Lunar Glasses and Micro-Breccias: Properties and Origin

Abstract. *Impact has been an important rock-forming process on the moon. Electron- and ion-probe analyses of major and minor elements show that most glasses and chondrule-like particles formed by shock melting of various proportions of mainly pyroxene, plagioclase, and ilmenite. This is the first direct evidence that chondrule-like molten droplets can form in impact events. Welding and shock lithification resulted in rocks texturally similar to chondrites but composition rules out the moon as source for chondrites. Impact craters on a nickel-iron sample evidence the importance of secondary impacts by accelerated lunar matter.*

Glass fragments and particles occur in a wide variety of shapes and colors in the lunar soil and breccias (*1*). The glasses could be traced back to melting of the main minerals in the Apollo 11 lunar materials. Furthermore, all the crystalline rocks and their minerals could be found in the soil samples as well as in the "micro-breccias" (*1*). We have concentrated our work on rock fragments, and especially glasses, in the soil samples and breccias 21, 61, and 73, although major and trace elements in the various phases of several crystalline rocks have been analyzed.

Major elements were determined in some 60 glasses ranging from spheres, and irregular fragments, to vesicular "crust" adhering to rock fragments and semidevitrified veins in breccias. In general no correlation was found between morphology or size and chemical composition. However, the color in the thin sections changes from colorless to brown to opaque with increasing concentration of Fe and Ti. Silica with a few exceptions ranges from 33 to 48 weight percent; Na_2O from <0.1 to 0.4 percent which indicates some over all loss of these elements. Also, norm calculations for the glasses and the rocks (*1*) indicate more olivine in the former. For Si this is consistent with Walter's (*2*) studies of volatilization of glasses, and although he did not observe a preferential loss of Na the more reduced condition of the lunar rocks may explain this discrepancy.

A strong and consistent anticorrelation of Al_2O_3 with TiO_2 is apparent (Fig 1). On the other hand TiO_2 and FeO show positive correlation. It thus appears clear that most glasses formed by shock melting and quenching of different proportions of ilmenite, pyroxene and plagioclase, the principal minerals in the crystalline rocks. The possibility that some glasses represent material condensed from hot, high density gases cannot be excluded. However, many particles are definitely not such condensates (Fig. 2). One sphere with almost no TiO_2 or Al_2O_3 has pyroxene compositon and may be of meteoritic origin, and two with low TiO_2 and intermediate Al_2O_3 may be mixtures of lunar and meteoritic materials. In Fig. 1 the spheres from a breccia fragment (in 85) appear to form a distinct family. However, only brown, transparent spheres were analyzed in this sample while the spherules in breccias 21 and 61 (Fig. 1) range from colorless through green, yellow and brown to opaque.

Ion-probe analysis (*3*) of trace elements in one brown sphere, a clear individual fragment, two different parts of "crust" on a breccia fragment, and a clear fragment embedded in the same breccia show only small variations and a general similarity with the micro-breccias and soil (*1*). The ranges for some of the elements analyzed were, expressed in atoms per 10^6 Si: Li 107 to 182, B 90 to 230, Na 1.93 to 2.28 $\times 10^4$, Sr 320 to 548, Zr 253 to 357, and Ba 146 to 177 (with exception for the sphere which has high iron and 82 Ba/10^6 Si). Some elements such as V, Cr, and Mn show stronger variation and are positively correlated with iron content.

Figure 2 shows a composite, unusually large (0.4 mm) spherule which graphically illustrates the process of glass formation. Part of the sphere is glass, but some of the original material is still crystalline, severely shocked pyroxene, plagioclase, and ilmenite; the latter mineral is partly dissolved in the glass giving darker colors locally.

The glass spheres may be called chondrules, that is quenched silicate droplets. A few directly resemble glassy chondrules described from the Chainpur chondrite (*4*) in that they have skeletal olivine (Fa_{24-26}) in a glass depleted in Mg and Fe but enriched in Si, Al. The chemical differentiation is weaker, however, than in the Chainpur chondrule, indicating less reducing conditions. Lithification by welding and/or shock has produced rocks texturally resembling types II and III carbonaceous chondrites. The lunar breccias are also, texturally, somewhat similar to terrestrial impactites and some ignimbrites. Still they can be more favorably com-

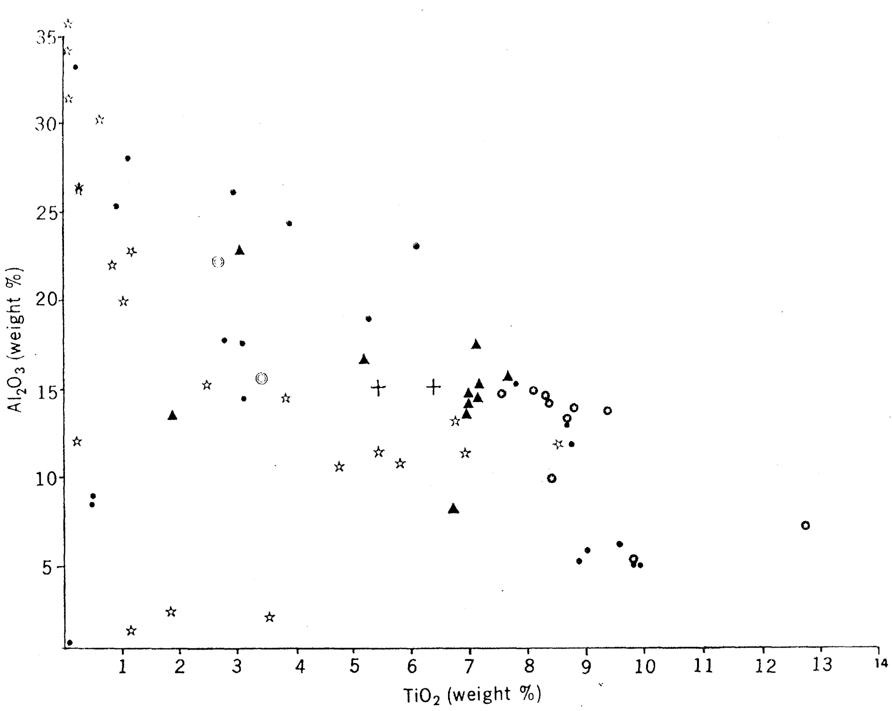
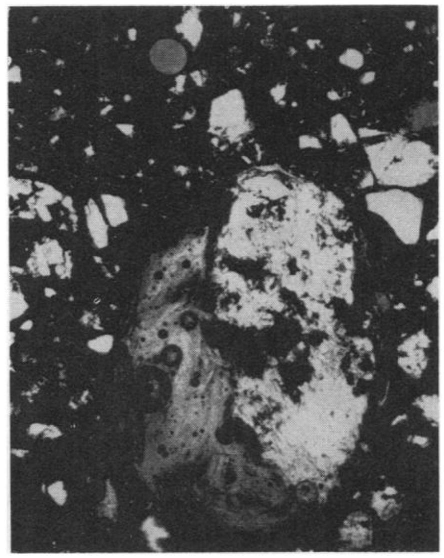


Fig. 1. The TiO_2 and Al_2O_3 in lunar glasses. Circles with stars in them, spherules (breccia in 85); solid circles, spherules (breccias 21 and 61); stars, fragments (84, 85, and 61); triangles, "crust" glass on fragments (85); concentric circles, glass on Ni-Fe particle; crosses, average 84, <43 μm, and glasses, 85.

Fig. 2. The left part plus the entire rim of the 0.4-mm long, oval bead is yellowish glass with darker flow lines. The right, lighter part is severely shocked pyroxene and plagioclase. The ilmenite, center, is partly dissolved in the glass causing brown coloring. At top center is a typical, brown glass spherule.



pared to chondrites, although their composition apparently eliminates the moon as a source (*5*) for any type of chondrite.

Our soil sample 84,22 was somewhat finer, that is, 50 percent < 43 μm than reported (*1*). In the size fraction 0.25 to 0.5 mm we found, among 596 grains studied, 37 percent igneous rock fragments similar to types A and B (*1*), 6 percent other igneous rock types, 38 percent breccias, 10 percent "bubbly" glasses with crystallites and/or inclusions, and 9 percent clear glasses including spherules. The fraction 70 to 100 μm is similar and x-ray diffraction analysis (*6*) showed little variation with grain size. Bulk analysis of the fines (<43 μm) in 84 and of randomly selected glasses from 85 (*6*) are almost identical with the soil (*1*). However, preliminary electron-probe analysis of the matrix in breccias 21 and 61 indicates lower Ti/Al, Ti/Si, and Fe/Si ratios than in any bulk samples.

Among the rock fragments are several with low contents of opaque minerals, especially ilmenite. Some are also rather coarse grained and may be similar to rocks apparently present in the Apollo 12 samples. Sample 85,17 (*6*) contained a 4-mm, lens shaped, apparently meteoritic, nickel-iron particle (see cover). Its surface shows craters caused by high velocity impact of high TiO_2 lunar matter which has been transformed to glasses similar to those described above (Fig. 1). Apparently secondary impacts may play an important role in modifying the lunar surface.

Most minerals in the soil are similar to those in the crystalline rocks. However, we have also found unusually pure anorthite (< 0.1 Na_2O), and a pyroxene displaying 10 to 20 μm-wide exsolutions. The host pyroxene is $En_{43}Fs_{15}Wo_{42}$ with 1 to 3 percent TiO_2 and Al_2O_3; the lamellae are $En_{64}Fs_{36}$. The metal and sulfide grains particularly in the glassy fragments have more Ni (up to 12 and 2 percent, respectively) than do the crystalline rocks. Whereas the latter may have been reduced out *in situ*, the metal in the glassy fragments and mostly in the breccias is probably of meteoritic origin.

The crystalline rocks have a narrow range in chemistry (*1*), mineralogy and modal composition (*2*) but vary in grain size and texture. We have analyzed individual minerals in rocks 3, 20, 22, 47, and 50. However, consultation with several colleagues indicates that, with a few exceptions, our data have no exceptional trends or implications. An Fe-rich pyroxene-like mineral, $En_4Fs_{78}Wo_{17}$, was found in 47 (and in the soil), and a trace of pigeonite, $En_{53}Fs_{39}Wo_8$, in rock 3. Olivines in 20 and in a type B fragment were zoned with sharp increase in Fe by about 15 percent in the outer 30 to 40 μm of grains 0.2 to 0.4 mm in size. The centers were rather homogeneous with Fa_{30}. The CaO content is relatively high ~ 0.4 percent and Cr enriched to about 0.15 weight percent in the center parts. Metal in 3 and 47 is low in Ni but has ~ 0.5 percent Co. We learned (*7*) that the metal in 22 had about 1 percent Ni; we found 0.6 and 1.7 percent Ni, and 1.2 and 2.6 percent Co, respectively, in two grains both minute exsolutions in troilite (Ni, Co, Mn, Cr, < 0.05 percent).

Some of our ion-probe trace element analysis in individual phases in one type B rock fragment are summarized (Fig. 3). It must be emphasized, however, that large variations have been observed. For example, 1 ppm (atomic) Ba and 100 ppm K were found in plagioclase from type B while a grain in the soil had ~ 1500 ppm Ba and 500 ppm K. Similarly B and Ba vary by a factor of 40 or more, and Zr by a factor of 20, in

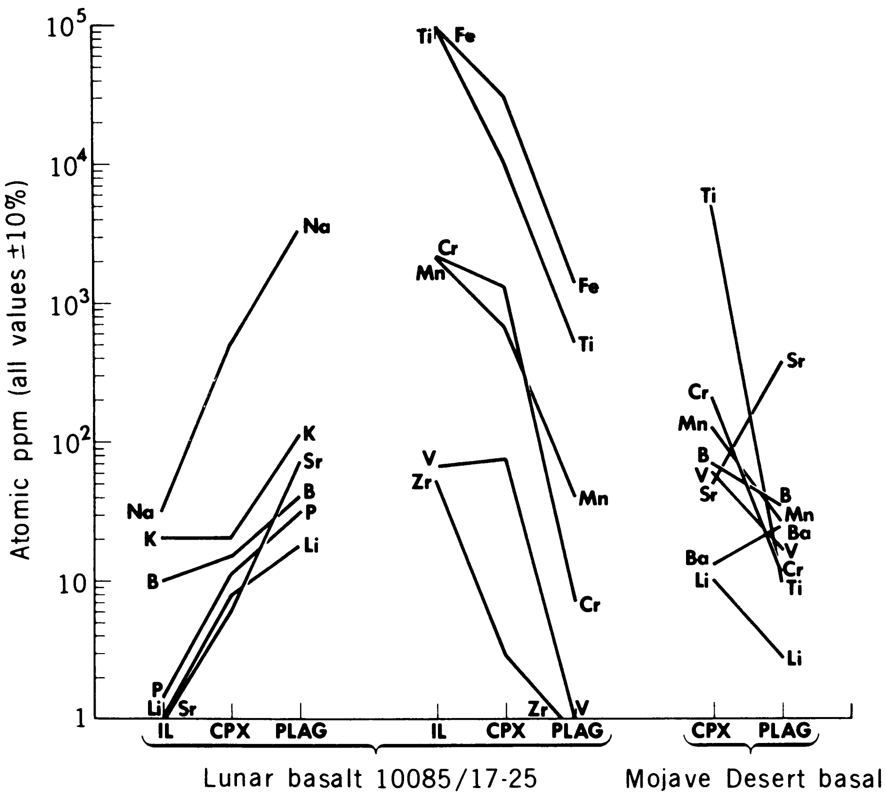


Fig. 3. Trace element distribution in the main minerals of a lunar rock, type B, and a terrestrial basalt. Elements in the lunar sample showing similar trends are grouped together for convenience. IL, ilmenite; CPX, clinopyroxene; PLAG; plagioclase.

otherwise similar pyroxenes from different rocks. This indicates that these minerals have different sources, that is parent magmas.

The origin of the parent magma for the crystalline rocks is uncertain. It may have been derived by partial fusion at depth caused by radiogenic heating or perhaps by melting triggered by impact of very large bodies. In any event, the textures are typical of igneous rocks which cooled mainly under static conditions. It is of course possible that the magma from which they crystallized flowed a long distance before crystallization began, as is the case in many terrestrial basalts. The high TiO_2 contents and other composition characteristics of the lunar crystalline rocks indicate that either the processes which produced them or their parent materials were quite unlike terrestrial processes and parent materials. If the great age (*1*) of these rocks holds, one can either presume that the moon was accreted from already differentiated material, or that early in the moon's (and earth's) history large numbers of impacts were a major geological agent creating superheated melts over considerable areas. Similar origins have been suggested for chondrites, that is, that they were created by impacts on relatively small, low density (compared to the moon) bodies (*8*).

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Deformation of Silicates from the Sea of Tranquillity

Abstract. *Plagioclase and olivine crystals in the crystalline rocks from the Sea of Tranquillity show little or no evidence of either static or dynamic deformation. The large disorientations in many of the pyroxene crystals are commonly consistent with slip on the system* T = {*100*}, t = [*001*], *but these distortions are not due to plastic flow. They are ascribed to rapid growth and quenching phenomena as deduced from studies of chondrules and of quenched natural and experimentally produced melts. Some of the silicates in the breccias and regolith show evidence of shock deformation, from mild to intense, as indicated by pervasive fracturing, shock lamallae, and partial transformation of pyroxene and plagioclase crystals to glass.*

Recent static experiments on silica and silicates have demonstrated that the plastic flow mechanisms vary with temperature, with strain rate, and, for some materials, with pressure. The slip mechanisms observed at the higher temperatures and lower strain rates have been successfully correlated with those operative in natural slow deformations. The primary objective of the present investigation of silicates returned from the Sea of Tranquillity was to determine the presence or absence of such deformation features. Given a representative sample from various provinces of the lunar surface, such studies should discern the importance of tectonic activity during the history of the moon. In addition, we have examined the lunar material for evidence of dynamic deformation due to the impact of foreign bodies. In our studies to date we have used primarily optical microscopy and x-ray Laue and precession methods.

Plagioclase in euhedral and subhedral crystals is a common constituent of both the fine- and coarse-grained igneous rocks but shows little or no evidence either of static or dynamic deformation. Thin plagioclase laths are commonly bent slightly, but such bending is also evident in thin laths from experimentally and naturally quenched terrestrial basalts. Olivine crystals in the fine-grained igneous rocks show no deformation whatever. Most of the pyroxenes (chiefly augite), however, show large distortions within individual grains. The disorientations resemble, in many respects, those produced by both static and dynamic deformation of pyroxenes and will be discussed in more detail below.

Three types of disorientations are observed in the pyroxene grains: (i) uniform sweeping undulatory extinction (Fig. 1a) over angles ranging to 100°; (ii) discontinuous changes in extinction with subboundaries separating zones of uniform extinction—somewhat similar to kink bands or polygonization in crystals; and (iii) more irregular disorientations in which the grains are composed of mosaics of irregularly shaped blocks having different orientations. Universal stage measurements of the variation in crystal orientations in grains showing disorientations of types i and ii generally indicate that an axis near [010] (rotation axis) is common to the various subgrains with [001] nearly normal to zones of undulatory extinction or subgrain boundaries. If the bending is interpreted as being due to plastic flow, the slip system T (slip plane) = {100} and t (slip direction) = [001] is inferred from the measurements. The slip system {100} [001] has been observed in clinopyroxenes deformed experimentally at high temperatures (*1*).

Six small grains extracted from both the crystalline rocks and regolith have been examined by x-ray Laue and precession methods. All of these crystals except one show some disorientation or mosaic structure; the disorientations differ in degree, but the rotational patterns are similar. In each crystal, rotations are greatest about the [010] axis, as is shown by a representative precession photograph in Fig. 2. Most of the Laue and precession photographs also show complexities that are not yet fully understood.

The more irregular disorientations (type iii) do not exhibit any simple crystallographic relationship between subgrains. For the simplest of these, the "hour glass" structure, the various zones tend to share the [010] axis, but the boundaries between zones are not, in general, rational. Optic angle-measurements suggest that the disorientations generally are not related to changes in