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Effects of Shock Pressures on Calcic Plagioclase*

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Abstract. Samples of single crystal calcic plagioclase (labradorite, An63, from Chihuahua, Mexico) have been shock-loaded to pressures up to 496 kbar. Optical and electron microscopic studies of the recovered samples show the effects of increasing shock pressures on this mineral. At pressures up to 287 kbar, the recovered specimens are still essentially crystalline, with only a trace amount of optically unresolvable glass present at 287 kbar. Samples recovered after shock-loading to pressures between 300 and 400 kbar are almost 100% diaplectic glasses; that is formed by shock transformation presumably in the solid-state. Above about 400 kbar, glasses with refractive indices similar to thermally fused glass were produced. The general behavior of the index of refraction with shock pressures agrees closely with previous work, however, the absence of planar features is striking. At pressures less than 300 kbar, the most prominent physical feature is the pervasive irregular fracturing caused by the shock crushing, although some (001) and (010) cleavages are observed. No fine-scale shock deformation structures, i.e. planar features, were noted in any of the specimens. We conclude, in contrast to previous studies of shocked rocks that planar features are not necessarily definitive shock indicators, in contrast to diaplectic glass (e.g., maskelynite) and high-pressure phases, but are rather likely indicative of the local heterogeneous dynamic stress experienced by plagioclase grains within shocked rocks.

Introduction

In the past decade there has been increased research on naturally shocked plagioclase in terrestrial and lunar rocks, and in meteorites as well as plagioclase shocked to known pressure levels in the laboratory. The major motivation

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** Present address: Department of Mines and Energy, St. John's, Newfoundland for these studies is to develop quantitative and qualitative knowledge of the range of shock-induced effects in plagioclase and their correlation with concomitant effects in coexisting minerals, as well as to obtain a quantitative calibration of the occurrence of specific shock effects with pressure and temperature conditions of shock-loading. We expect to apply such data to interpreting and understanding the metamorphic histories of shocked rocks. This research has included extensive studies of shocked glasses of plagioclase composition and apparently shock-induced deformation features of plagioclase in meteorites (for example, in shergottite class meteorites by Duke, 1968 and Bunch et al., 1967 and in chondritic meteorites by Levi-Donati, 1971), in lunar rocks (for example, Englehardt et al., 1970; Chao et al., 1970; and numerous others), and in rocks from terrestrial impact craters (for example, Bunch et al., 1968; Chao, 1968; and Englehardt and Stöffler, 1968). There has also been some research on artifically shocked plagioclase, primarily, in rocks from man-made explosion craters (Bunch, 1968; James, 1969) and exploratory laboratory experiments (Milton and DeCarli, 1963; Jamieson and DeCarli, unpublished data). Recently, more systematic shock-loading experiments have been carried out (Gibbons, 1973, Stöffler and Hornemann, 1972, and Stöffler, 1974) to characterize the effects of shock compression on plagioclase. The relation of the formation of shock glasses to the Hugoniot equation-of-state and release adiabats of plagioclase has also been studied (e.g., Ahrens and Rosenberg, 1968; Ahrens et al., 1969).

The nomenclature applied to shock-produced deformation features and glasses of feldspar composition has been discussed by Stöffler (1972). Here we will use the term "diaplectic" to describe shock-produced solid-state glass and "shock-fused" glass to describe glass produced by shock-melting. The latter are glasses with indices of refraction corresponding to thermal glass, or which demonstrate flow textures. In toto both types will be referred to as "shock" glasses. This latter term is useful as often it is apparent that a rock containing a homogeneous glass has been shocked, but it may not be obvious whether the glass was formed by shock-induced melting or solid-state transformation if flow textures are not present. The term "maskelynite" is a name that has been used to describe terrestrial, meteoritic, lunar and experimentally-produced diaplectic *plagioclase* glass (for example, Dworak, 1969; Binns, 1968; and Milton and DeCarli, 1963, respectively).

Shock Experiments

Laboratory shock experiments on calcic plagioclase (An 63) were performed at controlled peak pressures up to 496 kbar.

The original sample material was small, sub-rounded fragments of translucent, essentially colorless semi-precious gemstone-quality single crystal plagioclase. It was obtained from Burminco, Monrovia, California, where it was described as bytownite from Chihuahua, Mexico. Electron micro-probe analysis revealed its composition as labradorite, An63 (mole %). The analysis and some measured physical properties are given in Table 1.

Table 1. Analysis of labradorite from Chihuahua, Mexico[a]

Oxide	Weight (%)
SiO_2	53.38
Al_2O_3	31.23
CaO	11.85
Na_2O	3.59
K_2O	0.37
FeO[b]	0.35
	100.77
Mole %	
Albite (Ab)	34.6
Anorthite (An)	63.1
Orthoclase (Or)	2.3
Refractive Indices	
n_α	1.560 ± 0.001
n_β	1.565 ± 0.001
n_γ	1.570 ± 0.001
Density	
D	2.70 ± 0.02 g/cm^3

[a] Single chemical analysis by A. Chodos using the California Institute of Technology electron microprobe, May 26, 1972
[b] Total Fe as FeO

For shock-loading, the samples were sawn into small slabs which were cored into 4.75 mm diameter discs. The discs were hand-ground to final thicknesses; two samples (113, 133) were ground to 0.875 mm and all the others to 0.5 mm. The crystallographic orientation of the shock-loaded discs was random relative to the impact direction of the flyer plates and the propagation direction of the shock wave.

The sample discs of the feldspar were shocked to a series of pressures between 58 and 496 kbar. Most of these specimens were completely recovered, intact, after the shock-loading. All the discs were shocked in stainless steel 304 containers. Tungsten flyer plates were used on all except the 58 kbar and 106 kbar shots, where aluminum 2024 and stainless steel 304 were used, respectively. The peak shock pressures were determined graphically using the measured projectile velocities and the "impedance matching" technique (Duvall and Fowles, 1963). The pressures are accurate to approximately $\pm 3\%$. The uncertainty is due mainly to inaccuracies of approximately 1% in measuring the projectile velocity and about 2% arising from uncertainty in the Hugoniot data.

After recovery, fragments of the recovered discs were used for refractive index measurements. Standard immersion techniques and interference microscopy were used.

Grain mounts were examined with a polarizing microscope to study shock-produced deformation features. Such features are best observed in doubly polished thin sections (private communication, Stöffler, 1976). Attempts were made to prepare thin sections from parts of the discs from shots 163 and 173 but the fragments were too fragile because of the pervasive fracturing and were destroyed. The universal stage technique was used on several specially prepared grain mounts for observation of the physical features of the crystalline recovered samples (for example, Turner, 1947).

In a further search for vitrification and fine planar deformation features in the crystalline samples, fragments from shot 163 (287 kbar, the highest pressure plagioclase not transformed to glass) and shot 174 (106 kbar) were examined by transmission electron microscopy using the methods of Phakey, et al. (1972).

Shock Vitrification

The data on the refractive index measurements of the shocked plagioclase are given in Table 2. These data are graphically presented in Figure 1 with some similar data for oligoclase, labradorite, quartz, orthoclase, and microcline (Kleeman and Ahrens, 1973; Kleeman, 1971; Robertson, 1972; and Stöffler, 1974). Refractive indices of the crystalline and amorphous phases are correlated with the peak shock pressure to which each specimen was loaded. The qualitative agreement of the present data for An63 is close with respect to the results given in Stöffler (1974) for An51 composition.

For shock-loading to peak pressures of 287 kbar and less, the amount of vitrification of the plagioclase was insignificant on the basis of refractive index measurements. No change in refractive index was observed within the error of measurement (± 0.001) of the immersion technique used. In our 287 kbar labradorite sample, no glass was observed optically, but vestiges were observed in the otherwise totally crystalline sample in grain amounts examined by transmission electron microscopy using a JEM-7A 120 kv microscope. However, for peak shock pressures higher than ~ 300 kbar, the recovered samples were essentially amorphous. This was also shown by the changes in refractive indices observed. For the 340 kbar sample, indices were 0.0086 to 0.0180 lower than the mean index, $n = 1.565$, of the unshocked crystalline plagioclase. Similar changes were observed in the sample shocked to 363 kbar, and changes of 0.0180 to 0.0261 were observed in the 350 kbar sample. In the discs shock-loaded to 484 and 496 kbar, a mean refractive index change of 0.025 was measured.

These measurements are consistent with formation of glasses at shock pressures between ~ 300 and 400 kbar by shock destruction of the plagioclase crystal structure in the solid state at temperatures below the glass transition temperature,

Table 2. Refractive index measurements of glass shock-produced from plagioclase, An63[a]

Shot number	Shock[b] pressure (kb)	Refractive index (n)
145	340	1.5470 to 1.5564
144	350	1.5389 to 1.5468
133	363 ± 17	1.5472 to 1.5534
147	484	1.540 ± 0.002
113	496	1.540 ± 0.001

[a] The refractive indices of the crystalline plagioclase were $n_\alpha = 1.560$, $n_\gamma = 1.570 \pm 0.001$

[b] Uncertainty, $\pm 3\%$

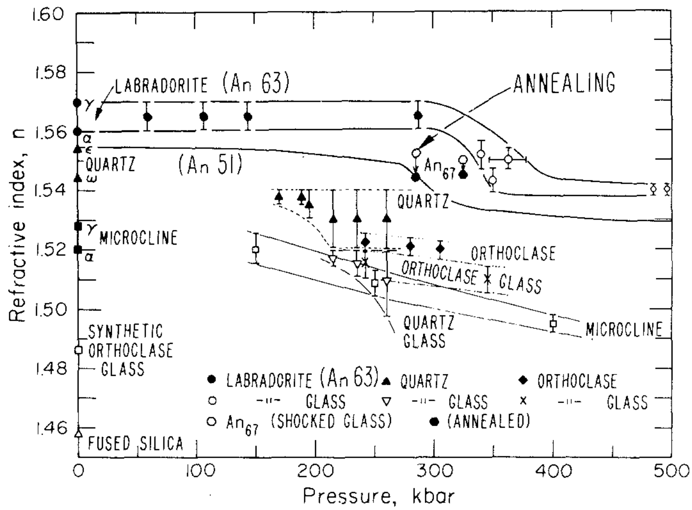

Fig. 1. Refractive index versus peak pressure for experimentally shocked labradorite An63 (this work), labradorite An51 (Stöffler, 1974), orthoclase (Kleeman, 1971), quartz (Kleeman and Ahrens, 1973), microcline (Robertson, 1972), An67 (Bell and Chao, 1969). Similar results on quartz have been obtained by Hörz (1968) and Stöffler (1974)

T_g (Rawson, 1967); that is, they are diaplectic glasses. The glasses formed at pressures greater than ~400 kb, appear on the basis of the indices, to be produced by shock-melting above T_g. Shock temperature calculations (Ahrens et al., 1969) show that temperatures are high enough to form shock-fused glasses. In Figure 2 the refractive indices of our shock glasses completely intersect the field of diaplectic glasses, as defined by Stöffler and Hornemann (1972) and Stöffler (1974). The indices of the glasses produced around 350 kbar fall within the diaplectic field; those of the glasses formed at >400 kbar fall near the line of indices for normal plagioclase glasses.

Of course, it is not an absolute rule that diaplectic glasses must fall within this defined field, as Stöffler and Hornemann point out. There are examples of calcic plagioclase shock glasses from shergottite class meteorites (Shergotty: Duke, 1968 and Bunch et al., 1967; Padvarninkai: Binns, 1967) and anorthitic lunar glasses (for example, Apollo 11, Engelhardt et al., 1970) which have refractive indices much higher than the diaplectic field shown in Figure 2, but which are believed by their investigators to be diaplectic glasses. Some of these glasses have indices near the mean indices of crystalline plagioclase. The reason for their high indices may be that those glasses were subjected to high pressures subsequent to shock formation. Such pressures, which could have been produced by additional later impacts in the case of both lunar rocks and meteorites, could result in permanent densification sufficient to move them out of the diaplectic glass field of Figure 2 (e.g., Gibbons and Ahrens, 1971). Another possibility is that diaplectic glasses with peculiarly high refractive indices could have formed from feldspar having a significant Fe-content (Engelhardt et al., 1970).

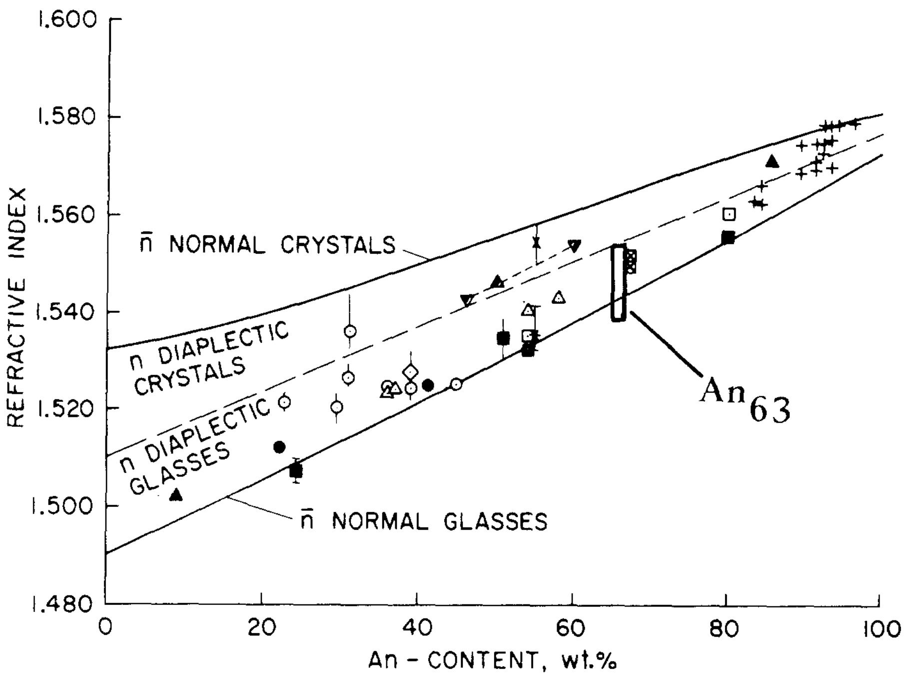

Fig. 2. Refractive index versus anorthite-content of plagioclase glasses after Stöffler (1974). Solid lines represent mean refractive indices of plagioclase crystals and synthetic plagioclase glasses (Barth, 1969). Vertical bars indicate measured variations of refractive indices. ⊙ Ries crater (Stöffler, 1967 and Stöffler and Hornemann, 1972). ◇ Ries crater (Engelhardt et al., 1967). △ Ries crater (An_{37}), Sedan nuclear crater (An_{36}), Manicouagan crater (An_{54}), Clearwater Lake West (An_{58}) (Bunch et al., 1968). ◬ Shergotty meteorite (Bunch et al., 1967). × *, Manicouagan crater (Dworak, 1969). ▽ Shergotty meteorite (Duke, 1968). ▲ Chateau Renard (An_9) and Padvarninkai meteorites (Binns, 1967). + Mare Tranquillitatis ($An_{83}-An_{96}$), Apollo 11, 10084,106; 10085,25 and 10085,26 (Engelhardt et al., 1970). ● Ries crater (Bell and Chao, 1970). ⊠ Shock experiments (Bell and Chao, 1970) ■ (An_{80}), shock experiments (Milton and DeCarli, 1963). ■ Shock experiments, (An_{24} = No. 12; An_{51} = No. 13, Stöffler and Hornemann, 1972). ■ (An_{54}), shock experiment (Muller and Hornemann, 1967). ▯ Data from this work for An63 (otherwise this figure is the data compiled by Stöffler and Hornemann (1972) for their Figure 5)

Thus, negligible vitrification of nonporous, single crystal plagioclase is caused by shock pressures less than ~300 kbar. Diaplectic glass is caused by shock-loading to pressures between ~300 and 400 kbar, and what is probably shock-fused glass is caused by peak shock pressures greater than ~400 kbar. Other experimental data on plagioclase agree with these results. Diaplectic and shock-fused glasses were produced from plagioclase, An80, by Milton and DeCarli (1963) in two gabbro specimens shock-loaded to estimated pressures of 250 to 350 kbar and 600 to 800 kbar, respectively. Diaplectic glass was formed from two fragments of labradorite, An67, single crystal shock-loaded to pressures of approximately 285 and 325 kbar by DeCarli and Ahrens (in Bell and Chao, 1969). Stöffler and Hornemann (1972) also produced diaplectic and shock-fused glasses by shock-loading plagioclase of compositions An_{24} and An_{51}; their

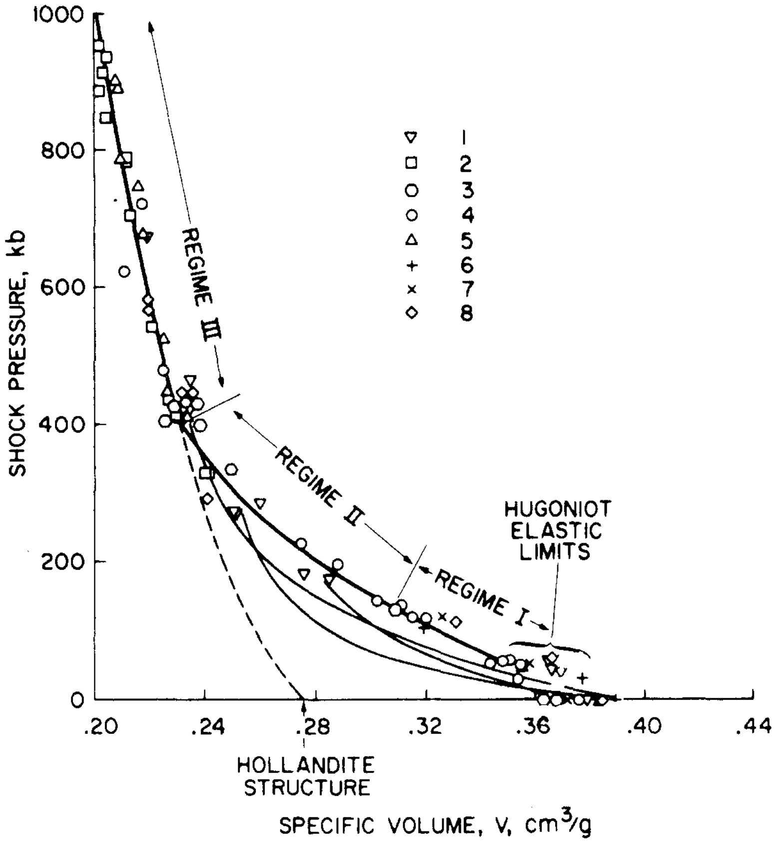

Fig. 3. Composite Hugoniot of the feldspars (Ahrens et al., 1969). *1* oligoclase, *2*, *3*, *4* anorthosite (polycrystalline andesine), *5* albitite, *6* albite, *7* labradorite, *8* microcline. The three distinct phase regimes (I, low pressure; II, mixed; and III, high pressure) are indicated as well as a range of Hugoniot elastic limits. Three release adiabats are shown for oligoclase. Note their positions relative to the Hugoniot. The density of zero pressure hollandite structure feldspar is also noted

pressure regimes for the diaplectic and shock-fused glasses do not quite match ours. They concluded from their data that *diaplectic* glasses were formed from feldspars at shock pressures between about 300 and 450 kbar, but that pressures exceeding about *430* kbar were necessary to produce *shock-fused* glasses. This is close to the value inferred for melting by Stöffler (1974). Their lower bound of 300 kbar is compatible with our data for the formation of diaplectic glass and their infrared spectra remain almost unchanged above 300 kbar. However, we prefer a slightly lower figure of ~400 kbar for the beginning of shock-fusion; the infrared results provide no basis for differentiating diaplectic glass from shock-fused glass under these conditions. Recent results on the experimental shock metamorphism of plagioclase-containing lunar soil analogs (Gibbons et al., 1975a) and terrestrial basalt (Gibbons et al., 1975b; Kieffer et al., 1975) support these conclusions.

Other representative tectosilicate data (orthoclase, quartz, and microcline) (Kleeman, 1971; Kleeman and Ahrens, 1973; and Robertson, 1972), are also shown in Figure 1 for comparison with the present results. Their behavior is similar. At pressures less than 150–200 kb, no significant changes in refractive index were observed. At higher pressures partial transformation to shock glass occurs; finally, the crystalline mineral is completely transformed to shock glass. A difference between the labradorite and the quartz and alkali feldspars is that for the latter there is apparently a larger pressure range over which diaplectic glass and crystal coexist. This was also observed by Robertson in microline and by Kleeman in both quartz and orthoclase.

One may estimate where the position of the recovered materials fit on a typical tectosilicate Hugoniot graph, in Figure 3 (Ahrens et al., 1969). The Hugoniot is divided into three regimes based on the high pressure states of the shocked material as discussed previously by Stöffler (1972, 1974). Regime I consists of the original low-pressure phase material and Regime III, of material that has been compressed to a dense high pressure phase; Regime II is a mixed phase regime containing both high and low pressure phase materials. Considering all the available tectosilicate data, we may take exposure to ~200 kbar as a boundary for the first appearance of diaplectic glass in tectosilicates. This is clearly within the mixed phase regime along the Hugoniot. On the basis of our data, and that of Stöffler and Hornemann (1972) on plagioclase, we consider 400 kbar an appropriate boundary for the onset of complete fusion of shock-recovered tectosilicates. This pressure is approximately the boundary between the Hugoniot mixed and high pressure phase regimes although it is not clear that this correlation is more than fortuitous. One conclusion from these results is that no vitrification is caused by shock-loading to pressures within the low-pressure phase regime, increasing amounts of diaplectic tectosilicate glass are formed by exposure to shock pressures of ~200 to 400 kbar within the mixed phase regime (with possibly complete transformation at ~300 kbar), and shock-fused glasses are produced as a result of shock-loading to pressures greater than 400 kbar to high pressure phase states within Regime III.

Shock-Produced Deformation Features

Considerable study has been carried out in describing shock-induced deformation features observed in rocks from terrestrial impact craters (see, for example, Chao, 1967a, b, 1968; Robertson et al., 1968; Dworak, 1969; and Stöffler, 1972). Studies on shock-induced planar features in plagioclase have mainly been on materials from the Ries crater (Stöffler, 1967; Chao, 1968) and from impact craters in Canada (for example, Robertson et al., 1968 and Dworak, 1969). Some studies have also been made on plagioclase artificially shocked in nuclear and chemical explosion craters (for example, James, 1969).

Most of the deformation features previously identified in labradorite have been parallel to crystallographic planes of low Miller indices, many of which are also common cleavage and twin lamellae planes. Other features include irregular fractures not assignable to any rational crystallographic planes. Electron microscopy indicates that the micron-scale planar features appear to result from a variety of mechanisms (Christie and Ardell, 1976). These measured features in feldspars commonly occur on (001), (010), (100), (101), (111), (120), (012), and (203) (Stöffler, 1967; Robertson et al., 1968 and Dworak, 1969). These appear to be structurally-controlled and their production are generally assigned to a pressure range of 150 to 300 kbar (for example, Stöffler, 1972). However, a lower limit is more difficult to define; planar features in certain orientations may result from static yielding at very low stresses. Studies have been made of such features by static deformation techniques at (for example, Carter, 1971; Borg and Heard, 1970) and some of the common apparent shock orientations have been produced statically at pressures as low as 2 kbar at 700–800° C (for example, (010) slip and albite and pericline twins, Carter, 1971). We note also that Borg (1972) has observed a distinct lack of such shock-induced features in a Na-rich plagioclase. Accordingly, it is clear that the lack of planar features in plagioclase, does not appear to preclude exposure to shock. Planar features certainly indicate deformation, however, it appears likely to us that they may only form within plagioclase grains exposed to dynamic heterogeneous stress such as undoubtedly is present within a rock undergoing shock compression. We emphasize that in this work the samples were gem quality material with no initial cleavages or twinning. In the shocked metal containers, these samples were no longer colorless and translucent, but finely crushed, opaque white, with no significant difference in appearance in 58 kbar to 287 kbar experiments. The material was very fragile and flaked very readily from needle point.

Upon examination with an optical polarizing microscope, the most prominent feature of the sample shocked to 58 kbar was the abundant irregular fracturing. No fine deformation lamellae or mechanical twinning was detected at magnification up to 1000×. No undulatory extinction was observed.

Likewise, the specimen shocked to 106 kbar was irregularly fracturing and crushed in appearance. Occasional fragments contain coarse cleavage or parting features; one cleavage is parallel to (001) and a less pronounced cleavage (010) (Fig. 4). It shows the mosaic pattern created by the irregular crushing which might have resulted from tensional fracture during pressure release. This section was ion-thinned and examined using a 800 kV transmission electron microscope at U.S. Steel Research Center, Pennsylvania (Radcliffe et al., 1974). At a magnification of 22,700×, no vitrification or fine planar elements were recognized.

Plagioclase shocked to 143 kbar is optically similar to that shocked to 106 kbar. However, some small fragments show undulatory extinction between crossed nicols.

In the labradorite shocked to 287 kbar, the observed shock features include the predominant irregular fractures and two sets of approximately perpendicular coarse cleavages, as described for the lower pressure shots, with the (001) cleavage generally the better developed. Some undulatory extinction but no planar features were observed optically. A similar result was obtained using the 120 kV transmission electron microscope at the University of California, Los Angeles.

The diaplectic and shock-fused glasses were also examined for deformation features. None were observed. The only physical features observed in those

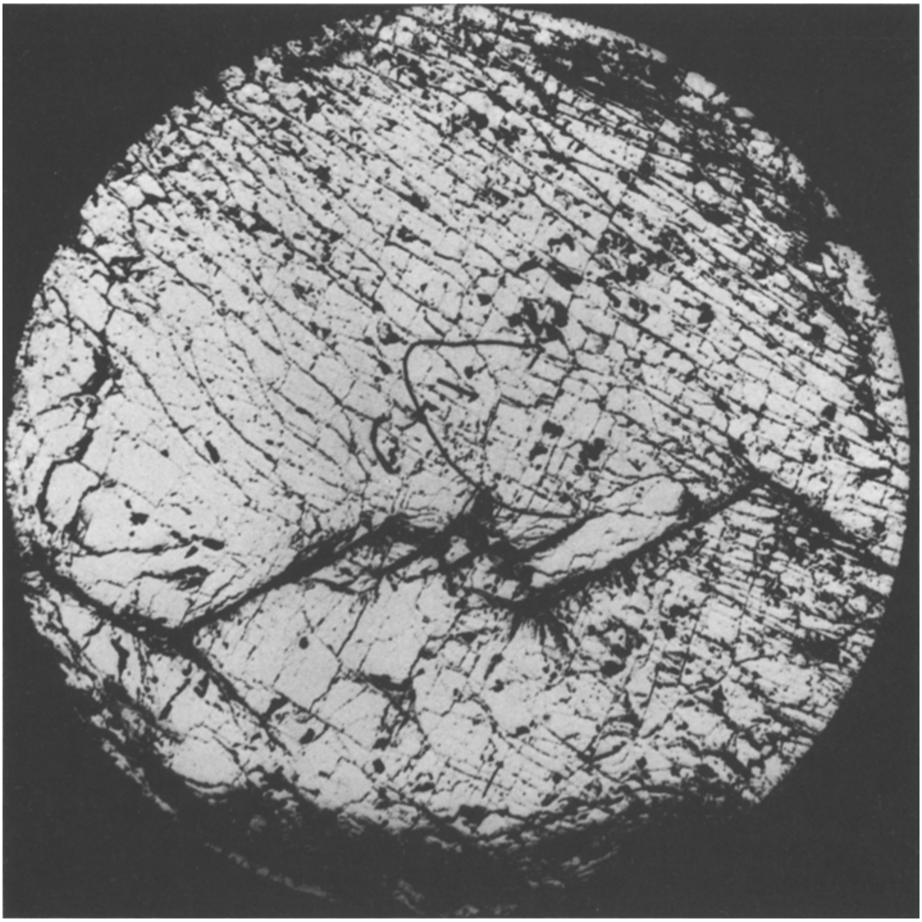

Fig. 4. Thin section of shot 174, 106 kbar, plagioclase. Note the mosaic-like appearance of the irregular fracturing caused by the shock-loading. Disc diameter equals 4.75 mm

glasses were pseudo-conchoidal fractures possibly produced in removing the sample material from the stainless steeel containers.

It is not clear why none of the very fine planar features so often observed in naturally shocked plagioclase are not present in the labradorite studied here. One possibility is that the lack of planar features may be related to the original gem quality state of the specimen. It is possible that the presence of cleavage and twinning in most natural materials affects the shock production of fine deformation features. A more likely explanation of this surprising result is, the already mentioned, local inhomogeneous stresses developed at grain contacts in polycrystalline rocks. Stöffler (private communication, 1976) has pointed out that in the shocked rocks of the Ries crater, planar features are more often seen in amphibolites (where the shock impedance of amphiboles and plagioclases are expected to differ) than in granites (where the shock impedance between quartz and feldspars is slight).

Conclusions

Gem quality labradorite shock-loaded to pressures up to ~300 kbar remains in the crystalline state upon adiabatic release to zero pressure. The indices of refraction of the shock recovered samples behave similarly to that observed in other tectosilicates.

Samples shock-loaded to 300 and 400 kbar are vitrified to diaplectic glasses (i.e., maskelynite); whereas samples shock-loaded to pressures greater than 400 kbar are transformed to (presumed) shock-fused glass according to their refractive indices. Excessive shock-induced cracks and fractures result, and some coarse cleavage along (001) and (010) develops, but no fine shock deformation "planar" features are produced upon recovery from pressures as high as 496 kbar. This, and the production of planar features in static experiments implies that these features by themselves do not provide uniquivical evidence to demonstrate a shock history in plagioclase. It, however, appears likely that shock-induced planar features in plagioclase in rocks are *not* intrinsically associated with shock pressure, per se, but rather arise because of the inhomogeneous stresses imposed on the mineral grains.

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