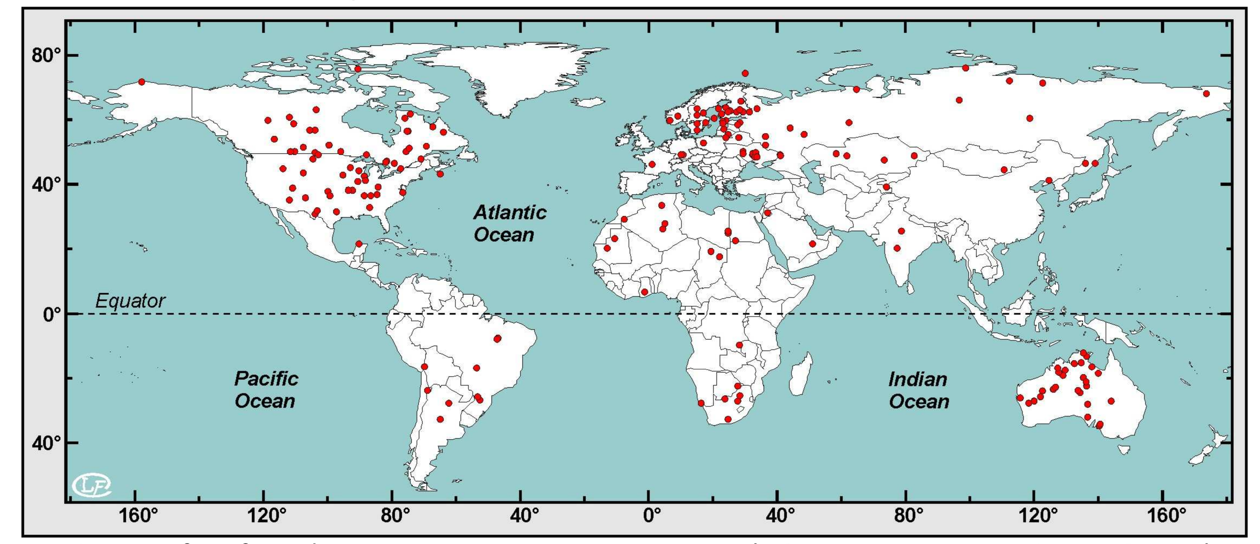



*Figure 1. Map of confirmed meteorite impact structures on Earth. Source: www.MeteorImpactOnEarth.com*

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 (Figure 2) [e.g., 1,2]. PDFs in quartz grains are the most commonly used diagnostic criteria for the recognition of hypervelocity impact structures. Specific combinations of PDF orientations provide information on the peak shock pressure recorded in the rocks, within the range of ~5 to 35 GPa (e.g., [2, 3]). The PDF formation mechanism is not well understood (although many hypotheses have been proposed), but we know that the formation and orientation of PDFs are controlled by the crystal structure of the mineral in which they form [e.g., 3].

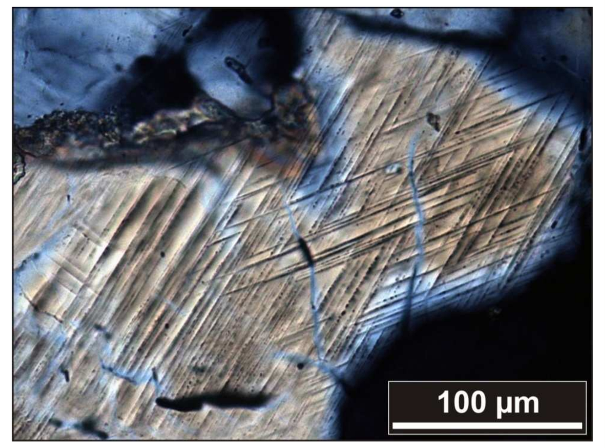



*Figure 2. Example of planar deformation features in quartz from the Bosumtwi crater.*

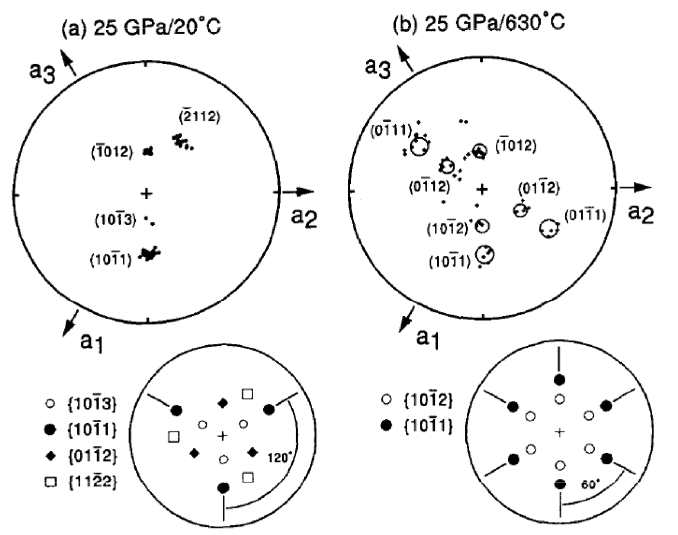



*Figure 3. Standard stereoplots of experimentally shocked α-quartz (a) and β-quartz (b). The combinations of PDF orientations characteristic for α-quartz include: 1) PDFs of the same index located 120° from each other, 2) PDFs of different but neighboring PDFs (e.g., {10-12} and {10-13} located 180° from each other. The most characteristic combinations of PDF orientations for β-quartz consist of PDFs of the same type located 60° from each other (from [4]).*

Alpha-quartz has 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 of β-quartz cannot occur in α-quartz (Figures 3 and 4). 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) and also in samples from the Charlevoix impact structure [5].

The aim of this study is to estimate how commonly grains with combinations of PDF orientations characteristic for β-quartz occur in craters of different sizes and with different target lithologies, and to evaluate possible mechanisms of β-quartz formation by shock metamorphism.

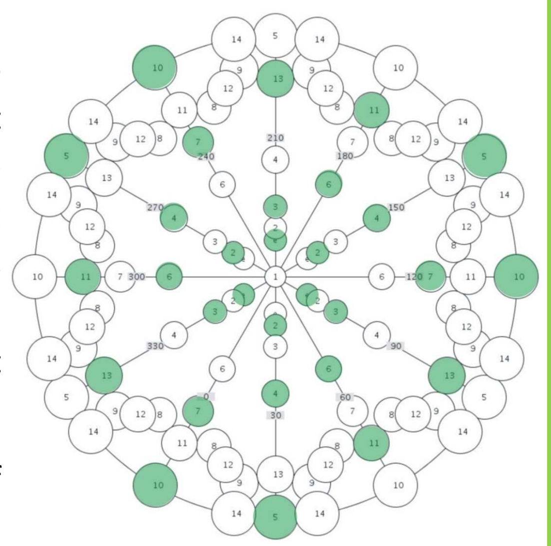


Figure 4. Stereoplot of PDFs orientations for α- (green) and β-quartz (white and green).

## HOW WE STUDY PDFs

A web-based program for automatic indexing PDFs was recently developed [6]. In addition to indexing PDFs in quartz, the program also generates diagrams and statistics related to PDF occurrence in a sample.

1. Measurement of c-axis and planar features with an universal stage:
- At least 50 sets of PDFs in every sample should be measured [3].
- Azimuths and inclinations given as intervals.

2. Preparation of an appropriate input file.

3. Transformation of data by the program:
-Data are transformed from thin section-oriented coordinates to crystal structure-oriented coordinates.
-Transformation is done using equations of a spherical triangle.
- Thin section-oriented coordinates are common for all grains from the same sample, however, each grain has its own crystal structure-oriented coordinates.

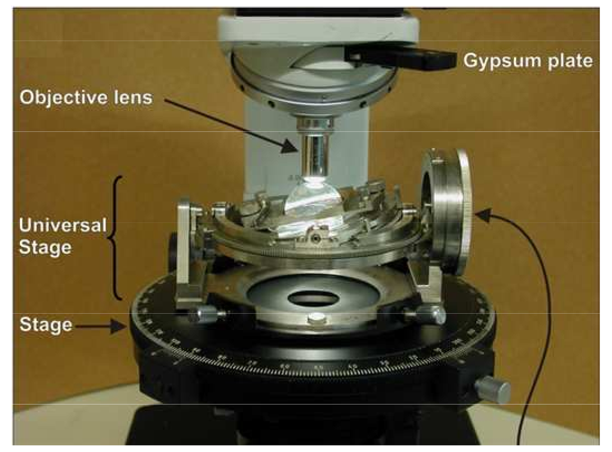



*Figure 2. Photograph of a four axis universal stage mounted on the optical microscope at the University of Vienna.*

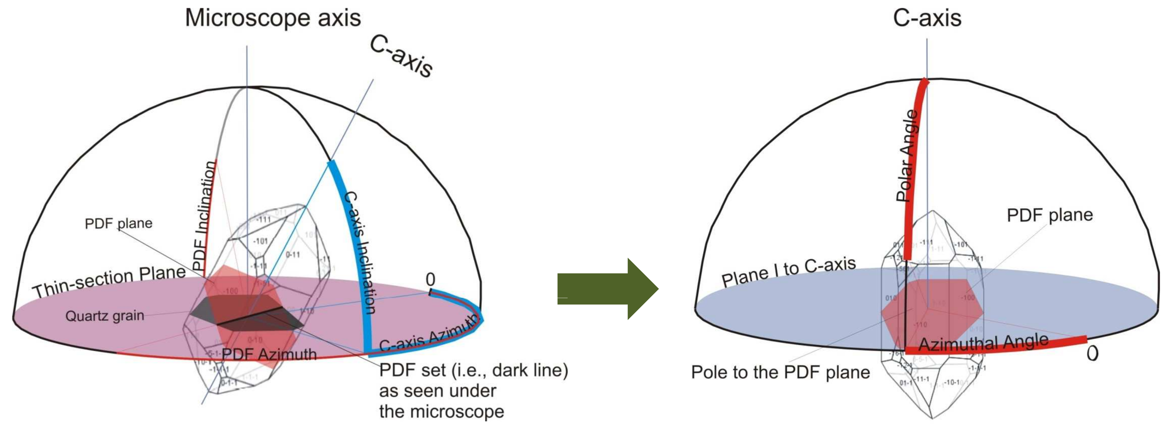



*Figure 3. Process of transformation of coordinates from thin section-oriented to crystal structure-oriented coordinates. To avoid confusion, after transformation to the crystal structure-oriented coordinates, an azimuthal angle becomes an "azimuthal angle", and inclination angle a "polar angle".*

4. Program compares positions measured features (transformed to crystal-structure oriented coordinates) with the position of known PDFs.

*Figure 5. Comparison of result diagrams for grain 1 of the example input file produced with different program parameters: a) using a "min-max" method and 5° error, b) using an "average" method and 5° error, c) using an "average" method and 3° error. Note that in c) the feature "3" is not indexed.*

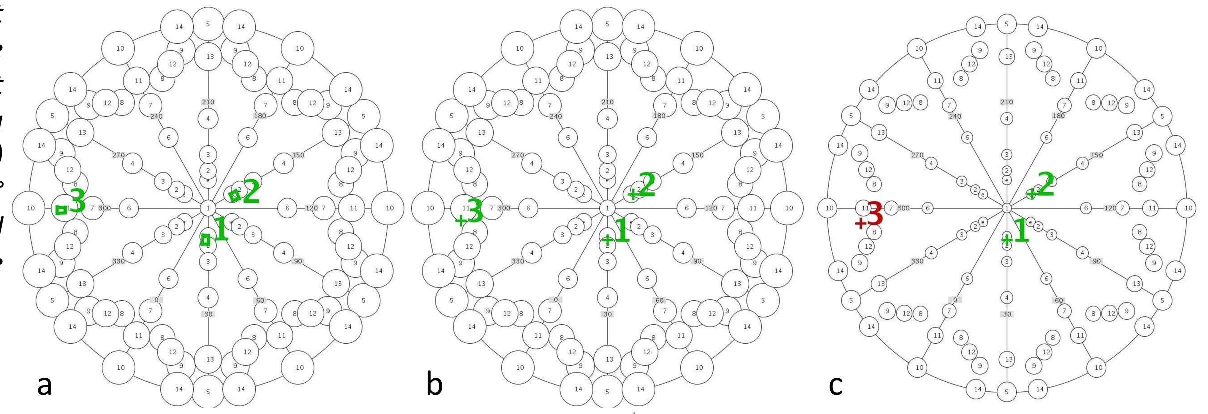



*Table 3. Comparison between manually and automatically indexed PDFs from three samples studied by [4]). A total of 74, 65, and 71 grains were measured in Gosses Bluff, Bosumtwi, and Manson impact structures, respectively. Data given as number of measured PDFs.*

| Crater, lithology | Method | 1 $(0001)$ | e $\{10\bar{1}4\}$ | 2 $\{10\bar{1}3\}$ | 3 $\{10\bar{1}2\}$ | 6 $\{10\bar{2}2\}$ | 4 $\{10\bar{1}1\}$ | 7 $\{11\bar{2}1\}$ | 8 $\{21\bar{3}1\}$ | 11 $\{22\bar{4}1\}$ | 12 $\{31\bar{4}1\}$ | 13 $\{40\bar{4}1\}$ | 9 $\{51\bar{6}1\}$ | 5 $\{10\bar{1}0\}$ | 10 $\{11\bar{2}0\}$ | 14 $\{51\bar{6}0\}$ | Not indexed |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Gosses Bluff, sandstone | program | 59 | 39 | 70 | 2 | 2 | 13 | 1 | 2 | 2 | 2 | 1 | 2 | 1 | 0 | 1 | 11 |
| | manual | 59 | 110 | | 2 | 5 | 10 | 0 | 3 | 0 | 3 | 2 | 1 | 1 | 1 | 1 | 10 |
| Bosumtwi, meta-greywacke | program | 0 | 29 | 53 | 29 | 2 | 8 | 2 | 2 | 7 | 3 | 1 | 2 | 1 | 1 | 0 | 5 |
| | manual | 0 | 81 | | 28 | 4 | 5 | 2 | 3 | 6 | 3 | 2 | 1 | 1 | 1 | 0 | 8 |
| Manson, biotite-gneiss | program | 4 | 46 | 117 | 4 | 2 | 15 | 0 | 5 | 10 | 2 | 1 | 0 | 0 | 0 | 1 | 5 |
| | manual | 4 | 166 | | 2 | 3 | 13 | 0 | 3 | 10 | 2 | 2 | 1 | 0 | 0 | 1 | 5 |

## WHAT DID WE FIND OUT?

Theoretically, β-quartz should not occur in the investigated samples if they were subjected only to stable state geothermal gradient heating, but we have strong evidence showing that the β-quartz form was occurring.
The formation of β-quartz due to shock metamorphism, described by Trepmann and Spray [5], seems to be common in medium- to large-scale impact craters.

| Crater name | Crater size | Lithology | Temperature at the depth of sample origin (*2) | Temperature of α-β transition (*3) | Total number of grains with two or more indexed PDFs | Number of grains with " β-PDFs" | % of grains with "β-PDFs" (*4) |
|---|---|---|---|---|---|---|---|
| Bosumtwi | 10,5 | meta-greywacke | 50 | 582 | 50 | 5 | 10.0% |
| Bosumtwi (*1) | 10,5 | | 50 | 582 | 198 | 50 | 25.3% |
| Gosses Bluff | 22 | sandstone | 272 | 637 | 44 | 13 | 29.5% |
| Luizi | 17 | | 260 | 630 | 52 | 22 | 42.3% |
| Manson | 35 | biotite gneiss | 300 | 644 | 64 | 29 | 45.3% |
| Keurusselkä | 30 | ortho-gneiss | 290 | 630 | 35 | 6 | 17.1% |

(*1) Average of 8 samples from different depths within the profile
(*2) Assuming geothermal gradient of 30°/km and a maximal depth of origin equal to the transient cavity depth (based on [5]) minus estimated depth of erosion (Gosses Bluff = 3 km, Manson = 1 km, Luizi = 0.3 km, Keurusselkä = 1 km). For Bosumtwi sample depth of origin (1 km) was taken from [9].
(*3) Based on equation by [10].
(*4) in relation to a number of grains with two or more indexed PDFs (excluding basal PDFs).

*Table 1. Number of grains with combinations of PDF orientations characteristic for β-quartz in samples from five craters. Samples were previously studied in [3], [7], [8].*

| Sample number | Depth | Number of grains with two or more indexed PDFs | Number of grains with PDFs characteristic for β-quartz | % of grains with PDFs characteristic for β-quartz | ± (2 sigma) | Average number of PDF sets in a grain | % of decorated PDFs | % of toasted quartz grains |
|---|---|---|---|---|---|---|---|---|
| KR8 029 | 271.4 | 22 | 6 | 27% | 18% | 1.65 | 53 | 25 |
| KR8 031 | 274.0 | 37 | 6 | 16% | 12% | 1.49 | 66 | 36 |
| KR8 037 | 283.5 | 28 | 8 | 29% | 16% | 1.40 | 60 | 25 |
| KR8 045 | 300.4 | 24 | 8 | 33% | 18% | 1.28 | 64 | 24 |
| KR8 056 | 326.8 | 22 | 11 | 50% | 19% | 1.32 | 70 | 29 |
| KR8 067 | 356.6 | 25 | 3 | 12% | 14% | 1.30 | 61 | 20 |
| KR8 096 | 406.3 | 16 | 3 | 19% | 19% | 1.31 | 44 | 17 |
| KR8 119 | 441.9 | 24 | 5 | 21% | 16% | 1.19 | 17 | 2 |

*Table 2. Number of grains with combinations of PDF orientations characteristic for β-quartz in samples from the Bosumtwi crater, arranged in a sequence of decreasing recorded pressure. Samples were previously studied by [7].*

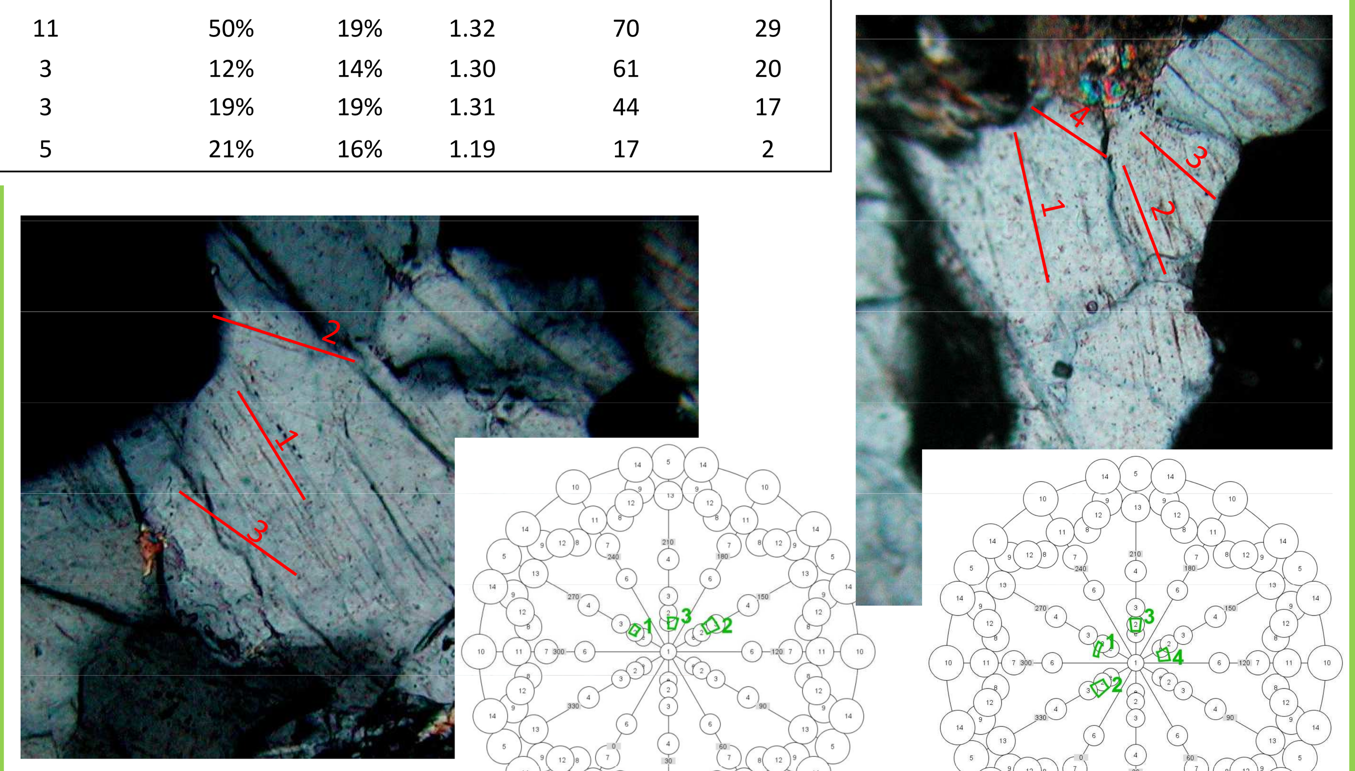


*Figure 6. Microphotographs and associated stereoplots of quartz grains from Bosumtwi sample KR8-029 with combinations of PDFs orientations characteristic for β-quartz.*

We report on numerous grains with combination of PDF orientations uniquely characteristic for β-quartz (see Table 1, Table 2, and Figure 6). For all investigated samples from different impact craters, even considering the most pessimistic estimations, temperature at the depth of origin of the studied samples was not high enough for β-quartz to exist.

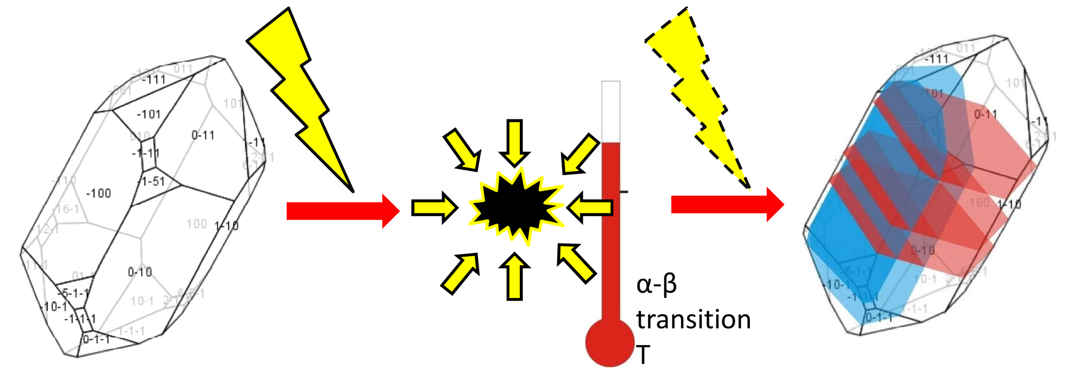
Interestingly, the relative abundance of grains with combination of PDF orientations characteristic for β-quartz increases with increasing crater diameter (see Table 1).

The lithology and the average pressure recorded by the samples do not seem to directly influence the number of grains with a combination of PDF orientations that are characteristic for β-quartz (Table 1).

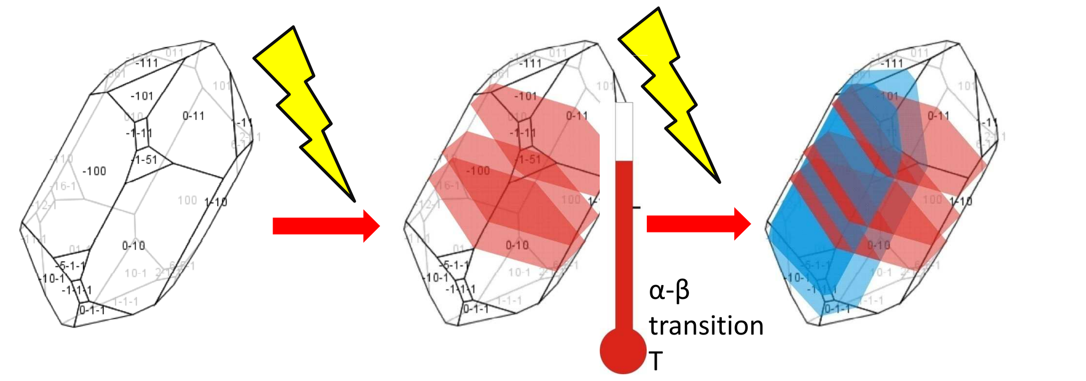
## WHAT IS OUR INTERPRETATION?

Different scenarios are possible:

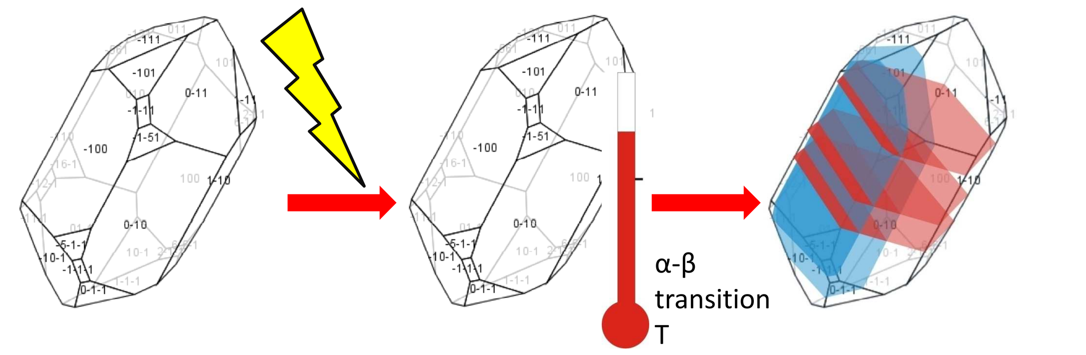
1. Compaction of pore space due to the shock wave propagation can locally increase the temperature [11] so high that β-quartz can be stable. If reverberation of the shock wave hits the same grain again, PDFs can be formed in a combination that is characteristic of β-quartz.
   - If this is true, grains with β- combination of PDF orientations should occur in groups. In addition the relative distribution of those "β-groups" should match in some respects the relative distribution of pore spaces in unshocked target rocks. Additionally, grains with β-combination of PDF orientations should not develop in non-porous rocks.




2. Formation of PDFs in α-quartz is sufficient to heat the entire crystal (or part of a crystal) quickly, so that the crystal can be transformed to β-quartz before a reverberation of the shock wave hits again the same crystal.
   - If this is true, multiple generations of PDFs should be observable, and planar features from negative and positive forms should systematically belong to different generations.




2. PDFs are not formed at the shock front, but later, during decompression.




**References:** [1] French B.M. and Koeberl C. (2010) *Earth Sci. Rev.*, 98, 123–170. [2] Stöffler D. and Langenhorst F. (1994) *Meteoritics Planet. Sci.*, 29, 155–181. [3] Ferrière L. et al. (2009) *Meteoritics Planet. Sci.*, 44, 925–940. [4] Langenhorst F. and Deutsch A. (1994) *Earth Planet. Sci. Lett.*, 125, 407–420. [5] Trepmann C.A. and Spray J.G. (2005) *Geol. Soc. of Amer. Special Paper* 384, 315–328. [6] Losiak A. et al. (2011) 42nd *LPSC* abstract no *1286*. [7] Ferrière L. et al. (2008) *Science*, 322, 1678–1681. [8] Ferrière L. et al. (2011), 42nd LPSC, abstract no 1642. [9] Collins G. et al. (2005) *Meteoritics Planet. Sci.*, 40, 817–840. [10] Shen A.H. et al. (1993) *Am. Mineral.*, 78, 694–698. [11] Wuennemann et al. (2008) *Earth Planet. Sci. Lett.*, 269, 529-538.

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