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SHOCK METAMORPHIC EFFECTS IN THE LUNA 16 SOIL SAMPLE FROM MARE FECUNDITATIS

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Shock metamorphic effects characteristic of meteorite impact and virtually identical to those observed in Apollo samples are common in fragments of the Luna 16 soil sample from Mare Fecunditatis. Two types of shock effects are present: (1) deformation and partial melting features in rock and mineral fragments (1–2 per cent of fragments); (2) heterogeneous glasses and glassy breccias produced by shock melting (70–80 per cent of fragments). Shock effects were observed in pyroxene (deformation twin lamellae; multiple planar shock lamellae; extreme mosaicism; partial isotropization); in plagioclase (planar shock lamellae; complete isotropization to form maskelynite); and in basalt fragments (plagioclase isotropization; selective partial melting). The glasses and glassy aggregates exhibit several characteristics of shock melting, especially: (1) diversity in chemical composition; (2) association with shocked mineral fragments and Ni-Fe spherules; (3) heterogeneous schlieren and incipient fusion of mineral inclusions. The shock metamorphic effects in Luna 16 soil and its similarity to Apollo material indicate that regolith formation by meteorite impact has occurred in Mare Fecunditatis and is a general process over the entire moon.

1. Introduction

Intensive studies of returned lunar samples have confirmed the theory that the bedrock on lunar maria is overlain by a fragmental layer (regolith) of varying thickness which has been produced by continuing meteorite bombardment [1]. The major evidence for this conclusion is the occurrence of distinctive shock metamorphic effects, uniquely indicative of meteorite impact, in returned samples of fragmental lunar material. Virtually identical suites of shock features, including unique mineral deformation structures and unusual heterogeneous glasses, have been observed in samples from the Apollo 11 [2–7], Apollo 12 [8–11], and Apollo 14 [12] missions.

The Russian Luna 16 automated probe landed on Mare Fecunditatis on September 20, 1970 and returned with 101 g of fine-fragmental material obtained by drilling 35 cm into the regolith. Preliminary examination of the sample [13] showed that it consisted of diverse fragments generally about 0.1 mm in size, including both basaltic and anorthositic rock fragments, 'cindery' and 'slaggy' aggregates of glass and rock fragments, and glass fragments and free-form glasses similar to material obtained from the Apollo 11 and 12 missions. The Luna 16 sample is relatively low in TiO_2 [13] and is thus chemically more similar to Apollo 12 material.

The purpose of this study was to examine the fragments for evidence of shock metamorphism in order to evaluate the role of meteorite impact in forming the lunar regolith at a new site relatively distant from the Apollo landing sites. The study was carried out as part of a consortium for mineralogy and petrology headed by J.A. Wood, Smithsonian Astrophysical Observatory (SAO).

The samples were obtained from SAO as fragments mounted on individually numbered polished thin sections, accompanied by index photographs giving each fragment a specific number (e.g., SAO 301,16). In the time available, four sections (301, 303, 315, and 318) containing about 1000 individual grains were examined by conventional flat-stage petrographic microscopy in both transmitted and reflected light (for details and additional data, see ref. [14]).

2. Shock metamorphic effects

2.1. *Introduction*

The Luna 16 soil fragments display numerous features characteristic of shock metamorphism produced by meteorite impact and virtually identical to features observed in Apollo 11 and Apollo 12 material. Two chief types of shock metamorphic effects were observed: (1) unusual deformational features in individual rock and mineral fragments; (2) homogeneous and heterogeneous glassses apparently formed by shock melting. Shock-deformed rock and mineral fragments constitute only 1–2 per cent of the fragments examined, and glasses and glass-bearing aggregates produced by shock melting and mixing constitute as much as 70–80 per cent. Both percentages are comparable to those observed in Apollo 11 samples [2–7].

2.2. *Shocked rock and mineral fragments*

Shock metamorphic effects observed in rock and mineral fragments from the Luna 16 sample include deformation twinning, development of multiple parallel sets of shock lamellae, partial to complete isotropization of minerals, and selective partial melting.

A relative scale of shock deformation based on plagioclase has been established from the Apollo 11 material [2]. However, in the small number of shocked fragments observed in the Luna 16 material, pyroxene grains exhibit the greatest variety of shock-produced deformation effects. In order of apparently increasing shock pressure, these include: (1) deformation twin lamellae, probably parallel to (001) [15]; (2) multiple sets of finer parallel lamellae, apparently produced at higher shock pressures [3, 16] (fig. 1); (3) extreme mosaicism; (4) possible partial isotropization (fig. 2).

Only a few shock-deformed fragments of plagioclase were observed. Multiple planar features (shock lamellae) were observed in one fragment (311,25). Completely isotropic plagioclase (maskelynite) was identified in another fragment (figs. 3, 4). The occurrence of colorless glasses with a plagioclase-rich composition implies the existence of shock-melted plagioclase in the Luna 16 material as well (e.g., [2]).

Neither shock-produced deformation twins in ilmenite [17] or deformation structures in olivine [15] were observed in the Luna 16 material examined. The presence of shock effects in both pyroxene and plagioclase implies that analogous shock effects are present in other minerals and should be observed with more intensive study.

Only two shocked basaltic rock fragments were observed. In one specimen (fragment 315,53), fractured pyroxene is associated with isotropic plagioclase (maskelynite) in a manner similar to that observed in some shocked Apollo 11 rocks [2, 4, 6]. In the other fragment, plagioclase is only partially isotropic, but part of the fragment has fused to an orange-brown glass apparently generated by the post-stock melting of opaque phases (fig. 5). In this specimen, the formation of glass, combined with the rapid quench implied by the preservation of plagioclase, is good evidence for shock-induced melting.

2.3. *Impact-produced glasses*

A variety of glasses occurs in the Luna 16 sample, both as individual fragments and in the matrix of aggregate particles. The glasses are virtually identical to those described from Apollo 11 and Apollo 12 material and are almost certainly of impact origin. The glasses display several features characteristic of origin by shock-induced melting (for more details and additional illustrations, see ref. [14]):

(1) Diversity in color (and presumably in chemical composition) [7]. The colors of dense, homogeneous glass fragments range from colorless through light green, greenish-brown, and brown, to dark reddish-brown and brownish-black. Several free-form fragments (spherules, droplets, etc.) were observed.

(2) Brightly reflecting spherules (Ni-Fe or troilite?) commonly present in the flowed heterogeneous glass fragments or in the glassy matrices of aggregate particles.

(3) Distinctive flow lines (schlieren) in heterogeneous glasses, composed of bands of glasses of different colors and implying partial mixing of materials of different compositions (fig. 6).

(4) Intimate mixing of glass and diverse rock fragments, some of which show shock metamorphic effects (fig. 6).

(5) Incipient fusion of some mineral grains included

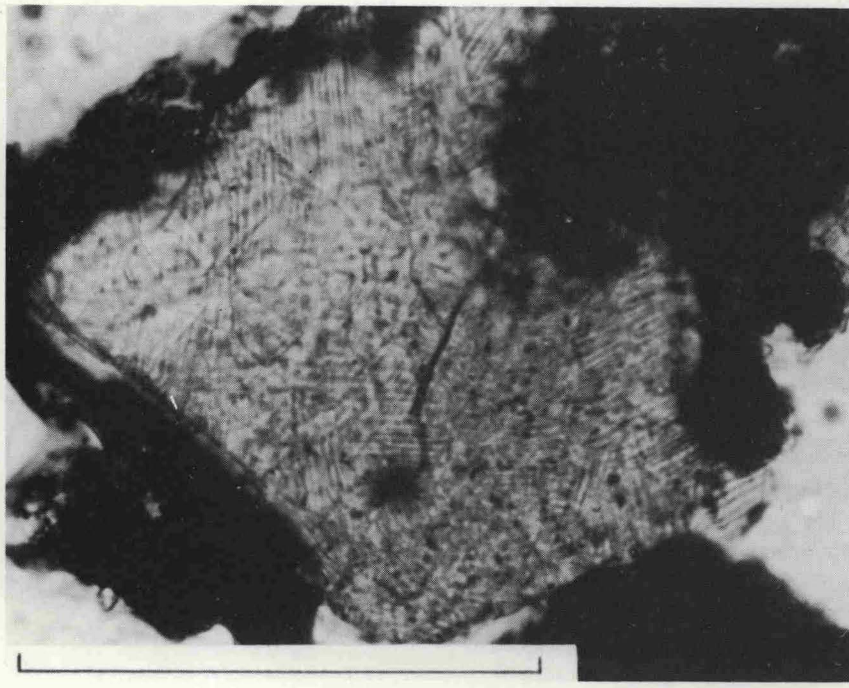

Fig. 1. Well-developed multiple sets of parallel shock lamellae in a pyroxene crystal. At least six separate sets can be distinguished. Fragment 318,512; plane polarized light; scale bar 0.1 mm.

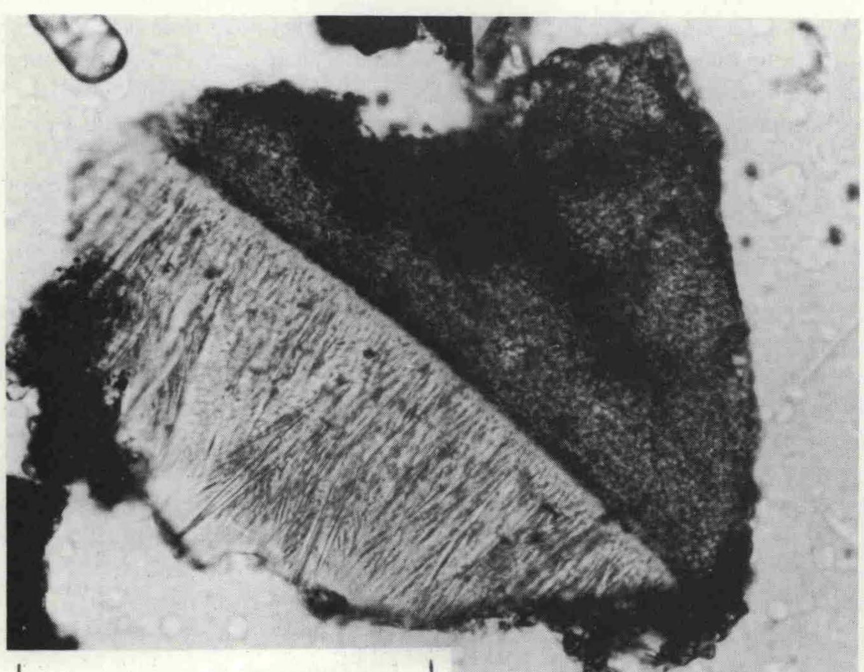

Fig. 2. Sharp contact between clear (plagioclase?) glass and a red-brown pyroxene(?) crystal which shows intense mosaic extinction and partial isotropization along dark veinlike regions. The plagioclase area, which was either maskelynite or shock-melted glass, is now partly devitrified to radiating and sheaflike plagioclase microlites. Fragment 318,362; plane polarized light; scale bar 0.1 mm.

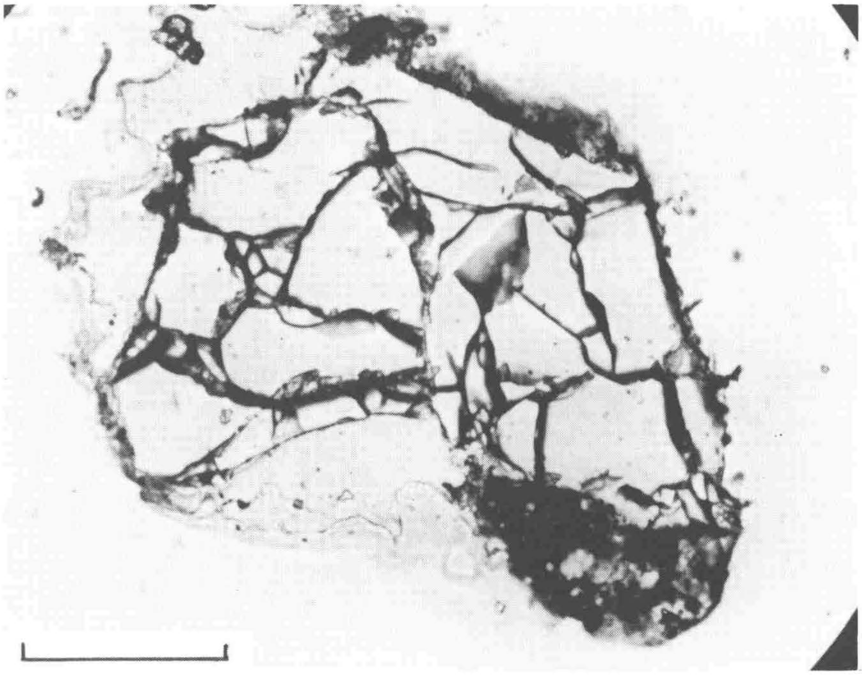

Fig. 3. Fractured fragment of shock-produced glass of plagioclase composition (maskelynite) with a small amount of dark microbreccia adhering at lower right. Fragment 301,42; plane polarized light; scale bar 0.1 mm.

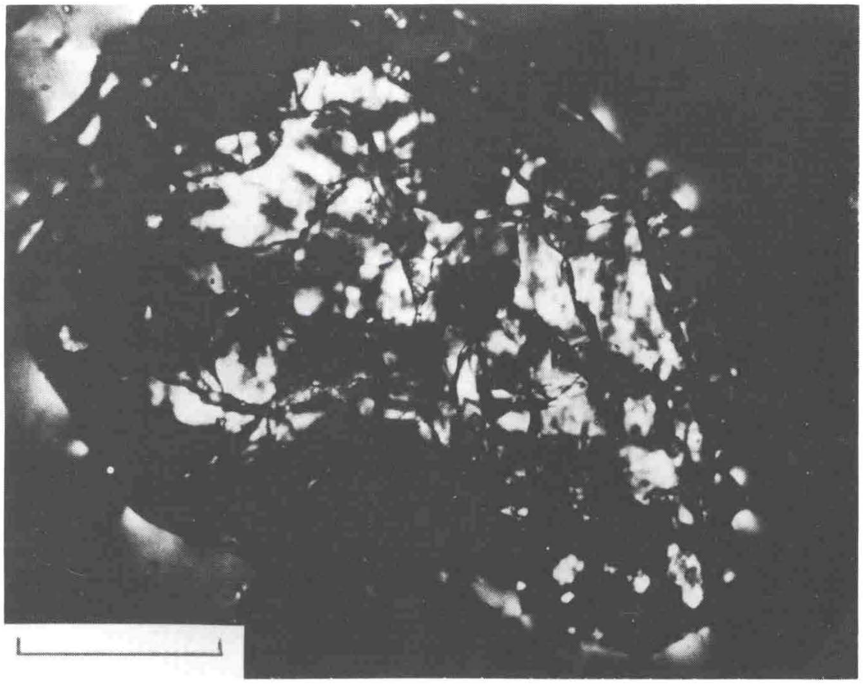

Fig. 4. Same view as in fig. 3, crossed polarizers. The fragment is largely isotropic with some internal birefringence. The birefringence pattern is patchy and irregular rather than spherulitic, suggesting that it may arise from relict crystalline structure in the maskelynite rather than from post-shock devitrification.

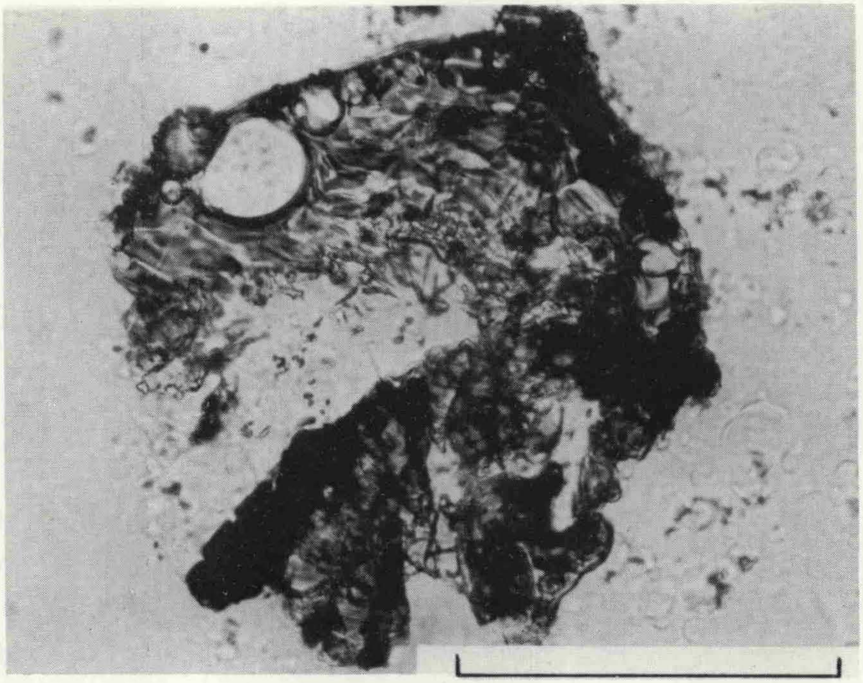

Fig. 5. Partly shock-melted basalt fragment. The crystalline texture of the basalt (lower), composed of plagioclase (white), pyroxene (gray), and opaques (black), grades into heterogeneous, flow-structured, vesicular, orange glass (upper), possibly produced by partial melting of opaque phases and plagioclase. The plagioclase crystal (center) is apparently being absorbed into the glass. Fragment 318,460; plane polarized light; scale bar 0.1 mm.

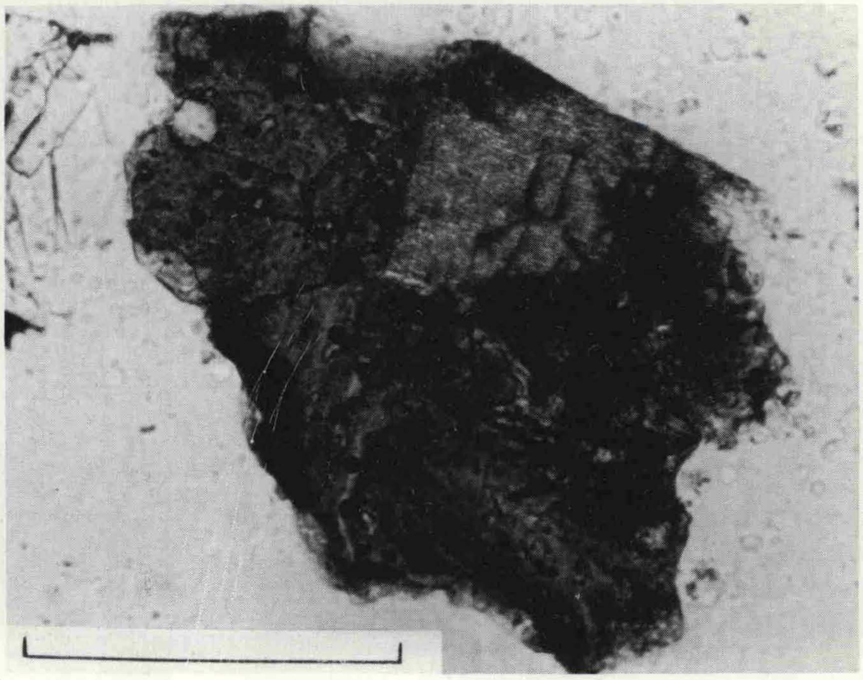

Fig. 6. Dark olive-brown, heterogeneous, flow-banded glass with distinct schlieren, enclosing an angular fragment of strongly shocked pyroxene(?) which shows strongly mosaic extinction accompanied by possible partial isotropization along dark fractures. Fragment 318,37; plane polarized light; scale bar 0.1 mm.

in glassy fragments, indicating superheating of the glass and disequilibrium between crystals and glass.

The character of the glassy material in the Luna 16 sample is virtually identical to that observed in Apollo specimens (e.g., [7]) and almost certainly reflects origin by meteorite impact. The preponderance of impact-produced glasses over shocked rock and mineral fragments is likewise consistent with observations on the returned Apollo samples.

Some glass fragments in the Luna 16 sample also exhibit quenching and devitrification textures similar to those reported in Apollo material (e.g., [2, 3, 4]). The textures suggest that crystal growth took place both during rapid cooling in the liquid state (quenching) and in the solid state (devitrification).

The more strongly colored yellow-brown to dark brown fragments display elongate, highly birefringent crystals and microlites, probably pyroxene, as well as parallel and dendritic growths of quench opaques (e.g., [3, 17]). In some fragments, quenching has proceeded to the point where the fragment is largely crystalline and may display an intersertal texture [14]. It is not clear whether such textures have been produced by rapid cooling of a primary magma or by quenching of an impact-produced melt of basaltic composition.

The colorless to pale green glasses with plagioclase-rich compositions [7] are generally less crystallized. Where present, crystallization has apparently taken place in the solid state and is strongly controlled by the shape of the fragments. The most common devitrification effect is the development of radiating or spherulitic textures of plagioclase crystals (fig. 2).

3. Conclusions

The Luna 16 soil particles exhibit distinctive shock metamorphic effects, uniquely produced by meteorite impact and virtually identical to those observed in other lunar samples. Distinctive rock and mineral deformation effects are observed in only 1–2 per cent of the fragments, a result consistent with studies of the Apollo samples. However, shock-produced glasses and glassy breccias constitute 70–80 per cent of the fragments studied. The generally high shock level of material in the regolith on Mare Fecunditatis is consistent with continuous meteorite impact [6] and suggests that the reworking and overturning of the surface fragmental layer indicated for the Apollo sites [1, 5, 11] is also occurring on Mare Fecunditatis.

The strong evidence for the formation of a fragmental layer at the Luna 16 site by repetitive meteorite impact strengthens the view that this process operates generally over the whole moon. The establishment of such general conclusions about lunar processes by examination of such a small amount of material emphasizes both the usefulness of petrographic methods and the unique character of the shock metamorphic effects themselves.

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