OBSERVATIONS ON QUARTZ DEFORMATION IN THE BRECCIAS OF WEST CLEARWATER LAKE, CANADA, AND THE RIES BASIN, GERMANY

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Planar elements in shocked quartz grains from Clearwater Lake and the Ries basin are parallel to {0001}, {10$\bar{1}$3}, {10$\bar{1}$1}, {10$\bar{1}$2}, {10$\bar{1}$0}, and to other planes of the quartz lattice; they show a characteristic frequency distribution. Quartz grains containing planar elements also have reduced refractive indices, reduced birefringence, and reduced density; the measurements extend over nearly the whole range between normal quartz and fused quartz glass.

Two principal types of planar elements can be distinguished. *Decorated planar elements* consist of planar arrangements of very small inclusions or cavities. *Non-decorated planar elements* are not resolvable with the microscope. Preferential, cleavage-like separation occurs parallel to planes of non-decorated elements. Refractive indices and density of quartz with non-decorated elements are lower than those of quartz with decorated planes. The latter are apparently produced by lower shock wave pressures than the former.

Planar elements in quartz are assumed to have been formed by plastic deformation and by non-conservative movements of dislocation lines under high shock pressures.

QUARTZ FROM CLEARWATER LAKE, QUEBEC

In a breccia from Hole No. 4 (depth 179 ft.), drilled in 1963 by the Dominion Observatory within the circle of islands of West Clearwater Lake, Quebec (Dence, 1965), small fragments of granitic rock were found containing quartz which had been strongly affected by shock waves. The quartz appears as a white, silky, and friable mass similar to fine-grained sericite. Under the microscope, it can be seen that the individual grains contain several closely-spaced sets of planes, visible as some kind of optical heterogeneity which forms a plane, the orientation of which can be determined by universal stage methods. Similar planar features have been described from quartz in many impact craters under a variety of different terms (Bunch and Cohen, 1963; Bunch and Cohen, 1964; Dence, 1964; Dence, 1965; Engelhardt and Stöffler, 1965; Carter, 1965; Engelhardt *et al.*, 1967b; Robertson *et al.*, *this vol.*, p. 433). These planar features are here called planar elements (Fig. 1).

Orientations of planar elements and of the optic axes of quartz were measured in 30 grains of a thin section and in 32 grains of a powder mount. For every grain, stereographic projections were drawn containing the positions of the optic axis and the poles of all measurable planar elements. An example of such a plot is shown in Figure 2. There are, in this particular grain, six different sets of planar elements. The "blind circle" encloses the area not accessible to the universal stage. The stereographic projection can then be rotated into a position with the optic axis in the center (Fig. 3). In this projection, the measured planar elements can be identified with crystallographic directions. The dots and the crosses in Figure 3 indicate the ideal poles to crystallographic planes and the poles to sets of planar elements, respectively. A planar element was assumed to coincide with a crystallographic plane if the angle between measured and ideal poles was less than 6 degrees. This allowance corresponds to the accuracy of the universal stage measurements.

It is remarkable that, in most grains, sets of all planes equivalent by symmetry were often not completely developed. For example, in the grain described in Figure 3, the planes (1$\bar{3}$21) and ($\bar{3}$211) are symmetrically equivalent to the observed (21$\bar{3}$1). The plane ($\bar{3}$211) falls within

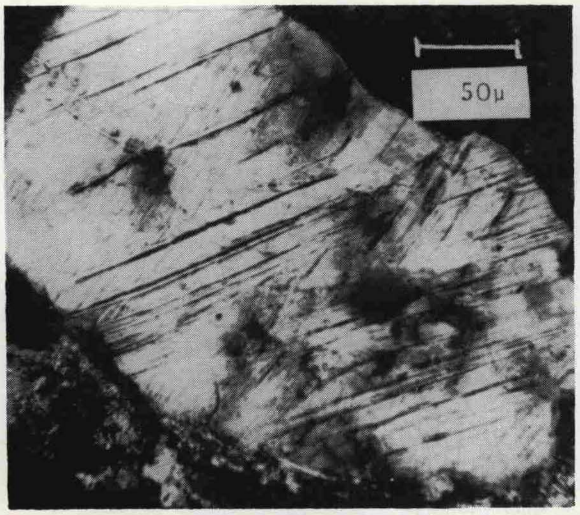

Fig. 1. Quartz grain with planar elements. Granite, hole No. 4 (1963), depth 179 ft, West Clearwater Lake, Quebec.

the "blind circle"; but (1$\bar{3}$21) could have been observed and was not found as a planar element.

There were, on the average, five different sets of measurable planar elements in each grain. Out of a total of 319 measured planar elements, 278, or 87 percent, could be identified with definite crystallographic planes (growth planes) of quartz, by means of the stereographic projections. The results of our measurements are summarized in Table 1.

In order to compare planar elements of different orientation, three methods for calculating frequencies (F_{I}, F_{II} and F_{III}) were used.[1]

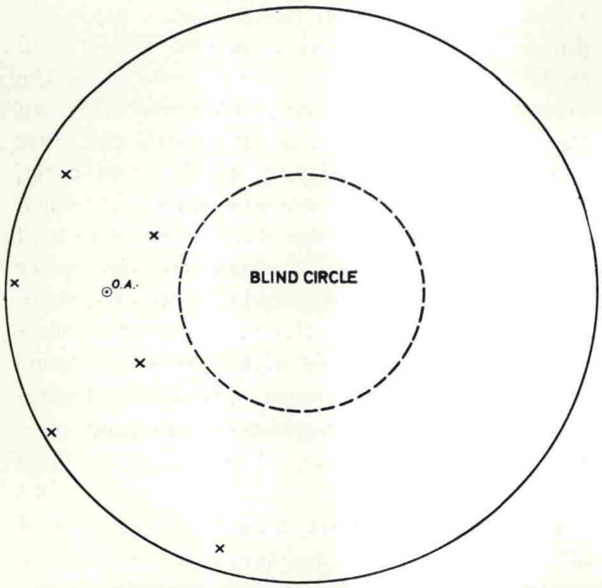

Fig. 2. Quartz grain (No. 31a), from a thin section of granite, hole No. 4 (1963), depth 179 ft, West Clearwater Lake, Quebec. The diagram is a stereographic projection of the poles of six sets of planar elements and of the optic axis.

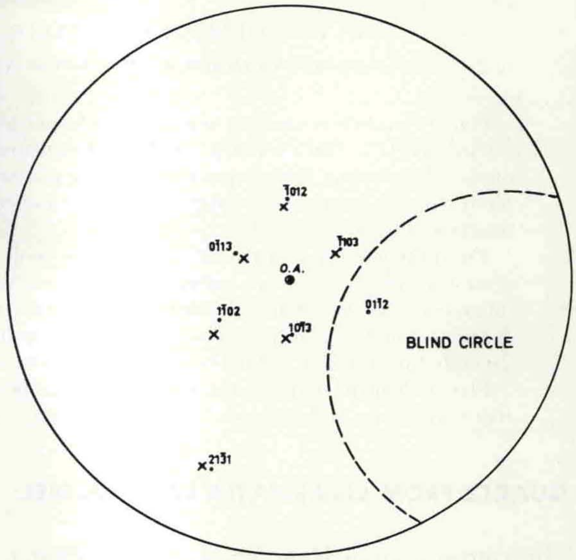

Fig. 3. Stereographic projection of the same quartz grain as shown in Figure 2, with the optic axis rotated into the center. Points indicate ideal positions of crystallographic planes. Crosses indicate measured positions of the poles to sets of planar elements.

[1] *Editor's note*. The statistical treatment of the petrofabric data outlined here is more complicated than that performed by some other investigators. The authors here include corrections for two factors: (1) the possible non-observation of planar sets due to inherent spatial limitations on the use of universal stage; (2) the fact that only one set of planes may develop parallel to {0001} in quartz, whereas six symmetrically equivalent planar sets can develop parallel to other forms.

Other investigators have used a simpler treatment, in which frequency diagrams are constructed directly from the number of *observed* planar sets (see Carter, *this vol.*, p. 453; French, *this vol.*, p. 383; Robertson *et al.*, *this vol.*, p. 433). Aside from possible debates on the relative merits of each method, it should be noted that frequency distributions constructed by the two different methods will not be entirely comparable; for instance, relative peak heights will differ. However, the grouping of planar sets into orientations closely related to a small number of specific crystal directions appears to be a unique property of quartz from such rocks, and will be apparent regardless of how the petrofabric data are treated.

TABLE 1

Frequency distribution of planar elements in quartz grains from West Clearwater Lake, Quebec

	Thin section (30 grains)					Powder (32 grains)				
			Frequency (%)					Frequency (%)		
$\{hkil\}_r$	q_r observable	p_r observed	F_{I}	F_{II}	F_{III}	q_r observable	p_r observed	F_{I}	F_{II}	F_{III}
$\{0001\}$	30	10	33	6.8	30	28	5	18	3.8	19
$\{10\bar{1}3\}$	173	51	30	35	26	156	32	21	24	21
$\{10\bar{1}1\}$	147	24	16	16	12	151	22	15	17	14
$\{10\bar{1}2\}$	163	23	14	16	12	154	24	16	18	15
$\{21\bar{3}1\}$	120	8	6.7	5.4	4.1	145	9	6.2	6.9	5.8
$\{11\bar{2}1\}$	124	7	5.6	4.8	3.6	142	7	4.9	5.3	4.5
$\{10\bar{1}0\}$	220	12	5.5	8.2	6.1	274	17	6.2	13	11
$\{11\bar{2}2\}$	151	5	3.2	3.4	2.5	142	7	4.9	5.3	4.5
$\{51\bar{6}1\}$	231	6	2.6	4.1	3.0	272	7	2.6	5.3	4.5
$\{31\bar{4}1\}$	116	1	0.8	0.7	0.5	140	1	0.7	0.8	0.6
not identified	...	15	...	...	...	...	26	...	...	...
Total	...	162	...	100	100	...	157	...	100	100

$$F_{\mathrm{I}}=(p_r/q_r)\times 100 \quad (\%)$$

$$F_{\mathrm{II}}=(p_r/\textstyle\sum_r p_r)\times 100 \quad (\%)$$

$$F_{\mathrm{III}}=[(p_r/\alpha_r)/\textstyle\sum_r(p_r/\alpha_r)]\times 100 \quad (\%)$$

where

q_r = the number of symmetrically equivalent planar elements $\{hkil\}_r$ which are observable in a sample of n grains, considering the limitations due to grain orientation and the "blind circle."

p_r = the number of symmetrically equivalent planar elements $\{hkil\}_r$ actually observed in the n grains.

$\sum_r p_r$ = the number of all observed planar elements in n grains which could be identified with crystallographic planes.

α_r = the number of symmetrically equivalent planes of the same form $\{hkil\}_r$ ($\alpha=1$ for $\{0001\}$ and $\alpha=6$ for all other planes).

As though it were a mineral with perfect cleavage, quartz from the Clearwater Lake breccia disintegrates easily into a powder consisting of fine flat fragments. The planes which bound these fragments are identical with the planar elements; this conclusion was demonstrated in the following way.

By gently pressing the cover glass, Canada balsam powder mounts could be prepared with all flat fragments lying with their largest faces (main fracture planes) nearly parallel to the slide. The angles were then measured between optic axes of the grains and the microscope axis, which was normal to the slide. If there were no preferred orientation of the grains, the probability of finding optic axes at angles between ϕ and $\phi+\Delta\phi$ would be given by the function of statistical distribution, i.e.,

$$P_{\phi+\Delta\phi}=\int_{\phi}^{\phi+\Delta\phi}\sin\phi\cdot d\phi=\cos\phi-\cos(\phi+\Delta\phi).$$

Figure 4 shows the difference ΔP between the measured and statistical distribution functions, derived from the above formula. Intervals of $\Delta\phi=4°$ were used. Positive values of ΔP mean that there are, in the particular range of orientation, more grains present than calculated for a random distribution. The maxima are situated at the same angles where the most frequent planar elements were found, indicating that fracturing of this quartz occurs preferentially parallel to planes which, in unbroken grains, are visible as planar elements.

QUARTZ FROM THE RIES BASIN, GERMANY

Similar planar elements in quartz are also very common in fragments of shocked granite and gneiss from the suevite breccia of the Ries Basin,

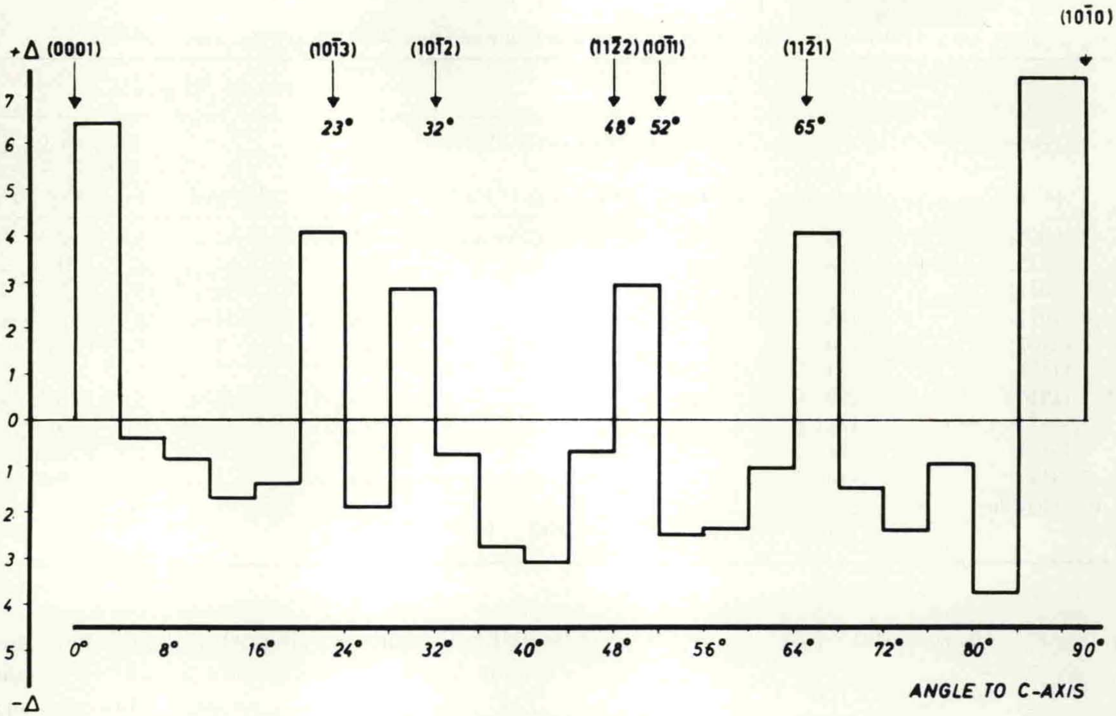

Fig. 4. Frequency diagram, indicating the preferred orientations of fractures in quartz grains, parallel to planar elements. Granite, West Clearwater Lake, Quebec (explanation in text).

Germany (Engelhardt and Stöffler, 1965; Stöffler, 1966). The results of measurements within a thin section of a granite inclusion from the suevite of Zipplingen are presented in Table 2. In this sample, the *average* number of measurable planar elements is 10 sets per quartz grain. The planes have the same crystallographic orientation as those found in Clearwater Lake quartz. The frequency distribution is similar, but not identical. In quartz grains from other Ries samples, we found the same orientations of the principal planar elements, but variable frequency distributions. It thus seems that the frequencies of planar sets are controlled by factors other than the peak pressure of the shock waves alone.

OPTICAL STUDIES OF SHOCKED QUARTZ

Quartz grains which contain planar elements also display lower refractive indices, lower birefringence, and lower densities than those of normal quartz. The distribution of refractive indices of Clearwater Lake quartz is shown in Figure 5. Using seven different immersion liquids, the frequency distribution functions of refractive indices of Clearwater Lake quartz grains were measured. There is an appreciable scattering, with mean values of $\epsilon = 1.539$ and $\omega = 1.542$, both

TABLE 2

Frequency distribution of planar elements in quartz from a granite inclusion in Suevite, Zipplingen, Ries Basin, Germany

	Frequency (%)		
$\{hkil\}_r$	F_{I}	F_{II}	F_{III}
{0001}	33	2.7	16
{10$\bar{1}$3}	68	34	30
{10$\bar{1}$1}	40	20	18
{10$\bar{1}$2}	59	30	26
{21$\bar{3}$1}	14	6.5	6
{11$\bar{2}$1}	3	1.3	1
{10$\bar{1}$0}	6	3	1
{11$\bar{2}$2}	1	0.3	0.3
{51$\bar{6}$1}	2	2	1

of which are lower than the principal indices of normal quartz.

Using samples from the Ries basin containing planar elements, we measured, on individual quartz grains, both refractive indices and density. We found refractive indices between 1.474 and 1.541, and corresponding densities between 2.263 and 2.648. Data for the shocked quartz of the Ries (Fig. 9) covers an appreciable part of the refractive index and density range between normal quartz ($\epsilon=1.544$; $\omega=1.553$; $d=2.65$) and fused quartz glass ($n=1.458$; $d=2.20$).

It appears that the refractive index and/or density of shocked quartz may be used as a

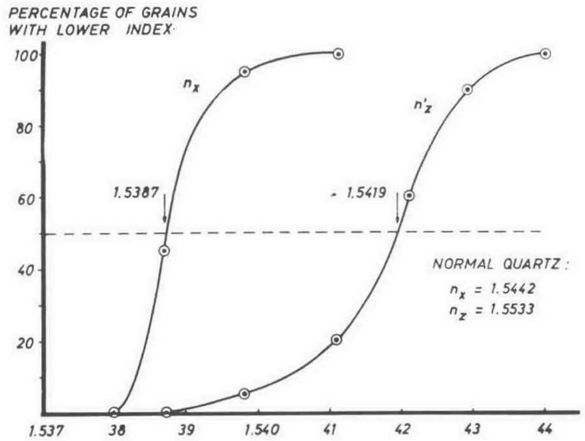

Fig. 5. Frequency distribution of refractive indices of quartz grains containing planar elements. Granite, West Clearwater Lake, Quebec.

rough indicator of shock wave intensity. In the Ries samples we found the lowest refractive indices and densities in rocks which show the highest degree of shock deformation of associated plagioclase (isotropization).

THE NATURE OF PLANAR ELEMENTS IN SHOCKED QUARTZ

The nature of planar elements in quartz is still under investigation, using optical methods, electron microscopy, and x-ray techniques. We can give here only some preliminary results and conclusions.

Two main types of planar elements can be distinguished:

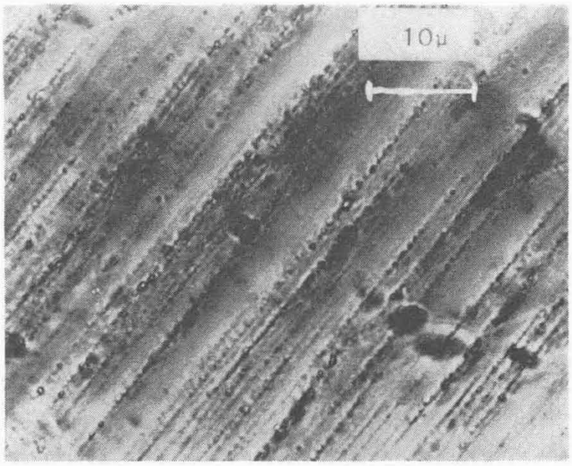

Fig. 6. Decorated planar elements in quartz. Granite inclusion, Zipplingen, Ries.

Decorated planar elements. These planar elements can be resolved under high magnification (oil immersion lens) into planar arrangements of very small inclusions, which appear to be either empty voids or cavities filled with gas or a liquid. The planar elements in quartz from the granite of Zipplingen (Table 2) belong to this type (Fig. 6).

Non-decorated planar elements. Planar elements of this type, if viewed in a direction parallel to

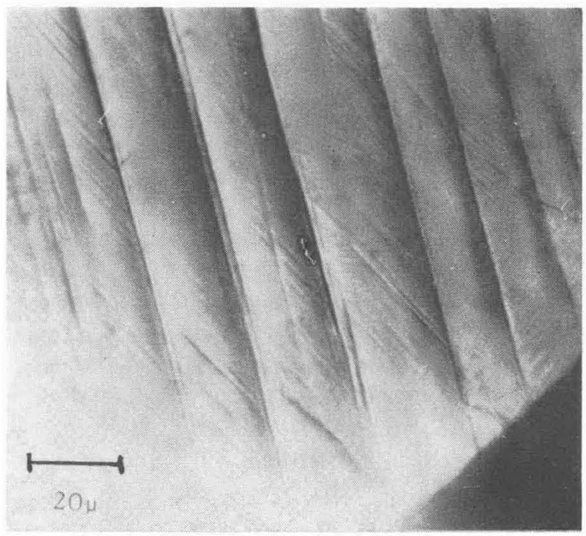

Fig. 7. Non-decorated planar elements in quartz. Granite, West Clearwater Lake, Quebec, Hole No. 4 (1963) depth 179 ft.

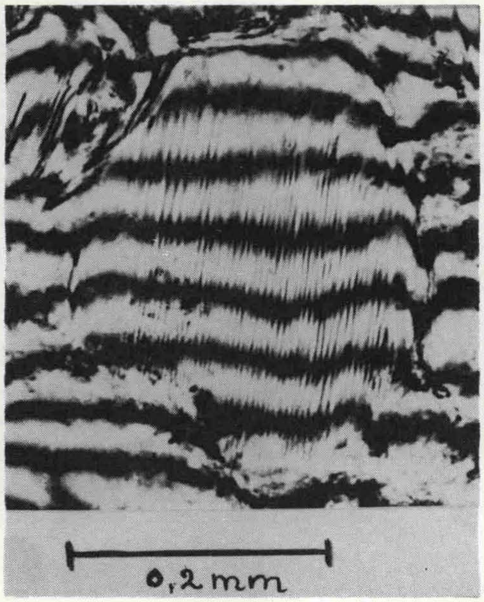

Fig. 8. Non-decorated planar elements in quartz. Two-ray-interference microscope (Leitz).

their planes, appear as unresolvable lines, even at the highest magnification. In some cases, they appear as very thin lamellae of lower refractive index and birefringence than the host quartz. The quartz from Clearwater Lake, described in this paper, contains planar elements of this type (Fig. 7).

Figure 8 shows a quartz grain with non-decorated planar elements as it appears under a Leitz two-ray interference microscope (green Hg line). The zig-zag course of the dark streaks is probably caused by discontinuous changes of the refractive index.

Separation along planar elements, observed in the Clearwater Lake sample and also in some quartz from the Ries basin, seems to occur only with the non-decorated type.

Quartz with decorated planar elements differs in density and refractive index from quartz with non-decorated planar elements. In samples from the Ries basin, we found the following ranges:

	$\bar{n}$	d
Quartz with decorated planar elements	1.546–1.529	2.648–2.577
Quartz with non-decorated planar elements	1.480–1.478	2.280–2.263

There seems to exist no distinct relation between crystallographic orientation and the type of planar element. Planar elements of all crystallographic orientations occur as both the non-decorated and the decorated form. The non-decorated elements are generally more narrowly spaced than are the decorated planes.

Our observations in the Ries basin seem to indicate that decorated planar elements are produced by shock waves of lower peak pressure than are the non-decorated elements.[2]

ORIGIN OF PLANAR ELEMENTS

Regarding the origin of planar elements in quartz, the following hypothesis is suggested. Shock waves of at least 100 kb peak pressure can cause plastic deformation of quartz by forcing dislocation lines, which at lower stresses are locked and immobile, producing non-conservative movements along lattice planes. These movements produce cavities or holes of macroscopic or atomic dimensions, as well as narrow layers along the gliding planes in which the crystal lattice is more or less destroyed. The reduced densities and refractive indices indicate that shocked quartz is in a kind of "spongy" state.

Quartz with planar elements represents transitional stages of order between normal α-quartz and the x-ray-amorphous SiO_2-glasses which are formed, without melting, at still higher shock

[2] *Editor's note.* An alternative explanation, proposed by other investigators, is that decorated planar elements are produced from originally non-decorated planar elements during post-shock annealing and recrystallization of the quartz, during which the planes may act as preferential growth sites for small liquid inclusions, (see e.g., Carter, *this vol.*, p. 453; French, *this vol.*, p. 383; Robertson *et al.*, *this vol.*, p. 433). Such alteration might occur either immediately after impact, during cooling of the ejecta blanket, or much later, during unrelated metamorphism.

In this connection, it is worth noting that planar elements from older structures of Precambrian or Early Paleozoic age are dominantly of the decorated type. By contrast, the planar elements formed in quartz by shock waves generated experimentally in nuclear or chemical explosions have never been observed to be of the decorated type. (see, e.g., Short, *this vol.*, p. 185). These observations also suggest that the decoration process itself is not directly related to the shock itself, but must depend on the post-event environment.

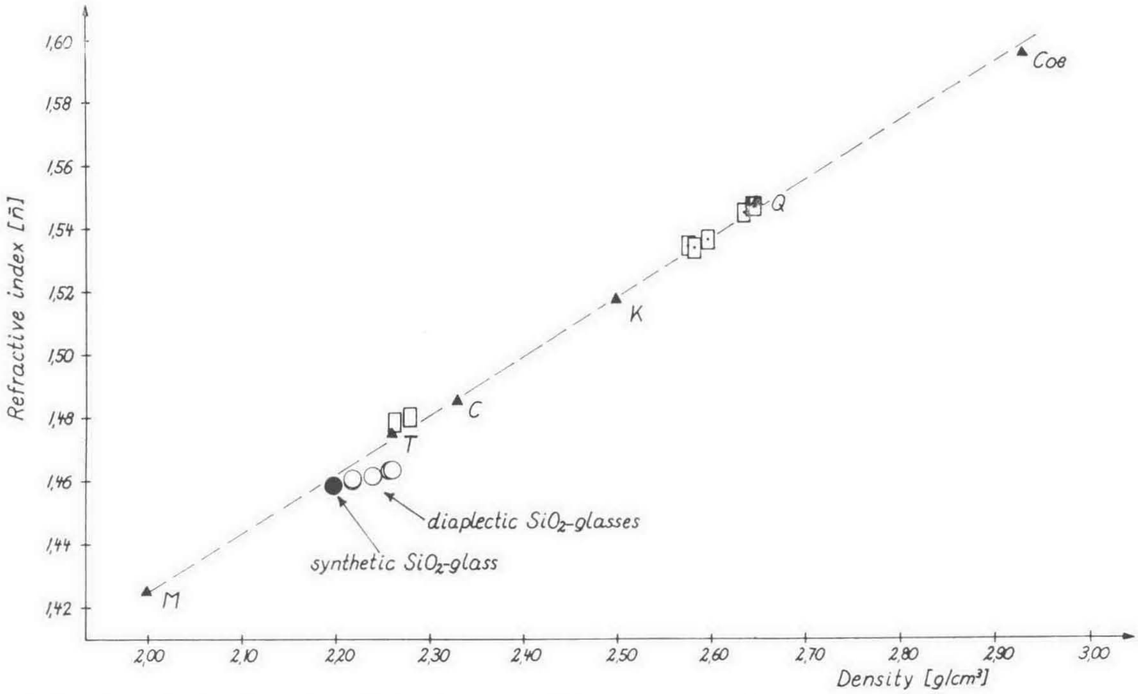

Fig. 9. Density and refractive index of SiO_2 phases. ▲ Solid triangle: crystalline phases—Coe, coesite; Q, quartz; K, keatite; C, cristobalite; T, tridymite; M, melanophlogite. ● Solid circle: fused silica glass. ○ Open circle: diaplectic silica glasses (Ries). ⊡ Dotted square: diaplectic quartz with planar elements of the decorated type (Ries). □ Open square: diaplectic quartz with planar elements of the non-decorated type (Ries).

pressures (>350 kb). Figure 9 shows the densities and mean refractive indices of these SiO_2-glasses and of quartz with planar elements from Ries samples. These shock-produced phases are distinctly different, in their physical properties, from both α-quartz and from fused silica. We propose to call them *diaplectic quartz* (quartz with planar elements) and *diaplectic quartz glass*, respectively (Engelhardt and Stöffler, *this vol.*, p. 159; Engelhardt *et al.*, 1967a).

Further investigations are desirable in order to elucidate the similarities and differences which exist between planar elements found in quartz from impact craters and deformation features which have been artificially produced by static high pressure experiments (Christie *et al.*, 1964; Carter *et al.*, 1964; Carter, 1965; Christie, *this vol.*, p. 624).

ACKNOWLEDGMENTS

One of the authors (W. v. E.) expresses his thanks to the Dominion Observatory, Ottawa, and especially to Dr. M. J. S. Innes and to Mr. M. R. Dence for the opportunity of working with the rock specimens from the Clearwater Lake drill holes. Thanks are also due to Prof. Dr. H. Haselmann, Dr. F. Habermalz and Dipl. Phys. J. Rienitz, Tübingen, for their help with the interference microscope. The authors thank the Deutsche Forschungsgemeinschaft for financial support.

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