PLANAR FRACTURES AND FEATHER FEATURES AS INDICATORS FOR THE ORIENTATION OF THE DEVIATORIC STRESS FIELD IN THE SHOCK WAVE.

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Introduction: Shock waves of hypervelocity impacts into solids are generally composed of a differential stress field with longitudinal and transverse stresses (σ_L and σ_P, or σ_1 and σ_3; [1]). Close to the point of impact, the difference between the two stresses is small relative to the mean shock pressure, but as the shock pressure decreases with increasing distance from the impact point, the differential stress becomes relevant for the failure of the target rock, resulting in shear deformation of rocks and minerals [1,2]

Microscopic indicators for shear deformation include brazil-twinned basal planar deformation features (PDFs) and planar fractures (PFs) that commonly occur in quartz. These elements are suggested to form at pressures below 15-20 GPa (e.g., [2,3]). Feather features (FFs) are a further shock-derived element found in quartz that consist of a PF and a row of lamellae that emanate to one side of the PF at an angle >35° [4,5]. FFs are a useful tool for determining the local sense of shearing in a sample, and can be used to constrain the orientation of the principal axis of maximum stress, σ_1, which in turn can be used to determine the orientation of the shock wave [5]. FFs thus have the potential to yield insights into the influence of differential stress field conditions on the formation of PFs and PDFs.

Sample analysis: To determine if the orientation between FFs, PFs and PDFs can be correlated, a sample from the Nördlinger Ries was analyzed. The rock is a granitic gneiss clast found in a suevite deposit at a road cut on the northwestern crater rim near Zipplingen. Two thin sections of the sample were prepared that were oriented perpendicular to each other. The orientations of c-axes, FFs, PFs and PDFs were measured in 50 quartz grains in both thin sections using a Leitz universal stage mounted on a polarizing microscope. The crystallographic orientations of the planar elements were indexed, and the "unrotated" orientations of the planar elements were compiled within the reference system of the thin section and sample.

Results: The Ries sample has an abundance of $\{10\bar{1}3\}$ and $\{10\bar{1}2\}$ PDFs, which indicate shock pressures well above 10 GPa [3]. Surprisingly, few (0001) PDFs were found. Basal PDFs generally indicate high differential stresses [2]. PFs occur as large "microfaults" that normally crosscut the quartz grains. These PFs mainly have (0001) and $\{10\bar{1}1\}$ orientations. Five FFs were measured.

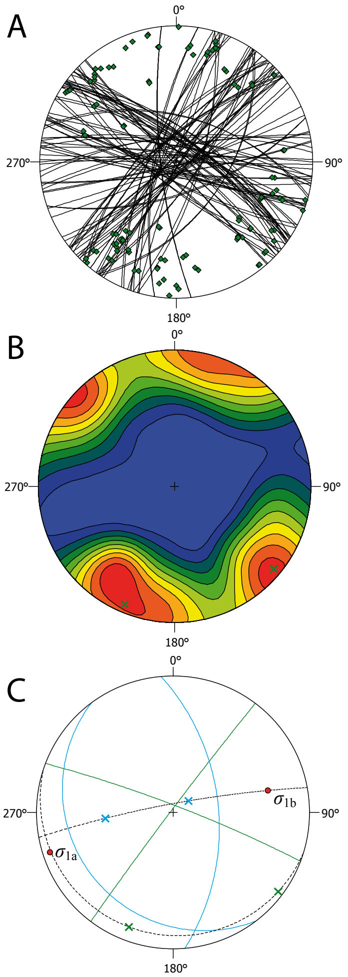

Fig. 1: Stereoplots of PF measurements from a Ries sample. A) PFs form a conjugate set of fractures. The surface poles of PFs (n=110) have a density distribution that shows two local maxima in B). Based on the angle between these maxima, σ_1 can be derived. σ_{1a} is based on data in A) and B), data for σ_{1b} not shown.

Planar fractures: Stereoplots of the unrotated PF data show a strong concentration of two orientations, as can be seen in both the density distribution of surface poles, which has two maxima (Fig. 1b), as well as the distribution of great circles of the surface poles (Fig. 1a), which form a conjugate set of fractures. Conjugate fracture sets form under deviatoric stresses, where the angle α between the two conjugate shear fractures sets increases with increasing confining pressure, and the maximum angle is α=90°. α opens in the direction of

σ_1. Using the two maxima of the density distribution, σ_1 can be located (Fig. 1c). For the two thin sections, σ_1 is oriented E-W, and the two values are in good agreement, lying only ~22° apart. For the two sets of maxima α is 73° and 66°.

Feather features: FFs have been shown to form in conjugate sets (i.e., their PFs), while the lamellae of the FFs run parallel to σ_1 [5], (Fig. 2). Furthermore, the shear sense of a conjugate set of FFs is an unambiguous indicator for the orientation of σ_1 (Fig. 2). For the Ries sample, σ_1 was determined to run N-S and thus perpendicular to the direction indicated by the PFs.

Planar deformation features: Stereoplots of the unrotated PDF data show a weak preferential orientation in their density distribution (Fig. 3), with E-W and NNW-SSE oriented maxima.

Discussion: A surprising result is that the σ_1 orientation determined by PFs is at a 90° angle to the orientation determined from FFs. As FFs are seen here as the "strong" indicator for the stress field orientation, this implies that the conjugate fracture set of PFs has an opening angle α that is larger than 90° (107° and 114°), at least as determined by the maxima. The sequence of formation of the microstructures is probably relevant here. PFs are formed before PDF generation during shock loading [5-7] and FFs are developed thereafter during pressure release [5]. Thus, PF sets could be initially formed at an angle α<90° and then flattened through local grain rotation during the subsequent stages of deformation.

The weak preferred orientation of PDF values may infer a correlation between PDF generation and the orientation of the differential stress field, although it appears that more data are necessary for a statistically robust confirmation. U-stage data collection from a single thin section results in a "blind spot", visible in Figs. 1b and 3. This can be corrected by measuring three thin sections cut perpendicular to each other. The Ries sample does show a weak preferential orientation of quartz c-axes that lie N-S, which may also have an influence on the distribution of PDF orientations.

A further interesting observation is the occurrence of shear-derived FFs and conjugate PFs together with PDFs in a sample that lacks basal PDFs formed by brazil twinning. These (0001) PDFs presumably require a higher differential stress than necessary for the formation of FFs or conjugate sets of PFs. On the other hand, the authors have observed FFs together with (0001) PDFs in samples from Spider Crater, Australia, that are generally oriented parallel to each other, which suggests that FFs can form under a larger range of differential stresses than (0001) PDFs. It also seems plausible that the size of deviatoric stress within a shock wave varies between the shock front, pressure plateau and pressure release, thus making the formation of PFs, PDFs and FFs at different points in the shock wave not only dependent on the change in mean pressure but also on the development of differential stress states within the shock wave.

Outlook: We intend to gather more microstructural data from the Ries and other craters to improve the statistical validity of this study.

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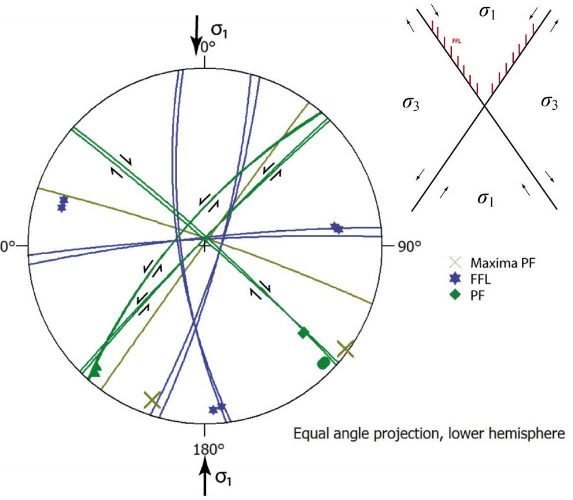

Fig. 2: FFs are a strong indicator for the orientation of σ_1, which is oriented N-S in the Ries sample. The inset shows how the shear orientation, feather feature lamellae (FFL), σ_1 and σ_3 are geometrically related.

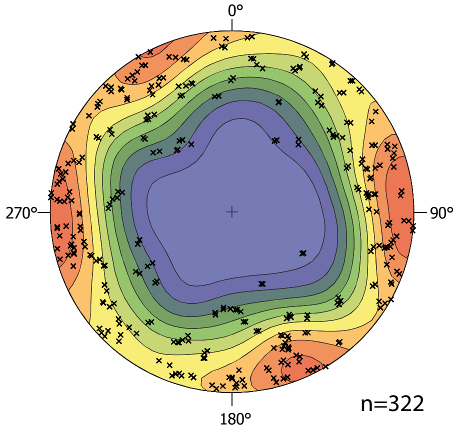

Fig. 3: PDFs from the Ries sample show a weak preferential orientation that may be related to the orientation of the differential stress field of the shock wave.