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