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)

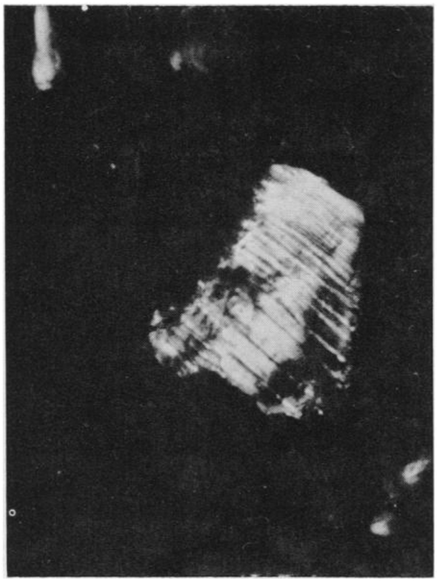

Fig. 1. Photomicrograph of clinopyroxene fragment in microbreccia (10060) showing multiple twinning parallel to (001). × 530. Crossed Nicols.

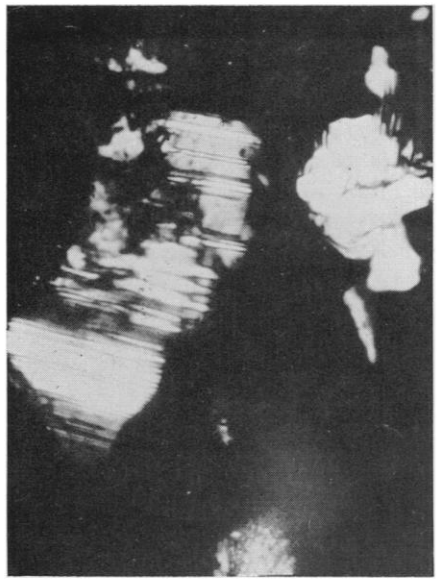

Fig. 2. Photomicrograph of diopside experimentally shock loaded at about 200 kb showing shock-induced multiple twinning parallel to (001). × 530. Crossed Nicols.

microbreccia which appears to be shock-lithified ejecta from impact events, (ii) angular fragments of microbreccia within a matrix of microbreccia, (iii) spherules, broken spherules, and angular fragments of glass of variable composition, (iv) glass-splashed exposed surfaces of microbreccia, (v) nickel-iron spherules, and (vi) undulatory extinction of birefringent minerals in microbreccia and fines. Small-scale shock-induced microstructural damage in minerals of the rocks and fines was studied in detail by light and electron microscopy. Additional evidence supporting the concept of multiple shock events on the lunar surface was found.

In general, the minerals of the fine- and medium-grained crystalline igneous rocks show little or no evidence of shock-wave damage. A striking feature of the minerals that constitute the microbreccia and fines, however, is their extreme heterogeneity in terms of the degree of shock recorded in co-existing fragments. so that in a highly magnified microscopical field of view one may observe fragments that were structurally damaged by high transient pressures, fragments that show high-temperature melting phenomena ascribable to shock processes, and fragments that are apparently unshocked. Such variability is characteristic of materials from terrestrial impact craters (*2*) and surface or near-surface experimental explosion craters (*3*).

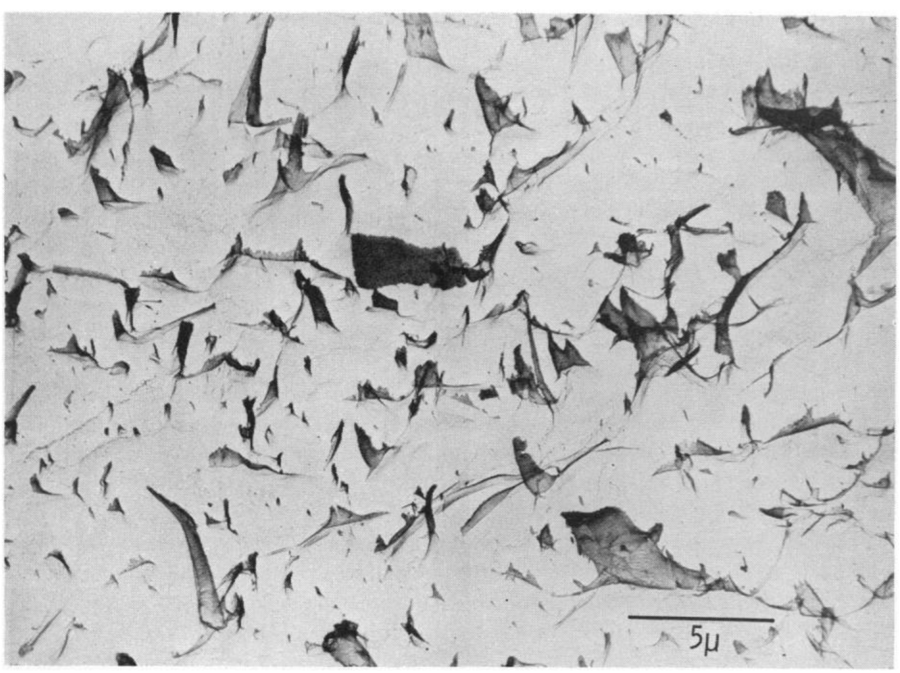

Fig. 3. Electron micrograph of replica of etched polished surface of olivine grain in crystalline fragment from fines showing incipient development of shock-induced planar features interpreted as lattice-controlled fractures.

Many of the plagioclase fragments in the microbreccia and fines are shattered and now consist of a number of contiguous subunits. Some show microfaulting, as revealed by offsets of twin lamellae, and others are highly strained, as shown petrographically by undulatory extinction effects. Correspondingly, many of the clinopyroxene fragments have been shattered into subunits and appear highly bent around axes roughly normal to the *c* axis as revealed by the traces of the prismatic cleavage planes. Some clinopyroxene grains are microfaulted as revealed by offsets in the prismatic cleavage traces and, rarely, by offsets in what appear to be exsolution lamellae of orthopyroxene(?) parallel to (100). In addition, many of the clinopyroxene fragments are highly strained as shown by undulatory extinction effects. On the other hand, the extent of mechanical damage recorded in the olivines appears, in general, to be much less, although a small percentage of the olivine fragments in the microbreccia and fines show abundant microfractures and undulatory extinction. All these features are indicative of shock but are not conclusive.

Many clinopyroxene fragments in the microbreccia show multiple narrow twin lamellae parallel to (001) (Fig. 1). It has been experimentally demonstrated on this program that multiple lamellar twinning parallel to (001) is developed in diopside (variety alalite, Mussa Alp, Piedmont, Italy) by shock-loading fine particulate material at about 200 kb (Fig. 2). Some of the unshocked diopside particles are twinned parallel to (100), so that the superimposed shock-induced basal-plane twinning produces a distinctive quadrille or microcline-like structure. The minimum peak pressure required to produce this structure, however, is not known, but it has just been reported (*4*) that augite in weakly shocked basalt from a nuclear explosion crater at the Nevada Test Site shows shock-induced multiple twinning on (001). It must be noted that, although rare, twinning of clinopyroxene on (001) can be developed by tectonic processes and has been produced experimentally at low strain rates (*5*). Nevertheless, the evidence strongly suggests that the multiple basal-plane twinning observed in clinopyroxene fragments in Apollo 11 material is the result of shock.

Although some of the olivine fragments in the microbreccia and fines show irregular microfracturing and undulatory extinction, only a few grains were found that showed any development of planar or lamellar features considered to be indicative of shock. One olivine from a crystalline igneous rock fragment in the fines showed in the electron microscope (Fig. 3) the incipient development of lattice-controlled discontinuities of the type that are highly developed in particulate olivine samples experimentally shock loaded at about 200 kb (*6*). Such planar features, interpreted as microfractures, constitute excellent evidence of shock-wave damage. Several olivine grains were observed to contain one set of optically resolvable thin lamellae, which appear to be similar to those described in olivine from shocked basalt [fig. 8D in (*4*)]; another olivine grain in a microbreccia (10061) showed some recrystallization (development of tiny new grains) similar to the well-developed recrystallization effects in dunite experimentally shock loaded to 1 Mb (*7*).

In a thin section of microbreccia (10060,20) are three grains of a colorless untwinned mineral with a low birefringence of section which show several close-spaced sets of planar features that resemble those observed in shocked quartz (*8*) and shocked plagioclase (*9*). These grains show no cleavage and are biaxial positive with $2V$ in the range 25° to 32°. They are either shocked and strained quartz or shocked plagioclase in which the optical indicatrix has been changed markedly, or, possibly, shocked clinopyroxene. Chao (*2*, p. 146) has reported that shocked quartz may be biaxial positive with an optic angle as high as 28°, and Bunch (*10*, p. 425) has found that shocked labradorite may have an optic angle as much as 20 percent smaller than its unshocked compositional equivalent. Evidently these grains should be checked with the electron microprobe, inasmuch as the possible occurrence of quartz could have significant petrological implications.

Each of two magnetic particles from the fines was found to contain an angular grain of metallic iron containing about 5 percent nickel as revealed by the electron microprobe. The grains are probably kamacite fragments from a metallic meteorite. When etched with Nital, one grain developed what appear to be Neumann bands typical of lightly shocked iron meteorites [fig. 3a in (*11*)]; the other shows an exceedingly fine microstructure near the resolution limit of the light microscope which may represent the $\alpha \rightleftarrows \varepsilon$ transformation as recorded in meteorites shocked between 100 and 200 kb [fig. 3b in (*11*)]. Electron micrographs of the latter show a fine granular structure with a tendency toward a "woven cloth" appearance.

Shock-induced thermal effects are manifested in the microbreccia and fines by spherules and angular fragments of glass of variable composition. In addition, many of the spherules and angular fragments show the development of quench crystals, which are typically skeletal or dendritic and are enclosed in a matrix of glass or devitrified glass. Finally, less common are fragments of partly melted pyroxene and plagioclase enclosed in brown and colorless vesiculated glass, respectively.

Although the crystalline igneous rocks show little or no effect of shock, selected mineral fragments in the microbreccia and fines show shock-induced structural damage and shock-induced thermal effects. These phenomena suggest that the Apollo 11 rocks were subjected to relatively weak to moderate shocks with associated peak pressures of the order of 100 to 200 kb.

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Cathodoluminescence Properties of Lunar Rocks

Abstract. *Calcic plagioclase is the dominant luminescent mineral in crystalline rocks and breccias. Minor amounts of cristobalite and tridymite are also luminescent, as are trace grains of potassium feldspar. Two types of intergrowths of potassium feldspar with a silica phase, possibly quartz, were found in the breccias. Luminescence spectra of plagioclase show significant similarities to, and differences from, spectra of terrestrial plagioclase. Shock damage in the breccias is reflected in systematic changes in the plagioclase spectra, thus giving evidence of disordering on the angstrom scale. Associated extinction patterns seen between crossed Nicol prisms give evidence of disordering on the micrometer scale.*

Luminescence petrography, the microscopic study of rock luminescence in thin section, is a significant extension of petrographic technique. Studies of terrestrial rocks have shown that this technique can provide information unobtainable by any other method (*1*). By means of auxiliary equipment one can measure the spectra of luminescing regions as small as 40 μm in diameter. Such measurements are important in the work reported here.

Crystalline rocks. The crystalline igneous rocks studied (samples 10020 and 10045) are intermediate in grain size between rocks of types A and B (*2*). Both specimens are similar and contain cristobalite and olivine. The dominant luminescent mineral is calcic plagioclase which has an abundance of $\approx$ 25 percent. Its luminescence is blue to yellowish-blue. Cristobalite ($\approx$ 1 percent abundance) emits blue luminescence and, like terrestrial quartz, shows development of red-emitting luminescence centers under electron bombardment. Tridymite ($\ll$1 percent abundance) is disseminated throughout as pink luminescing crystals 10 to 50 μm in diameter and is often closely associated with plagioclase. Pyroxene ($\approx$ 45 percent abundance), olivine ($\approx$ 5 percent abundance), and several unidentified iron-bearing trace minerals are nonluminescent, as are terrestrial mafic minerals containing more than a few percent iron. Apatite and zircon, although brightly luminescent in terrestrial rocks, were not found.

The plagioclase luminescence shows a range of intensity and color. Central regions of many laths are more yellow and more intensely luminescent than peripheral regions. Some small plagio-