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Shock metamorphism and origin of regolith and breccias at the Apollo 11 and Apollo 12 landing sites

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Abstract—Shock-induced fracturing, mosaicism, and planar deformation structures in plagioclase, clinopyroxene, ilmenite, and tridymite, and diaplectic plagioclase glass have been observed in soils, breccias, and crystalline rocks. Shocked crystalline rocks can be classified into 5 stages of progressive shock metamorphism.

Glasses produced by shock melting of minerals and rocks have been classified into 6 morphological types. From the chemical composition five main groups of glasses are derived which originate from following parent rock types: mare basalts, basaltic differentiates of the "KREEP"-type, anorthositic, and pyroxenitic rocks.

Based on grain size, and modal and chemical composition, the regolith is interpreted as the product of repeated impacts which mixed rocks and minerals of a dominantly local origin together with shock fused glasses from local and farther distant sources.

Breccia modes show close relationships to the modes of adjacent soil. Some breccias containing unshocked, shocked, and shock-melted crystalline rocks of rather uniform composition are products of large impacts penetrating into the crystalline basement. The majority of breccias were formed by smaller impacts affecting only the regolith. They are consolidated by various amounts of shock-melted soil formed by the increased heat production characteristic of shock compression of porous materials. Of these breccias five types are distinguished which are based on differences in texture, matrix glass, and content of shocked minerals.

INTRODUCTION

OBJECTIVES OF THE present paper are (1) detection and interpretation of shock effects in rocks and minerals, (2) chemical composition and origin of shock-fused glasses, (3) grain size distribution, modal composition, and impact origin of the regolith, and (4) modal composition, texture, and impact origin of breccias. Results of studies on Apollo 11 samples have been published in ENGELHARDT *et al.* (1970). This paper reports additional and new results on Apollo 11 and Apollo 12 materials.

From the following Apollo 12 samples single grains, grain mounts, and thin sections have been investigated: 12001,84 (< 1 mm), 12070,139 (< 1 mm), 12033,74 (1–2 mm), breccia 12034,11, breccia 12010,21, breccia 12010,4, basalt 12057,14, and basaltic vitrophyr 12009,31. Methods and apparatus used in this investigation have been described in ENGELHARDT *et al.* (1970).

SHOCK EFFECTS IN MINERALS

Plagioclase

Shock-induced lamellae of low refractive index and low or no birefringence (ENGELHARDT *et al.*, 1970; STÖFFLER, 1967) occur in single plagioclase grains of breccias and soils and in shocked basalt fragments. Small fragments of diaplectic plagioclase glass (ENGELHARDT *et al.*, 1970, footnote p. 370) occur in the regolith and as inclusions in the brown glasses of samples 12033 (fines) and 12034 (breccia) designated as "KREEP" by HUBBARD *et al.* (1971). The amount of diaplectic glass in Apollo 12 soils is less than in Apollo 11 soil. Less than 1% of the grains of plagioclase composition in Apollo 12 soil are diaplectic glasses. Diaplectic plagioclase glass has also been found in the shocked basalt fragment 12057,14 (see below).

Clinopyroxene

Pyroxene with shock-induced lamellae as they have been described from Apollo 11 samples (ENGELHARDT *et al.*, 1970) occurs in Apollo 12 soil, breccias, and fragments of shocked basalt. Pyroxene grains with lamellae always show additional indications of mechanical deformation such as mosaic or undulatory extinction and irregular fractures or cleavages. Some grains contain only a few thin lamellae. More strongly shocked grains show many closely spaced lamellae. Most grains contain only one lamellae set. Rarely two lamellae systems cross each other at angles not far from 90°. In general, the lamellae do not extend through the whole grain, but prefer limited areas. Because these areas are often bounded by fractures it seems likely that brittle fracturing preceded lamellae formation. Bending of lamellae may indicate gliding parallel to lamellae planes.

We have measured the orientation of pyroxene lamellae against the optical directions n_x, n_y, n_z (Fig. 1). Some of the lamellae within the zone n_x–n_z may be parallel to (001) corresponding to lamellae known from shock experiments (SCLAR, 1970, HORNEMANN and MÜLLER, 1971); nuclear explosions (SHORT, 1969, JAMES, 1969); and the Ries crater (STÖFFLER, unpublished data). Lamellae of very irregular orientations which we have found in the majority of shocked pyroxene grains seem to be typical for shock deformation. Similar orientations have been found by HORNEMANN and MÜLLER (1971) in pyroxene, shock-loaded at pressures from below 100 up to 390 kbars. In accordance with these experiments, pyroxene with lamellae occurs in shocked basalt fragments together with still birefringent plagioclase. The lowest peak pressure for lamellae formation must be appreciably lower than the pressure which produces diaplectic plagioclase glass.

In Apollo 12 soils and breccias investigated by us, the amount of pyroxene grains

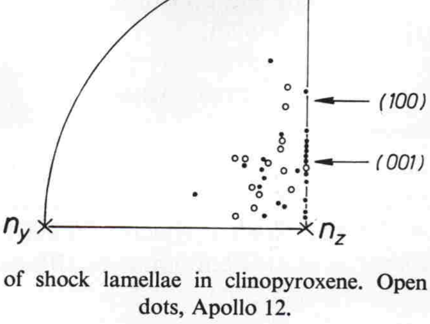

Fig. 1. Orientation of shock lamellae in clinopyroxene. Open circles, Apollo 11; dots, Apollo 12.