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THE NATURE OF THE MOON'S SURFACE: EVIDENCE FROM SHOCK METAMORPHISM IN APOLLO 11 AND 12 SAMPLES

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ABSTRACT

Evidence of shock effects resulting from impact-induced pressures (hundreds of kilobars range) and temperatures occurs in varying abundance in the lunar soil and microbreccias collected around the Apollo 11 site. These effects include: 1) multiple sets of planar features in silica phase(s) and plagioclase, 2) planar features (?), shock-induced twin or deformation lamellae, and kink bands in clinopyroxenes, 3) thetomorphic plagioclase glass (maskelynite) in crystalline rock fragments within the breccias, 4) isotropization or partial decomposition of clinopyroxenes leading to anomalously low refractive indices with respect to initial compositions, 5) partial fusion of mineral and rock fragments; heterogeneous glasses; glass spherules (some with Ni-Fe inclusions) of both mineral and rock compositions, 6) variable loss of Na and Ca in shocked feldspar samples, and 7) quench crystals in shock-melted glasses and extensive recrystallization of these and thetomorphic glass phases.

The three Apollo 12 samples thus far examined show less diversity of shock effects and the average intensity of shock damage is reduced. Planar features were not found and the number of glass spherules per unit volume has apparently decreased. These observations suggest that the regolith at the 12 site is younger and thus has been subjected to fewer impacts, which also accounts for its lesser thickness compared with the 11 site.

Microbreccias at both sites appear to derive by shock-lithification of the lunar soil to produce a variably cohesive, sometimes glass-cemented rock. Within both soil and microbreccias, occasional fragments consisting mainly of anorthite-rich (An_{85-95}) feldspar crystals may be microanorthosites introduced from nearby sources or from more distant highlands areas. Some of these fragments appear to be microanorthosite masses granulated by shock into coherent aggregates. Several, however, seemingly consist of once-loose feldspar grains which had comprised a regolithic layer originated from impact comminution of anorthosite hardrock units probably located in the lunar highlands that was then shock-lithified during later impacts and ejected to the 11 and 12 sites.

Implications of shock metamorphism in these lunar materials relative to the origin of the Moon's circular structures, the regolith on the maria, and the microbreccias respectively are considered mainly from the viewpoint of Apollo 11 data.

CONTENTS

THE NATURE OF THE MOON'S SURFACE: EVIDENCE FROM SHOCK METAMORPHISM IN APOLLO 11 AND 12 SAMPLES

INTRODUCTION

Until Apollo 11 planetologists have relied primarily on morphological evidence, supported by experimental and statistical analyses, to distinguish meteorite impact craters from volcanic and possible collapse or drainage craters on the lunar surface. However, this approach has proved ambiguous because two or more genetic processes can lead to crater-like structures whose outward appearances are closely similar. The origin of most lunar craters will ultimately be established by evidence from rock materials collected at or correlated with these circular structures (Short, 1967). If notable proportions of such rocks were subjected to shock metamorphism, that is, unique solid state and melting phenomena caused by transient pressure waves of amplitudes extending to megabar levels, then their association with impact events can safely be assumed. If, also, the lunar regolith contains a significant fraction of shocked rock materials, its derivation or modification, in part at least, by impact-related processes can be inferred as highly probable even though the contributions from specific craters normally cannot be ascertained. Absence or scarcity of shocked rocks at any sampling site on the Moon, while not necessarily ruling out impacts elsewhere, would generally support the predominance of non-impact processes such as volcanism in producing the local rock types and shaping the surface features.

The presence of basic rock types at the lunar surface, first indicated from Surveyor V-VII alpha back-scattering results (Turkevich et al., 1968) and now confirmed by Apollo 11 analyses (LSPET, 1969), gave impetus to investigation of shock damage in terrestrial basalts and related rocks. In response, two studies (Short, 1969b; James, 1969) of shock effects in basalt from a small nuclear explosion crater (Danny Boy event; 0.42 kt) at the Nevada Test Site demonstrated a sequence of progressive shock metamorphism of the basalt as follows: (i) fracturing of mineral grains; (ii) development of lamellar structures; (iii) shock-vitrification of feldspars; (iv) formation of mosaic structure in mafic minerals; (v) melting of feldspars; (vi) granulation and dispersal of mafic minerals into feldspar melt, with possible chemical reactions to form new minerals; (vii) structural breakdown of mafic minerals; (viii) vesiculation; (ix) melting of mafic minerals, with mixing to produce heterogeneous glass; (x) homogeneous glass. It was also concluded (Short, 1969b) that only 1-2% of the total volume of ejecta from this nuclear explosion crater experienced pressures sufficient to impose diagnostic shock effects on the rock fragments. Quaide and Oberbeck (1969) report a similar value for the fraction of rocks undergoing notable shock damage during an impact event in basic rocks, as extrapolated from studies of experimental craters in basalt. Rocks containing considerable amounts (> 30%) of olivine, pyroxenes, amphiboles, and other Fe-Mg minerals that are less compressible than the tectosilicates tend to be more "shock resistant" over lower shock pressure intervals, so that such permanent, diagnostic effects as planar features or thetomorphic glasses occur over narrower pressure ranges or do not form to the extent characteristic of rocks composed mainly of tectosilicates (Short, 1970b).

Results of these studies of shock effects in the Danny Boy basalt prove especially pertinent to interpretation of shock-produced changes in the Apollo samples.

EVIDENCE FOR SHOCK DAMAGE IN THE LUNAR SAMPLES

Petrographic and electron microprobe analyses of Apollo 11 materials were carried out on polished sections from 10 crystalline (Types A and B) lunar rocks and 12 microbreccia samples (Type C) and on more than 60 grains picked from two split fractions (+1 and -1 mm.) of fines (Type D) from soil sample 10084. One section each from three Apollo 12 samples were examined in less detail. Effects directly or indirectly attributed to shock metamorphism in these lunar samples are described under the following headings, arranged generally in the order of increasing shock damage; Apollo 12 results are treated separately at the end of this sequence.

Shock-Induced Fracturing: Cleavage and irregular microfractures are imposed by shock waves on mineral grains within rocks over a wide range of peak pressures. However, at lower shock pressures (possibly to less than 10 kb. for rarefaction waves), discernible damage is often confined to fracturing so that a much larger fraction of ejecta from any crater will show only this type of deformation relative to those fractions nearer the center of energy release that exhibit unique and diagnostic shock effects associated with higher pressures. The problem, when examining displaced ejecta fragments whose positions around that center cannot be reconstructed, is to determine the initial (pre-shock) fracture state in each major phase so as to separate discontinuities caused by cooling or tectonic stresses from those generated by shock events.

A qualitative assessment of fracture state in the 10 crystalline rocks leads to the conclusion that no abnormal numbers of microfractures or cleavage planes are present in the feldspars and that more variable numbers occur in the clinopyroxenes. In some samples only a few irregular cracks are noted in the clinopyroxenes whereas other sections show extensive, often well-developed cleavage in the larger crystals. Generally, an apparent increase in fracture density with increasing grain size holds for the crystalline rocks.

Although no unequivocal proof of shock-induced cleavage or fractures in any of the lunar crystalline rocks is set forth here, the observed range of such microfracturing in the clinopyroxenes is consistent with variations noted in olivine and pyroxene in the Danny Boy basalt. Distinct increases in microfracture density below the Danny Boy crater floor were observable only in the region subjected to peak pressures estimated from crater geometry to exceed 150 kb (Short, 1964). Well over 90% of the ejecta from craters never undergo pressures above 100 kb and thus normally fail to show recognizable effects of shock action other than larger scale fractures (including block surface boundaries) or non-definitive microfractures or cleavage.

These observations are relevant to the question of apparent lack of distinct shock effects in Types A and B rock fragments from the Apollo 11 site. Most, if not all, of these fragments were probably involved in shock-producing impact events even though obvious signs of shock damage are generally absent. Those lunar crystalline rocks in which clinopyroxenes have higher cleavage densities may well be more shocked than rocks with lesser numbers. Douglas et al. (1970) consider tensional fractures in some lunar rock samples to result from weak shock stresses but they attribute other styles of deformation, especially for pyroxenes, to stresses accompanying crystal emplacement and growth. Likewise, Carter et al. (1970) describe several types of disorientations in pyroxene grains which they relate to rapid growth and quenching.

In contrast, fractures and cleavage in rock and mineral fragments from the lunar microbreccias and soil fines show a much wider range in frequency than noted in the suite of crystalline rocks. A few fragments of Type B rocks in the microbreccias, for example, are marked by distinctly fractured states of both feldspars and clinopyroxenes. Judging from observable fracture densities, some smaller fragments, including single mineral grains, can be described as crushed although it is reasonable to expect that such fragments usually would granulate into individual pieces if they are so severely fractured. The general state of comminution of constituents (Duke et al., 1970), and the increase in fracture densities (qualitatively assessed) within the soil and microbreccias indicate a process that repeatedly shocked these rock materials so as to increase the average level of shock damage.

Shock-Induced Lamellar Structures: Various workers have described certain types of shock-induced (dynamic) microdeformation that result in distinctive planer discontinuities in crystals differing from those produced by slower-load-time (static) stresses (Bunch et al., 1968; Carter, 1965, 1968; Engelhardt and Bertsch, 1968; Robertson et al., 1968; Short, 1970c). In tectosilicates, particularly, these shock lamellae or planer features tend to orient subparallel to one or more planes of certain crystallographic forms whose indices (e.g., $\{10\bar{1}3\}$, $\{22\bar{4}1\}$) are not characteristic of deformation lamellae in tectonites. Another distinction is occurrence within each lamellar feature of mineral matter having the same composition as the host grain but arranged in a more disordered structural state as indicated by lower refractive indices.

In all lunar samples examined in the present study, only eight grains or fragments out of hundreds of individuals observed in section or as loose soil displayed lamellar structures for which a shock origin seems a reasonable possibility. Figure 1a illustrates planar features, with reduced refractive indices, in a silica grain from 10060-30; a second grain with the same characteristics also occurs in this section. This is the same grain described by Douglas et al. (1970) and alluded to by Sclar (1970) as possibly quartz with anomalously high 2V (28-35°). From my measurement of 2V = 40-45° for this grain, I initially assumed it to be strongly shocked feldspar. Chao (1967) indicates that such low 2V's are possible, although rare, in plagioclase and he has reported that the 2V of biaxial quartz is within the 10-20° range (largest value cited is 28°). I am indebted to M. Dence (Douglas et al., 1970 and pers. comm., 1970) for the information that a probe analysis of these two grains indicates a silica, rather than feldspar, composition. The mineral phase is still unknown but reports of tridymite and cristobalite in the lunar samples and the apparent rarity of megascopic quartz (Frondel et al., 1970; Ware and Lovering, 1970) would suggest that the planar features are formed in one of these higher temperature forms of silica. The biaxial character of these grains indicates low (α) -tridymite (orthorhombic) for which a 2V as low as 35° has been reported (Frondel, 1962).

Both silica grains are colorless, clear, and untwinned. Their birefringence is variably lower than normal quartz; extinction is somewhat patchy. One grain is attached to a glassy phase tentatively identified as feldspar-rich in composition (Dence, pers. comm.). If this material is maskelynite, then pressures greater than 250 kb. acted on the silica as well. The silica grain contains at least 5 sets of planar features. Owing to uncertainty of phase identification and absence of other crystallographic elements, attempts to determine the crystal orientations of these planar features proved ambiguous. For the assumption Z = c, the distribution of poles to planar features on a stereonet bore no relation to the in quartz, in which most poles plot near angles of 23° and 33° relative to the c-axis for the ω $\{10\bar{1}3\}$ and π $\{10\bar{1}2\}$ forms respectively.

Only one grain of twinned feldspar (sample 10060-39) with typical planar features was found in the 12 microbreccia sections examined (Fig. 1b). From curves given by Slemmons (1962), optical data for X, Y, and Z and composition plane orientations were used to identify the twinning as following the pericline law; the $Z \wedge c$ relation indicates an anorthite content near An_{80}. This grain (Fig. 1c) is so strongly shocked that one set of these twins has been isotropized (maskelynite) and an entire corner of the grain is now completely isotropic. At least 7 different sets of planar features appear during rotation on the universal stage. These sets are less than 1 micrometer wide and are seldom more than 20 micrometers long in the section plane. They occur mainly in the broad twin bands of crystalline plagioclase with lowered birefringence and are best seen at higher magnifications (> 500x). When poles to these sets are plotted, along with optic directions, on a stereonet (Fig. 2a) on which crystal form poles are fixed in a symmetry diagram relative to a vertical c-axis and X, Y, and Z are positioned for an An_{80} composition, the planar feature poles tend to fall near (001), (010), ($\bar{1}$10), (1$\bar{1}$1), and (021) poles. The pole to the composition plane dividing the crystalline-isotropic twin pairs plots within 5° of the pole to the rhombic section followed by pericline twins for An_{80} (at + 16° from the c-axis in the (010) plane).

Unusual sets of lamellae are present in two fragments from 10046-12. Microprobe analysis confirms that these are plagioclases with 73 and 68 mole percent anorthite molecule respectively. Both fragments appear reddish-brown and translucent in plane polarized light and show lower birefringence than normal feldspars under crossed Nicols. This coloration, reduced birefringence, and dusky, somewhat granular character resemble very closely the highly shocked feldspars from many terrestrial impact structures (e. g., Ries, Manson, Clearwater Lakes).

One fragment (Fig. 1d) is subdivided into two grains with different crystal orientations. The larger grain is almost completely occupied by at least 5 separate sets of lamellae; the smaller area contains 3 sets. The largest of the three grains in the second fragment contains 5 sets and the remaining grains each show 4 sets. Average widths of lamellae in the first fragment are 2-3 μm whereas widths in the second fragment can exceed 10 μm.

The orientations of these lamellae in both fragments could not be determined because absence of cleavage or twinning prevents precise fixation of their crystallography relative to optic directions. The broader widths of the lamellae compared with those in 10060-39 and with planar features in shocked plagioclases from terrestrial impact structures (Engelhardt and Bertsch, 1969; Robertson et al., 1968) cast suspicion on their identity as shock-produced mechanical discontinuities. Instead, they may be peculiar types of quench crystal structures (H. Yoder, pers. comm, 1969) or perhaps are related to certain recrystallization textures.

Certain lamellar features in the lunar clinopyroxenes may represent a form of shock damage. Figure 3a shows a single set of close-spaced lamellae (~5 μm wide) in a fragment of clinopyroxene (augite: $z \wedge c = 50°$) within a microbreccia (10065-21). When rotated on the universal stage, this fragment is seen to contain a second prominent set of close-spaced lamellae and a third, weaker and broadly-spaced set. Poles to these sets, plotted on a stereonet with crystal form poles located relative to clinopyroxene with $Z \wedge c = 45°$ (Fig. 2b), lie close to (100), ($\bar{3}31$), and (001) planes respectively. Examination under crossed Nicols discloses a pronounced microtexture superimposed on the lamellae (Fig. 3b). The anhedral crystals, about 2-5 μm wide, have slightly different orientations that give a blotchy, granulose appearance to the entire fragment. This microtexture is similar to that described by Carter et al. (1968) as characteristic of recrystallization brought on by annealing at high temperatures resulting from shock pressures of 500 kb. or more. The lamellae also resemble those formed in enstatite by experimental shock loading (Short, 1968b, Fig. 23). The lunar lamellae are similar in both appearance and orientation to those reported by Raleigh and Talbot (1967) for mechanical (deformation) twins with twin-glide planes on (100) and (001).

Another clinopyroxene grain (Ca-rich) recovered from the soil fines (10084) showed an unusual group of thin, somewhat curved and criss-crossing lamellae (Fig. 3c). Each lamella apparently contains material between its boundaries (marked by dark borders) and is thus not a hair-line fracture. At high magnifications, short en echelon lamellae emanate from some larger lamellae. In one area, 5 distinct sets of lamellae can be distinguished. Poles to these sets orient near (100), ($\bar{1}00$), (110), ($\bar{1}10$), and ($\bar{1}20$) planes (Fig. 2b). Other evidence (p. 11) confirms that this grain has been very strongly shocked but it is not clear whether these lamellae formed by slipping or gliding in a manner similar to planar feature formation or result from some shattering process which produces unseparated fractures.

A small clinopyroxene grains (Fig. 3d) in 10060-30 consists of a large and a smaller domain whose c-axes are about 15° apart. Several broad kink bands were formed in this grain; their boundaries orient subparallel to (100) if the prominent cleavage is assumed to follow (110) (Fig. 2b). Despite lack of other evidence, the kink bands and incipient mosaicism are interpreted to be shock-produced.

The general scarcity of planar features in Apollo 11 materials, particularly the feldspar-bearing specimens, deserve special comment in view of the indications of a multiple shock history for both soil and microbreccias. Germane to this point are the observations of comparative rarity of planar features in feldspars from both the Danny Boy basalt (Short, 1969b) and the amphibolites within the shock breccias at the West Hawk Lake impact structure (Short, 1970b). In each case, mafic minerals comprise 30-50% of the rock by volume. Planar features in feldspars are fairly common in silicic crystalline rocks (granite, gneisses) (Engelhardt et al., 1968; Robertson et al., 1968). These features tend to develop in feldspars over a lower pressure interval than that appropriate to quartz (Short, 1970c).

A general hypothesis to explain the limited formation of planar features in feldspars within certain rock types is given by Short (1970b). Supporting experiments (Short, 1969a) using the implosion tube method (Short, 1968b) to shock-load feldspar up to pressures calculated to be near 400 kb at the tube-sample interface are summarized as follows: Where single-crystal feldspar cores were used, numerous planar features are produced; where the same feldspar is ground up into small fragments and packed loosely in the tubes, only a few planar features develop; where this loose feldspar is mixed 50:50 by volume with small grains of olivine, no planar features form. From these observations it is concluded that the presence of relatively incompressible mineral phases (pyroxene; ilmenite?) retards the compression of associated feldspars during the time interval (and other shock-loading conditions) in which planar features normally would form. These mafic minerals thus act as "shock buffers;" their occurrence in notable amounts tend to make co-existing tectosilicates somewhat more "shock-resistant" over a given pressure range.

If this hypothesis is correct, then the apparent scarcity of planar features in feldspars within strongly shocked lunar materials is simply a reflection of their coexistence with the usually more abundant clinopyroxenes, olivine, and Fe-Ti minerals in the lunar crystalline rocks. A test of this hypothesis will result when more of the feldspar-rich rock fragments (lunar anorthosites) are collected and examined.

Shock-Isotropization: Shock waves can produce disordered states in crystal structures such that these phases become optically isotropic while showing only short-range ordering when examined by x-ray diffraction methods. This solid state process results in a glassy state (shock-vitrification) in which no actual melting occurs and initial external morphologies (crystal shapes) are retained. The index of refraction of this glass is higher than that of corresponding melt glass of the same composition. The resulting shock-isotropized phases have been termed thetomorphs (Chao, 1967) or diaplectic glass (Engelhardt and Stöffler, 1968).

Manifestations of this phenomenon are quite uncommon in the microbreccias. In most instances, the feldspars (which isotropize to form maskelynite, first discovered in the Shergotty meteorite (Duke, 1968)) were shocked to states in which some melting has destroyed the thetomorphic form (Chao, 1967). However, one exceptional example of thetomorphic feldspar glass in microbreccia section 10065-21 is illustrated in Figure 4a. Feldspar laths in a strongly shocked Type B fragment are completely isotropic under crossed Nicols (Fig. 4b) even though they have undergone no shape distortions or interior melting and flow. Associated pyroxene grains are still crystalline but show reduced birefringence and such signs of strain as mosaic and undulatory extinction. The fragment is surrounded by vesicular, orange-brown glass, not related to any general melting of the inner rock. This is typical of "cored inclusions" in which fragments encounter, and are wrapped by, shock-melted materials during their mutual passage through the ejecta cloud or base surge accompanying an impact.

A possible single thetomorph after plagioclase is shown in Figure 4c. This isotropic grain is cut by two sets of cleavages meeting at angles characteristic of feldspars which indicates that the fragment is actually a shock-vitrified crystal. The spotty region in part of this grain appears to be a zone of incipient melting, representing a transitional stage between isotropization and total thermal fluidization.

The relatively few examples of thetomorphs in the shocked lunar materials conforms to a comparable infrequency in the Danny Boy basalt, although James (1969) describes occasional occurrences of such glass in this basalt. This scarcity may result from the same factors of shock-resistance of tectosilicates that reduce planar feature development when these phases are part of an assemblage of more incompressible minerals. Also, the range of pressures over which thetomorphs form is on the order of a hundred kilobars or less (Chao, 1968) so that the volume of rock undergoing selective transformations of mineral phases to isotropized products is only a very small fraction of the total volume of ejecta.

Partial Fusion: As shock pressures increase beyond the limits in which isotropization takes place, individual mineral phases being to melt. With rising pressures, the relative contributions from residual (waste) heat accompanying decompression of the shocked materials produce a thermal effect which progressively outweighs the mechanical effect of bond rupture directly associated with shock compression. Further melting may occur as heated fragments are carried along in base surges or come to rest in hot ejecta deposits.

A striking example of partial fusion of a crystalline (Type B?) rock fragment (10060-39) is presented in Figure 4d. A light-colored, almost clear mass of plagioclase glass shows internal flow lines as evidence that it actually melted. Much of the darker (medium gray in photo) material is pinkish in plane polarized light and slightly birefringent under crossed Nicols. Although crystal boundaries are difficult to define, this material is evidently the remnants of anhedral clinopyroxene in which the crystal structure has been severely altered without however undergoing melting. Elsewhere in the fragment, several dark brownish, translucent zones show the same rod or plate-like morphology of ilmenite in the crystalline rocks and may be the sites of ingested or decomposed opaque minerals.

Melt Glass: Many investigators of Apollo 11 samples have reported on the character, types, composition, and distribution of dense to vesicular, homogeneous to heterogeneous glasses in the lunar soil and microbreccias (e.g., Agrell et al.; Carter et al.; Chao et al.; Duke et al.; Engelhardt et al.; King et al.;

McKay et al., 1970). This phenomenon constitutes one of the most prevalent and diagnostic signs of shock damage in the lunar materials.

A glass fragment (10018-22) shows bands and streaks of higher refractive indices representing unmixed smears of melted materials that flowed through a melt of feldspar composition. (Fig. 5a.) The brownish, blotchy glass (10046-21) depicted in Figure 5b is heterogeneous in composition and contains specks and patches of still birefringent materials. Similar glass formed from Danny Boy basalt in which the more or less fused olivine mixes in swirls and streaks with more completely molten (presumably less viscous) feldspar. Lack of compositional or optical homogeneity is attributed mainly to the short time in which the mixed melt remained fluid. This is the expected condition for shock-melted rock expelled from a forming crater as blebs and large drops which then rapidly cool to preserve the turbulent flow patterns that attest to incomplete mixing. In contrast, melt driven out from volcanic magma to form pumice, bombs, spatter, etc. is normally already homogenized (Short, 1969b).

Shock-related Crystallization: Many fragments, grains, irregular masses, and spheres within the lunar soils and microbreccias contain crystals considered to represent growth from shock-isotropized or melt glasses (see also Agrell et al., 1970). Two types may be differentiated on the basis of presumed period of growth relative to the time when glasses first formed. In some instances, the possibility that changes occurred during subsequent (multiple) impacts leads to ambiguities of time relationships.

The first type is composed of quench crystals which apparently formed soon after solidification of glasses from shock-melted masses. These crystals have characteristic shapes and growth patterns usually described as dendritic, radiating, reticulate, or skeletal by experimental petrologists. Feathery, radiate crystals are exemplified by Figure 5c in which clinopyroxene (?) is growing from a brownish glass which, overall, shows a weak birefringence. The crystals shown in Figure 5d are a light, brownish-pink clinopyroxene set in a clear, colorless glass. These crystals consist of thin needles, arranged normal to the principal growth direction, that form a tapering, Christmas-tree-like pattern. Although quench crystals have been reported in the crystalline Types A and B rocks (Roedder and Weiblen, 1970), their rarity, differences in crystal habits, localization mainly in the mesostasis, and association with several well-crystallized phases in those rocks seemingly preclude the likelihood that they comprise the bulk of the quench crystal-bearing masses in lunar soils and microbreccias.

The second type can be described as polycrystalline mattes and interlocking grains attributed to recrystallization of vitric phases at times long in relation to melting and cooling of the original materials. The resulting textures are found most frequently in small fragments of feldspar-rich composition (Fig. 6a) or in thetomorphs after feldspar in shocked Types A and B fragments (Fig. 6b). Figures 6c and 6d illustrate very similar recrystallization textures in feldspars from two completely unrelated source areas. The first occurs as a fragment in lunar microbreccia section 10065-21. The second comes from an intensely shocked feldspar-rich granitic rock inclusion from the central peak region of the West Clearwater Lakes meteorite impact crater in Quebec, Canada. Rocks from other terrestrial impact structures display several styles of recrystallization textures which are counterparts of those observed in the lunar samples. In these terrestrial structures water plays an important role in activating recrystallization, as indicated by zeolites, micaceous minerals, etc. in the recrystallized phases. Absence of hydrous mineral phases and the extremely low water content in lunar materials (Friedman et al., 1970) indicate that recrystallization of shocked fragments in the regolith (and microbreccias?) proceeds mainly as a thermally-activated process operating on the metastable glasses. Support for the argument that this type of recrystallization is not inherited directly from the Types A and B lavas as a primary feature is illustrated in Figure 7a which shows an interlocking matte of crystals in a round body presumed to have been a plagioclase glass sphere that was recrystallized within the regolith.

Some fragments have a distinctive intersertal texture best described as felty to hyalopilitic; no orientation of the crystals resulting from an inferred directional flow is evident (Fig. 7b). Almost identical rock types have been found at some terrestrial impact structures. At the Tenoumer structure in Mauritania, inclusions of shocked granite are held in what has been interpreted (French et al., 1970) as an impact melt, formed by fusion of the target rock and injected along with the fragments into crater wall fractures. Cooling of this melt-fragmental mixture produced a texture (Fig. 7c) directly comparable to rock types found at both Apollo 11 and 12 sites (see Fig. 8c).

Chemical Changes: Analyses for Na, Ca, and Si in feldspar masses or crystals within 14 fragments in microbreccia section 10046-21 were carried out on an ARL-EMX three-channel electron microprobe. Linear working curves were prepared from analyzed feldspar standards; no corrections for absorption, fluorescence, atomic number effects, etc. were made. The mole percent of the anorthite molecule within each feldspar fragment has been calculated by comparing with CaO contents in plagioclases of different composition (Deer, Howie, & Zussman, 1963, v. IV, pp. 118-20). This same approach was used to estimate the albite mole percent based solely on Na_2O content.

Feldspars in two unshocked Type B fragments in 10046-21 have their CaO and Na_2O contents both equivalent to An_{83-85} (for Na_2O: An = 100 - Ab). Extensively recrystallized feldspars in two shocked type B fragments show anorthite contents (CaO only) between An_{63} and An_{68} whereas their albite contents have dropped to Ab_9 and Ab_7 respectively. Three single fragments of recrystallized feldspar glass have An_{73} , An_{80} , and An_{91} contents with corresponding albite contents between 3 and 7 percent. Two fragments with possible planar features contain 70 and 75 mole percent anorthite and 4 and 6 mole percent albite respectively. A colorless glass spherule of approximate plagioclase composition analyzes as An_{77} - Ab_2.

The generally lower anorthite contents in planar feature-bearing, recrystallized, and glassy fragments relative to the crystalline fragments is interpreted to indicate actual loss of calcium by some unspecified process(es). Of greater significance are the larger relative losses of sodium. These losses are about equal in the altered and recrystallized feldspars, become greater in the very strongly shocked feldspars with planar features, and reach a maximum in the clear glass spherules. This suggests that the small amounts of sodium originally present in the feldspars from the lavas are further depleted by selective volatilization during shock-vitrification or melting.

Refractive Indices and Asterism: Several very strongly shocked grains of clinopyroxene have anomalously low indices. One, typical of these, serves to illustrate the successful application of a general test for recognition of shock damage in mafic minerals, as devised from the Danny Boy basalt study (Short, 1969b, p. 92). The procedure for this test involves sequentially: (i) determination of the degree of asterism (Dachille et al., 1968) by x-ray diffraction (usually with identification of phases(s)), (ii) measurement of refractive indices, and (iii) analysis by electron microprobe to determine appropriate elements (or element ratios) that define initial compositions for minerals that form solid solution series. An FeO/MgO ratio representing 30 mole percent fayalite was found in two intensely shocked olivine grains from the Danny Boy basalt. For that composition, α = 1.686 is normal; the shocked grains had α values of 1.60 and 1.53 respectively, well below the value of 1.636 for pure forsterite. Both grains give rise to continuous rings when x-rayed.

The clinopyroxene grain, from the lunar soil, pictured in Figure 3b showing possible planar features, also has a high degree of x-ray asterism. (Fig. 7d provides another example of a single crystal of clinopyroxene that was shocked to a granulated mass which produces a ring pattern from x-ray asterism analysis.) Its calcium content, determined by microprobe analysis, places it in the augite compositional field. In the microscope, the grain displays a clear area with α = 1.618 ±0.002 between two "cloudy" areas with α values of 1.588 and 1.608. All values are well below the α values of 1.68 - 1.70 for the augite group. The cloudy areas, viewed at high magnification, resolve into colloidal sized blotches of dark brown material that appear to be decomposition products of unknown identity.

Apollo 12 Samples: Examinations were made on a thin section each from 12034-3 and 12073-6, listed in the Apollo 12 Lunar Sample Information Catalog as microbreccias, and from 12057-29, identified as a fragment of recrystallized, vesiculated melt with numerous inclusions taken from the documented collection of chips bearing this sample number.

The two microbreccias have been described as lighter gray in color and more compact and cohesive than the microbreccias (Type C) characteristic of Apollo 11. Photographs of the two Apollo 12 microbreccias (the only large samples of this rock type returned from the site) shown in the Sample Catalog impress me as having a pronounced similarity in overall appearance to samples of shock-lithified alluvium which I have collected from explosion craters at the Nevada Test Site (p. 20). The broken, irregular to crudely planar fracture surfaces, especially in 12034, resemble shear surfaces formed in the compacted alluvium as it was compressed and ejected from the high pressure region near the point of energy release.

Under the microscope, these microbreccias display many of the features attributed to shock damage in equivalent Apollo 11 rocks. Thus, the presence of numerous rock and mineral fragments with varying degrees of microfracturing (Fig. 8a), the occurrence of variably heterogeneous blebs and pieces of glass derived by rapid melting of several kinds of rock material, and the finely granulated character of the matrix particles are common to the microbreccias from both sites. However, in the two Apollo 12 microbreccia sections, certain of the features that are diagnostic of shock effects in the Apollo 11 samples are conspicuously absent. Thus, no definite examples of planar features in either feldspars or pyroxenes were noted. Several plagioclase grains did show thin, parallel planes (sometimes in two sets of criss-crossing lines as seen in section) but these could not be distinguished from fine twinning or intergrowths observable in normal, unshocked feldspars from terrestrial rocks. Although some clinopyroxene fragments show exsolution lamellae and a few others may contain deformation twins similar to those depicted in Figure 1d, none of these can be unequivocally identified as shock-produced. Several clinopyroxene grains, however, "look" shocked (incipient mosaic structure; variable birefringence); presumably pre-shock lamellae within these grains are marked by even lower birefringence and concentrations of unidentified species of altered materials (Fig. 8b) relative to the broader areas between the bands. No thetomorphic glass or other signs of isotropization were detected in fragments containing preserved crystal outlines. Only one or two possible glass spherules were seen, compared with 6 to 10 such bodies distributed in equivalent section areas within Apollo 11 microbreccias. Quench crystals and, particularly, recrystallizations textures, which were conspicuous features in Type C rocks from 11, are greatly reduced in extent of development and distribution in these Apollo 12 samples.

Of course, the statistical bias inherent in having just two thin rock slices from which to obtain these observations may foster misleading conclusions. Nonetheless, the microbreccia sections from Apollo 11 consistently gave evidence of a higher average level of shock, so it would appear that these 12 samples are indeed representative of the range of shock effects recorded in the two microbreccia samples. Factors to account for this reduction in shock intensities are considered on p. 16.

A much higher level of shock is presumed to pervade sample 12057-29. Over 50% of the samples consists of small ($\sim$ 20 micrometers in length on average) laths of feldspar, elongate pyroxene crystals, and patches of brown glass (Fig. 8c). Tiny mineral fragments are scattered throughout this volcanic-melt-like material. Larger rock and mineral fragments (up to 1 - 2 mm.) are embedded in the crystalline matrix. Most are either pieces of single crystals of plagioclase or multicrystalline aggregates of anorthositic rock but some pyroxenes and olivine also are present. At least one feldspar fragment may be part of a larger thetomorph and several fragments appear to be partially shock-melted. (Fig. 8d). Rarely, possibly planar features occur in individual feldspar masses. This sample is interpreted to be part of an impact melt mass, similar to the fragment shown in Figure 7b, and possibly the result of melting by shock-lithification of loose rubbly material in which compression generated excessive heat (see p. 17).

ORIGIN OF THE LUNAR FRAGMENTAL MATERIALS

Microbreccias constitute a common - and possibly abundant - lithotype on the lunar surface around the Apollo 11 landing site (LSPET, 1969) but are apparently scarce at the 12 site (LSPET, 1970). The origin of this unusual rock is an important question in interpreting the nature and history of this part of the Moon.

There is no evidence for water on the Moon or in the returned samples so that an aqueous origin for the microbreccias is unlikely. A tectonic origin is also ruled out owing to absence of appropriate textures (e.g., schistose; cataclastic) and to the lack of definite evidence for lunar tectonism. The mare surface materials could be pyroclastic deposits, including welded tuffs or pyroclastic ashflows (O'Keefe, 1966). Superficial comparison of such volcanic rocks with the lunar microbreccias would reveal many broad similarities (especially if Types A and B rocks derive from vents undergoing explosive activity). However, the wide diversity of shock features developed in the microbreccia fragments, combined with absence of typical volcanic features such as phenocrysts, are strong evidence against a primary volcanic origin of the microbreccias because shock features require peak pressures in the 100 - 500+kb range whose only known natural cause is meteorite impact (Chao, 1968; Hörz, 1968; Müller &Defourneaux, 1968; Short, 1968a). The observed broad range of shock effects in the microbreccias also eliminates the alternative that these rocks are ejecta from original pyroclastic deposits that were subsequently subjected to single impact events inasmuch as nearly constant levels of shock damage would be imposed on all of the constituent particles in individual blocks.

Origin of the microbreccias appears clearly related to the conspicuous evidence of shock metamorphism within these rocks and to the lithologic kinships of fragments in the microbreccias, the regolith, and the crystalline rocks (Duke et al.; King et al.; McKay et al.; Quaide et al.; Shoemaker et al.; Ware & Lovering, 1970). Studies of shocked rocks from terrestrial impact and explosion structures suggest, by analogy, three plausible origins for the microbreccias:

First, they may be consolidated fragmental debris redeposited in an impact crater immediately after formation, comparable to the suevite from the Rieskessel in Bavaria. In such a breccia lens, the size range of fragments extends from micrometers to meters and sorting is generally poor. These breccia deposits consist of fragments showing varying degrees of shock damage, mixed with finer granular material and glass, and are held together more or less strongly by mineral cements, by thermal welding arising from initially high residual temperatures, and by compaction.

Larger lunar craters should contain such materials, produced either from the craters themselves or by chance infall as ejecta from neighboring impacts. It is unlikely that any of the Apollo 11 microbreccia samples represent fragments derived directly from crater fallback deposits from these larger structures (none near the Apollo 11 site appear big enough to have volumetricallly significant infill). The high <u>average</u> level of shock in the microbreccias, together with the generally small particle sizes, does not conform to the characteristics of suevite-like deposits in which larger fragments and blocks are present, sorting is poor, and the overall level of shock is usually low (Short, 1970b).

Secondly, the microbreccias may form from a base surge deposit, as proposed by McKay et al. (1970) and Anderson et al. (1970) and predicted earlier as a possible mechanism by Fisher & Waters (1969). However, little is yet known about such deposits around terrestrial impact craters and few criteria for recognizing consolidated base surge materials have been specified. Volcanic base surge deposits show distinct layering and systematic variations in size and sorting away from the source. Base surge deposits emanating from the Sedan nuclear explosion are also layered (Roberts, 1968) but contain relatively little shocked materials. Lunar base surge deposits would be expected to be only slightly shocked and to be well-sorted and layered.

Finally, several lines of reasoning indicate that formation of the microbreccias is directly related to the nature and history of the lunar regolith:

(i) The regolith around the Apollo 11 site appears to be thin (~ 4 meters) (Oberbeck & Quaide, 1968; Shoemaker et al., 1970) and presumably overlies a hard rock floor assumed to be the source of some (if not all) of the Types A and B rock fragments.

(ii) Fragments of the crystalline rocks are a major constituent of both regolith and microbreccias (King et al.; McKay et al.; Ware & Lovering, 1970).

(iii) The higher degrees of shock damage observed in the regolith (King et al.; Quaide et al., 1970) and its extensive fine comminution (Duke et al., 1970) support the interpretation that the regolith has been continually subjected to multiple meteorite impacts which have increased the overall level of shock and reduced the average particle size. This inference is further supported by cosmic ray exposure ages (Fireman et al.; Funkhouser et al.; Marti et al., 1970) and particle track data (Fleischer et al; Crozaz et al., 1970) which indicate continuous churning and turnover of the upper horizons of the regolith (see also Shoemaker et al., 1970).

(iv) The ages of the soil and microbreccias determined by radiometric dating methods do not preclude a mutual relationship, including derivation of one from the other, but they fail to indicate which was the original material. Generally, shock metamorphism tends to lower K-Ar and He ages, particularly if glassy phases are formed (Hartung et al., 1970) but should not affect Rb-Sr and U-Th-Pb ages. The apparent discrepancy in Rb-Sr ages between the crystalline rocks ($\sim 3.6 \times 10^9$ yrs) and the fragmental materials ($\sim 4.6 \times 10^9$ yrs) has received several explanations (Hurley & Pinson; Albee et al., 1970) but seemingly remains an open, not fully understood question.

However, some aspects of the relationship between the regolith and microbreccias are still obscure. Although the soil could be derived from the microbreccias by erosion (e.g., micrometeorite bombardment), the location of the microbreccia source rocks has not been established. No definite outcrops of either crystalline rocks or microbreccia units were observed by the Apollo 11 crew or in the TV and photo imagery.

The present evidence indicates that the microbreccias are somehow formed out of regolithic materials. It is unreasonable to believe that microbreccias result from simple compaction of the thin veneer of regolith at the Apollo 11 site, unless some process such as electrostatic attraction or solar wind-induced adhesion operates to reinforce the slight overburden pressures. Careful inspection of sections ground thin along the edges of the sample slice indicates that most microbraccias are bonded together by a glass phase (Fig. 9a) which occupies most of the matrix between discernible particles and fragments. The bulk of the very fine (< 5 μm) material in the soil also appears to be glass (Quaide et al., 1970) but the general deficiency of particles smaller than 15 microns may indicate that comminution towards the finer sizes is reversed by some aggregation process that enlarges the particles (Duke et al., 1970).

The process which forms microbreccias from a thin regolith cannot yet be precisely defined. It seems likely, however, that the microbreccias are produced by the action of shock waves on the loose lunar soil by a process (shock-lithification) previously observed in terrestrial explosion experiments (Short, 1966) carried out in loose sand and in alluvium. The cohesion in the sand aggregates is apparently developed by grain interlocking and possible fusion of shattered mineral grains during compression behind the advancing shock front.

Natural alluvium is similarly transformed into a more coherent substance (Short, 1968a). Under shock compression from chemical explosions, porosity is reduced by the compaction and deformation of smaller mineral grains. Large grains are fractured and exhibit signs of weak shock damage suggesting that peak pressure did not exceed 150 kb. Alluvium surrounding exploded nuclear devices experienced much higher pressures (> 300 kb) that isotropize quartz grains and melt the water-rich silt and clay fractions to produce a frothy, glassy mass enclosing strongly shocked fragments (Fig. 9b). Because of the high initial porosities of such loose materials, a wide range of shock pressures is capable of converting a substantial amount of the materials into large, consolidated rock fragments as a result of the excessive "waste heat" developed in compression.

Shock-lithification of desert sands may have produced the glass-coated "sandstone" lumps around the Wabar meteorite craters (Short, 1966). Compacted and sintered "claystone" is formed by impacts into soil at the Campo del Cielo crater swarm in Argentina and Wolf Creek crater, Australia (Cassidy, 1968).

Based on these observations, this scheme for development of microbreccias on the lunar surface can be constructed: After emplacement of lavas in Mare Tranquillitatis, continued meteorite impacts (both local and distant) produced ejecta deposits which gradually built up to form regoliths. These regoliths are constantly stirred by small meteorites and micrometeorites whose impacts raise the overall level of observed shock effects even as they lower the average particle size. The regoliths attain thicknesses that range mainly between ~ 1 and 20 meters (Oberbeck & Quaide, 1968) and vary depending on the ages of their underlying mare lavas relative to changes in meteorite flux densities over time. Less commonly, impacts of larger bodies produce craters in which substantial volumes of loose material are compressed near the point of impact. Probably 2-4% of such excavated material experiences pressures above 200 kb, which are sufficient to melt fine particles or remelt the small glass bodies. The ejected materials thus become shock-lithified, glass-cemented microbreccias. Materials shocked at somewhat lower pressures may lithify to form weakly cohesive microbreccias (King et al., 1970). The greater part of the target rock will, however, experience pressures too low to produce permanent cohesion. Such material is ejected as fragmental debris and deposited in the regolith elsewhere. Smaller microbreccia fragments accumulate in the soil with time. Later shock-lithification of this regolith can then lead to breccia-within-breccia fragments (King et al.; McKay et al., 1970) representing several generations of production.

Work is still needed to verify this hypothesis and to evaluate other possible mechanisms of microbreccia formation. Two tests of the shock-lithification hypothesis can be advanced:

(i) Microbreccias should be less common in areas with very thin regoliths. In such places, most cratering will engulf the subjacent "bedrock" and the regolith would consist mainly of crystalline rock fragments. At the Apollo 12 site, the predominance of igneous rock samples and apparent scarcity of microbreccias (two samples), if not due to sampling bias, may reflect the thin regolith (± 1 meter) reported for this site. When compared with Apollo 11 microbreccias, these samples contain a greater proportion of fragmental inclusions that show no recognizable shock damage, conforming to the assumption that multiple impacts over time are needed to impose a high average level of shock damage throughout the repeatedly reworked soil prior to shock-lithification of selected portions during any one impact (Short, 1966). Continuous impacting is also responsible for the gradual build-up or thickening of the regolithic cover.

(ii) Shock-lithified microbreccias should be more abundant on the lunar highlands if these are covered by thicker, unconsolidated ejecta deposits (Short, 1970d). Over much of the highlands this ejecta blanket should be composed mainly of rock types excavated from submare basins but in some regions, such as parts of the southern highlands containing the craters Maurolycus, Sacrobosco, Abufelda, and Playfair, the ejecta cover may have been derived primarily from underlying bedrock or crust.

LUNAR ANORTHOSITES

A number of fragments in lunar samples from both Apollo 11 and 12 are composed mainly of calcic plagioclase crystals. This rock type has been described by several investigators (Wood et al.; King et al.; Short; 1970) who proposed independently that the fragments come from the lunar highlands and may represent the most common lithology there. Others consider the fragments to derive from feldspar-rich cumulate segregations within mare lavas at locations near the collection sites. Wood estimates these fragments to make up as much as 3.6% of the Apollo 11 microbreccia inclusions and McKay et al., (1970) report that 0.8% of the soil materials they examined consists of feldspar-rich rock chips. The conclusion that these anorthositic fragments come from the highlands is re-enforced by Surveyor VII chemical analysis data (Turkevich et al., 1968) from which I have calculated a simplified normative mineralogy comprised of 63% anorthite, 35% pigeonite, and 2% ilmenite making up a rock with a density of 2.97.

One feldspar-rich fragment in microbreccia sample 10046-53 has a particularly unusual texture (Fig. 9c). The fragment consists of many small (50 - 100μm) crystals of plagioclase in a matrix of smaller (5 - 50 μm) feldspar crystals and occasional (5 - 10% by volume) greenish crystals (olivine and/or pyroxene). Probe analysis indicates an anorthite content of 93 mole percent in the feldspar. Nearly all feldspar crystals have subhedral to anhedral boundaries. The texture is best described as granular. Most grains exhibit crushing and shattering; several show bent twin lamellae. Extinction directions of the grains are random. Measurement of c-axis orientation relative to the optic directions (for An_{93}) in 50 grains confirms a random distribution, ruling out the possibility that this is a shattered single crystal in which individual fragments have been rotated only a few degrees.

This texture appears very similar to that of shock-lithified sandstones from explosion experiments and the Wabar (Arabia) craters (Short, 1966, Fig. 1). There is also a striking resemblance (Fig. 9d) to the texture produce by shock-lithification of loose grains of albite in implosion tube experiments (Short, 1968b).

From these similarities, I suggest that this anorthosite fragment is a piece of ejecta from a part of the lunar highlands where anorthosites comprise much of the bedrock and/or ejecta blanket material. Cratering there would produce a regolith similar to, but probably much deeper than, that formed at the Apollo 11 and 12 sites. This highlands regolith would thus consist of a fragmental deposit of feldspar-rich debris. At some time when a major impact occurred, a part of this regolith was shock-lithified into anorthosite aggregates, with at least some of the resulting fragments being ejected and deposited over considerable distances from the crater source. For the fragment at the Apollo 11 site, this event could have taken place at any time following extrusion and cooling of the crystalline pyroxene-ilmenite lavas ($\sim$3.6 aeons ago) and the fragment could have been redistributed many times within the regolith before eventual incorporation in the material that was shock-lithified to form microbreccia sample 10046.

This hypothesis receives further support from my interpretation of the genetic implications of the Apollo 12 sample 12057-29. The two critical facts relevant to this sample are: 1) most of the melted, variably shocked inclusions are pieces of anorthositic gabbros, anorthosites, and single crystals of feldspar, and 2) a large proportion of the crystalline fractions of the matrix melt consists of plagioclase laths. These observations can be explained by assuming this sample to represent a more extreme degree of shock-lithification of an anorthositic regolith in which the fine fractions were more or less completely melted. The sample, in this view, would than constitute a ball or "bomb" of partially molten material ejected during an impact on the highlands at some distance from the Apollo 12 site. However, the 12 site lies across a broad ray extending from Copernicus on the north (LSPET, 1970.) If this sample came from that mare crater, it probably was derived from crystal bedrock below the near-surface lavas covering that region.

Probably only a fraction of all anorthosite fragments in Apollo 11 and 12 samples have directly experienced a shock-lithification process. Other fragments appear similar in character but some look more like single pieces of anorthosite bedrock (below any regolith); their lack of shock damage places them in the lower pressure region of any forming crater as ejection occurred. However, some grains, although still intact, are strongly fractured and a few are variably shattered (see Fig. 8a). It is possible that such grains would be misinterpreted as shock-lithified if only the shattered areas are exposed to inspection in thin section. The degree of c-axis dispersion in these grains should define some preferred orientation in contrast to the random distribution expected in shock-lithified regolithic material.

If the entire outer shell of the Moon were originally anorthositic (Anderson et al.; Wood et al., 1970), most material ejected from the lowlands during formation of the major circular submare basins would have this lithologic character where deposited on the highlands. Rubble accumulating there would then be a composite of local and distant anorthositic debris. However, if the anorthosite layer were thin, many larger craters would tap subcrustal rocks of other lithologies and such material will then be common in highlands ejecta deposits. Local anorthositic regolith units, in that case, would derive from intrusions (or extrusions) after the bulk of the rubble blanket had been emplaced. It follows that, if anorthosite is proved to be the prevailing rock type of the lunar highlands crust, the pyroxene-ilmenite lavas of the maria are volumetrically less abundant near the lunar surface. As many have suggested, these lavas would then be representative of subcrustal layers which were mobilized and introduced into the basins after those structures were formed.

CONCLUSIONS

The samples obtained during the Apollo 11 and 12 missions have provided specialists in impact craters and shock metamorphism with three invaluable observations. First, some pits and cavities found on the surfaces of many hand specimens (Frondel et al.; McKay et al., 1970) demonstrate that, on an atmosphere-free terrane, the limits of cratering and concommitant shock effects extend to the microscope level (Shoemaker et al., 1970). Second, the fragmental rocks present an unexcelled opportunity to examine and describe relatively fresh (although reworked) thrown ejecta from lunar impact craters that is rarely preserved around the erosion-prone terrestrial impact structures. Third, prediction that some lunar regolith can be converted by shock-lithification into cohesive rock masses (Short, 1966) received strong support from the microbreccias.

Furthermore, the recognition of shock effects in the fragmental rocks and soil samples brought back from Man's first landings on the Moon confirms that impact events have occurred somewhere on the lunar surface. The generally high abundance of shock effects noted, but not yet quantitatively assessed, in these samples is most readily explained by assuming that the fragmental materials were subjected to repeated impacts which collectively have raised the average intensity level of shock damage. These conclusions support, and are consistent with, the fundamental premise made in the introduction that we must verify that shock metamorphism has acted on lunar rocks as both a necessary and sufficient proof of an impact-related origin for many of the lunar craters.

However, this hypothesis still has not received the rigorous proof demanded by proponents of volcanism or other endogenetic processes as the basic causes of the Moon's craters. Neither the microbreccias nor regolith around the two Apollo sites can be related directly to outcrops at any specific crater, depression, or prominence. Until more extensive field and geophysical investigations at future landing site areas on the Moon are completed, and coupled with further analyses of rock samples returned from suitable localities, the question of how the larger lunar craters were formed must presently stand as insufficiently answered by Apollo 11 and 12 results.

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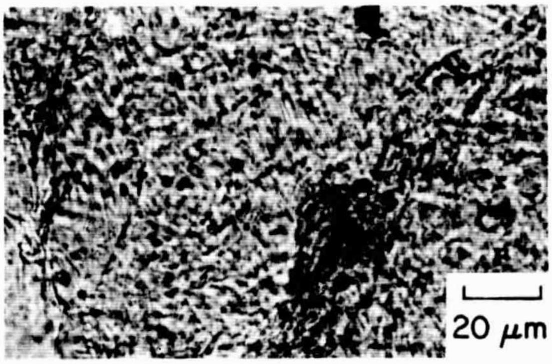


Figure 1a. Three sets of planar features in a silica (tridymite?) fragment in microbreccia sample 10060-30. Two other sets become visible when the section is rotated on the universal stage.

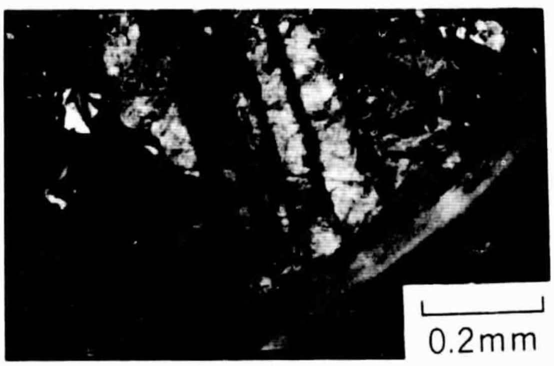


Figure 1b. Part of a plagioclase crystal in which one set of pericline twins has been isotropized (dark areas) while the alternate, broader set remains crystalline. Very small planar features (7 sets) occur within the high shocked crystalline twins. Sample 10060-39. Crossed Nicols.

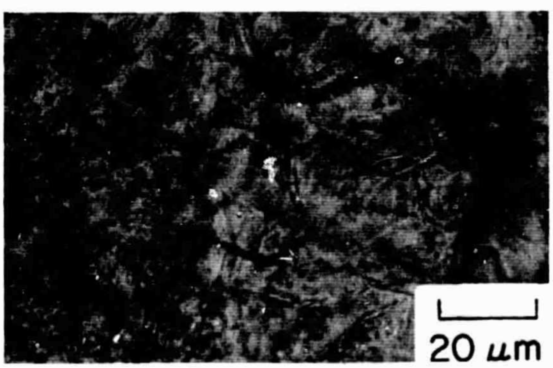


Figure 1c. Detailed view within a region of the still crystalline twins shown in Fig. 1b. Several of the faint, small planar feature sets are visible here.

Figure 1d. A small fragment of highly shocked plagioclase (An_{75}) containing close-spaced lamellar structures which may be planar features. Most of the grain (sample 10060-30) is a single crystal having 5 sets of lamellae; a second crystal (upper right) follows a different orientation and has three sets of lamellae.

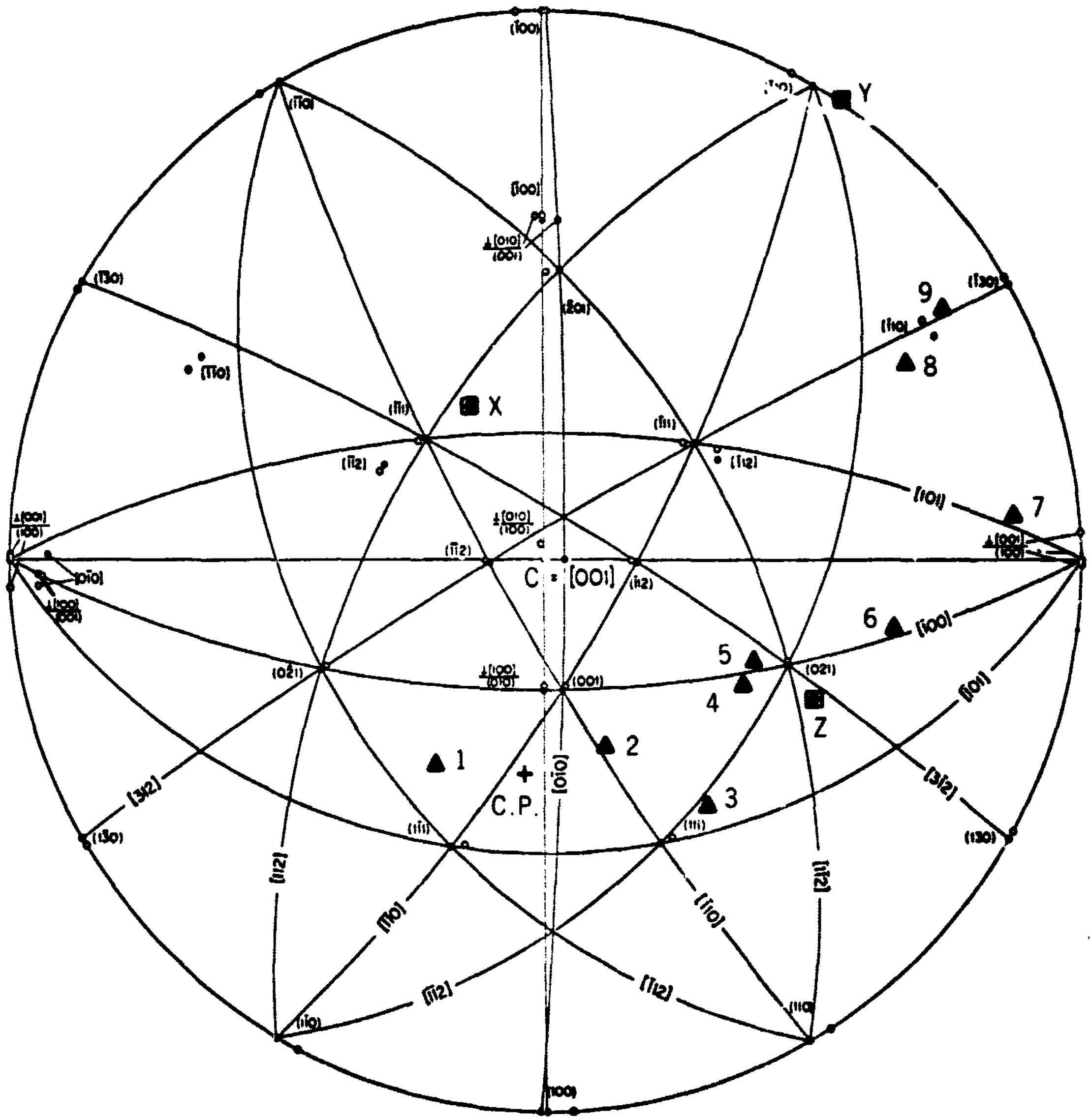
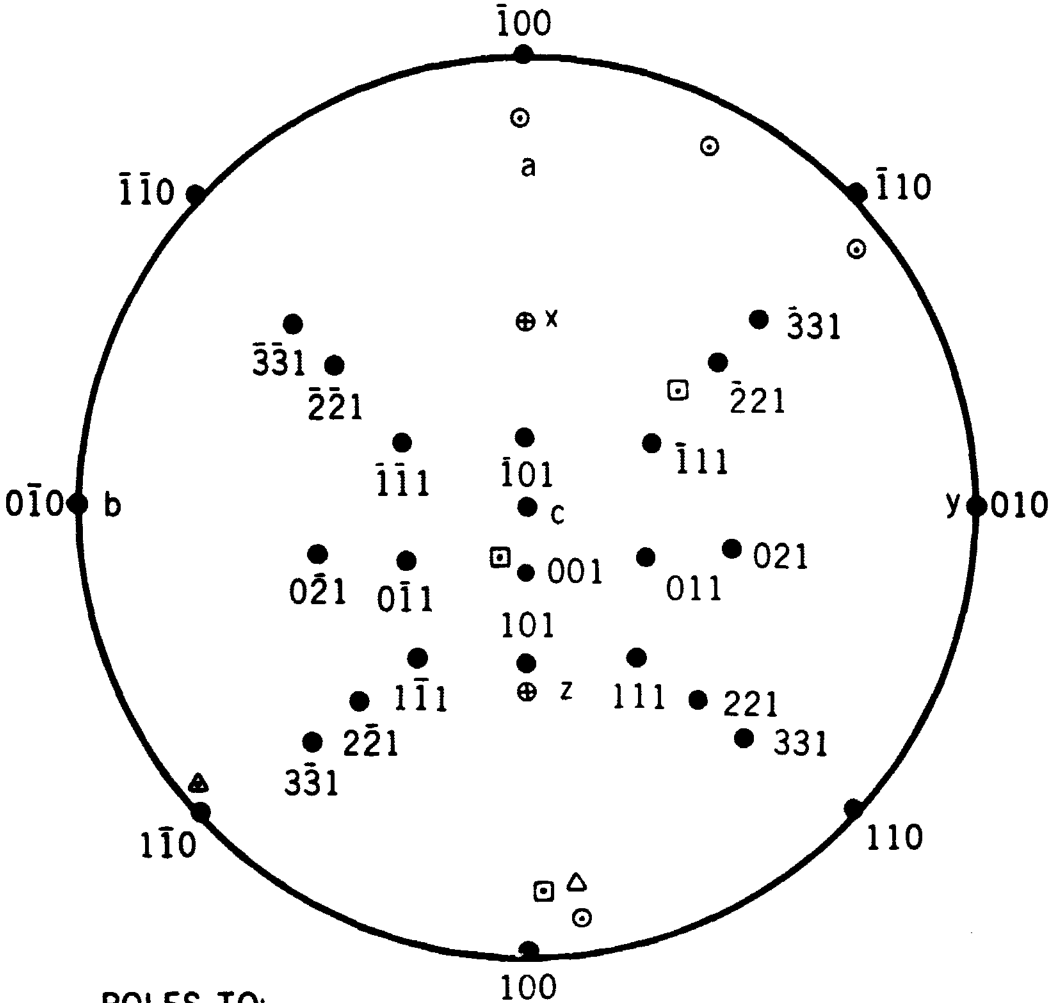


Figure 2a. Stereographic projection perpendicular to [001] showing orientation of poles to common crystallographic planes and directions (adapted from Plate IV in Burri, Parker, and Wenk, 1968) on which the optic directions for the partly isotropized plagioclase grain shown in Fig. 1b are plotted in positions appropriate to An_{80} content for volcanic plagioclase (squares). Poles to planar features (triangles) and to the pericline twin composition plane (+) are also positioned in relation to these orientations. Projection on upper hemisphere.

CLINOPYROXENE

X $\wedge$ c = 45°



POLES TO:

- ● CRYSTAL PLANES
- △ KINK BAND IN GRAIN FROM 10060
- ▲ CLEAVAGE IN 10060 GRAIN
- ⊡ DEFORMATION LAMELLAE IN GRAIN FROM 10065
- ⊙ PLANAR FEATURES (?) IN GRAIN FROM 10084

Figure 2b. Stereogram showing orientations of selected deformation features within clinopyroxene grains from several microbreccia samples. Pole to indexed crystal planes are plotted with respect to crystal axes and optic directions for a clinopyroxene with X$\wedge$c = 45° (typical of augite); all poles have been rotated so as to locate crystal and optic directions in symmetry positions as shown. Projection on upper hemisphere.

Figure 3a. An augite fragment in microbreccia sample 10065-21 showing a single set of close-spaced lamellae; two other sets become visible on rotation on the universal stage. These lamellae are interpreted to be deformation twins.

Figure 3b. View with Nicols crossed of augite fragment in Fig. 3a in which a pronounced recrystallization fabric is now evident.

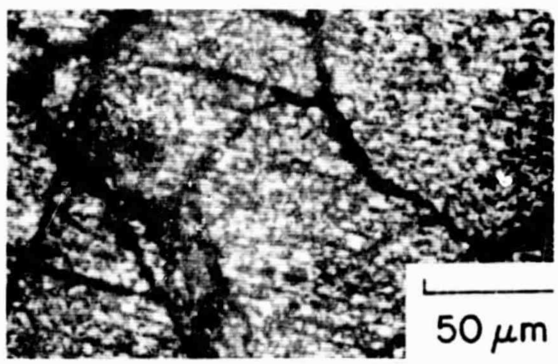


Figure 3c. Several sets of intersecting thin lamellae, seen at high magnification, in a calcic clinopyroxene grain extracted from lunar soil sample 10084.

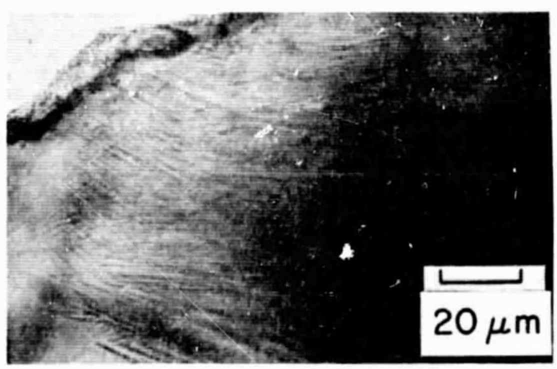
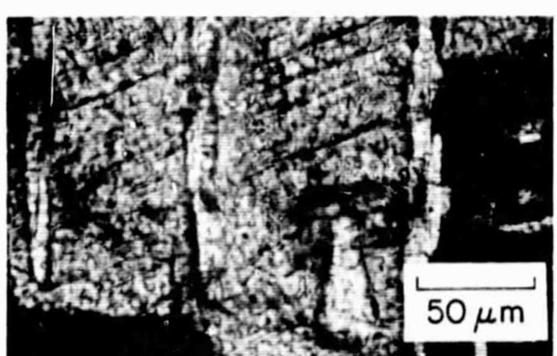


Figure 3d. Part of a single clinopyroxene grain (section 10060-30) containing several kink bands (N-S) within which cleavage (NNW) has been rotated about 20°. Note the smaller crystalline domain (lower right) now at extinction under crossed Nicols.



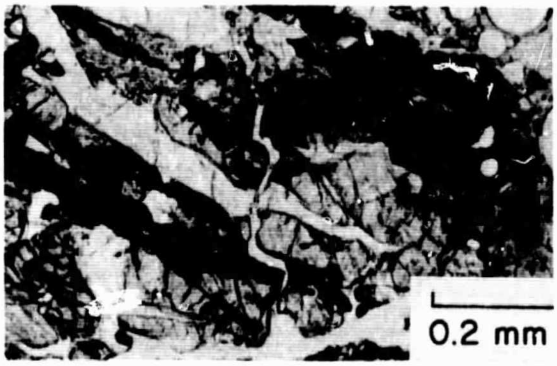


Figure 4a. Fragment of a Type B crystalline rock in microbreccia sample 10065-21 in which feldspar laths (light gray) are completely isotropized to maskelynite. Pyroxene grains (darker gray) contain numerous small fractures and show reduced birefringence under crossed Nicols; Note glass with vesicles (upper right) encrusting the fragment.

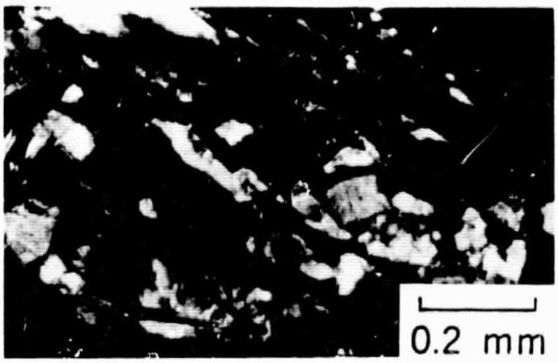


Figure 4b. View of fragment shown in Fig. 4a in same position but with Nicols crossed. All feldspar laths now are isotropic in any rotation position. Pyroxene grains show characteristic shock-induced mosaic extinction pattern.

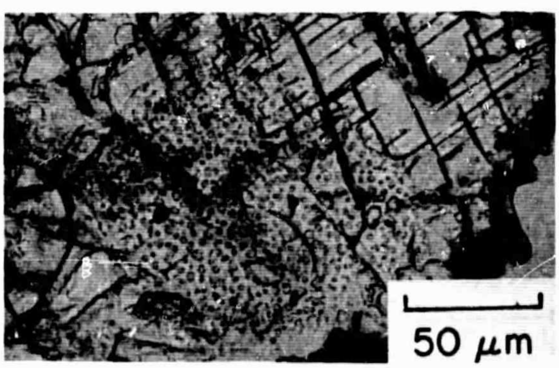


Figure 4c. An isotropized feldspar fragment (totally dark under crossed Nicols) in which cleavage directions appear to be preserved (upper right). Part of this thetomorph may have undergone incipient melting.

Figure 4d. A partly fused Type B crystalline rock fragment in microbreccia section 10060-39. The plagioclase crystals (e.g., lower center) have melted but clinopyroxene is still crystalline (slightly darker areas), although now only weakly birefingent.

Figure 5a. A glassy fragment in section 10013-14 in which the darker bands (also glass) have light brownish tints and show slightly higher indices of refraction.

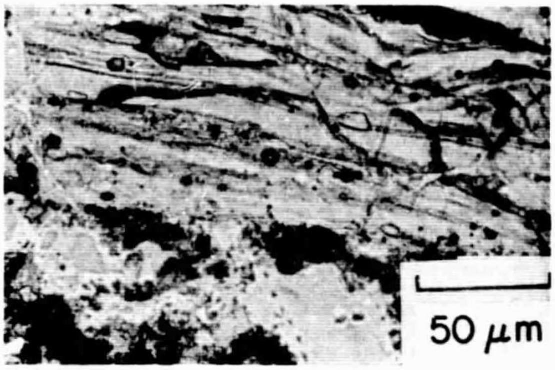


Figure 5b. A light brownish glass (10046-53) containing darker brownish streaks and blotches and small inclusions of birefringent minerals, indicating rapid (possibly incomplete) melting, poor mixing, and quick cooling to form this heterogeneous glass.

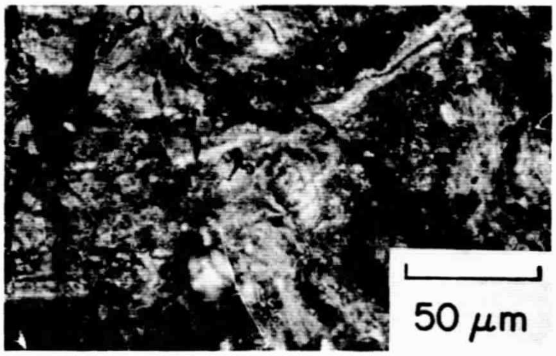


Figure 5c. A fragment of dark brownish glass (10023-9) in which quench crystals of clinopyroxene (?) grew in radiating clusters from a series of centers.

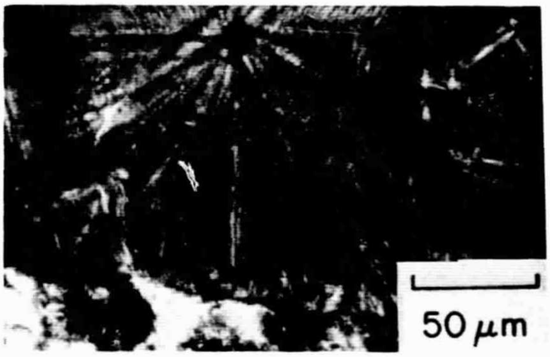
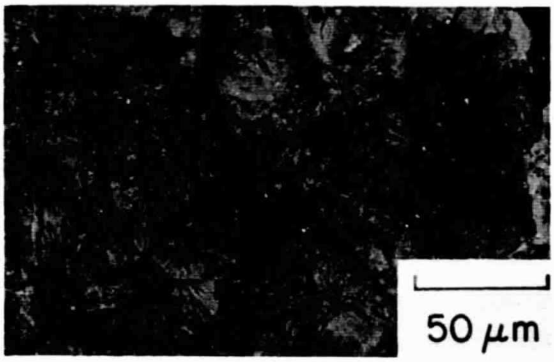


Figure 5d. Quench crystals of light-pinkish-brown clinopyroxene that grew during rapid cooling of a brownish glass (light gray areas; still isotropic) fragment in microbreccia sample 10023-9.



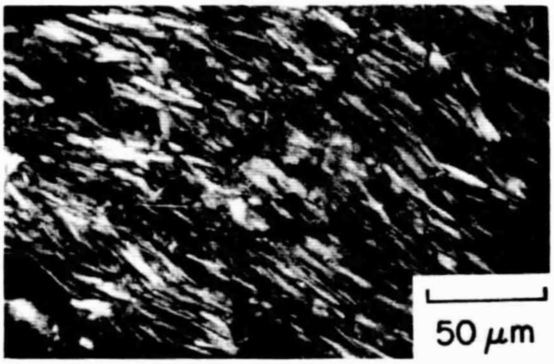


Figure 6a. A fragment within section 10018-14 composed almost entirely of small, subparallel feldspar crystals possibly formed by recrystallization of feldspar-rich glass. Crossed Nicols.

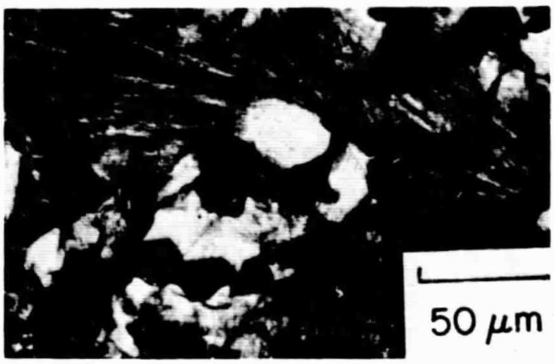


Figure 6b. Part of a fragment of a Type B crystalline rock in microbreccia sample 10018-14 which apparently was very strongly shocked. Regions that may have been thetomorphic plagioclase glass are now recrystallized to narrow, subparallel feldspar crystals.

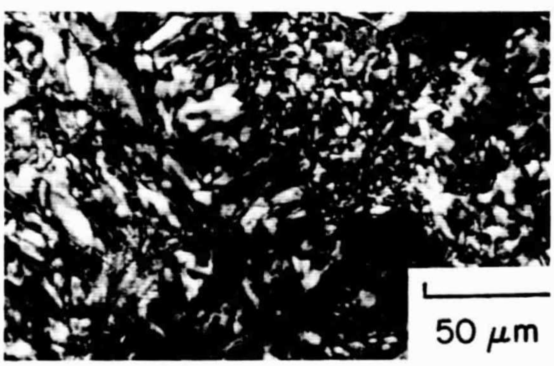


Figure 6c. Recrystallization texture in part of a feldspar fragment in microbreccia sample 10065-21. Compare with texture shown in Fig. 6d. Crossed Nicols.

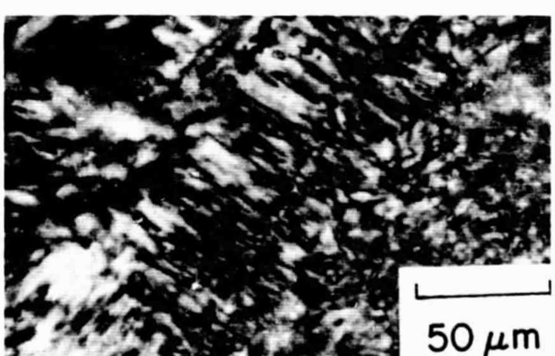


Figure 6d. Texture characteristic of recrystallized feldspar grains in highly shocked granitic fragments from West Clearwater Lakes, Canada impact structure. Cross Nicols.

Figure 7a. A matte of intergrown feldspar laths formed by recrystallization of a glass spherule of plagioclase composition; sample 10065-21. Crossed Nicols.

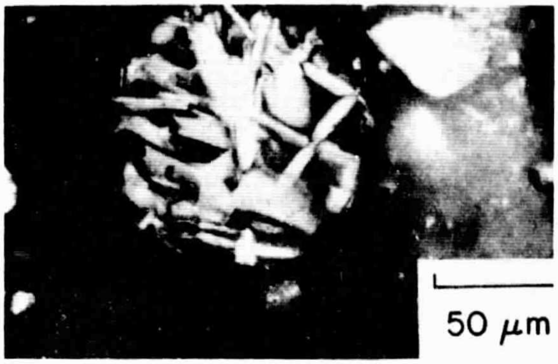


Figure 7b. An inclusion within 10060-39 in which fragment contains interlocking feldspar crystals, some pyroxene, and glass, forming a texture characteristic of some impact melts from terrestrial impact structures. Compare with Figures 7c and 8c. Crossed Nicols.

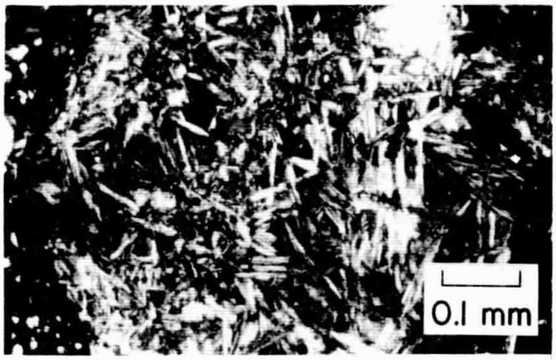


Figure 7c. Part of an impact melt injected into wall rock at the Tenoumer crater, Mauritania. Elongate feldspar crystals are common in an otherwise glassy matrix that encloses shocked rock and mineral fragments. One fragment (left center) is quartz containing several sets of planar features.

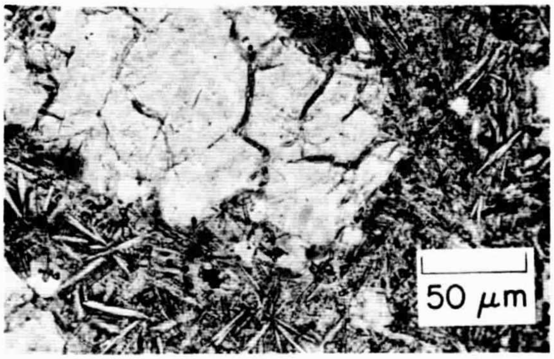
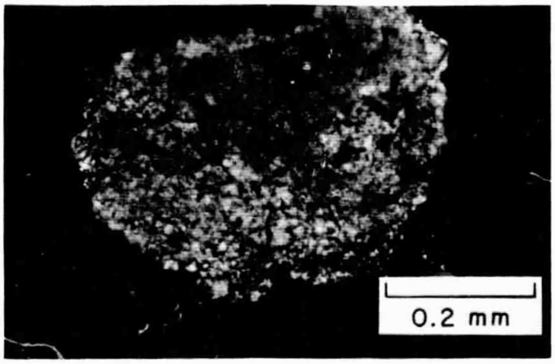


Figure 7d. A fragment of a clinopyroxene crystal shattered into a micro-mosaic of displaced crystallites that produce continuous rings when grain is x-rayed. Sample 10084.



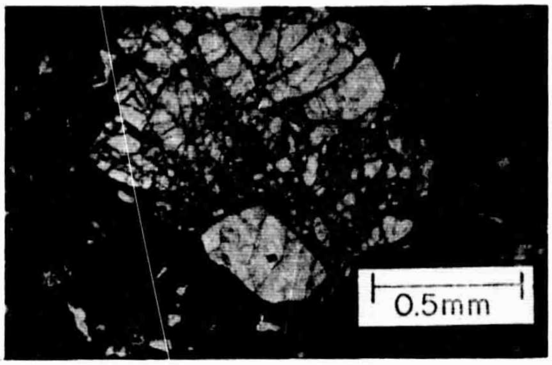


Figure 8a. Large fragment of feldspar within microbreccia sample 12034-3. Continuity of extinction during rotation under crossed Nicols suggests this fragment to have been a single crystal of plagioclase that was shattered and granulated by shock either during its initial ejection from an impacted crystalline target or possibly during shock-lithification of a regolith to form the present microbreccia. Crossed Nicols.

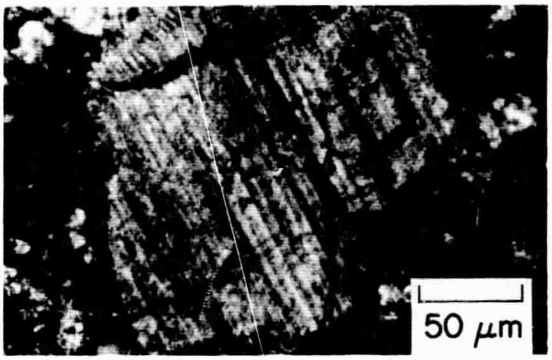


Figure 8b. An apparently shocked clinopyroxene fragment in which zones of alteration have concentrated along exsolution(?) lamellae of presumably preshock origin. Sample 12034-3.

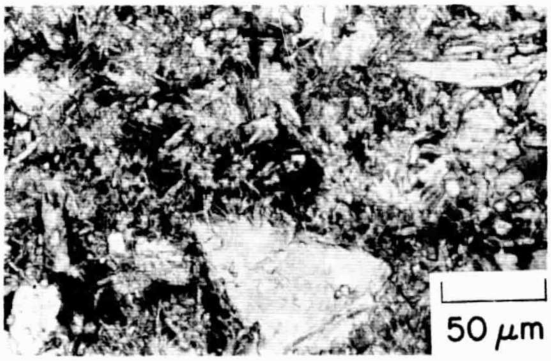


Figure 8c. Laths and crystals of plagioclase and some clinopyroxene associated with intersertal brown glass in the crystallized "matrix" of sample 12057-29. Most larger fragments are inclusions of plagioclase within this so-called "impact melt."

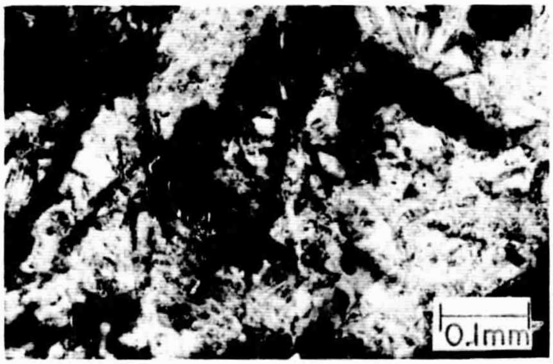


Figure 8d. A fragment of shock-melted anorthositic rock in sample 12057-29. The feldspar appears to have been completely melted and now has very low birefringence in cross-polarized light except for some elongate feldspar laths which may have resulted from quench crystallization. The dark, elongate areas are brownish and subopaque in plane polarized light and show weak birefringence under crossed Nicols; they probably represent decomposed pyroxene crystals.

Figure 9a. Texture of a microbreccia (10065-21) towards edge of a polished section that was thin-ground. The individual rock and mineral fragments (clear are mostly feldspar and clinopyroxene; dark are ilmenite) held in a glassy matrix (dark clear).

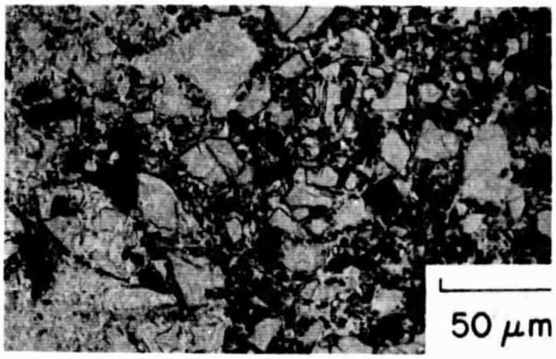


Figure 9b. Texture of shock-lithified (originally weakly cohesive) alluvium found as glassy ejecta around the Sedan nuclear explosion crater, Nevada Test Site. The darkish areas containing elongate blebs are flowed glassy masses formed by shock-melting of the silt-clay fractions. Large fragments are isotropized grains.

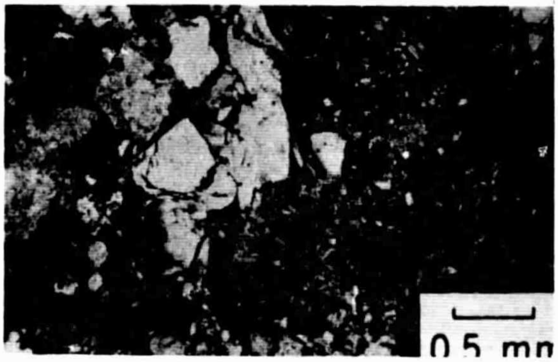


Figure 9c. Part of a 15-mm wide anorthosite fragment in microbreccia sample 10046-53. About 85% of the shattered individual grains are plagioclase (An_{85-95}); the remainder are mostly light-green olivine. Individual grains are randomly oriented; this fragment is possibly a shock-lithified granular aggregate. Crossed Nicols.

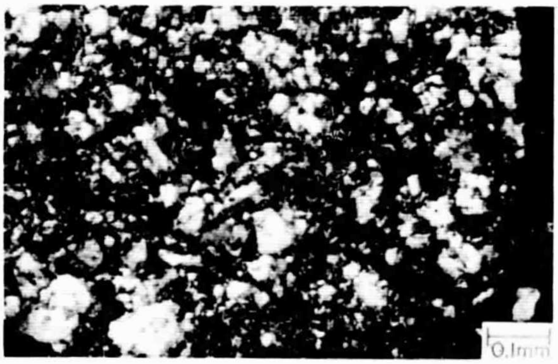


Figure 9d. A shock-lithified assemblage of feldspar fragments loaded as loose grains in an implosion tube. Compression produced a coherent, granular aggregate whose texture resembles that shown by the anorthositic fragment in Fig. 9c. Crossed Nicols.