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Shock Metamorphism in Lunar Samples

Abstract. *Indications of shock metamorphism produced by pressures up to the megabar region have been observed in the fine material and the breccias, but very rarely in the coarser fragments of crystalline rocks. These indications are deformation structures in plagioclase and pyroxene, diaplectic plagioclase glasses, and glasses formed by shock-induced melting of lunar rocks. Two sources of shock waves have been distinguished: primary impact of meteorites and secondary impact of crater ejecta. There are two major chemical types of shock-induced melts. The differences in chemistry may be related to impact sites in mare and highland areas.*

The following shock-induced transformations produced by solid-state reactions and melting have been observed in breccias (59, 60, 65, and 27) and fine material (85, 84), besides weaker effects of plastic deformation and fracturing probably due to shock: (i) deformation structures in plagioclase and pyroxene; (ii) diaplectic feldspar glasses; and (iii) glasses produced by shock-induced melting.

Plagioclase grains with lamellae of low index of refraction and low or no birefringence, which might be classed with those from terrestrial meteorite craters and shock experiments, are very rare in the samples studied. For the most part they display only one set of lamellae that are isotropic or of low birefringence. Apparently, the conditions (duration of shock waves, composition of plagioclase, and texture of lunar rocks) do not favor the formation of these structures. This is confirmed by the absence of deformation lamellae in the shocked rock fragment described below.

Very few of the pyroxene grains found in the fine material exhibit multiple sets of closely spaced lamellae similar to those that are well known from shocked quartz.

In the fine material and in the breccias, colorless and isotropic grains of plagioclase composition occur which exhibit no indications of fusion, such as vesicles or flow structures. Some of them show straight grain boundaries and cleavage. Microprobe analyses and refractive index measurements were made on 14 grains, isolated from samples 84,106; 85,25; and 85,26 (Table 1). The densities of six grains were also determined. Figure 1 demonstrates that the refractive indices of these glasses are distinctively higher than those of normal glasses produced by fusion. Likewise, the density is higher than that of fused plagioclase. These observations show that the glasses are not fusion products but are diaplectic glasses (*1*) formed in the solid state by shock waves with amplitudes between about 300 kb and about 500 kb. They have been produced by meteoritic impact on plagioclase-bearing crystalline rocks of the lunar surface which were broken during excavation into fragmental mineral grains. Fragments of such rocks with diaplectic plagioclase glass (very seldom with small isotropic alkali feldspar inclusions) in its original paragenesis with pyroxene and ilmenite are rarely found in the fines and breccias. Diaplectic plagioclase glasses are also known from terrestrial impact craters (*2*), from the Shergotty meteorite (*3*), and from shock wave experiments (*3*). To check further on the

Table 1. Refractive index n_D, density d, and anorthite (An) content of lunar diaplectic plagioclase glasses.

No.	An (mole percent)	n_D	d
1	74	1.5620	2.650
2	75	1.5651	
3	75	1.5675	2.653
4	83	1.5702	
5	86	1.5709	
6	86	1.5720	
7	86	1.5760	2.673
8	88	1.5747	2.684
9	88	1.5762	
10	89	1.5716	
11	89	1.5772	
12	89	1.5797	2.684
13	91	1.5802	2.684
14	93	1.5807	

diaplectic nature of the lunar glasses, annealing experiments were carried out on various fragments of a large grain (Fig. 2). Annealing at 700° and 800°C increased the index of refraction. The beginning of recrystallization was observed at 900°C, and complete recrystallization at 1000°C. The same increase of refraction on annealing was observed on diaplectic plagioclase glass of the Manicouagan crater (*4*), whereas fused plagioclase shows no change on annealing at temperatures below the transformation point.

Glasses in the fine material and in the breccias occur as (i) bodies of regular spheroidal, ellipsoidal, dumbbell, or teardrop shape, (ii) irregular fragments, and (iii) vesicular coatings on fragments of breccias and crystalline rocks.

1) The spheroidal, ellipsoidal, dumbbell, and teardrop glass bodies form about 10 percent of all glass in the fine material. Their sizes are in the range between 2 mm and 0.3 μm. Red, brownish, and yellow glass bodies are most frequent. About half as many are colorless or greenish. Violet-brownish-colored spherules are rarer. The glasses are generally homogeneous. Some contain vesicles. Schlieren and inclusions of mineral grains (plagioclase, pyroxene), often partially fused, are rarer. Very small spherules of metallic Fe occur in some glasses. Apparently the very regular shape of these bodies and their rotational symmetry resulted from an equilibrium between surface tension and inertial forces acting on liquid drops rotating and falling in the lunar vacuum. Divitrification is rare, but a few devitrified spherules have been found which resemble orthopyroxene chondrules of chondrites. The homogeneity of most of these glasses indicates their initially high temperatures. The rarity of devitrification indicates the predominantly rapid rates of cooling.

2) There are colorless and greenish irregular fragments and about as many red, yellow, and brown pieces. Violet-brownish colors are rarer. Some of these glasses are homogeneous. Glasses containing vesicles, mineral fragments, and flow structures are more frequent than in group 1. Minute Fe spherules are rather frequent in this kind of glass. Devitrified glass fragments with dendritic and skeletal crystals have been frequently found in the breccias.

Microprobe analyses of 13 rounded glass bodies (group 1) and 26 glass fragments (group 2) showed a broad

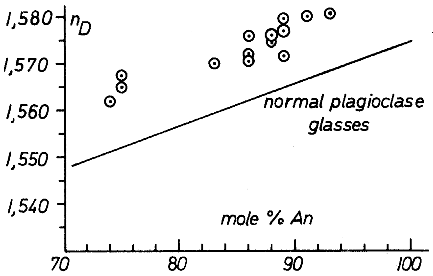

Fig. 1. Refractive indices of lunar diaplectic plagioclase glasses. (Solid line) Refractive indices of fused plagioclase. [After Barth (5)]

variability of chemical composition, with the SiO_2 content ranging from 33 to 50 percent. Each individual piece of glass can be interpreted as a fusion product of a particular mixture of the lunar rock-forming minerals plagioclase, pyroxene, and ilmenite, in some cases with admixtures of free SiO_2, olivine, or even metallic Fe.

The chemical heterogeneity of the lunar glass bodies and fragments distinguishes lunar fine material and breccias from terrestrial pyroclastic rocks. The individual glass pieces constituting the latter are all of essentially the same chemical composition. Because of their heterogeneity, it is concluded that the lunar glass bodies and fragments did not originate in large and homogeneous lava pools. Instead, they must have been formed, individually, by fusions of relatively small rock volumes.

Notwithstanding the chemical differences between the individual glasses, at least two major chemical types can be distinguished.

Type 1: colorless to green glasses. Average composition (weight percent; 13 microprobe analyses): SiO_2, 46; TiO_2, 0.8; Al_2O_3, 24; FeO, 7; MnO, 0.08; MgO, 8; CaO, 13; Na_2O, 0.6; and K_2O, 0.1. Average norm: plagioclase, 67; pyroxene, 21; olivine, 9; and ilmenite, 1.5.

Type 2: yellow, brown, red, and violet glasses. Average composition (13 microprobe analyses): SiO_2, 40; TiO_2, 9; Al_2O_3, 11; FeO, 19; MnO, 0.2; MgO, 10; CaO, 11; Na_2O, 0.5; and K_2O, 0.1. Average norm: plagioclase, 32; pyroxene, 35; olivine, 16; and ilmenite, 17.

Generally, spherules and the other regular bodies of both types contain less SiO_2 than the corresponding fragments, so that calculation of the norm results in relatively high percentages of olivine and, in the case of two green spherules, even of metallic Fe (2 and 4 percent). Metallic Fe occurs in many lunar glasses as minute Fe spherules. There are two possible explanations for their formation: (i) admixture of meteoritic Fe, condensing from the vapor phase, produced by the impacts of Fe-bearing meteorites, or (ii) preferential volatilization of SiO_2 (or SiO) from a rock-melt heated to very high temperatures in the lunar vacuum.

3) Coatings of vesicular glass are frequent on breccia and rock fragments occurring in breccias and fine material. The glasses of this kind so far investigated belong to type 2. Microprobe analyses of some glassy coatings showed that the crust was not formed by fusion of the coated rock and has taken up, at most, minor amounts of it. The glass crusts may be considered in most cases projectiles ejected from meteorite craters as splashes of melt or small rock fragments which have impacted rock fragments on the lunar surface, causing progressive shock metamorphism within them. This could be best demonstrated by a small gabbroidic fragment ($10 \times 6 \times 4$ mm). In the immediate vicinity of the glass crust (up to 0.3 mm thick), within a zone of 2.5 mm maximum thickness, all plagioclase is transformed into isotropic diaplectic glass. A very narrow transition zone (maximum thickness, 0.2 mm) with partially isotropic plagioclase separates the outer zone from the interior of the rock, where the plagioclase shows normal birefringence.

The boundary between diaplectic glass and birefringent plagioclase represents a shock wave amplitude of about 300 kb. The small extension of the transition zone indicates a rapid decay of the shock wave along its path into the rock. Therefore, the thickness of the impacting projectile must have been rather small, probably not more than 2 mm.

We conclude that all types of glasses have been produced by shock-induced fusion of lunar rocks due to meteoritic impacts, presumably at pressures up to the megabar region. Some parts of the melt have been dispersed as fine droplets which are preserved as regularly shaped bodies of rotational symmetry. Larger masses have been broken into fragmental grains, and still other parts of impact melts are found as crusts adhering to the surface of rocks.

The obvious division of the glasses into two major chemical types indicates that, at the Apollo 11 landing site, material occurs which has been produced by meteoritic impact events in at least two areas of the lunar surface which differ in chemical composition. The yellow, brown, red, and violet glasses of high TiO_2 and FeO content (type 2) have a composition similar to that of mare material represented by the alpha-scattering experiments of Surveyor 5 and 6 and the rocks of Apollo 11. They may be products of impacts within the Sea of Tranquillity area. The colorless and greenish glasses of higher SiO_2 and Al_2O_3 and lower TiO_2 and FeO content (type 1) correspond to the highland material north of Tycho analyzed by Surveyor 7. We suggest that these glasses came from an impact site at the highlands.

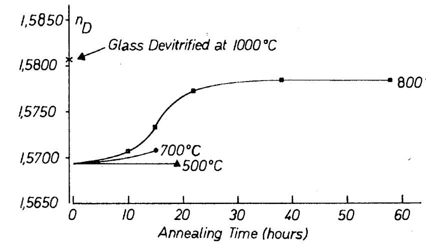

Fig. 2. Results of annealing experiments with lunar diaplectic plagioclase glass (anorthite, 86 mole percent).

The two types of shock-melted material may perhaps be connected with the two ray systems in the vicinity of the Apollo 11 landing site. The north-northeast-trending ray, which is perhaps related to Tycho or another crater on the highlands, may have delivered the colorless and greenish glasses of type 1.

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