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

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 Sept. 20, 1970 and returned with 101 gm 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). A shorter version of this paper has appeared in Earth and Planetary Science Letters (Special Luna-16 issue, vol. 13, no. 2, pp. 316-322, January, 1972).

METHODS OF STUDY

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) were examined in detail, covering about 1000 fragments generally ranging in size from 50 to 200 μm. The total weight of material studied was thus about 5-10 mg, and the importance of petrographic methods in studying shock effects is strongly emphasized by the fact that significant results were obtained nondestructively on such a small amount of material.

The samples were studied by conventional flat-stage petrographic microscopy in both transmitted and reflected light. A small number of electron microprobe analyses were made to verify visual mineral identifications and to investigate the chemical diversity of the glass fragments which is an indication of impact melting (e.g., 7). The probe analyses were made with an ARL/EMX instrument, using spectrometer detectors and analyzing for three elements at a time (Ca, Si, Mg/Fe, Ti, Al). The standards used were synthetic glasses kindly provided by F. R. Boyd, Geophysical Laboratory (14). The data were reduced by a modified Bence-Albee computer program (15).

COMPOSITION OF THE LUNAR SOIL

The fragmental layer on Mare Fecunditatis, like that at the Apollo 11 and 12 sites, is composed of rock and mineral fragments, dense varicolored glass particles (both homogeneous and heterogeneous), and particles composed of mixtures of glass and rock fragments (13). The latter fragments are most common (Table 1) and are designated as microbreccias.* They consist of small diverse rock, mineral, and glass fragments in a variable glass-bearing matrix. Three textural types of matrix can be distinguished in the Luna-16 material (Table 1), but the types are gradational and one fragment may often exhibit two or more different textures in the matrix. The fragments are very similar in character and abundance to those observed in Apollo material (17, 18).

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* The nomenclature of lunar soil particles is somewhat complicated, and a wide variety of terms has been used by other workers (13, 16-21) to describe virtually identical particles. In this study, microbreccia is a general term designating all fragments which are themselves composed of various small individual clasts of rocks, minerals, and glasses, contained in a matrix which may display a variety of textures ranging from finely-fragmental to completely glassy. The individual clasts may come from different sources and may record multiple events of brecciation and accretion.

The dark, probably basaltic microbreccias in the Luna-16 soil can be subdivided into three categories (Table 1) on the basis of the character of the matrix, and, to a lesser extent, on the ratio of fragments to matrix: (1) fine-fragmental matrix, composed of small angular clasts with little or no glass; (2) glassy/vesicular matrix, consisting of heterogeneous, flow-banded, generally vesicular glass which may contain Ni-Fe spherules; (3) welded/sintered matrix, which is dense and lacks both fine-fragmental texture and significant vesicularity. The textural types are gradational, and single fragments displaying two different textures are commonly observed.

The use of microbreccia as a general term to include all the particulate soil fragments is preferred because these particles evidently represent a continuum of textures, all reflecting impact-produced brecciation and melting. Furthermore, a subdivision based on recognizable textural differences seems preferable at the present time, particularly since there is considerable discussion about the origin of certain textures. Most of the glassy-vesicular fragments are probably the result of ballistic accretion of glass and rock fragments ejected from meteorite impact craters, but the fragmental-matrix and welded/sintered types may be produced by shock lithification (6) or by postdepositional welding of hot ejecta (18).

The terms used here can be closely related to those developed for the predominant, dark, and basaltic particles observed in other studies of Apollo 11, Apollo 12, and Luna-16 samples (13, 16-21). The fine-fragmental matrix breccias are equivalent to the "microbreccias" (19) or "soil breccias" (20). The glassy/vesicular matrix fragments correspond to the "microagglutinate particles" (16), "glazed aggregates" and "dark, inclusion-laden glass" (17), "cindery glasses" (18), "agglomerates and glass spatter" (19), and "cinders and slags" (13). The welded/sintered matrix fragments have not been separately distinguished by other workers, but they probably correspond to the "dense" or "coherent" "microbreccias" observed in the Apollo 11 soils (17-19) and in other samples.

A similar, though less detailed, subdivision based on matrix characteristics was also used for the lighter feldspathic microbreccias in the Luna-16 soil. Although such fragments are much less common, a sufficient number were observed to recognize two different types: (1) a glassy matrix variety, and (2) a crystalline or aphanitic matrix which may represent partly crystallized glass. The two types are approximately equivalent, respectively, to the Type B and Type C anorthosite fragments studied by Marvin and others in the Apollo 12 and Luna-16 soils (21, 24).