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Fractures induced by shock in quartz and feldspar

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SUMMARY. This study is devoted to fractures produced by natural and artificial shock processes in non-porous rocks consisting essentially of quartz and feldspar. Petrological and textural investigations were performed using optical and scanning electron microscopic techniques. A microfracturation index is adapted from Short (1966, 1968*a*, *b*) in order to compare the fracture densities in different materials shocked in different ways. In all cases, the density of fractures in quartz and feldspar increases with increasing pressure to about 200 kb. At higher pressure this trend is reversed. Fracturing is more intense in feldspar than in quartz. Plane shock waves produced in laboratory scale experiments induce more fracturing than natural shock waves. However, such an increase is no larger than the scatter among the data and the experimental technique used in the laboratory can be considered realistic in terms of fracturing. Finally the correlation between pressure and fracture density is too poor to be of use for quantitative pressure calibrations of naturally shocked materials.

There is no direct correlation between the density of fractures and the number of planar elements observed. There is a negative correlation between fracturing and formation of diaplectic glass. Diaplectic glasses are remarkably weakly fractured compared with shocked minerals. The abrupt change in the slope of the curve giving the dependency of the density of fractures with pressure corresponds to the pressure at which diaplectic glass is formed. From petrographic considerations it is deduced that fracturing occurs at the end of the shock sequence, on pressure release, while diaplectic glasses are forming or already formed. Hypotheses of mechanical and thermal fracturing are examined; both are plausible, but a thermal origin may be preferred. The mechanism of formation of diaplectic glass is discussed with respect to results and deductions obtained by the study of fracturing. Diaplectic glass could represent a decompressed high-density glass resulting from a single state transformation of a mineral, at high pressure.

FRACTURES in minerals are a common feature of natural (impact craters) and artificial shock events (chemical-nuclear explosions, laboratory scale impacts, etc.). However, as the same effects are often generated by endogenic processes and by static experiments, fractures due to impact are at the threshold of non-ambiguous shock features. Because of this, they are relatively poorly studied compared with other shock effects. We still do not know exactly why, how, and when fractures occur in the minerals of shocked rocks. The purpose of this paper is to try to answer these questions, restricting the study to the behaviour of quartz and feldspar in non-porous rocks. Arguments will be supported by the examination of the correlations between fractures and the shock geometry, fractures and other shock effects, and also fractures and pressure. Previous studies have demonstrated a general increase in the density of fractures in shocked quartz and feldspars with increasing peak pressure in nuclear explosion studies (Short, 1966, 1968*a*, *b*; Faure, 1972; Borg, 1972), in laboratory cratering experiments (Hörz, 1969; Siegfried *et al.*, 1977) and in laboratory shock experiments (Short, 1968*a*, *b*).

Materials and methods

This work is based on the study of artificially and naturally shocked minerals. Gneiss (series 119) and leptynite (series 70) samples were collected from the undisturbed basement of the Rochechouart crater (Limousin, France). Small discs were drilled and artificially shocked by R. Jeanloz at the California Institute of Technology, using an impedance match method. Experimental conditions and resulting pressures are listed in Table I.

This material is complemented by artificially shocked quartz (140, 180, 220, 260 kb) obtained through the courtesy of D. Stöffler (1974), and by naturally shocked rocks from the Rochechouart (France), Mistastin Lake and Charlevoix astroblemes (Canada), and from the Ries crater (Germany).

The petrology and textures of these samples were studied using optical and scanning electron microscopic techniques. A microfracture index was adapted from Short (1966; 1968*a*, *b*) in order to compare the density of fractures from sample to sample. This density is the number of all extension fractures encountered in two orthogonal traverses across one microscope field of view averaged over 20-100 fields per thin section. According to the nature of the sample, different magnifications were

TABLE I. *Experimental shock data on gneiss from Rochechouart*

	119-2	119-3	119-4	119-7	70-05
Characteristics of the discs					
thickness (µm)	297 (±3)	274 (±3)	272 (±3)	434 (±10)	371 (±5)
diameter (mm)	4.7	4.7/4.2	4.6	4.6	4.5
mass (mg)	12.3	10.7	11.5	17.55	14.9
Characteristics of the projectile					
nature	W	Al	Al	W	Stainless steel 304
velocity (km/sec)	1.184 (±0.005)	1.41 (±0.01)	1.63 (±0.01)	1.11 (±0.01)	1.29 (±0.01)
Shock pressure (kb)	353 (±2)	180 (±2)	213.5 (±2)	327 (±3)	282 (±2)

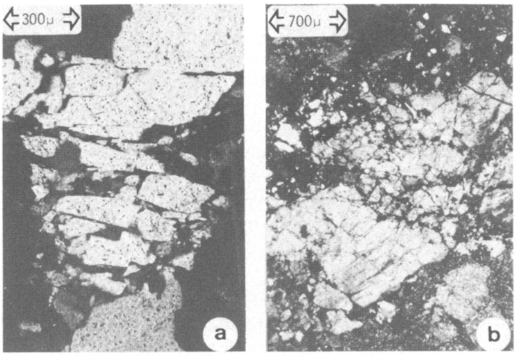
used from thin section to thin section. As the equivalent counting conditions were not maintained, each average number of fractures was normalized to one millimetre.

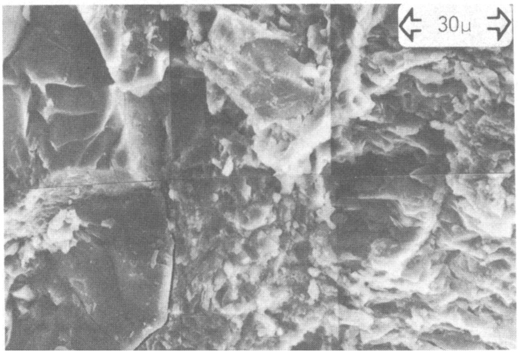
The most important limitation of the validity of the microfracture index comes from the concept of microfractures. Here, all surfaces of microscopic discontinuity in a crystal (twins, cleavages, planar elements excepted) are considered as microfractures. Some are produced in the preparation of the thin section. As far as possible they must be eliminated. The distinction is based mainly on subjective criteria resulting from experience. Edges of sections are avoided as well as sections where feldspars exhibit cleavage cracks (for more details see Simmons *et al.*, 1975). Possible errors induced by such selection are not important for highly fractured minerals, but can be critical for weakly or unshocked minerals.

Characteristics of fractures by shock

Macroscopically, highly fractured quartz is no longer transparent. When microfracturing is very intense, quartz and feldspars are pulverulent. Observed under the microscope fractures in quartz and feldspars may be irregular or planar (i.e. lattice controlled). These latter are well known in the literature: however most of the fractures in quartz and feldspars of shocked rocks are irregular surfaces, randomly oriented (fig. 1).

Fractures may be closed or open. In the first case, the fractured mineral is characterized by a very complex extinction when observed under polarized light (fig. 1*a*). When fractures are open, they often bound more or less displaced and rotated mineral fragments giving a breccia-like texture (fig. 1*b*). Usually the observed displacements are non-directional. Unidirectional gliding along fractures exists (Robertson *et al.*, 1968) but is relatively rare.





FIGS. 1 and 2. FIG. 1 (*top*). Shocked crystalline basement from the Rochechouart astrobleme. Thin sections observed under transmitted light and crossed nicols. (*a*) complex extinction of quartz due to fractures locally closed or open. (*b*) open fractures associated with small displacement and rotation of blocks giving a breccia like texture to the feldspar. FIG. 2 (*bottom*). SEM view of a fragment of a gneiss sample from Rochechouart, experimentally shocked to 180 kb (119-3). The irregular broken surface is due to and reflects the intense fracturing of minerals (closed fractures). Feldspar on the right is more highly fractured than quartz on the left.

High densities of fractures may be observed locally at the vicinity of grain boundaries, for instance, or along pre-existing fractures. In strongly fractured minerals, fractures generally tend to be equally distributed throughout the whole mineral.

Results

The different values of the microfracture index (*F/mm*) and the corresponding shock pressures are plotted in fig. 3 for each series of artificially and naturally shocked quartz and feldspars. The figure also includes previously published data. For each series *F/mm* increases with increasing pressure, but pressure is not the only parameter controlling the density of fractures. For a fixed value of the microfracture index, the corresponding pressures may vary by two orders of magnitude from series to series (see series 1 and 3). Among the other parameters to be considered are the pre-shock density of fractures, the characteristics of the mineral assemblage (grain size, porosity) the nature of the mineral, and the shock event itself.

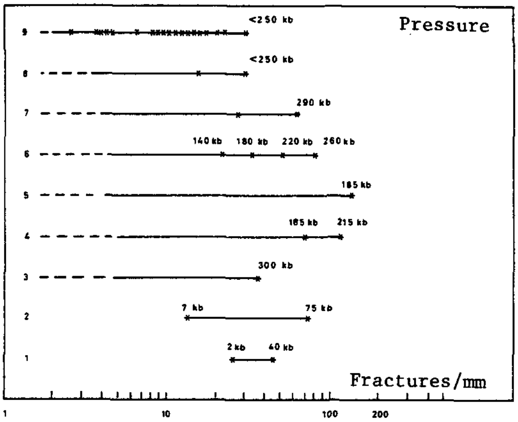


FIG. 3. Average fractures/mm in quartz and/or feldspar determined in thin section (see the text).

1. Quartz and feldspars of a granite specimen artificially shocked by a laboratory scale impact (Hörz, 1969).
2. Quartz and feldspars in a granodiorite artificially shocked by the Hardhat nuclear explosion (Short, 1968*b*).
3. Quartz and feldspars in a granite artificially shocked by a French nuclear explosion in Hoggar (Faure, 1972).
4. Quartz in a gneiss sample from Rochechouart, artificially shocked in laboratory (series 119).
5. Plagioclases (An 27) from the same material as 4.
6. Single crystals of quartz artificially shocked in laboratory. (Stoffler, 1974). The microfracture index is determined from analysis of each grain under microscope coupled with SEM observations.
7–8. Pyroxenes and plagioclases (An 50) from naturally shocked anorthosites from Lake Mistastin (Canada). Pressure is estimated by measurement of the refractive index (Lambert, 1977).
9. Quartz in naturally shocked granites of the Rochechouart structure.

Density of fracture and shock event. In the case of the Rochechouart structure, the characteristics of the rock samples before they were experimentally shocked are comparable to those of the pre-impact rocks of the basement (Lambert, 1977). Consequently values of *F/mm* in naturally and artificially shocked quartz can be directly compared in fig. 3 (series 4 and 9). The weakest shock experiment (185 kb) gives *F/mm* in quartz which is double the highest values in naturally shocked materials.

Density of fracture and nature of mineral. The individual properties of each type of mineral in a shocked rock are of course responsible for great differences in the resulting fracture. Quartz, harder than feldspar and without cleavage, is usually less highly fractured than feldspar (fig. 1). The direct comparison of their *F/mm* reveals significant differences.

Density of fracture and pressure. For this investigation the first priority is the precise knowledge of the pressure. Experimentally shocked materials are of course the most appropriate since the pressures can be calculated. We have also studied samples with diaplectic glasses of quartz and feldspar produced by artificial shock processes as well as by natural ones. In these cases shock pressures were determined at the mineral scale using a microreflectometry technique and the correlation between refractive index, composition and pressure (Lambert, 1977, 1979).

In order to consider the possible effect of differences in the pre-shock fracture density of the various materials studied here we use a relative microfracture index defined as the ratio of the difference between post- and pre-shock densities of fractures, to the pre-shock density of fracture. i.e. (*F/mm*)/(*F/mm initial*).

The results are presented in fig. 4, showing a general correlation between shock pressure and density of fracture, whatever the type of shock responsible. The correlation cloud is larger for the lowest pressure range because the errors in pressure determinations and in fracture densities are larger for low pressures and weakly fractured minerals.

From fig. 4 it is clear that the variation of the number of fractures as a function of the pressure is not uniform, but exhibits two trends. In the low pressure range (0–200 kb), fig. 4 confirms the well-established increase in microfractures with increasing pressure. Around 200 kb, the density of fractures in shocked quartz and feldspars can be

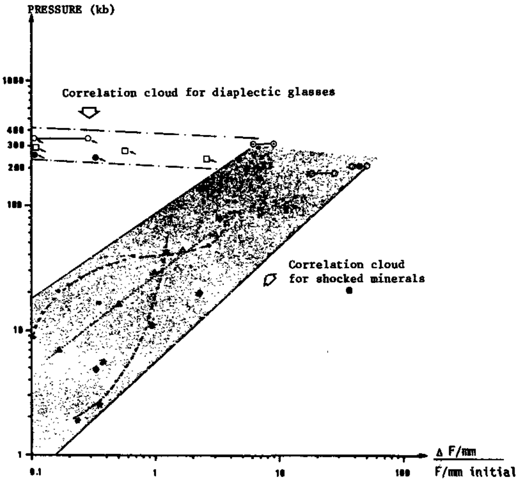


FIG. 4. Variation of the relative fracture index (difference between post- and pre-shock density of fractures divided by the pre-shock density of fractures) as function of the pressure.

open triangles: quartz and feldspars in a granodiorite shocked by the Hardhat nuclear explosion (Short, 1968*b*),

small full circles: quartz and feldspars in a granite shocked by the Hoggar nuclear explosion (Faure, 1972),

full lozenges: quartz and feldspars in a granodiorite specimen from Hardhat artificially shocked in laboratory (Short, 1968*b*),

stars: quartz and feldspars in a granite sample shocked by laboratory scale impact (Hörz, 1969),

open circles: quartz in a gneiss from Rochechouart (series 119) artificially shocked in laboratory (calculated pressure: see Table I),

full circles: quartz from the same material (series 119): pressure estimated for each grain separately from measurement of the refractive index (Lambert, 1977, 1979),

squares: plagioclases in granodiorite and anorthosite naturally shocked (Lake Mistastin, Canada). Pressure estimated from the measurement of the refractive index and determination of the chemistry of each mineral.

Arrows designate quartz and/or feldspars reversed as diaplectic glasses. Connected symbols give the spread of values from repetitive measurements as well as determination of the *F/mm* under reflected light.

5–50 times greater than the pre-shock density. For the high-pressure range (200–400 kb), values for artificially and naturally shocked samples are still in agreement, but the slope of the curve is reversed, and the density of fracture decreases with increasing pressure. Finally the microfracture index falls to the pre-shock values for the highest pressures.

Fractures and other shock effects in minerals. Fractures in minerals of shocked rock are known to be sometimes associated with so-called 'confirmed shock effects'. Planar elements and diaplectic glasses are of concern since they are well developed in quartz and feldspars.

Fractures and planar elements. The gneiss 119-7 and leptynite 70-05 artificially shocked to 327 and 282 kb respectively, exhibit numerous non-decorated planar elements in quartz and feldspar, as well as pronounced fracturing of these minerals. The *F/mm* are about ten times those of the original pre-shock. The planar elements are only visible at the highest magnifications making any quantitative study difficult. Moreover, such planar elements are observed only in these experiments, although they are suspected to be present in all the other tests but to be unresolvable (Lambert, 1977). In order to determine the geometry of the associated fractures and planar elements and their relative abundances in quartz and feldspars, it was decided to study naturally shocked rocks of granitic composition exhibiting decorated planar elements in quartz.

Since fractures do not clearly offset planar features, or the inverse, we determined and compared the number of fractures showing any evidence of discontinuity with respect to the geometry of the planar elements (such as gliding, planar-elements which do not cross the fracture) and the number of fractures without any effect on the planar element distribution. The latter represent the great majority of the studied cases (more than 90 %). It was noted that the proportions of fractures affecting planar elements are comparable to the number of pre-shock fractures in these minerals. The number of planar-elements per millimetre was also determined along the same traverses. Such measurements were made on eighteen samples from Rochechouart and six from Charlevoix. Comparative results are presented in fig. 5. There is no

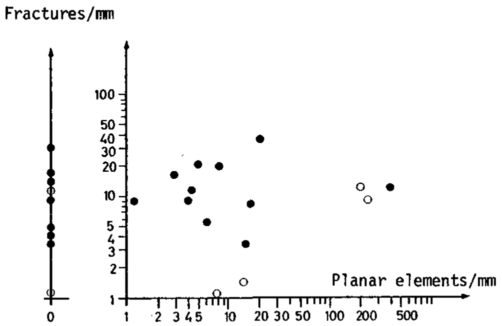


FIG. 5. Variation of the number of fracture/mm as function of the number of planar element traces in quartz naturally shocked from Rochechouart (full circles) and from Charlevoix (open circles). In the margin on the left are plotted values of *F/mm* of quartz without any planar elements.

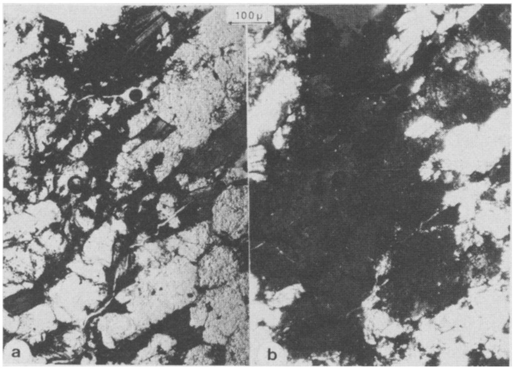


FIG. 6. Gneiss from Rochechouart artificially shocked to 215 kb (119-4). (*a*) In thin section diaplectic glasses are white and transparent, whereas quartz and feldspar appear grey and granular because of the high density of fractures. (*b*) Crossed nicols.

clear correlation between the density of fractures and the density of planar elements.

Fractures and diaplectic glasses. In contrast with the shocked quartz and feldspars, the corresponding diaplectic glasses are transparent since they are remarkably free of fracture. This difference appears in fig. 4 as a drop in fracture density in the pressure range characterized by the development of diaplectic glasses explaining the change of the slope of the curve. There is a significant negative correlation between the formation of fractures and the formation of the diaplectic glasses. Such divergence in the behaviour of minerals and glasses was clearly demonstrated by a petrographic analysis of gneiss 119-4, artificially shocked to 215 kb. Whereas most of the recovered sample observed in thin section revealed the expected highly fractured minerals, in a small region where the shock pressure must have been higher, all quartz and feldspar were transformed to diaplectic glasses (fig. 6). This region was weakly fractured compared with the minerals, consistent with the data of fig. 4.

Discussion

The correlation between pressure and microfracture is definitely too weak to allow any quantitative use for the estimation of the shock pressure registered by naturally shocked minerals. However, it can be helpful for qualitative investigations in the low-pressure range where fractures are the unique shock features exhibited by minerals, especially when the original density of fracture can be determined. For the higher pressure range a more appropriate barometer is needed such as the variation of properties of diaplectic glasses, if present (Lambert, 1979).

The difficulty of isolating the sample from its support in the experimental procedure is often argued as proof that shock experiments are not realistic with respect to the fracturing process. The relative overestimation of the number of fractures in quartz and feldspar of the artificially shocked gneiss is likely to be due to parasitic shock waves produced by multiple reverberations on and in the support. The exaggeration has been quantitatively estimated here, and it is not significantly different from the scattering of values obtained for the different types of shock wave generators (HE explosions, nuclear explosions, natural impacts: see fig. 4).

Finally the experimental technique, as used here, can be considered as realistic in term of fracturing processes. This means that the effect of the multiple reverberations on the support in the experiment is not significantly higher than the effect of the multiple reverberations on large heterogeneities or discontinuities of rock (such as fracture, boundary of two lithologies, etc.) in a natural event, reverberations which are avoided in the experiment because of the small size and the careful selection of the sample.

The number of planar elements per shocked mineral is expressed in a very general way as an increasing function of the shock pressure (Robertson *et al.*, 1968). From our results such correlation cannot be much more accurate than the relation between fractures and pressure in order to explain the poor correlation between fractures and planar elements.

Since there is usually no displacement at the junction of fractures and planar elements, their relative chronology is not directly accessible. However we would expect a higher proportion of fractures terminating planar elements if the latter were younger than the fractures. Fractures in such case would act as grain boundaries. The nearly identical proportions of pre-shock fractures and fractures effectively stopping planar elements in our experimentally shocked gneisses support such a hypothesis. On the other hand, if fractures occur before planar elements, there is no simple way to explain why planar elements can usually be recovered in diaplectic glasses (Robertson *et al.*, 1968; Engelhardt and Bertsch, 1969; Stoffler, 1972) and not fractures. As a result we think that fractures take place after the phenomenon generating planar elements. This is consistent with Klein's observations (1965) in explosively shocked MgO crystal which suggested that fracture followed the occurrence of planar features in the shock sequence.

The negative correlation between fractures and diaplectic glasses is the most illuminating result in terms of chronology and mechanism of fractures by shock. Theoretically fractures can be produced before, during, or after the formation of diaplectic glasses. The first hypothesis can be ruled out since, as we said previously, there is apparently no way to explain why the mechanism of formation of diaplectic glass cannot preserve fractures whereas it preserves grain shape, solid inclusions, planar fractures and other textural characteristics of the original mineral.

This leaves the two last hypotheses as the more plausible and this deduction is consistent with the previous results concerning the timing relation between fractures and planar elements. Since they are parallel to the planes of the crystal lattice of the original low-density mineral (i.e. unshocked mineral), planar elements must be formed early in the shock process, very likely during the compressional stage (first stage of the shock sequence).

Diaplectic glass must form relatively late, evidently after planar elements, otherwise the crystallographic control of planar elements could not be explained. On the other hand, diaplectic glass is found among the final low-pressure phases recovered after the shock event. It is deduced that diaplectic glass very likely forms after the compressional stage, during pressure release. Experimental studies of Ahrens *et al.* (1969) and Grady *et al.* (1974) on quartz, and Grady and Murri (1976) on feldspars show that a high-to-low density phase transition effectively occurs in some portion of the shocked constituents during pressure release. It can be concluded that fractures are formed at the end of the shock sequence, very likely during pressure release or after.

Fractures are usually considered to be the result of mechanical stresses. It is well known that cracks can propagate under tension. The pressure release is effectively characterized by a tensional wave and it seems reasonable that fracturing is produced mechanically during unloading. It can also be noted that the various features produced at shock pressure have different anisotropic elastic properties which, upon release, can lead to stress concentrations which can open fractures. On the other hand, the distribution of stress in the mineral is perhaps heterogeneous during the shock compression itself. According to a theoretical analysis of Grady (1977), large variations could be expected. Apparently, systematic, but small variations of the shock pressure have already been demonstrated in experimentally shocked rocks (Lambert, 1977, 1979). In any case pressure equilibration proceeds very rapidly, and it seems unlikely that strong pressure gradient can persist and create fracture. But thermal gradients can persist after the compressional stage because of the low thermal conductivity of minerals. If they are strong enough they create thermal stresses that can produce the forces necessary to cause fracture. The variability of physical properties of minerals, as well as porosity and water content are enough to lead to a heterogeneous distribution of heat inside the shocked mineral. Evidence of effects of high temperature gradients during unloading in experimentally shocked minerals have already been described (Anan'in *et al.*, 1974; Kanel *et al.*, 1977). Finally a thermal origin of fractures in minerals of shocked rocks must also be considered.

The problem of the mechanism of fracturing and the problem of the mechanism of formation of diaplectic glass must be considered together in order to explain the negative correlation between fractures and diaplectic glass. The easiest alternative would be to suppose diaplectic glass is at a liquid state (or near liquid) when the stresses are involved. Such a hypothesis must be ruled out. Melting is theoretically possible (Grady, 1977) but is difficult to reconcile with the preservation of fine and ultra-fine textures of the original mineral in the glass (Lambert, 1977). Diaplectic glass is more likely formed by solid state transformation. Since both phases are solid when the fracturing occurs, the negative correlation mentioned above implies that diaplectic glass readjusts to stresses in a more ductile fashion than the corresponding mineral. Such behaviour is not incompatible with the mechanical origin of fractures but it may be especially true if thermal stresses are involved; classically, glass tends to readjust to transient (i.e. thermal) stresses in a more ductile fashion, while minerals may behave in a more brittle manner.

Diaplectic glasses are generally considered as reversion products of the corresponding high-pressure phases which were formed during the compressional stage (Stöffler, 1972). Their behaviour on fracturing suggests that diaplectic glass is more compressible than the corresponding mineral. The density of the diaplectic glass may have been significantly higher under pressure. If such a hypothesis is valid, diaplectic glass could form directly by a single solid state transformation, at high pressure, as a high-pressure and high-density short-range order phase which would expand on unloading to give the resultant low-density glass.

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