Evidence and Implications of Shock Metamorphism in Lunar Samples

Abstract. *Lunar microbreccias and loose regolith materials contain abundant evidence of shock metamorphism related to crater-forming meteorite impacts. Diagnostic shock effects include (i) planar features in a silica phase and feldspars, and lamellae in clinopyroxene, (ii) thetomorphic feldspar glass, (iii) heterogeneous glasses of rock and mineral composition, (iv) distinctive recrystallization textures, and (v) characteristic changes in crystal structure as indicated by x-ray diffraction analysis and measurements of refractive index. The microbreccias are produced from regolith materials (ejected from craters) by shock lithification. Some feldspar-rich fragments may represent ejecta introduced from nonlocal sources, such as the lunar highlands.*

The most conspicuous features on the moon (and Mars) are circular depressions covering much of the exposed surface. Many planetologists regard them as meteorite impact craters, but others argue that they are dominantly volcanic forms. I have previously pointed out (*1*) that the origin of most lunar craters will ultimately be established by evidence from rock materials directly associated with these structures. If significant proportions of such rocks display signs of shock metamorphism, then correlation with impact events can be safely assumed (*2*).

Studies of ejecta from a small nuclear explosion crater in basalt (Danny Boy event) (*3*, *4*) indicate the following effects to be specific indicators of shock damage in crystalline rocks of basic composition: (i) planar features in feldspar; (ii) feldspar glass thetomorphs (maskelynite); (iii) dispersion of fragmented (and variably decomposed) mafic minerals within shock-melted feldspar glass, thus leading to glasses of heterogeneous composition; (iv) intense alterations of crystal structure, revealed by measurements of refractive index, x-ray diffraction asterism, and infrared absorption. However, considering the relative resistance of rocks rich in mafic minerals to shock damage at lower (<300 kb) pressures (*5*), I concluded (*3*) that only 1 to 2 percent of a basaltic target rock surrounding a meteorite impact point would experience sufficiently high pressures to produce recognizable shock-metamorphic effects.

These observations apply directly to the lunar samples. I did not identify diagnostic shock effects in four crystalline rocks (types A and B) from the Apollo 11 site. If such samples were ever shocked, they must represent fragments originally located in the low-pressure region at varying distances from each impact point prior to ejection from nearby craters. Abundant shock-metamorphic effects were noted in lunar soil and microbreccias, thus indicating that these materials (i) contain variably shocked ejecta from positions closer to impact points of primary craters formed in the crystalline lavas of Mare Tranquillitatis, and (ii) are probably shocked further by repeated impacts or "gardening" during buildup of the lunar regolith (*6*). These effects, similar to those in shocked Danny Boy basalt and in nonbasaltic rocks from some terrestrial impact structures, are here documented.

Lamellar structures. Possible planar features (shock lamellae) (*7*) were detected in only six individual feldspar fragments during examination of 14 polished sections from 12 microbreccia samples. Planar features in two silica grains (phase unknown) (Fig. 1a) in a section from sample 10060-30 are definitely like those commonly observed in shocked terrestrial quartz. These grains displayed four and five discrete sets of planar features, respectively, when rotated on the universal stage. Numerous close-spaced, crisscrossing lamellar structures in two other fragments (sample 10046-12) (Fig. 1b), identified by microprobe analysis as plagioclase [An_{70-75} (70 to 75 mole percent anorthite)], meet some of the criteria for planar features defined by Carter (*8*). The fragments are untwinned, composite crystals, having a reddish-brown translucency and low birefringence typical of some highly shocked feldspars from terrestrial impact sites. The lamellae, however, also resemble certain quench crystallization structures. Poles to these lamellae, measured by universal stage techniques and plotted on a stereogram, tend to align in a girdle roughly normal to the *c*-axis.

The general scarcity of planar features in lunar feldspars, considering the wide range of shock damage observed in the fragmental samples, is consistent with studies of terrestrial samples (*5*) which indicate that these shock lamellae develop less readily in feldspars from basic igneous rocks than from quartz-bearing silicic rocks.

One clinopyroxene fragment (sample 10065-21) displayed three sets of closely spaced lamellae (deformation twins?) (Fig. 1c) which are oriented subparallel to (001), (100), and ($\bar{2}21$) planes. Under crossed Nicol prisms, this fragment shows a pronounced blotchy, granulose texture, characteristic of thermal recrystallization of heavily shocked mafic minerals in meteorites (*9*). Another clinopyroxene fragment (sample 10060-30) contains well-developed kink bands associated with a type of mosaic structure noted in mafic minerals (*9*).

Isotropization. Glassy phases that retain the initial shapes of shock-isotropized crystals (thetomorphs) were rare in the lunar samples I examined. An excellent example of thetomorphic feldspar glass occurs in a type B crystalline rock fragment (Fig. 1d) in microbreccia in which original feldspar laths are completely isotropic.

In another fragment (sample 10060-39) internal flow lines within feldspar thetomorphs with distorted crystal shapes, a marked lowering of birefringence in pinkish pyroxene, and a "blurring" of pyroxene and ilmenite boundaries into feldspar glass attest to more advanced breakdown of crystal structures accompanying the first stages of fusion. A single fragment from the soil, consisting of several broad isotropic zones within an irregular network of slightly birefringent pigeonite (giving a weak x-ray diffraction pattern), may be representative of thetomorphic pyroxene glass.

Shock-produced glasses. Numerous spheres and irregular fragments of glassy materials occur in the microbreccias and soil. Such glassy bodies resemble shock-melted masses found in breccia deposits at terrestrial impact craters. Many lunar glass fragments contain highly shocked crystalline inclusions. Relict textures within some fragments indicate partial fusion of granular materials or individual crystals, or selective isotropization of specific phases. Many glassy fragments exhibit heterogeneous compositions in the regions scanned by microprobe. Some glasses show Ni-Fe concentrations, thus supporting derivation by shock pressures and temperatures generated during impact with iron meteorites.

Quench crystals. Certain fragments within the microbreccias contain distinctive reticular, radial, or skeletal crystal groups indicating quench-crystal growth during rapid cooling of shock-melted glasses. Some fragments consist entirely of such crystals whereas glassy phases remain in others.

Recrystallization. In the microbreccias and soils, many small crystalline fragments, presumably once thetomorphs or shock-melted glasses, possess microtextures comparable to devitrified or recrystallized phases found in strongly shocked rocks from terrestrial impact craters. Feldspar-rich fragments, particularly, show a variety of characteristic textures (Fig. 1e)—small interlocked laths, new tiny grains with sutured interfaces, sheath-like crystal bundles—similar to those observed in feldspar at Clearwater Lakes, Manicouagan, Rieskessel, and other impact structures (*7*).

Chemical changes. Feldspars in 12 fragments from sample 10046-12 were analyzed by electron microprobe for their Ca, Na, and Si contents. Feldspars in two unshocked type B fragments have both CaO and Na_2O contents equivalent to An_{80-85}, whereas extensively recrystallized feldspars in two shocked type B fragments show apparent anorthite contents (expressed by CaO only) between An_{63} and An_{68}. Three single fragments of recrystallized feldspar glass have An_{73}, An_{80}, and An_{91} contents, respectively. A colorless glass spherule of approximate plagioclase composition analyzes as An_{77}. In all shocked feldspar masses, CaO loss is moderate (1 to 3 percent less than values for unshocked type B feldspar masses) but the Na_2O content drops from between 1.4 and 1.7 percent [Ab_{14-18} (14 to 18 mole percent albite)] to between 0.4 and 0.6 percent (Ab_{4-6}) in three grains with planar features, to values in the clear glass near 0.1 percent (Ab_{1-2}). The silica content in all shocked feldspar masses decreases, except in one recrystallized type B fragment.

X-ray diffraction asterism. Shock damage in lunar materials was also detected by rotation of apparent single-crystal grains in an x-ray beam. This technique produces diffraction patterns on film that range from spots to streaks to arcs (asterism), depending on the degree of polygonization, mosaicism, or other crystal structure disorientations developed by increasing shock pressures (*10*). Diffraction patterns for grains (three each) of plagioclase, clinopyroxene, and ilmenite from an unshocked type B crystalline rock (sample 10047-9) photographed in MoKα radiation consisted of narrow spots.

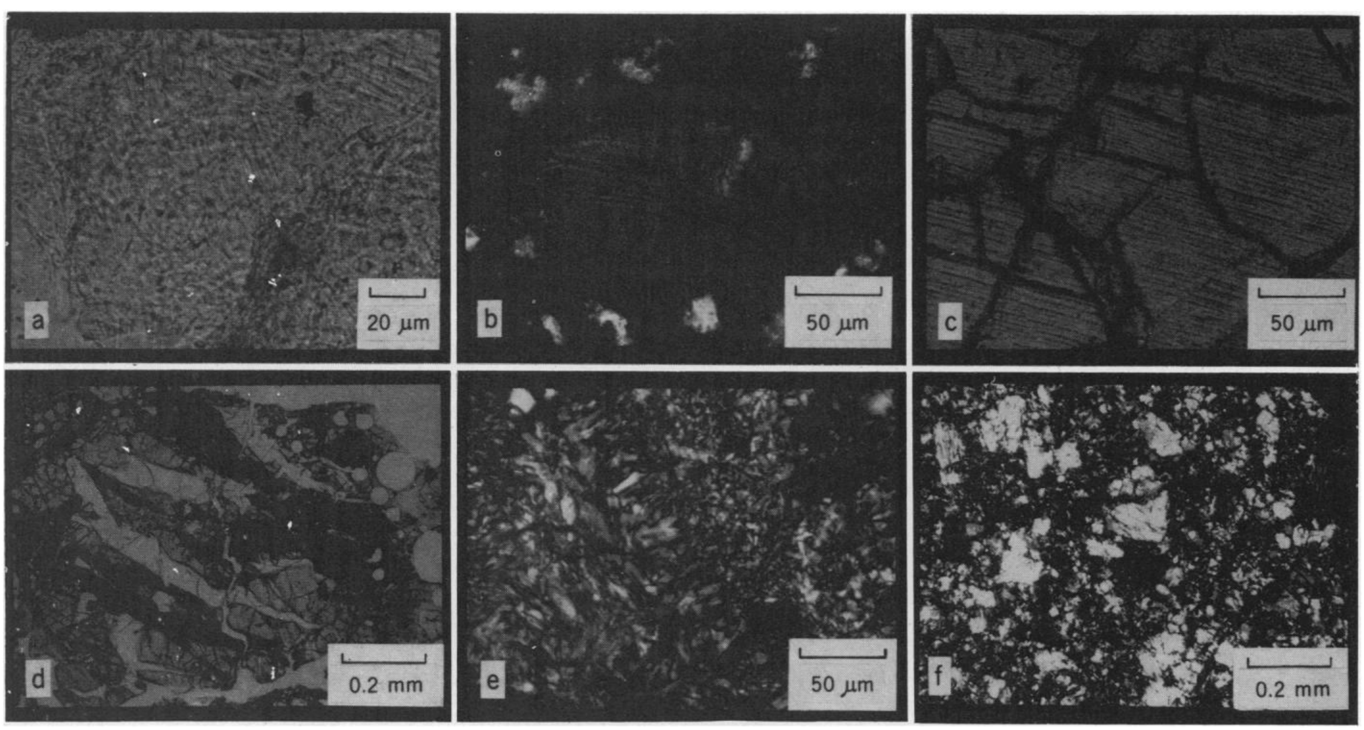

Fig. 1. (a) Three sets of planar features in a silica (quartz?) fragment in microbreccia sample 10060-30. Two other sets become visible when the section is rotated on the universal stage. Plane polarized light. (b) A small fragment of highly shocked plagioclase (An_{75}) containing closely spaced lamellar structures interpreted to be planar features. Most of the grain is a single crystal with five distinct sets of lamellae. A second crystal (upper right) follows a different orientation and has three sets of shock lamellae. Plane polarized light. (c) Detailed view of a single clinopyroxene fragment showing closely spaced lamellae (west-northwest) oriented subparrallel to (100). Two other distinct sets become visible as the section is rotated on the universal stage. Plane polarized light; under crossed Nicol prisms, the grain shows a prominent recrystallization texture. (d) Fragment of a type B crystalline lava rock, now in microbreccia (sample 10065-21). Feldspar laths (light-gray) are completely isotropic (maskelynite) when viewed in cross-polarized light. Pyroxene grains (darker gray) show reduced birefringence and a characteristic shock-induced mosaic extinction pattern. Note glass with vesicles (upper right) encrusting the fragment. Plane polarized light. (e) Portion of a completely recrystallized feldspar (glass?) grain from microbreccia sample 10065-21. This texture is identical to that observed in highly shocked and recrystallized feldspar crystals in rocks from the impact structure at Clearwater Lakes, Canada. Crossed Nicol prisms. (f) Part of a 15-mm wide fragment in microbreccia sample 10046-12. About 85 percent of the shattered individual grains are plagioclase (An_{93}); the remainder are mostly light-green olivine. Individual grains are randomly oriented; this suggests that this fragment is a (possibly shock-lithified) granular aggregate. Crossed Nicol prisms.

Several grains from lunar soil produced similar, sometimes slightly elongated, spot patterns. Most other crystals from the soil exhibited patterns of elongate streaks or continuous arcs. Microscope examination indicates that some grains are crystalline aggregates formed in the parent rocks or by later recrystallization. However, many feldspar, clinopyroxene, and ilmenite grains were originally single crystals until conversion, by shock, to assemblages of displaced mosaic blocks.

Refractive indices. Several strongly shocked feldspar crystals (unrecrystallized), whose asterism patterns consist of coalesced streaks, have N_X values as low as 1.554 to 1.562, equivalent to An_{45-65}. Clear to green-tinted, feldspar-rich glass gave N_D values from 1.56 to 1.59, depending on the amount of Fe-Mg contamination.

Clinopyroxenes that exhibit reduced birefringence and "cloudy" areas can also have anomalously low indices of refraction resulting from shock damage. Several grains picked from the soil met all conditions of a general test for shock metamorphism in lunar materials (*3*, p. 92). These grains show pronounced asterism, and one (sample 10084) contains possible planar features aligned near $(\bar{1}00)$, $(\bar{1}10)$, and $(\bar{2}10)$ planes. The clear crystalline region in that grain has $N_X = 1.618 \pm 0.002$ (compared with 1.70 to 1.72 for unshocked pyroxenes), whereas cloudy areas (decomposition products?) have values between 1.588 and 1.608.

Shock lithification. Comparison of fragment types and degrees of shock damage between lunar soils and microbreccias indicates that the latter are the consolidated (coherent) equivalent of regolith material. The thickness of rubble around the Apollo 11 site appears insufficient to have produced microbreccias by overburden compaction (*11*); the absence of water-bearing phases seemingly rules out fluid-controlled cementation. Although, conceivably, the soil could be derived from the disruption of microbreccia units, a more plausible explanation is that these microbreccias formed by an impact-related compaction process operating on loose, surficial rubble.

Earlier, I predicted the existence of cohesive breccias formed by shock lithification as possible lunar surface rocks (*12*). Similar materials occur as ejecta from terrestrial cratering explosions in loose alluvium. In that shock-produced "instant rock," coherence results from grain-interlocking and bonding by simple compression at lower (100 to 200 kb) pressures and from melting of the clay-silt fractions at higher pressures.

The less cohesive microbreccias may develop by simple compressive bonding during subsequent impacts on the lunar soil. More highly consolidated specimens, however, are held in a glassy matrix, readily visible where polished sections are thin-ground, that forms by compression melting of the "dust" and other fines that predominate in the soil.

A critical minimum thickness of regolith must be exceeded in order that significant amounts of "instant" microbreccia be produced at a given site. Microbreccias should be especially common in the lunar highlands, where ejecta deposits may exceed a thickness of 1 to 2 km (*13*).

Light-colored fragments. Small, whitish, granular masses are infrequent constituents of lunar microbreccias and soils. Some were identified as highly shocked olivine or clinopyroxene crystals. Others are feldspar-rich (70 to 90 percent) aggregates (Fig. 1f) in which plagioclase (An_{90-95}) shows random dispersion of crystal axes indicative of polycrystalline rock rather than shattered single grains. I suggest that those fragments are either fractured anorthosite (resembling the Serra de Mage meteorite) or shock-lithified feldspar rubble, perhaps introduced as ejecta from distant sources, including the lunar highlands (*14*).

In summary, the hypothesis that impact cratering has shaped and modified the moon's surface is supported by the widespread evidence of shock metamorphism in fragmental materials at the Apollo 11 site. The regolith there is largely a local accumulation of ejecta, derived mainly by cratering of underlying crystalline lavas, from which microbreccias were produced by shock lithification during later impacts. This regolith cannot have been a pyroclastic deposit prior to alteration by impact metamorphism, because of the broad range, rather than constant levels, of shock damage in fragments within individual soil and microbreccia samples.

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Shock-Wave Damage in Minerals of Lunar Rocks

Abstract. *The mineral fragments that constitute the Apollo 11 microbreccia and fines show a number of shock-induced microstructural effects including multiple twinning on (001) in clinopyroxene and incipient development of lattice-controlled discontinuities in olivine. These structures coupled with the effects of shock-induced melting as manifested by spherules and angular fragments of glass and their partly to completely crystallized equivalents indicate that Apollo 11 materials were subjected to weak to moderate shocks with associated peak pressures of the order of 100 to 200 kilobars.*

The results of preliminary examination of the Apollo 11 lunar rocks and fines (*1*) indicated that many of them had been subjected to one or more shock events presumably produced by meteorites striking the lunar surface. The evidence for this conclusion was based largely on the occurrence of (i)