

## Shock metamorphism of lunar rocks and origin of the regolith at the Apollo 11 landing site

W. VON ENGELHARDT, J. ARNDT, W. F. MÜLLER and D. STÖFFLER  
Mineralogisch-Petrographisches Institut der Universität Tübingen  
74 Tübingen, Wilhelmstr. 56, W. Germany

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**Abstract**—Indications of progressive shock metamorphism have been found in Apollo 11 soil and breccias. We define shock effects as permanent alterations of minerals due to pressures above the dynamic elastic limit. We have observed the following shock effects: deformation structures in plagioclase, pyroxene and olivine; solid state transformation of plagioclase into an amorphous phase (diaplectic glass); glasses formed by shock induced melting of various source materials.

The glasses represent two major chemical types related to basaltic and anorthositic rocks, respectively. The basaltic glasses (darker color) are richer in Fe, Ti, Mn and poorer in Si, Al than the anorthositic glasses (lighter color). The basaltic glasses are assumed to be ejecta from impact sites in mare areas, the anorthositic glasses from sites in the highlands.

The lunar regolith is an impact breccia similar to terrestrial breccias of suevite type. Differences between lunar and terrestrial impact breccias are due to multiple impact events on the moon and its lack of atmosphere.

### INTRODUCTION

THE LUNAR regolith of Mare Tranquillitatis, as represented by the Apollo 11 samples, was formed from primary magmatic rocks by disintegration, mechanical deformation and local heating to high temperatures (LSPET, 1969). Alterations of this kind can either be of volcanic origin or they may have been produced by the impact of meteoritic bodies on the lunar surface. In the first case the lunar unconsolidated soil and the consolidated breccias should be similar to terrestrial pyroclastics. In the second case they should be comparable to impact breccias as they occur in terrestrial meteorite craters.

If the lunar regolith is essentially an impact breccia, as has been assumed by several investigators, effects of shock waves, with pressure amplitudes higher than those which can be derived from endogenetic sources, should be detectable in the components of soil and breccias.

We will use the term shock wave according to the definition given by DORAN and LINDE (1966): "a compressional wave having an amplitude exceeding the elastic limit of the material in which it is propagating." Consequently, we call minerals "shocked" only if they have experienced pressures above the dynamic elastic limit (Hugoniot elastic limit, HEL). This limit can be determined by shock experiments and can be recognized by a break in the Hugoniot-curve. Above the HEL minerals yield by plastic deformations and can undergo transformations into high pressure phases. After pressure release the shocked minerals preserve traces of plastic deformations which are distinguishable from those formed under static or quasi-static conditions. If high pressure phases were formed, remnants of these phases or new phases derived from them during pressure release are to be expected in the shocked material. The residual temperature of high amplitude shock waves may exceed the melting point of the shocked minerals so that a melt is formed after pressure release (shock melting).

The elastic limits of quartz and silicates under dynamic conditions exceed 50 kbar or more. Pressures of this magnitude cannot be produced by volcanic events. They can only be generated by the impact of meteoritic bodies of all sizes striking the lunar surface at cosmic velocities.

In this paper we present observations on shock effects in Apollo 11 samples. Shock effects, as defined above, are planar structures in silicates due to dynamic plastic deformations, feldspar glasses formed in a solid state reaction (diaplectic feldspar glass) and shock melted rock fragments. Alterations of this kind are known from terrestrial impact craters and have been artificially produced in shock experiments.

#### SAMPLES AND EXPERIMENTAL

The following samples have been investigated: fine material of the 0.1–1 cm fraction (10085-25 and 10085-26) and of the <0.1 cm fraction (10084-106); breccias (10027-11; 10059-41; 10060-34; 10065-28; 10065-32); one thin section of a crystalline rock (10047-9—thin section number 6476 80).

Grain size distribution of sample 10084-106 has been determined by sieving (0.5 mm, 0.5–0.25 mm, 0.25–0.125 mm, 0.125–0.063 mm, 0.063–0.020 mm) and sedimentation in benzene (0.020–0.010 mm, 0.010–0.004 mm, <0.004 mm). The density of the <0.020 mm fraction has been measured by the pycnometer method in octane.

From the 0.1–1 cm fraction different types of minerals, rocks and glasses have been separated by hand under the stereo-microscope. Polished thin sections have been made of about 90 selected specimens from separated fractions.

Optical examination of all thin sections and of the sieve fractions has been carried out with a petrographic microscope. Universal stage methods have been used to determine the orientation of deformation structures in shocked minerals.

The refraction index of glasses has been measured using the Becke test with sodium light. The immersion liquids were butylcarbitol— $\alpha$ -monobromonaphthalene and methylene iodide— $\alpha$ -monobromonaphthalene mixtures. The refractive index of the liquids was changed by temperature variation. The accuracy was  $\pm 0.0002$ .

The density of glass pieces has been measured by suspension in mixtures of bromoform and N,N-dimethylformamide. The accuracy was  $\pm 0.0004 \text{ g/cm}^3$ .

Some plagioclase glasses have been annealed at different temperatures in an electric furnace in air. Each specimen was wrapped in platinum foil and air quenched.

Some single-crystal X-ray photographs have been taken of plagioclase glass and olivine grains.

Electron microscopy has been used to examine the minimum size of spherules.

Chemical analyses of feldspars, pyroxenes, plagioclase and alkali feldspar glasses and of fused glasses of different color and shape have been made with an ARL-EMX-SM-microprobe.

In the case of feldspars and feldspar glasses Ca, Na, and K only have been determined. The X-ray intensities have been corrected in accordance with the method described by SMITH (1965).

From all other specimens total analyses have been made (Si, Al, Ti, Fe, Mg, Mn, Ca, Na, K), Cr, Ni, P, S have been examined from only a few selected samples.

All quantitative determinations have been obtained by 5–20 point analyses set at random on each grain. Normally a spot size of 10–20  $\mu\text{m}$  dia. has been used. Iron spherules and alkali feldspar inclusions have been analyzed with a fully focused electron beam. Measurement conditions were as follows: 15 kV acceleration voltage, 10 nA sample current, 20 sec counting rate. Correction has been made for background, drift, mass absorption, secondary fluorescence and atomic number effect, using a computer program written by GOLDSTEIN and COMELLA (1969).

With some colored glasses a systematic deviation of up to 5 per cent from the total sum of 100 per cent has been observed. The error increases with increasing Fe-content and decreasing Si-content. We could not as yet check all possible sources of error. We assume that the glasses rich in Fe and low in Si are more instable against electron bombardment than those low in Fe and Si, so that partial volatilization of probably Si, alkalis or other elements may cause the deviations.

### COMPOSITION AND TEXTURE OF SOIL AND BRECCIA

The lunar soil—returned from the Apollo 11 landing site—is a loose sediment of rather unsorted angular to subrounded particles and regularly shaped bodies of different size and origin.

The constituents range in grain size from less than a few microns up to the decimeter size covering a broad variation in composition and structural state. Most conclusive is the presence of fragments of breccias. They are composed of about the same constituents as the soil but consolidated by a glassy fine-grained matrix.

A detailed knowledge of the petrographic composition and the relationships between unconsolidated and consolidated material may well be the key to the evaluation of the complex genesis and shock metamorphic history of the lunar soil.

In the next paragraphs a general description of the compositional and textural properties of the soil and of its constituents will be given to provide a basis for the discussion of shock effects described in the following chapter.

The main constituents of the soil are:

1. Fragments of minerals;
2. Fragments of glasses, some recrystallized;
3. Regular glass bodies of rotational symmetry and fragments of the same, some recrystallized;
4. Fragments of rocks;
5. Fragments of meteoritic material.

Genetically, the constituents belong to two different groups. The first group comprises particles formed by crystallization from a magma. The second group consists of particles formed by a metamorphic process which transformed minerals and rocks of the first group to glasses. This metamorphism was apparently caused by strong shock waves, as shall be demonstrated below.

*Mineral fragments* include, in order of decreasing frequency, pyroxenes of various composition, plagioclase (60–100 mole % An), ilmenite, olivine and a series of other minerals such as cristobalite, quartz, alkali-feldspar which are very rare and of subordinate importance in the shock history of the soil. The main minerals show varying degrees of shock deformation, which are especially recognizable in pyroxene and plagioclase. The grain size of all mineral fragments varies greatly ranging from some microns up to several millimeters.

*Glasses* in angular to subangular fragments occur up to some millimeters in size, but most frequently in the submillimeter fraction. Two kinds of glasses are present:

- (a) colorless clear glass fragments of pure plagioclase, or very rarely of alkali feldspar composition (diaplectic glasses);
- (b) colorless, pale, greenish, yellow, yellow-brown, red-brown, orange, brown and violet-brown fragments.

Most characteristic are *regular glass bodies* with rotational symmetry of different shape such as spherules, ellipsoids, dumbbell- and teardrop-shaped bodies. Most of them occur in the submillimeter fraction, a few are larger than one millimeter. The variation in color is quite similar to that of the angular glass fragments, type b.

Both, the type b angular fragments and the regular glass bodies are either very homogeneous or are heterogeneous to varying degrees in their vesicularity, schlieren, and amount and kind of inclusions. The most frequent inclusions are pyroxene, plagioclase and very tiny iron-nickel-spherules or opaque cube-shaped bodies. A small amount of all kind of glasses has been recrystallized.

*Rock fragments* may be divided into magmatic rocks and breccias. They range from particles consisting of only two or three mineral grains up to the decimeter size.

The *magmatic rocks* have a wide textural and grain size variety. The grain size ranges from a few microns to a few millimeters. Most frequent are rocks of basaltic composition with clinopyroxene, plagioclase, ilmenite and less common olivine and cristobalite. They are relatively uniform in mineralogical and chemical composition (LSPET, 1969). Rocks of anorthositic composition with plagioclase, olivine and/or pyroxene are less frequent and only present in the less than 1 cm grain size fraction.

Very rarely fragments of magmatic rocks are coated with brownish vesicular and streaky glass containing mineral inclusions like pyroxene and feldspar and minute iron-spherules.

The most abundant type of *breccias* principally consists of a mixture of all 5 types of constituents of the loose soil described above embedded in a matrix of vesicular, brownish glass (Fig. 1). The fragmental debris within the breccias has a grain size generally smaller than one centimeter and mostly even smaller than the millimeter range. The amount of matrix glass varies resulting in variable degrees of consolidation. The size range of the breccia fragments is similar to that of the crystalline rocks. However, breccias are more frequent than crystalline rocks in the less than 1 cm fraction.

Table 1. Grain size distribution of the soil <1 mm (10084-106)

Dia. ( $\mu\text{m}$ )	wt. %
1000-500	4.8
500-250	9.1
250-125	14.1
125-63	16.0
63-20	23.8
20-10	16.1
10-4	8.2
<4	7.7

Another type of *breccia* was found very rarely, as small fragments. It is composed mostly of fragments of plagioclase, pyroxene and colorless but recrystallized glass with some fragments of basaltic and anorthositic rocks embedded in a more or less homogeneous, recrystallized brownish glass matrix with large mostly spherical or irregular vesicles (Fig. 2). Colored glass fragments and colored glass globules are absent. This type of breccia was also observed as inclusions within the first type of breccia.

The grain size distribution of the less than 1 mm fraction of soil (10084-106) is given in Table 1. It is very nearly log-normal. The average diameter is 0.044 mm.

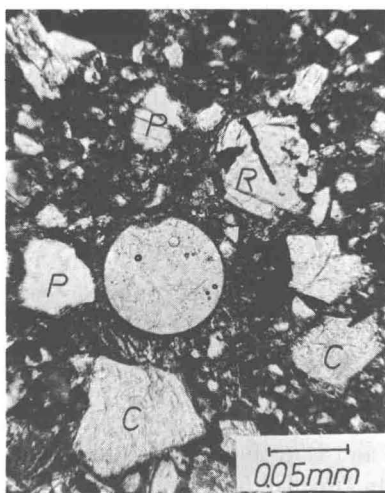


Fig. 1. Breccia with fragments of clinopyroxene (C), plagioclase (P), ilmenite (black), basaltic rock (R) and a yellow-brown glass-sphere embedded in a fine grained matrix. Plane light. (10027-11—M55a).



Fig. 2. Vesicular breccia with a glassy matrix including an older breccia fragment of the same type. Fragments and spheres of glass are absent. Plane light. (10085-25—M9).

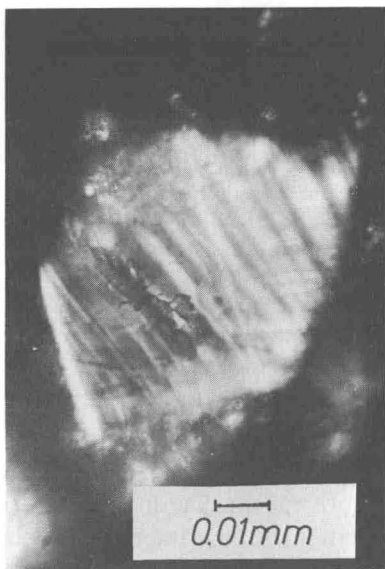


Fig. 3. Deformation lamellae in plagioclase. Crossed nicols (10059-41).

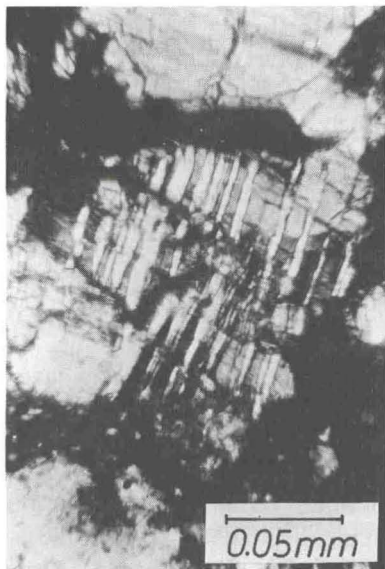


Fig. 4. Deformation lamellae in clinopyroxene of a shocked basaltic rock. Areas appearing dark are diaplectic plagioclase glass. Crossed nicols. (10085-25—M13).

The mineralogical composition of the grain size fractions is not uniform. Between 0.125 and 0.020 mm feldspar decreases, pyroxene and glass increase with decreasing grain size.

## SHOCK EFFECTS

### *Deformation structures*

(a) *Plagioclase*. Shock-induced deformation lamellae of low refractive index and low or no birefringence are frequent in plagioclase (<55 mole % An) from breccias of terrestrial impact craters (several papers in FRENCH and SHORT, 1968). In these rocks plagioclase grains with such lamellae always coexist with partially or completely isotropic plagioclase. Shock experiments carried out in this Institute with andesine and labradorite bearing rocks have shown that these lamellae are produced in the peak pressure range between about 250 and 300 kbar.

In two fragments of basaltic rocks from lunar soil (10085-25) we have found transition zones between regions with birefringent and isotropic plagioclase. Contrary to terrestrial shocked plagioclase no deformation lamellae have been observed in these rocks.

In soils and breccias we have very rarely found isolated plagioclase grains with deformation lamellae (Fig. 3). In these grains the regions between the lamellae show a decrease of birefringence and refractive index and locally total isotropization. Measurements on two grains (9 lamellae) have shown that the lamellae are not parallel to low index planes. The chemical composition of these plagioclase grains with deformation lamellae has not yet been determined.

The reason for the scarcity of plagioclase with deformation lamellae in the Apollo 11 samples is not yet understood. One reason may be the high anorthite content of lunar plagioclase. The terrestrial observations and experimental results refer to plagioclases with much lower anorthite content.

(b) *Clinopyroxene*. Some clinopyroxene fragments from breccias and soil as well as grains in shocked crystalline rocks contain one, seldom two sets of lamellae. They differ in optical orientation from the host crystal (Fig. 4), but seem to have the same refractive index and birefringence. Their average thickness is about 2–10  $\mu\text{m}$ . Most grains contain only a few thin lamellae. In some grains, however, the thickness of lamellae equals their separation from one another. The stereoplot of Fig. 5 shows the poles of 14 lamellae from 12 grains. In two grains (No. 1 and 6; in Fig. 5) additional closely spaced planar structures have been observed which are nearly perpendicular to the lamellae. They are not resolvable under highest magnification and may be submicroscopical lamellae.

Undulatory extinction and mosaicism limited the accuracy of measurement. In spite of this uncertainty it is obvious that the majority of lamellae and planar structures are not parallel to {001} or {100}, the usual orientations of twin and exsolution lamellae of rock forming clinopyroxene. Also in static and dynamic deformation experiments lamellae with orientations other than {100} and {001} have not yet been observed. In diopside twin lamellae parallel to {100} and {001} have been experimentally produced by static deformation (RALEIGH and TALBOT, 1967) and parallel to {001} by shock (SCLAR, 1970).

We assume that the lamellae shown in Fig. 4 are twin lamellae produced by shock waves. This assumption is strongly supported by the fact that lamellar clinopyroxene coexists in two rock fragments with isotropic plagioclase (diaplectic glass). In addition, lamellar clinopyroxene shows heavy mosaicism as is known from both artificially and naturally shocked pyroxene (CARTER *et al.*, 1968).

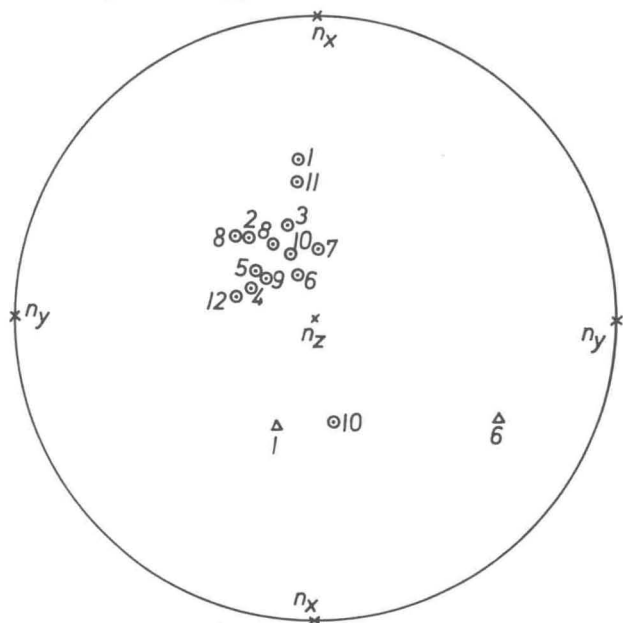


Fig. 5. Orientation of deformation structures in clinopyroxene.  $\odot$  Lamellae;  $\triangle$  Planar structures. Numbers refer to individual grains.

Clinopyroxene in paragenesis with diaplectic plagioclase glass has experienced shock pressures of at least  $\approx 300$  kbar. However, the minimum peak pressure of shock which is required to produce the lamellae may be considerably below 300 kbar, because in one of the above mentioned rock fragments lamellar clinopyroxene also occurs in parts where the plagioclase is still birefringent.

(c) *Olivine*. Planar deformation structures have been found in olivine grains within a diaplectic plagioclase glass fragment, about 1 mm in dia. The source rock is probably gabbroic anorthosite. These planar structures, measured in 5 grains, appear mostly to be very thin lamellae which are parallel to  $\{100\}$ ,  $\{010\}$ ,  $\{001\}$  and  $\{130\}$ . Planar structures parallel to  $\{130\}$ , observed in 3 grains, are characteristic of dynamic deformation. They have been produced in shock experiments with olivine single crystals and olivine nodules (MÜLLER and HORNE MANN, 1968, 1969), but have not been obtained in static compression tests (RIECKER and ROONEY, 1966; RALEIGH, 1968). The same planar structures have also been observed in some chondritic meteorites (MÜLLER and HORNE MANN, 1969). Although planar structures parallel to  $\{130\}$  in single crystals can already form at dynamic pressures as low as  $\approx 50$  kbar, coexistence with diaplectic plagioclase glass indicates that the olivine grains studied have been affected by shock pressures of at least 300 kbar.

X-ray photographs of single olivine grains from the investigated lunar glass fragment display elongated streaks demonstrating shock-induced mosaicism.

### Glasses

Isotropic glasses in the lunar soil and breccias are of two different kinds which should not be confused. We distinguish between fused and diaplectic glasses. Fused glasses solidified from liquid melts. They can be recognized by several features, such as vesicles, schlieren and other flow structures, and partially fused mineral grains. Their shapes are determined by surface tension. Diaplectic glasses\* are amorphous phases which were formed by shock waves in a subsolidus reaction. They probably originate from high pressure phases transformed to glass during pressure release (AHRENS and ROSENBERG, 1968; AHRENS *et al.*, 1969; ENGELHARDT and BERTSCH, 1969; STÖFFLER and ARNDT, 1969; ENGELHARDT *et al.*, 1970a).

Individual grains of diaplectic glasses have monomineralic chemical composition. All morphological characteristics of the molten state are lacking. Instead, the morphology of the previous crystalline state is sometimes preserved in features such as cleavage, twin boundaries, grain boundaries. The density and refractive index values are intermediate between those of the crystalline and the fused mineral.

Diaplectic quartz and feldspar glasses are known from terrestrial impact craters (see several papers in FRENCH and SHORT, 1968). The name maskelynite should be restricted to the diaplectic plagioclase glass of labradorite composition occurring in the Shergotty meteorite.

(a) *Diaplectic plagioclase and alkali feldspar glasses.* In the soil and breccias as well as in some crystalline rock fragments colorless and isotropic grains are observed which often show plane grain boundaries and cleavage but no indications of fusion such as vesicles or flow structures. A larger number of such isotropic fragments was selected by hand under the stereomicroscope from the fractions 1.0–0.5 mm and 0.25–0.5 mm of the samples 10084-106, 10085-25 and 10085-26. Sixteen grains were selected for refractive index determination. Since most of them contained inclusions of pyroxene and ilmenite only 6 grains were suitable for density measurement. Microprobe analyses of these selected grains yielded plagioclase compositions with An contents between 83 and 96 mole %.

The composition, density and refractive index values measured for each individual grain are listed in Table 2.† Figures 6 and 7 show refractive index and density versus the composition of these isotropic grains, and for comparison purposes refractive index and density of normal fused plagioclase glasses. As seen from both sets of data the values of normal glasses are lower than those of lunar isotropic grains of the same

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\* The term "diaplectic glass" was proposed in 1966 for "amorphous phases produced by shock waves without melting", at the First Conference on Shock Metamorphism of Natural Materials held at Greenbelt, April 14–16, 1966 (ENGELHARDT and STÖFFLER, 1968. See also: ENGELHARDT *et al.*, 1967). Later CHAO (1967) proposed the term "thetomorphic" to describe "any glassy phase transformed by shock from the crystalline host mineral in the solid state".

† An-contents given in Table 1 and Fig. 1 in ENGELHARDT *et al.* (1970b) are too low due to an error in the conversion of wt. % to mole %.



composition. These observations show that the latter are not fusion products but diaplectic glasses formed by a shock-induced phase transition in the solid state. Fragments of rocks containing diaplectic plagioclase glass in its original paragenesis with pyroxene and ilmenite are rarely to be found in the soil and breccias. In one rock fragment small inclusions of diaplectic alkali feldspar glass have been observed in a diaplectic plagioclase glass. Microprobe analysis of the inclusion yielded a composition of: Or 75, Ab 14 and An 7 in mole %.

Table 2. Refractive index  $n_D$ , density  $d$ , and composition (mole %) of lunar diaplectic plagioclase glasses

Sample	No.	An	Ab	Or	$n_D$	$d$
10085-25	M22	83	17	0.35	1.5620	2.650
10085-26	M52	84	13	0.3	1.5651	—
10084-106	M35	84	12	0.25	1.5675	2.653
10085-26	M42	89	6	0.2	1.5702	—
10085-26	M53	89	8	0.15	1.5760	—
10085-26	M39	91	6	0.1	1.5709	—
10085-25	M46	91	7	0.5	1.5723	—
10085-25	M40	91	5	0.1	1.5760	2.673
10084-106	M65	92	6	0.25	1.5807	—
10084-106	M34	92	5	0.25	1.5747	2.684
10085-25	M36	92	5	0.1	1.5762	—
10085-26	M51	93	5	0.2	1.5716	—
10085-25	M45	93	5	0.0	1.5772	—
10084-106	M21	93	4	0.1	1.5797	2.684
10084-106	M43	94	4	0.1	1.5802	2.684
10084-106	M48	96	5	0.1	1.5807	—

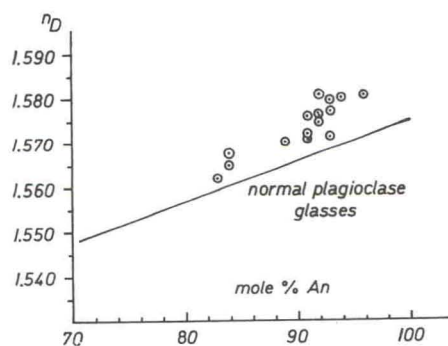


Fig. 6. Refractive indices of diaplectic plagioclase glasses. Solid line: Refractive indices of fused plagioclase (BARTH, 1969).

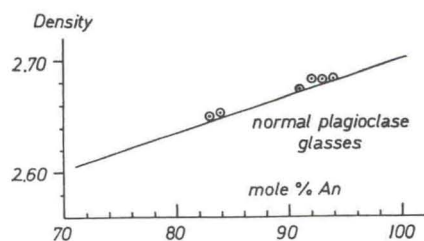


Fig. 7. Densities of diaplectic glasses. Solid line: Densities of fused plagioclase (BARTH, 1969).

Experimentally, diaplectic plagioclase glasses of various composition were obtained by several workers in recovery shock experiments (DECARLI and JAMIESON, 1959; MILTON and DECARLI, 1963; DECARLI *et al.*, 1967; MÜLLER and HORNEMANN, 1967). These experiments indicate the formation of diaplectic plagioclase glass in the range between about 300 and 550 kbar. Determinations of the Hugoniot curves and release adiabats of various plagioclases carried out by MCQUEEN *et al.* (1967),

AHRENS and ROSENBERG (1968) and AHRENS *et al.* (1969) indicate that at pressures exceeding about 300 kbar the plagioclases gradually transform to a high-pressure, high-density phase. AHRENS *et al.* (1969) conclude that this high-pressure polymorph probably corresponds to the rutile-like hollandite structure synthesized from microcline in static high pressure experiments by RINGWOOD *et al.* (1967). AHRENS *et al.* (1969) suggest that this high-pressure phase undergoes a reversion to an amorphous phase (diaplectic glass) on pressure release.

Diaplectic plagioclase glass differs from normal glass obtained by fusion in its behavior on annealing at temperatures below the glass transition temperature  $T_g$ . This was demonstrated by BUNCH *et al.* (1968) with diaplectic plagioclase glass from the Manicouagan crater and by DUKE (1968) with maskelynite from the Shergotty meteorite. Normal glasses show no or only slight variation in their physical properties on annealing at or below their glass transition temperature  $T_g$ . The  $T_g$  of anorthite rich plagioclase glass is not known. However, postulating from a  $T_g$  of 815°C for albite glass (VERGANO *et al.*, 1967) a value of about 850°C must be expected for anorthite glass.

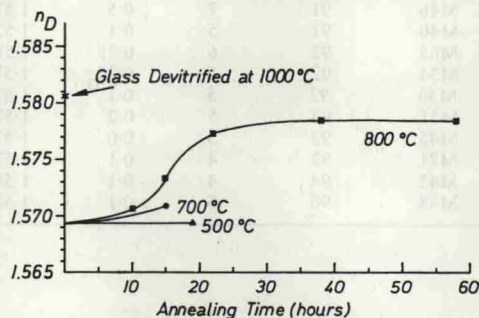


Fig. 8. Results of annealing experiments with diaplectic plagioclase glass (92 mole % An).

Figure 8 shows the results of annealing experiments made on 5 grains of one fragment of diaplectic plagioclase glass (92 mole % An). Annealing at 700 and 800°C, i.e. below  $T_g$ , increased the refractive index which at 800°C approached a saturation value of 1.5783. Beginning of partial crystallization was observed at 900°C after annealing for 7 hr. Complete recrystallization was obtained after annealing for 24 hr at 1000°C. The mean refractive index of the devitrified glass was 1.5807. These results are similar to those obtained by BUNCH *et al.* (1968) with diaplectic plagioclase glass of the Manicouagan crater. They do not correspond to the results of DUKE (1968) who found a steep decrease in refractive index of Shergotty maskelynite after annealing at temperatures as low as 450° and 500°C.

A number of lunar diaplectic plagioclase glasses in the soil and breccias show partial recrystallization which looks very similar to that of the experimentally devitrified grains. This indicates that some of the diaplectic plagioclase-bearing rock fragments were exposed to temperatures of at least 900°C over a time period in the order of days, but devitrification at lower temperatures over very long time periods is also possible.

(b) *Fused glasses.* Glasses, apparently formed by fusion of primary minerals and rocks, occur in soil and breccias as (1) bodies of regular spheroidal, ellipsoidal, dumbbell or teardrop shapes, (2) irregular fragments, and (3) vesicular coatings on pieces of breccias and crystalline rocks.

Regularly shaped glass bodies form about 10 per cent of all glasses in the soil. Their sizes range from 2 mm to 0.3  $\mu\text{m}$ . Light colored (green to colorless) glass bodies can be distinguished from a darker colored group containing yellow-brown, red-brown and violet-brown glasses. The darker colored glass bodies of regular shape occur about twice as frequently as the green and colorless ones.

Most of the regularly shaped glass bodies consist of very homogeneous glass with or without vesicles. The spherical vesicles are either distributed at random or concentrated near the periphery. Some of the homogeneous spheres include one single vesicle at the very center. Some glass bodies contain minute spherules of metallic iron which are very often accumulated in the surface of the bodies. These glasses originated from the rapid solidification of a silicate melt containing small droplets of liquid iron. The accumulation of iron spherules in the surface may have been caused by centrifugal forces acting in the rotating fluid body and/or by surface forces which held the iron droplets within the surface if their wettability by the silicate melt was low (contact angle, measured in the silicate melt, exceeding  $90^\circ$ ).

There are at least two possible mechanisms for the formation of the iron spherules: (1) Admixture of meteoritic iron condensing from the vapor phase produced by the impact of iron-bearing meteorites. (2) Segregation of free iron during melting of iron rich silicates under vacuum conditions, as was observed from a synthetic ferrobasalt glass by ANDERSON *et al.* (1970). A choice between these possibilities should be based on the level of Ni-concentration.

Instead of spheres some glass bodies contain small opaque cubes, probably of iron. Apparently, the cooling of these glasses proceeded in such a way that the temperature remained long enough close to the crystallization temperature of iron to allow the growth of one single crystal out of each liquid iron droplet.

In general, the cooling rate of the homogeneous glass bodies was so rapid that they were quenched without crystallization of silicates. However, devitrified glass bodies occur, which cooled more slowly. Most conspicuous are parallel or radiating crystals, probably pyroxene. Some of them resemble orthopyroxene chondrules of chondrites.

Some regularly shaped glass bodies are inhomogeneous. Besides vesicles, they contain inclusions of mineral grains (pyroxene, plagioclase, ilmenite) and/or a flow pattern of schlieren of different color and refractive index. The mineral grains are sometimes partially fused, showing a crystalline core surrounded by melt. Because all transitions occur between inhomogeneous and homogeneous glass bodies, it is probable that these glasses have been formed by fusion of small rock particles or mineral aggregates. The homogeneous glasses represent heating to very high temperatures. However, very homogeneous spherules, free of vesicles, may have been formed by condensing from silicate vapor.

As yet, the shapes of the regular glass bodies have not been studied systematically. A preliminary inspection has shown that they are either spheres or elongated bodies the longest axis of which is always an axis of rotational symmetry. We assume that

these forms were produced by the interaction of two forces upon drops of liquid melt which were propelled at high speeds and fell freely through the lunar vacuum. The one force was surface tension, the other resulted from the moments of inertia of the rotating bodies. If the liquid was very homogeneous or there was no or weak rotation, the surface tension prevailed and produced a perfect sphere. If the liquid drop contained inhomogeneities, such as vesicles or mineral grains, rotation raised inertia forces which distorted the sphere into an elongated body of rotational symmetry. The symmetry axis was the main axis of rotation and the axis of the lowest moment of inertia. If the viscosity was low enough, depending on initial temperature and cooling rate, rotation around the axis of highest moment of inertia led to dumbbell forms and

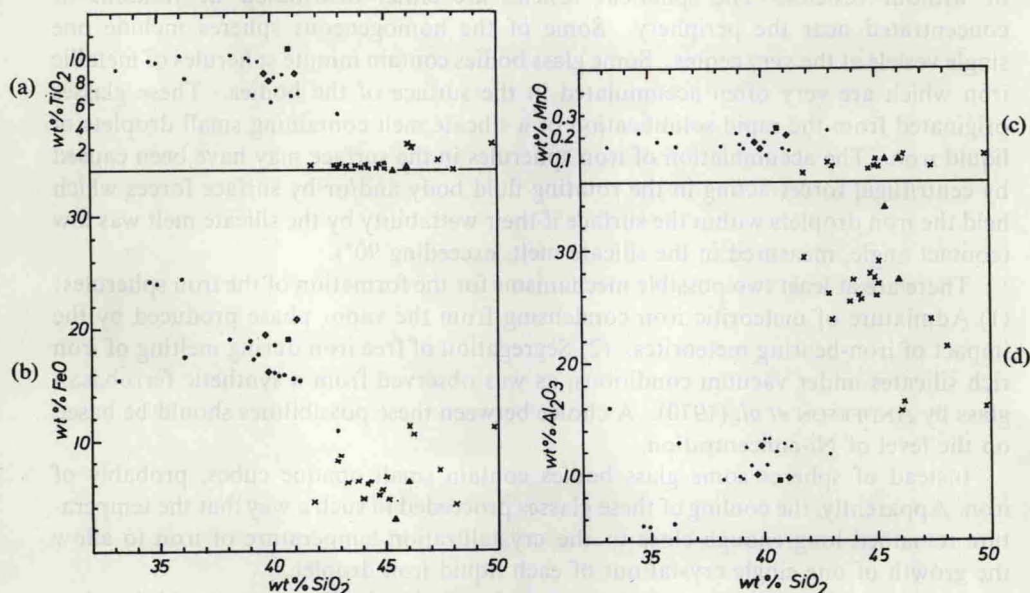


Fig. 9. Chemical composition of fused glasses (wt. %).

(a)  $\text{TiO}_2$  vs.  $\text{SiO}_2$ ; (b)  $\text{FeO}$  vs.  $\text{SiO}_2$ ; (c)  $\text{MnO}$  vs.  $\text{SiO}_2$ ; (d)  $\text{Al}_2\text{O}_3$  vs.  $\text{SiO}_2$ . ● Yellow-brown, red-brown and violet-brown glasses; × Colorless and green glasses; ◇ Vesicular glass coatings; ■ Lunar basalt, average; △ Lunar anorthositic rocks.

finally to separation into two teardrop bodies. Tektites and glass bodies in terrestrial pyroclastics and impact breccias do not show comparable regular shapes because liquid drops propelled through the atmosphere must adjust their shapes to aerodynamic forces. As no plastic distortions have been observed it is assumed that the regular glass bodies were cooled to a brittle state before they hit the ground and became embedded in the lunar soil. In the soil and breccias the glass bodies are often broken, especially the elongated dumbbells. This fracturing may have occurred when the bodies first hit the ground or during later reworkings of the soil, due to repeated meteorite impacts.

The majority of glass pieces in the soil and the breccias are irregular fragments. As with the regular glass bodies the same two groups of light colored (colorless to

green) and darker colored (yellow-brown, red-brown and violet-brown) glass fragments can be distinguished. Contrary to the regular bodies, the light colored fragments are about as frequent as the darker colored. Many of the fragments contain vesicles and mineral grains, sometimes partially fused. Flow textures revealed by schlieren of different colors and refractive index are frequent. Minute iron spherules are rather frequent, as are sometimes also opaque cubic crystals. Some fragments appear clear without any inhomogeneities. Devitrified glass fragments occur with dendritic and skeletal crystals.

Table 3. Chemical composition of colorless and green glasses  
(microprobe analysis, wt. %)

	Sample No.	SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	FeO	MnO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	Total	<i>n<sub>D</sub></i>	
Light green sphere	10084-106 M38	41.80	0.45	29.03	4.44	0.04	6.59	15.59	0.23	0.03	98.20	1.6027	
Green sphere	10084-106 M76	42.88	0.28	26.12	8.05	0.09	8.03	13.10	1.21	0.10	99.86	—	
Green sphere	10085-26 M37	43.04	0.33	23.77	8.63	0.07	8.66	13.08	0.23	0.03	97.84	1.6039	
Colorless fragment	10084-106 M63-4	43.75	0.41	25.36	6.33	n.d.	7.94	14.92	0.13	0.07	98.91	—	
Colorless fragment	10084-106 M63-5	44.01	0.22	27.74	4.69	n.d.	6.16	16.54	0.03	0.02	99.41	—	
Colorless fragment	10084-106 M63-2	44.27	0.38	25.56	6.20	n.d.	8.34	14.81	0.09	0.05	99.70	—	
Colorless fragment	10084-106 M63-6	44.39	0.41	25.85	6.13	n.d.	7.92	14.95	0.05	0.04	99.74	—	
Colorless fragment	10084-106 M71	44.67	0.20	27.84	5.07	0.06	7.12	14.18	0.27	0.02	99.43	—	
Colorless fragment	10084-106 M67	44.98	0.64	24.91	6.69	0.10	9.03	13.55	0.39	0.11	100.40	1.6054	
Colorless fragment	10084-106 M73	44.84	0.37	26.96	5.44	0.07	7.81	14.06	0.40	0.07	100.02	—	
Colorless-light green fragment	10084-106 M70	45.05	0.41	27.02	5.89	0.07	7.33	14.57	0.28	0.07	100.69	—	
Colorless fragment	10084-106 M63-3	45.12	0.20	26.95	4.69	n.d.	7.86	15.61	0.16	0.02	100.61	—	
Green fragment	10065-28	—	46.06	2.33	15.66	11.29	0.11	8.18	9.80	1.35	0.47	95.25	—
Green fragment	10065-28	—	46.24	2.05	16.44	10.56	0.12	8.13	9.98	0.97	0.50	94.99	—
Greenish ellipsoid	10065-28	—	47.39	0.87	23.82	7.35	0.07	8.31	13.14	0.37	0.09	101.41	—
Colorless fragment	10085-26 M50	48.08	0.13	21.38	4.22	n.d.	9.81	15.46	0.49	0.09	99.66	1.5890	
Green fragment	10084-106 M68	49.79	2.36	16.02	11.17	0.12	7.27	9.98	0.75	0.33	97.79	1.6012	
Average		45.08	0.71	24.14	6.87	0.08	7.91	13.72	0.43	0.12	99.05		
Anorthositic gabbro*		46.0	0.3	27.3	6.2	0.1	7.9	14.1	0.3	trace	102.5		
Anorthosite*		45.4	trace	33.8	2.8	0.1	1.7	17.5	0.4	trace	101.7		

n.d. = not determined.

\* Wood *et al.* (1970).

Table 4. Chemical composition of yellow-brown, red-brown and violet-brown glasses  
(Microprobe analysis, wt. %)

	Sample	No.	SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	FeO	MnO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	Total	n <sub>D</sub>
Yellow-brown ellipsoid	10065-28	—	33.19	8.93	15.97	15.37	0.16	8.33	13.21	0.00	0.00	95.16	—
Red-brown sphere	10065-28	—	34.56	9.73	5.36	24.21	0.22	12.96	7.03	0.37	0.05	94.49	—
Red-brown sphere	10065-28	—	34.88	9.83	5.28	23.99	0.18	13.12	7.06	0.40	0.05	94.79	—
Violet-brown sphere	10085-25	M28-A	35.98	10.19	5.57	24.47	0.22	12.58	7.58	0.44	0.03	97.06	—
Yellow-brown sphere	10065-28	—	36.22	8.21	12.86	17.51	0.16	8.40	11.47	0.21	0.05	95.09	—
Red-brown fragment	10065-28	—	38.16	10.20	9.62	19.12	0.16	6.95	10.38	0.71	0.14	95.44	—
Yellow-brown fragment	10084-106	M69	38.87	9.89	9.79	18.33	0.22	8.76	10.70	0.31	0.05	96.92	1.7234
Yellow-brown fragment	10065-28	—	39.20	6.74	12.47	17.26	0.15	8.97	10.61	0.71	0.07	96.18	—
Violet-brown fragment	10085-25	M28-C	39.04	9.70	18.89	0.17	0.17	6.99	10.67	0.26	0.49	95.98	—
Yellow fragment	10085-25	M74	39.41	9.63	10.83	17.73	0.21	7.56	11.43	0.61	0.15	97.56	—
Yellow-brown fragment	10065-28	—	40.02	6.00	13.29	16.06	0.15	8.44	10.80	0.68	0.13	95.57	—
Violet-brown fragment	10085-25	M28-B	40.09	8.19	10.91	18.46	0.18	8.07	10.95	0.69	0.16	97.70	—
Yellow fragment	10085-26	M56-A	40.25	7.06	13.26	15.76	0.12	8.06	10.67	0.12	0.04	95.34	—
Yellow fragment	10085-25	M75	40.54	8.46	12.10	15.76	0.22	7.70	11.65	0.64	0.15	97.22	—
Yellow-brown fragment	10065-28	—	40.90	6.56	12.88	15.52	0.15	8.74	10.65	0.60	0.14	96.14	—
Red-brown fragment	10084-106	M82	41.20	6.85	12.59	15.35	0.14	8.86	10.70	0.42	0.14	96.25	—
Yellow fragment	10084-106	M66	42.87	4.94	11.84	10.85	0.23	16.22	9.42	0.20	0.07	96.64	1.6528
Average			38.55	8.30	10.84	17.92	0.18	9.45	10.29	0.43	0.11	96.09	—
Apollo 11 basaltic rocks average*			40.69	10.78	9.49	19.16	0.24	7.55	10.97	0.46	0.18		

\* Average of analyses of crystalline Apollo 11 rocks by AGRELL *et al.* (1970), FRONDEL *et al.* (1970), ENGEL and ENGEL (1970), MAXWELL *et al.* (1970), PECK and SMITH (1970), WIHK and OJANPERÄ (1970).

The glass fragments were formed by later fracturing of larger bodies or flows of glass. Formation and transport mechanisms were different for the regular glass bodies and the fragments. However, both types of glass apparently originated from the fusion of the same source material.

Results of microprobe analyses of 17 regular bodies and fragments of light colored glasses and of 17 regular bodies and fragments of dark glasses are presented in Tables 3 and 4 and Figs. 9–11. The individual pieces have been either separated from

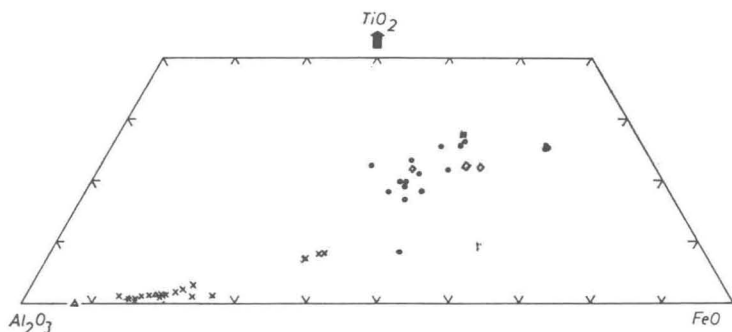


Fig. 10. Fused glasses:  $\text{Al}_2\text{O}_3$ ,  $\text{FeO}$  and  $\text{TiO}_2$  content (wt. %).

- Yellow-brown, red-brown and violet-brown glasses; × Colorless and green glasses;
- ◇ Vesicular glass coatings; ■ Lunar basalt, average; △ Lunar anorthositic rocks.

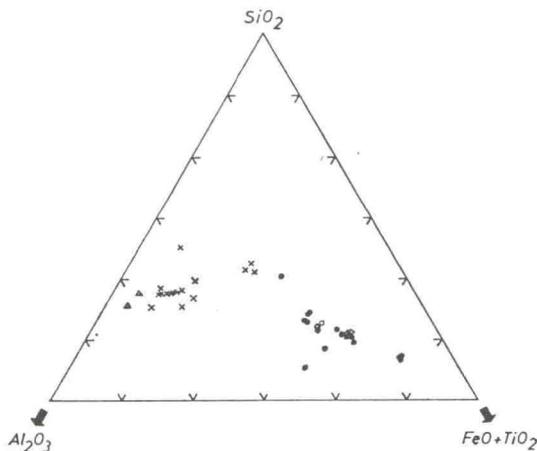


Fig. 11. Fused glasses:  $\text{Al}_2\text{O}_3$ ,  $\text{FeO} + \text{TiO}_2$  and  $\text{SiO}_2$  content (wt. %).

- Yellow-brown, red-brown and violet-brown glasses; × Colorless and green glasses;
- ◇ Vesicular glass coatings; ■ Lunar basalt, average; △ Lunar anorthositic rocks.

the soil or analyzed in polished sections of breccias and grain mounts of the soil. Within each group there is a broad variability of chemical composition. Calculation of norms showed that each individual 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 silica or olivine.

The chemical dissimilarity of the individual glass pieces distinguishes lunar soil and breccias from terrestrial pyroclastic rocks. Individual glass particles of pyroclastics are of essentially the same chemical composition because they are products of the dispersion of the same uniform magma.

It must therefore be concluded that the lunar glass bodies and fragments, constituting an essential part of the soil and breccia, are not of volcanic origin. They did not originate in large and homogeneous lava pools. Instead, they must have been formed individually, by fusion of relatively small rock volumes. We assume that all fused glasses in soil and breccias have been formed from melts produced by meteoritic impacts. Such impacts can provide sufficient energy for instant and local fusion and for a dispersion of these fusion products over large areas.

Notwithstanding the differences between the individual glasses, the light colored and dark glasses form two groups which are distinctively different in chemical composition. Major differences exist in the contents of  $\text{SiO}_2$ ,  $\text{TiO}_2$ ,  $\text{Al}_2\text{O}_3$ , FeO and MnO (see Tables 3 and 4 and Figs. 9–11). The colorless and green glasses contain more  $\text{SiO}_2$  (average 45%), less  $\text{TiO}_2$  (average 0.7%), more  $\text{Al}_2\text{O}_3$  (average 24%), less FeO (average 7%) and less MnO (average 0.1%). The yellow-brown, red-brown and violet-brown glasses have less  $\text{SiO}_2$  (average 39%), more  $\text{TiO}_2$  (average 8%), less  $\text{Al}_2\text{O}_3$  (average 11%), more FeO (average 18%) and more MnO (average 0.2%).

As can be seen in the linear plots of  $\text{Al}_2\text{O}_3$ ,  $\text{TiO}_2$ , FeO and MnO vs.  $\text{SiO}_2$  and in the triangular representations of  $\text{Al}_2\text{O}_3 - \text{FeO} + \text{TiO}_2 - \text{SiO}_2$  and  $\text{Al}_2\text{O}_3 - \text{TiO}_2 - \text{FeO}$ , resp., the two groups are fairly distinct from one another.

The average composition of the yellow-brown, red-brown and violet-brown glasses is very similar to the average composition of the Apollo 11 basaltic rocks (see Table 4 and Figs. 9–11).

We conclude that these glasses were formed from melts produced by meteoritic impacts on basaltic rocks or on breccias and soils of basaltic composition. Sources of the dark colored glasses may be craters in the vicinity of the Apollo 11 landing site. The colorless and green glasses, on the other hand, have a composition similar to that of the anorthositic rocks occurring in small pieces in Apollo 11 soil and breccias (see Table 3 and Figs. 9–11). We assume that the light colored glasses are products of meteoritic impacts on rocks of anorthositic composition. In the Apollo 11 soil and breccias such rocks occur only as minor constituents. The impact sites, sources of anorthositic rock fragments and light colored glasses, may perhaps be located somewhere on the highlands.

This hypothesis—also expressed for the anorthosites by KING *et al.* (1970) and WOOD *et al.* (1970)—is supported by the fact that the chemical composition of the surface north of Tycho, determined by the  $\alpha$ -scattering experiment of Surveyor 7, comes close to that of the light colored glasses and anorthositic rocks. It shows higher  $\text{SiO}_2$ - and  $\text{Al}_2\text{O}_3$ - and lower  $\text{TiO}_2$ - contents than the mare materials analyzed by Surveyor 5 (Sinus Medii) and Surveyor 6 (Mare Tranquillitatis) (Table 5).

The two types of impact-induced fused glasses deposited in the soil and breccias of Mare Tranquillitatis may be connected with the two ray-systems in the vicinity of the Apollo 11 landing site. The north-northwest trending ray which is perhaps related to Tycho or to another crater on the highlands may have delivered unshocked



anorthositic rock fragments and such of different stages of shock metamorphism including light colored fused glasses. The north-northeast trending ray may have furnished dark glasses of basaltic composition.

Another possibility is that anorthositic rocks and glass came from pre-mare rocks of highland type underlying the basaltic mare material. The mare material is assumed to form a relatively thin layer in the area of the Apollo 11 landing site. In this case the anorthositic rocks and glasses may have been ejected from larger mare craters such as Sabine E, D and Moltke (SHOEMAKER *et al.*, 1969).

Table 5. Comparison of Surveyor analytical results (PATTERSON *et al.*, 1969) with the composition of dark and light colored glasses (wt. %)

	Surveyor 5 (Mare Tranquillitatis)	Dark colored glasses Average	Surveyor 7 (Tycho)	Light colored glasses Average
SiO <sub>2</sub>	46	39	50	45
TiO <sub>2</sub>	8	8	—	0.7
Al <sub>2</sub> O <sub>3</sub>	14	11	21	24
FeO	12	18	7	7
MgO	4	9	7	8
CaO	14	10	15	14
Na <sub>2</sub> O	0.6	0.4	—	0.3

Coatings of brown, vesicular glass on pieces of breccia or crystalline rocks, and fragments of the same glass occur in the soil and breccias. This glass is more vesicular and richer in mineral inclusions and schlieren than the other glasses described above.

Three such glasses adhering to two basaltic rocks and one breccia have been analyzed. The results, given in Table 6 and in Figs. 9-11, show that these glasses

Table 6. Chemical composition of vesicular glass coatings (microprobe analysis, wt. %)

	Sample	No.	SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	FeO	MnO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	Total
Brown glass coating breccia	10085-26	M58A	39.86	8.03	12.62	16.13	0.16	7.32	11.49	0.24	0.85	95.93
Brown glass coating basaltic rock	10060-34	—	39.69	8.68	9.95	19.45	0.18	7.19	10.85	0.28	0.08	96.36
Brown glass coating basaltic rock	10085-25	M61	41.09	8.58	9.68	20.83	0.21	4.77	10.56	0.38	0.11	96.20
Inclusion of gray glass in the brown glass	10085-25	M61	45.91	3.40	4.59	13.85	0.20	12.67	15.77	0.08	0.00	96.47
Pyroxene in the basaltic rock	10085-25	M61-41	46.84	3.11	4.07	9.11	0.12	13.65	17.32	0.11	0.03	94.36

belong to the group of dark colored glasses of basaltic composition. The basaltic rocks, No. 2 and 3 of Table 6 show indications of shock metamorphism at the contact of the glass coating: pyroxene grains contain deformation lamellae and in the rock No. 3 plagioclase is transformed into diaplectic glass (see next section). We assume, therefore, that the glass coatings were produced by the impact of small rock fragments or splashes of melt, ejected from meteorite craters. The brown glass of coating No. 3 contains 0.07 wt. % Cr<sub>2</sub>O<sub>3</sub>, the pyroxene of the underlying basalt 0.4 wt. % Cr<sub>2</sub>O<sub>3</sub>.

It is therefore unlikely that this glass was formed by fusion of the impacted basalt. It probably represents mainly the material of the impacting projectile. However, some individual components of the impacted rock were fused without being dissolved in the melt. This is shown by an inclusion of a gray glass of pyroxene composition in the brown glass. The composition of the gray glass is nearly identical with that of the pyroxene in the basalt (see Table 6).

#### CONCLUSIONS

During the formation and excavation of an impact crater a large amount of rock will be subjected to stress waves with peak pressures below the dynamic elastic limit of the minerals affected. This material will be fractured, deformed and ejected. However, it will not contain shock effects *sensu stricto* as defined in the introduction, i.e. deformation structures, solid state transformations and fusion products which can be formed only by pressures above the dynamic elastic limit.

According to the geometry of dissipation of the energy set free by the impact of a meteorite the amount of rock affected by stresses below the dynamic elastic limit represents by far the greatest portion of all material ejected from the crater.

From the observed shock effects in Apollo 11 samples we establish the following simplified classification of 5 stages of progressive shock metamorphism in lunar rocks.

(1) The lowest degree of shock metamorphism is represented by rocks the pyroxenes and plagioclases of which contain deformation structures. The plagioclase has a normal or reduced birefringence and refraction index. Apparently, deformation structures in pyroxene begin to develop at lower peak pressures than those in plagioclase. The pressure range in which deformation lamellae are formed in lunar plagioclase seems to be rather narrow.

(2) The next stage of shock metamorphism is characterized by rocks containing diaplectic plagioclase glasses together with pyroxene and olivine both exhibiting deformation structures. We estimate the pressure range of this stage to be from  $\approx 300$  to  $\approx 550$  kbar.

(3) We have not yet observed selectively fused plagioclase in any lunar rocks; a stage of shock metamorphism frequently found in terrestrial impact craters (e.g. Ries Basin, Germany). This may be due to the similar values of the melting temperatures of lunar plagioclase and pyroxene, resulting in simultaneous melting of both minerals.

(4) A still higher stage of shock metamorphism is represented by complete melting of rocks resulting in the various glasses described above. Melting is achieved by shock pressures producing residual temperatures which exceed the liquidus temperature of the rocks. We assume the pressure range of this stage to be from  $\approx 600$  kbar to the Megabar region.

(5) The highest stage of shock metamorphism leads to vaporization of rocks. The very homogeneous glass bodies may be condensation products of silicate vapor. Vaporized meteoritical material may be incorporated.

Three of these stages have been observed, on a small scale, in one single fragment ( $1 \times 0.4 \times 0.6$  cm) of a basaltic rock, shown in Fig. 12. The surface of this fragment is covered with a brown glass (No. 3, Table 6), representative of stage 4. Beneath the glass follows a zone in which all plagioclase is converted into diaplectic glass. The

original texture of the rock is preserved (Fig. 13). Many pyroxene grains contain deformation lamellae. This zone corresponds to stage 2. A very narrow transition zone (maximum thickness about 0.2 mm) separates the stage 2 zone from the interior of the fragment where the plagioclase is birefringent but some pyroxene crystals still show deformation lamellae. The transition zone and the latter region belong to stage 1. The plagioclase in the transition zone shows no deformation lamellae.

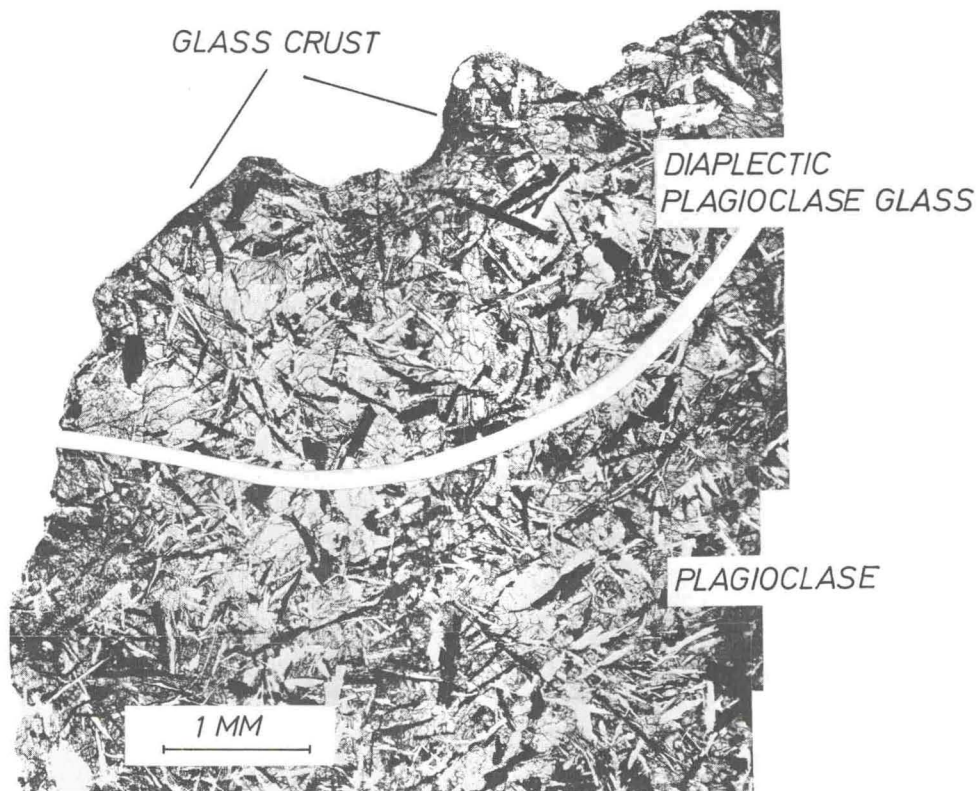


Fig. 12. Shocked basaltic rock coated with vesicular glass. Zones of progressive shock metamorphism. Plane light. (10085-25—M61).

Stages of progressive shock metamorphism have been established for shocked rocks from breccias of several terrestrial meteorite craters (STÖFFLER, 1966, 1967; CHAO, 1967, 1968; DENCE, 1968; ENGELHARDT and STÖFFLER, 1968).

The stages found in the fall-out breccia (suevite) of the Ries Basin are essentially conformable with those of lunar shock metamorphism as described above.

Hence, the lunar regolith can be compared with terrestrial suevite-like impact breccias. There are similarities and differences between both. The lunar regolith as well as suevite is a mixture of rock and mineral fragments in all stages of shock metamorphism together with unshocked fractured rocks and minerals. Characteristic of the regolith are indications of multiple impacts, whereas each terrestrial suevite is the

product of one single event. On the lunar surface impacts into the unconsolidated soil ejected from older impact craters produced breccias consolidated by a glassy matrix. The multiple repetition of such processes is evident from fragments of old breccias included in younger breccias (Fig. 2). Another peculiarity of the regolith, due to the lack of an atmosphere on the moon, is the occurrence of regularly shaped glass bodies which have not been found in terrestrial suevites.

In conclusion, no process other than multiple meteoritic impacts can have produced, transported and deposited a clastic sediment with the composition and texture of that of the lunar regolith.

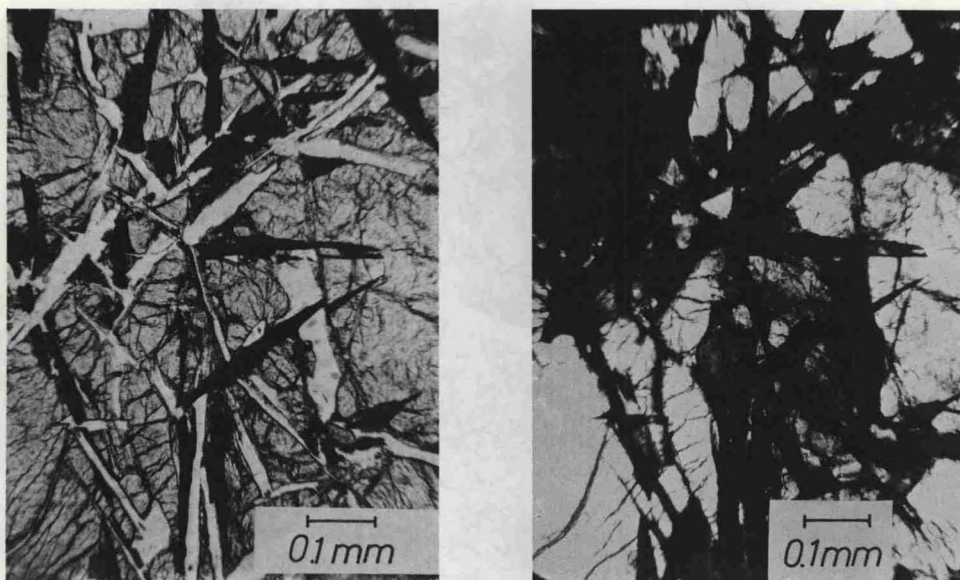


Fig. 13. Detail from Fig. 12.

(a)—(left) Laths of diaplectic plagioclase glass (white), ilmenite (black), pyroxene (gray). Plane light. (b)—(right) Crossed nicols.

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