PLANAR DEFORMATION FEATURES IN QUARTZ GRAINS FROM RESURGE DEPOSIT OF THE LOCKNE STRUCTURE, SWEDEN; A.M. Therriault[1] and M. Lindström;[2] [1]Geol. Survey of Canada, Geophys. Div., Ottawa, Ont. K1A 0Y3; [2]Stockholm University, Dept. of Geology and Geochemistry, Stockholm, Sweden.

The Lockne structure, located 20 km south of Östersund, Sweden, has a diameter of 7-8 km and was formed in the Middle Ordovician,[1,2] at 455 Ma, based on infilling sediments and sedimentary cover.[3] Strongly shattered Proterozoic crystalline rocks, which form the local basement,[4] and what have been interpreted as fragments of impact melt, and grains of shocked quartz are evidence of its possible origin by impact cratering.[2,5] The proposed impact occurred at sea in an area consisting of Proterozoic crystalline basement covered by several tens of meters of Lower Palaezoic sedimentary rocks.[2] Detailed description of the structure can be found in Lindström *et al.*[5] and Lindström and Sturkell.[2] No optical measurements of the proposed shocked quartz were made, moreover, the occurrence of shock metamorphism has not been confirmed according to the criteria of Grieve *et al.*[6] Accordingly, we have undertaken a preliminary study of the "shocked quartz" to confirm or deny the occurrence of shock features.

Sample FF6, used in this more detailed examination, was collected in an outcrop consisting of thick-bedded Loftarsten, which is the local vernacular name for what was considered to be a tuffaceous lithic greywacke.[7] In more recent interpretations, this deposit is considered to represent the final stages of resurge deposition after the marine impact at Lockne.[2] In this case, the Loftarsten is a coarse arenite with an estimated median grain size between 0.25 and 1 mm and is composed of 10-15% lithic fragments derived from crystalline basement rocks, 15-20% limestone clasts, 10-15% pyroclastics (in the impact interpretation, ejecta of impact melt origin), which are more or less altered, 10-20% fossil fragments (mainly arthropods and echinoderms), about 10% quartz and feldspar grains, and 15-20% matrix.[7] Our sample is about 2 kg, massive (i.e., laminations and other structures are missing on the scale of the sample), and has a uniform composition.

A characteristic feature of quartz grains, found at impact sites, is the development of microscopic planar deformation features (PDF).[e.g., 6,8,9,10,11,12] In the sample studied, single quartz grains reveal from one to five lamellae sets of PDF (Fig. 1). Individual PDF are usually decorated with <1-3 μm isotropic inclusions and have a spacing of 1 to 5 μm between individual PDF. In general, the lamellae sets are sharp, moderately continuous, straight to moderately curved, and cover more than half the length of the grains. In 25 grains of quartz, the orientations of 82 poles of lamellae planes relative to the optical axis were determined using a universal stage. As quartz is weakly biaxial and the grains are weakly to strongly recovered, i.e., show mosaicism and wavy extinction, the precision of measurement did not exceed 5°.

The poles to all sets of PDF and the optic axes of each quartz grains studied were plotted on a stereonet, and then, rotated to a c-axis vertical orientation. This standard projection allows the identification of the poles of PDF with the crystallographic planes of quartz[e.g. 13] by overlaying a template of all rational crystallographic orientations (c-axis vertical orientation) onto the data for each quartz grain and then rotating the template to get a best fit to the PDF. This method, although time consuming, retains the angular separation between multiple sets of PDF, and thus, more confidence may be placed in the assignment of particular PDF to specific crystallographic indices of quartz. Our results are shown in Table 1 and Figure 2. Two marked peaks are obtained: one which corresponds to the ω $\{10\bar{1}3\}$ crystallographic plane of quartz with 39.0% of the measured orientations falling within ±5° of 22°56', and another corresponding to the π plane of quartz $\{10\bar{1}2\}$ with 23.2% of the lamellae sets measured falling within ±5° of 32°25'. Of all the PDF measured, 18.3% did not correspond to rational crystallogaphic planes for PDF in quartz.

The distribution of the orientation of the lamellae sets indicated that their crystallographic arrangement corresponds well with the distributions found at known impact craters with similar target rocks.[e.g., 10,11,13,14,15,16] PDF formed in shock-metamorphosed quartz are commonly oriented parallel to the basal pinacoid, c {0001}, and to the rhombohedral forms ω and π.[e.g., 8,9,10] Recognition of the ω orientation is important because this is not a normal cleavage or twin plane and is rare as a growth plane. Our results show that ω features dominate and that π features are the next most common features in the Lockne sample studied. This would indicate moderate shock pressures of >10 GPa during formation of the PDF.[17] The PDF found in the Lockne structure fulfill the general criteria defined by Alexopoulos *et al.*[12] that must be met for microscopic lamellar features in shock-metamorphosed quartz, i.e., features are well defined and sharp, relatively straight, parallel, and continuous, cover more than 50% of the grain, occur in multiple sets, and have a spacing between features of <5 μm.

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The Lockne Breccia and Loftarsten are interpreted as having formed after impact in a shallow sea and consist of ejecta brought back int the crater by resurgent water immediately after the impact.[2] Resurge deposition began with the polymictic Lockne Breccia, which has the properties of a debris flow, continued, and ended with the overlaying Loftarsten, which has roughly the composition of the Lockne Breccia except constituted of particles in the silt to fine gravel size range sorted by grain size. Furthermore, a relatively greater content of single quartz, feldspar, and fossil grains follows with the smaller grain size. Fragments of what are believed to be impact melt and shocked grains of quartz are observed in the Lockne Breccia[5] and shocked grains of quartz for certain in the Loftarsten (as shown in this study). We concur with Simon[7] in regarding the Loftarsten as the terminal and finest precipitate of the flow(s) initiated with the introduction of the Lockne Breccia; there are in fact transitions between the two lithologies. However, the further interpretations diverge between Simon[7] and ourselves because the impact hypothesis was not put forward by Simon at the time.

This preliminary study strengthens the previous conclusion by Lindström *et al.*[5] and Lindström and Sturkell[2] that the Lockne structure is an impact crater.

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Table 1: Planar deformation features (PDF) in quartz grains versus crystallographic indices in quartz, for sample FF6 of the Lockne structure, Sweden, as obtained from stereonet plots.

Plane	Miller-Bravais index	Angle with c-axis	Number of PDF	Percentage
c	{0001}	0°	3	3.7%
ω	$\{10\bar{1}3\}$	22°56'	32	39.0%
π	$\{10\bar{1}2\}$	32°25'	19	23.2%
ξ	$\{11\bar{2}2\}$	47°43'	3	3.7%
r	$\{10\bar{1}1\}$	51°47'	0	-
z	$\{01\bar{1}1\}$	51°47'	1	1.2%
s	$\{11\bar{2}1\}$	65°33'	2	2.4%
ρ	$\{21\bar{3}1\}$	73°25'	1	1.2%
ζ	$\{22\bar{4}1\}$	76°	1	1.2%
Γ	$\{40\bar{4}1\}$	79°	1	1.2%
χ	$\{51\bar{6}1\}$	81°57'	2	2.4%
m	$\{10\bar{1}0\}$	90°	1	1.2%
a	$\{11\bar{2}0\}$	90°	1	1.2%
unindexed	-	-	15	18.3%
Total	-	-	82	99.9%

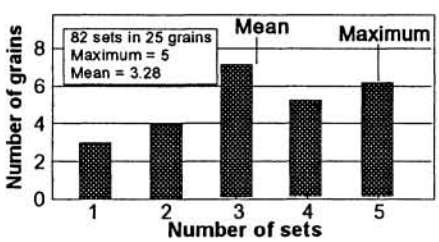

Figure 1: Histogram of the number of sets of planar deformation features per individual quartz grain from the resurge deposit of the Lockne structure, Sweden.

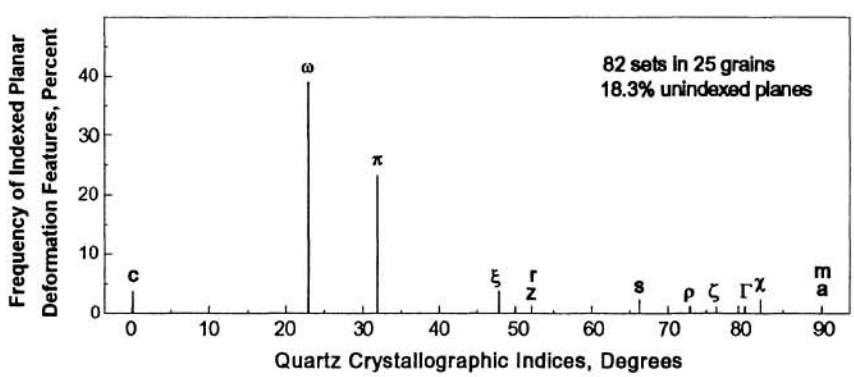

Figure 2: Histogram of indexed planar deformation features of quartz grains in relation to quartz crystallographic indices for the resurge deposit of the Lockne structure, Sweden.