STAGES OF SHOCK METAMORPHISM IN CRYSTALLINE ROCKS OF THE RIES BASIN, GERMANY

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The suevite of the Ries basin, Germany, is a breccia which occurs in small outcrops around the basin and also underlies the Tertiary lake sediments within the central depression. It contains few sedimentary rock fragments and many fragments of the crystalline basement. The latter show a continuous gradation of metamorphism by shock waves. Four main stages of shock metamorphism have been established. They are defined by critical alterations of rock-forming minerals (mainly quartz and feldspar), by the formation of high-pressure phases, and by shock-induced textures of the rock.

INTRODUCTION

Around the central basin, the fall-out breccia of the Ries impact event, called suevite, occurs in several outcrops which are the remnants of a formerly more extensive blanket. Suevite was also found in two drill holes below the Tertiary lake sediments in the central depression. The suevite contains, in a fine-grained matrix, fragments of all rocks involved in the impact event, in different stages of alteration by pressure and heat.

The amount of sedimentary rock fragments (limestone, shale, clay, and some sandstone, which form, in the Ries area, a sequence about 1500 feet thick) is variable, but it is always less than 10 percent of all rock fragments. We found that clay, shales, and sandstones are unaltered, and that limestones are only moderately altered by heat (Baranyi, 1966). The clay content of Upper Jurassic limestone was changed from a kaolinite-illite mixture to a dioctahedral chlorite with some amorphous material. Some limestone fragments have an outer rim (a few millimeters thick), which is different in color from the interior and which consists of fine-grained calcite. This rim was apparently produced by calcination of the limestone and later carbonation of the lime. We conclude from these observations that the sedimentary fragments in the suevite endured, for a short time (some minutes), temperatures between 400° and 600°C.

By contrast, fragments of the crystalline basement rocks occur in all stages of alteration ranging from fresh rock to molten material (glasses). The rock types include (1) granites, granodiorites and diorites, containing biotite and amphibole; (2) diorites and gabbros; (3) gneisses of the amphibolite facies with biotite and amphibole, some of them with garnet and sillimanite; and (4) plagioclase amphibolites. It was in these fragments of altered crystalline rocks that the high-pressure phases coesite and stishovite were found (Shoemaker and Chao, 1961; Chao and Littler, 1963), establishing the first mineralogical evidence for the impact origin of the Ries basin.

By means of microscopic studies of the basement rock fragments, a series of stages of increasing alteration can be established (Stöffler, 1965, 1966; Chao, 1967). We found that, in general, each crystalline rock fragment in the breccia can be classified into one of four main stages (Table 1) which are characterized by certain critical alterations of the rock-forming minerals (quartz, feldspar, biotite, and amphibole).

TABLE 1

A simplified, preliminary diagram, showing stages of progressive shock metamorphism of granitic crystalline rocks in the Ries basin, Germany. The stages are separated on the basis of distinctive petrographic effects in the rocks. The pressure and temperature values are estimated from experimental Hugoniot data for quartz, feldspar, and granite (Wackerle, 1962; Milton and DeCarli, 1963; David, 1966; Müller, 1967; Ahrens and Rosenberg, this vol., p. 59); their application to the petrographic data is only approximate.

Pressure (kbars)	Stage of shock metamorphism	Characteristic deformations and phase transitions	Residual temp. (°C)
ca. 100			ca. 100
	Stage I	Fracturing Plastic deformation (diaplectic quartz and feldspar)	
250–300			200–300
	Stage II	Phase transitions (diaplectic glasses of quartz and feldspar, high-pressure phases of SiO_2)	
500–550			1200–1500
	Stage III	Selective melting (normal glasses of quartz and feldspar, high-pressure phases of SiO_2)	
600–650			2000–3000
	Stage IV	Melting of all main rock forming minerals (inhomogeneous rock melts, Fladen)	
ca. 1000			ca. 5000
		Volatilization	

Such features may also be found in other impact structures. As in normal metamorphism, each shock stage corresponds to a particular range of physical conditions. However, in contrast to normal metamorphism, the assemblage of phases constituting a particular shock stage does not represent an equilibrium system, owing to the short duration of the impact.

The range of shock pressures and temperatures for these different stages of shock metamorphism cannot yet be given exactly. Shock wave experiments on quartz (Wackerle, 1962; Short, 1966; Müller, 1967) and plagioclase (Milton and DeCarli, 1963; Ahrens and Rosenberg, this vol., p. 59; Müller, 1967) establish pressure and temperature values for the most typical shock deformations and phase transitions in these minerals. The pressure data in Table 1 are based on these values, whereas the temperature data shown with them refer to the residual temperature in quartz found after pressure release, as calculated by Wackerle (1962). Table 1 gives only preliminary and approximate pressure and temperature values for natural shock metamorphism; these must be fixed more precisely by further experimental investigations.

Below, we describe the four main shock stages (see also Stöffler, 1965, 1966).

STAGE I

This stage is characterized by strong fracturing of minerals, and most typically by special plastic deformation phenomena in quartz, feldspar, and biotite, which are apparently generated in the pressure range from about 100 to 300 kilobars.

Quartz contains unique planar elements and exhibits lowered density and refractive index values, as described elsewhere in this symposium (Engelhardt *et al.*, *this vol.*, p. 475, Fig. 9).

Plagioclase displays such plastic deformations as bending of crystals, deformation bands, and multiple sets of planar features. The latter appear under the microscope as lamellae of lowered refractive index, in which birefringence is reduced or completely absent. These lamellae often pass gradually into completely isotropic areas of the same crystal or into areas with normal birefringence (Figs. 1 and 2).

Within one thin section, the occurrence of plagioclase grains containing lamellae of different thicknesses (ranging from less than 1 μ up to about 8 μ), together with irregular isotropic areas, seems to indicate that lamellae in plagioclase are formed within a smaller range of shock pressures than the planar elements produced in quartz (see also Robertson *et al.*, *this vol.*, p. 433).

Isotropic or nearly isotropic lamellae in plagioclase have been investigated in a specimen of dioritic gneiss (from Zipplingen) containing quartz, plagioclase (An_{31}), amphibole, and biotite. As many as three different sets of lamellae are to be found in one single plagioclase crystal. They are oriented parallel to crystallographic planes of low Miller indices. The measured planes are given in Table 2.

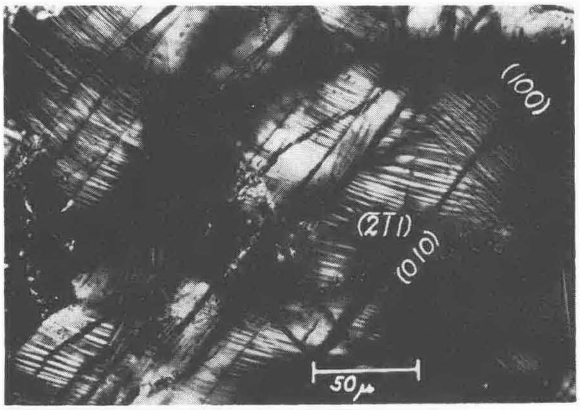

Fig. 1. Andesine in dioritic gneiss, Zipplingen. Isotropic slip bands (black) are parallel to (100) and $(\bar{2}\bar{1}1)$; isotropic twin lamellae (black) are parallel to (010). Irregular isotropic areas (black) are present. Crossed nicols.

Frequency is here defined as the number of measured sets of a particular crystallographic orientation as a fraction of all measured lamellae (it is identical with frequency, F_{II}, in the paper of Engelhardt *et al.*, *this vol.*, p. 475).

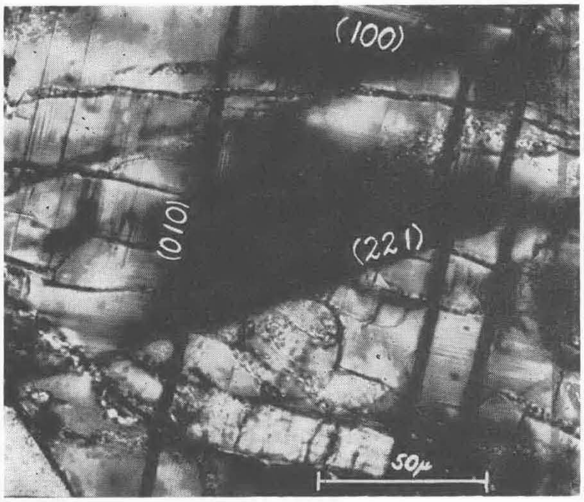

Fig. 2. Andesine in dioritic gneiss, Zipplingen. Isotropic slip bands (black) are parallel to (010) and (100). Irregular isotropic areas (black) are sharply separated from unaffected areas (light) by shear planes parallel to (221). Narrow albite twin lamellae (black) are at extinction. Crossed nicols.

Most lamellae are parallel to the shortest vectors of the Bravais lattice and to the greatest number of Si–O bonds. It is therefore assumed that they are produced by a peculiar form of shock-induced crystal gliding. This process produces a sequence of periodically repeated layers of disordered material which remain isotropic after pressure release. Similar deformation patterns in metals are known as slip bands (see, e.g. Seeger, 1958). Slip bands in plagioclase are unknown from rocks formed by normal processes within the earth's crust, and they must be therefore considered as a typical criterion for shock damage. In some plagioclase grains, unusual cleavages have been found, distinct from those

TABLE 2

Orientation of planar lamellae in plagioclase crystals in a dioritic gneiss from Zipplingen.

(hkl)	Frequency %	(hkl)	Frequency %	(hkl)	Frequency %
(001)	25	$(1\bar{1}0)$	2	$(\bar{1}02)$	1
(010)	11	(102)	2	$(0\bar{2}1)$	1
(100)	10	$(0\bar{1}2)$	2	$(2\bar{1}0)$	1
$(1\bar{2}0)$	10	(150)	2	$(\bar{2}01)$	1
(012)	7	$(1\bar{3}0)$	2	$(\bar{1}11)$	1
(130)	6	(101)	1	(211)	1
(201)	2	(011)	1	$(1\bar{1}2)$	1
$(\bar{1}01)$	2	(210)	1	$(\bar{2}21)$	1
				and others	

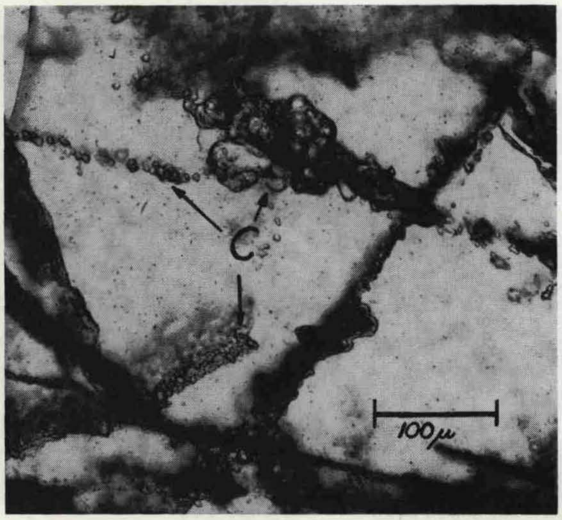

Fig. 3. Diaplectic quartz glass (light areas) with aggregates of fine-grained coesite (C) within a fragment of biotite granite from Aufhausen.

observed in normal feldspar, but parallel to definite crystallographic planes.

Plagioclase which shows these deformation phenomena also shows an unusually strong decrease of both refractive index and birefringence. Refractive indices between 1.550 and 1.533 (most grains having 1.537) have been measured in andesine (An_{31}) from Zipplingen, which normally should have an index of 1.550 (n_z). These andesine crystals have the optical properties of a highly disordered plagioclase, according to the optical orientation and optic axis angles. The average optic axis angle of 69 crystals was found to be 80.5 degrees instead of 88.5 degrees for ordered An_{31} (Burri *et al.*, 1967).

A strong decrease of optic axis angle has also been found in the orthoclase feldspar in these granitic inclusions. A detailed description of shocked plagioclase is given in another paper (Stöffler, 1967).

Biotite in rocks of this stage of shock metamorphism shows well-developed kink bands; these features are also produced in biotite during natural and experimental static deformation of rocks (Griggs *et al.*, 1960) and by dynamic deformation experiments on rocks (Cummings, 1965; Short, 1966).

STAGE II

Quartz is gradually transformed into an amorphous phase exhibiting a lower index of refraction and lacking birefringence. This phase does not produce X-ray diffraction lines. It still preserves original grain boundaries and sometimes preserves the shock-produced planar elements described above (Stage I).

Coesite and stishovite occur in these glasses. Coesite, which can be seen by the microscope (Fig. 3), forms very fine-grained aggregates often arranged in planes (shear planes?).

Feldspar is also gradually transformed into an amorphous phase. Isotropization begins either in irregular patches or as a lamellar pattern. In the first case, larger isotropic (or nearly isotropic) areas within one crystal are sometimes sharply separated from unaltered areas by uniform planes, commonly of definite crystallographic orientations (such as (101) (102) (221) etc.) which have apparently acted as shear planes (Fig. 2). In the latter case, the affected lamellae are either pre-existing twin lamellae or shock-produced multiple sets of lamellae (or planar elements) as described above (Stage I). Very often, in plagioclase twins following the albite law, one set of lamellae has lowered refractive index and birefringence, or is completely isotropic; while the other set of lamellae seems not to be affected. This asymmetrical behavior of such twins is not the result of chemical differences between the sets of lamellae, as was proved by electron microprobe analyses. It is rather the result of a favored orientation of the twin system relative to the direction of the deforming forces, by which slipping on (010) and isotropization is favored. Slipping may also be favored in one set of lamellae by a higher content of pre-existing lattice defects.

By means of fabric analysis of the dioritic gneiss specimen, it was shown that grains with asymmetrically isotropized twin lamellae have no preferred orientation in the rock (Stöffler, 1967). This randomness may reflect disorganization of the shock front due to interactions at free surfaces and grain boundaries, or may perhaps be due to the passage of multiple shock waves (see Rinehart, *this vol.*, p. 31).

In shock stage II *biotite* and *amphibole* show only effects of mechanical deformation; kink bands develop in biotite and lamellar features are observed in amphibole.

Typical phenomena in shock stages I and II are transitions of tectosilicates from undisturbed crystals to the disordered or amorphous phases described above. It can be concluded, from the preservation within the glassy grains of cleavage, grain boundaries, and twin boundaries, and from the absence of all flow structures, that these transformations took place as subsolidus reactions. Since there are, in the suevite, also glasses which have been clearly produced by true melting of quartz, feldspar, and other minerals (Stages III and IV), it seems useful to have proper terms designating these two types of amorphous phases which have apparently been produced under different conditions, and which differ from each other in physical properties, as, for instance, in the degree of short-range order.

It is therefore proposed to apply the term *diaplectic*[1] to all products produced by shock waves in such a way that morphological characteristics of the liquid state are lacking. The term *diaplectic minerals* thus applies to all disordered and deformed mineral crystals modified by shock waves without melting. *Diaplectic quartz* and *diaplectic feldspar* thus designate quartz and feldspar exhibiting planar elements, slip lamellae, lowered indices of refraction, and lowered birefringence (Stage I). *Diaplectic glasses* (of quartz, feldspar, or other minerals) are amorphous phases produced by shock waves without melting, and are distinguishable from ordinary molten glasses by the criteria presented in Table 3 (Engelhardt *et al.*, 1967).

Diaplectic glasses represent intermediate stages of structural order between the crystalline and normal glassy phases. This conclusion is supported by measurements of their physical properties; e.g., refractive index, density, and the calculated molar refractivity and ionic refractivity of oxygen.

TABLE 3

Diaplectic glasses	Normal glasses
Morphological features of the previous crystalline state are preserved (e.g., grain boundaries, twin boundaries, cleavage).	Morphology is determined by surface tension; no sharp corners, edges, or uniform boundary planes occur.
No flow structures. Vesicles absent.	Flow structures are present. Vesicles of circular or nearly circular shape are common.
Refractive index and density are higher than those of normal glass of the same chemical composition.	No transitional stages occur between the crystalline phases and normal glass.
Diaplectic quartz glasses often contain high-pressure phases (i.e., coesite and stishovite).	

These studies were made on diaplectic quartz and plagioclase glasses. Diaplectic quartz glasses separated from a biotite gneiss from Aufhausen have densities between 2.219 and 2.261, and corresponding refractive indices between 1.460 and 1.4635. These values are higher than those for synthetic, normal SiO_2-glass; i.e., $n=1.4585$, and $d=2.200$ (see Fig. 9 in Engelhardt *et al.*, *this vol.*, p. 475). The density of diaplectic plagioclase glass (An_{39}) separated from a plagioclase amphibolite from Bollstadt varies between 2.449 and 2.557; the corresponding refractive indices range between 1.523 and 1.532 (Fig. 4). Normal plagioclase glass of this composition has much lower values: 2.432 and 1.521, respectively (see Fig. 4).

Molar refractivity, calculated from density and refractive index using the Lorentz-Lorenz equation, decreases with increasing density for both quartz and plagioclase glasses (Fig. 3 in Engelhardt *et al.*, 1967 and Fig. 4, this paper). The same relation is true for the ionic refractivity of oxygen, calculated on the assumption that contributions from the cations remain constant with increasing density. This result indicates a smaller polarizability of oxygen in diaplectic glasses than in

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[1] From the Greek word *diaplesso* = to destroy by striking or beating.

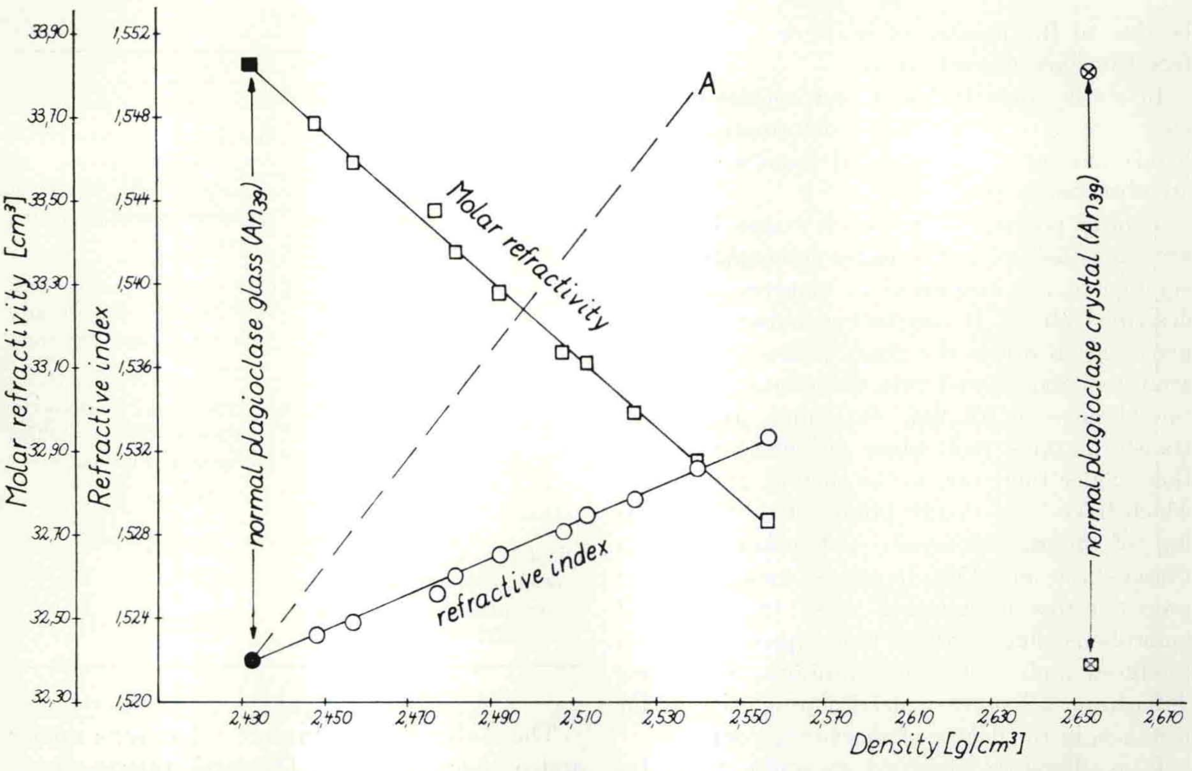

Fig. 4. Refractive index (circles) and molar refractivity (squares) as a function of density for different plagioclase (An_{39}) phases. Open circles and squares: Diaplectic andesine glass from Bollstadt. A: indicates the curve for calculated refractive index as a function of density for a constant molar refractivity of 33.83 cm^3 (normal andesine glass, An_{39}) (after Fig. 5, Engelhardt *et al.*, 1967).

normal glasses. Hence, the structural state of diaplectic glasses approaches that of the crystalline phases from which they were formed. Infra-red absorption spectra of diaplectic glasses from other craters (Bunch, Cohen, and Dence, *this vol.*, p. 509) seem to confirm this conclusion. A detailed description of diaplectic quartz and plagioclase glasses is given by Engelhardt *et al.* 1967).

Both the normal and diaplectic phases of any plagioclase composition can be characterized simply by the difference (n_1–n_2) between the refractive index of the normal crystal or diaplectic phase (n_1) and that of normal plagioclase glass (n_2) of the same composition. This relation is illustrated in Figure 5 for normal plagioclase crystals, for one diaplectic andesine (An_{31}), and for three diaplectic plagioclase glasses (An_{23}, An_{31}, and An_{36}) taken from crystalline fragments collected at different suevite outcrops. The difference (n_1–n_2) for shock-produced phases of a definite composition gives a rough scale for measuring shock intensities, assuming that shock intensity is inversely proportional to the difference (n_1–n_2) (Stöffler, 1967).

STAGE III

This stage of shock metamorphism is characterized by the selective melting of tectosilicates as a result of the very high residual temperatures produced by shock pressures in the range of about 500 to 650 kilobars. Normal glasses, containing vesicles, streaks (schlieren), and well-developed flow structures are formed by this process.

Plagioclase and *alkali feldspar* transform into normal glass (Fig. 6), showing typical morpholog-

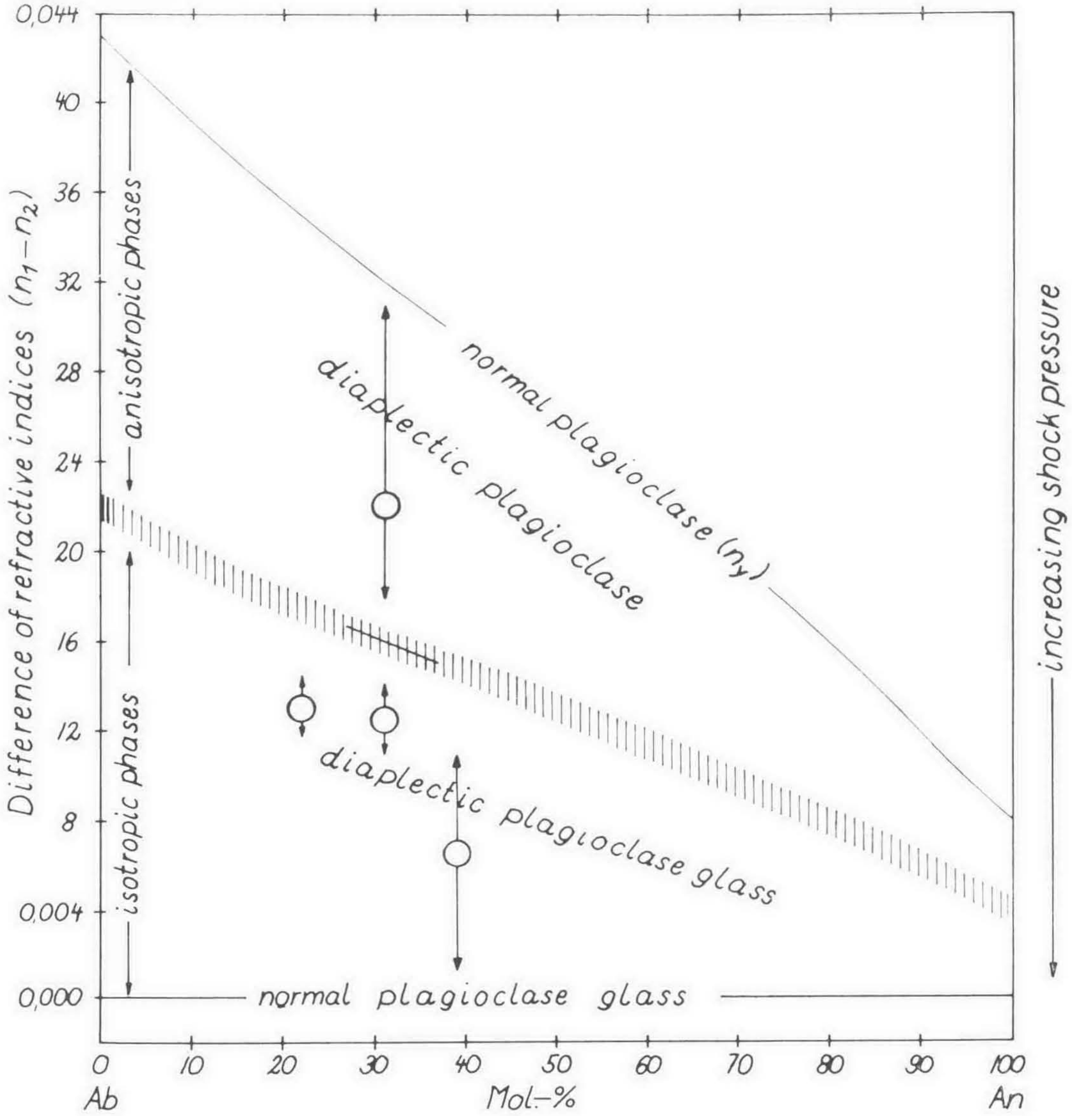

Fig. 5. States of plagioclase in shock metamorphism (Stöffler, 1967). n_1 is the refractive index or mean refractive index of the shocked phase; n_2 is the refractive index of normal glass of the same composition. Arrows indicate variation within 50 measured grains; circles indicate the calculated averages. The boundary between diaplectic crystalline and glassy phases is known only for An$_{31}$ and has been extrapolated for the other compositions.

ical characteristics of the liquid state—e.g., vesicles (now filled with gas or secondary minerals) and schlieren. The refractive index of this glass does not appear to be different from that of normal synthetic or natural plagioclase glass. Milton and DeCarli (1963) produced plagioclase glass of bytownite composition (An$_{80}$) by shock loading gabbro in the estimated pressure range of about 600 to 800 kilobars. The refractive index of this glass (1.560) is similar to that of synthetic bytownite glass (1.557).

In the lower range of stage III, *quartz* is still present in the form of diaplectic glass, together with fused feldspar. At higher pressures, quartz

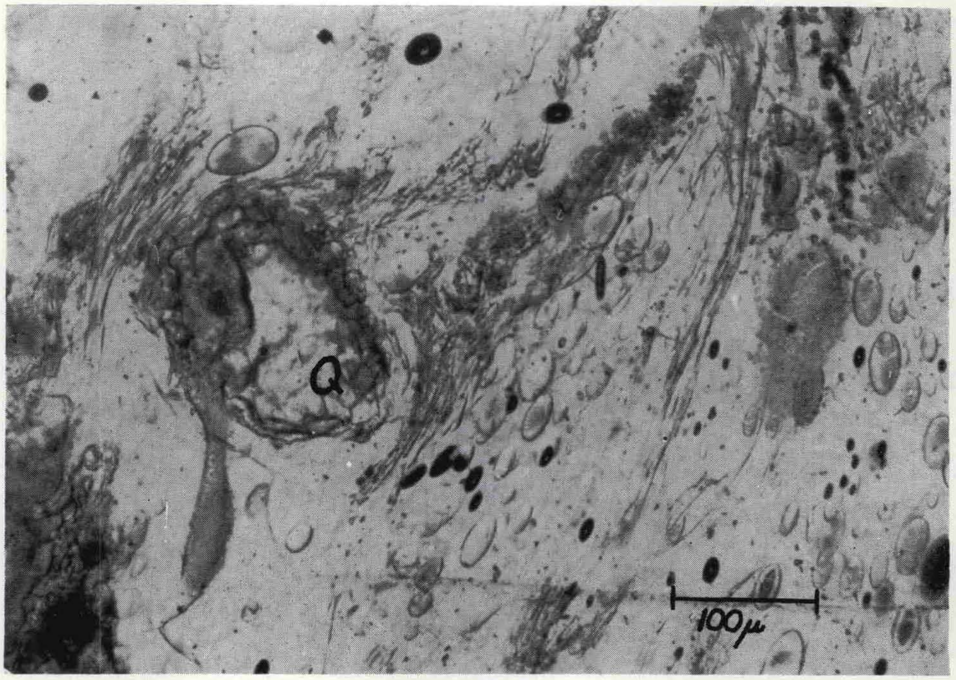

Fig. 6. Normal K-Na-feldspar glass, showing vesicles, schlieren, and an inclusion of quartz glass (Q), probably diaplectic. Specimen is from a fragment of crystalline rock (biotite gneiss?) from Otting.

also forms normal glass with all features of the liquid state. Coesite and stishovite occur in these glasses. The difference in shock melting of quartz and feldspar is apparently due to their different melting temperatures. No eutectic reactions between the minerals are observed.

Amphibole and *biotite* in stage III gradually lose birefringence and pleochroism and show decomposition to aggregates composed chiefly of opaque minerals. Shock-induced planar features or lamellar structures have been observed in amphibole, and they are now under investigation.

In stage III, the original texture of the crystalline rocks, which is still largely preserved in stages I and II, is destroyed. Partial melting and the formation of vesicles produce porous, pumice-like rocks.

STAGE IV

The so called *Fladen* (also *Flädle*), bodies rich in molten glass, belong to this facies. Their characteristic, generally flat, shapes (*Fladen* means "pancake") have been generated by aerodynamic forces during their rapid flight through the air, but the bodies were rigid and not deformed when they hit the ground. For details about their occurrence, shape, stratification, and chemical and mineralogical composition, see Hörz (1965) and Engelhardt (1967).

All *Fladen* contain many vesicles; they are mixtures of molten glasses and fine mineral fragments. Phases contained in the *Fladen* include unaltered quartz, diaplectic quartz, diaplectic quartz glass, molten quartz glass (lechatelierite), unaltered feldspars, diaplectic feldspars, normal feldspar glass, and diaplectic feldspar glass. Very few mafic minerals have been found among the mineral fragments. Quartz is the main constituent of the fragmental material (about 12 weight percent of the *Fladen*). In cross section the *Fladen* are seen to consist of multiple thin layers of glass, which are alternately poor and very rich in angular mineral grains. The texture suggests that a cooler "rock flour" has been embedded in a very hot, strongly flowing melt. The temperature then dropped quickly and movement stopped before melting of the mineral grains and complete mixing could be accomplished. The glass within the *Fladen* is heterogeneous and

TABLE 4

Chemical composition of glass bombs (Fladen) from suevite, collected at 9 different localities in the Ries basin (Amerbach, Aufhausen, Aumühle, Bollstadt, Doosweiher, Fünfstetten, Heerhof, Otting, Schmähingen).

	9 unrecrystallized glass bombs		17 recrystallized glass bombs	
	Average composition	Standard deviation	Average composition	Standard deviation
SiO_2	63.54	1.03	64.04	1.15
TiO_2	0.81	0.08	0.78	0.10
Al_2O_3	15.10	0.43	15.28	0.80
Fe_2O_3	0.99	0.19	1.42	0.72
FeO	3.75	0.19	2.39	1.26
MnO	0.10	0.01	0.08	0.03
MgO	2.71	0.19	1.71	0.92
CaO	3.45	0.34	3.98	0.54
Na_2O	2.86	0.29	3.59	0.68
K_2O	3.71	0.16	3.50	0.76
P_2O_5	0.36	0.12	0.32	0.08
H_2O^+	2.73	0.30	2.72	1.05
CO_2	0.37	0.22	0.33	0.19
Total	100.48	—	100.14	—
Fe^{2+}/total Fe	0.81	—	0.65	—

consists of fine schlieren which differ in refractive index and in color. The structure reflects the heterogeneous nature of the parent rock, the intense movement of the melt, and the short duration of the molten state (Fig. 7).

The chemical composition of the *Fladen* is very uniform. Table 4 shows the average chemical composition of 9 unrecrystallized and 17 recrystallized *Fladen*, collected at 9 different localities around the Ries basin. As can be seen from the standard deviations, the scattering is relatively low. The composition of the *Fladen* is consistent with the assumption that they were produced by melting of the granitic basement rocks. Their chemical composition differs appreciably from the composition of *Moldavite* tektites, and theories which derive the Moldavites from melt produced by the Ries impact event have to explain this discrepancy (Engelhardt and Hörz, 1965). The *Fladen* differ in their cooling histories. There are rapidly chilled *Fladen* which contain clear, undevitrified glass; specimens of more slowly cooled *Fladen* show different types of devitrification. Cristobalite, feldspar, and pyroxene are the main devitrification products; they crystallized after movement in the melt had ceased. This conclusion follows from the observations that orientation of the new crystals is not affected by the flow pattern of the glass and that there are no parallel arrangements of elongate crystals of the type so familiar in lava flows. Furthermore, it is certain that devitrification took place after deposition of the suevite breccia, because it can be seen that, in

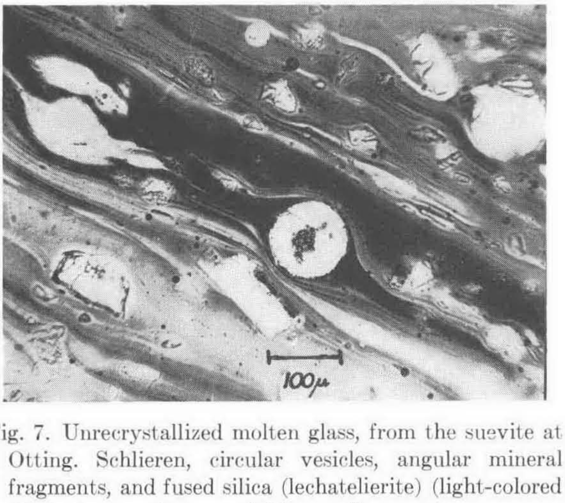

Fig. 7. Unrecrystallized molten glass, from the suevite at Otting. Schlieren, circular vesicles, angular mineral fragments, and fused silica (lechatelierite) (light-colored elongate areas in upper left) are all present.

some suevite quarries, the lowest, rapidly cooled layer of suevite contains only unrecrystallized glasses, whereas higher in the suevite, all the *Fladen* are devitrified. In the quarry of Otting, for instance, the chilled basal layer is about 1 m thick. Chilled layers with unrecrystallized glasses at the bottom and the top of suevite have also been found in the bore hole at Wörnitzostheim (Förstner, 1967).

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