Proceedings of the Apollo 11 Lunar Science Conference, Vol. 1, pp. 363 to 384.

# Shock metamorphism of lunar rocks and origin of the regolith at the Apollo 11 landing site

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(*Received* 3 *February* 1970; *accepted* 19 *February* 1970)

**Abstract**—Indications of progressive shock metamorphism have been found in Apollo 11 soil and breccias. We define shock effects as permanent alterations of minerals due to pressures above the dynamic elastic limit. We have observed the following shock effects: deformation structures in plagioclase, pyroxene and olivine; solid state transformation of plagioclase into an amorphous phase (diaplectic glass); glasses formed by shock induced melting of various source materials.

The glasses represent two major chemical types related to basaltic and anorthositic rocks, respectively. The basaltic glasses (darker color) are richer in Fe, Ti, Mn and poorer in Si, Al than the anorthositic glasses (lighter color). The basaltic glasses are assumed to be ejecta from impact sites in mare areas, the anorthositic glasses from sites in the highlands.

The lunar regolith is an impact breccia similar to terrestrial breccias of suevite type. Differences between lunar and terrestrial impact breccias are due to multiple impact events on the moon and its lack of atmosphere.

## INTRODUCTION

THE LUNAR regolith of Mare Tranquillitatis, as represented by the Apollo 11 samples, was formed from primary magmatic rocks by disintegration, mechanical deformation and local heating to high temperatures (LSPET, 1969). Alterations of this kind can either be of volcanic origin or they may have been produced by the impact of meteoritic bodies on the lunar surface. In the first case the lunar unconsolidated soil and the consolidated breccias should be similar to terrestrial pyroclastics. In the second case they should be comparable to impact breccias as they occur in terrestrial meteorite craters.

If the lunar regolith is essentially an impact breccia, as has been assumed by several investigators, effects of shock waves, with pressure amplitudes higher than those which can be derived from endogenetic sources, should be detectable in the components of soil and breccias.

We will use the term shock wave according to the definition given by DORAN and LINDE (1966): "a compressional wave having an amplitude exceeding the elastic limit of the material in which it is propagating." Consequently, we call minerals "shocked" only if they have experienced pressures above the dynamic elastic limit (Hugoniot elastic limit, HEL). This limit can be determined by shock experiments and can be recognized by a break in the Hugoniot-curve. Above the HEL minerals yield by plastic deformations and can undergo transformations into high pressure phases. After pressure release the shocked minerals preserve traces of plastic deformations which are distinguishable from those formed under static or quasi-static conditions. If high pressure phases were formed, remnants of these phases or new phases derived from them during pressure release are to be expected in the shocked material. The residual temperature of high amplitude shock waves may exceed the melting point of the shocked minerals so that a melt is formed after pressure release (shock melting).

The elastic limits of quartz and silicates under dynamic conditions exceed 50 kbar or more. Pressures of this magnitude cannot be produced by volcanic events. They can only be generated by the impact of meteoritic bodies of all sizes striking the lunar surface at cosmic velocities.

In this paper we present observations on shock effects in Apollo 11 samples. Shock effects, as defined above, are planar structures in silicates due to dynamic plastic deformations, feldspar glasses formed in a solid state reaction (diaplectic feldspar glass) and shock melted rock fragments. Alterations of this kind are known from terrestrial impact craters and have been artificially produced in shock experiments.

## Samples and Experimental

The following samples have been investigated: fine material of the 0·1–1 cm fraction (10085-25 and 10085-26) and of the <0·1 cm fraction (10084-106); breccias (10027-11; 10059-41; 10060-34; 10065-28; 10065-32); one thin section of a crystalline rock (10047-9—thin section number 6476 80).

Grain size distribution of sample 10084-106 has been determined by sieving (0·5 mm, 0·5–0·25 mm, 0·25–0·125 mm, 0·125–0·063 mm, 0·063–0·020 mm) and sedimentation in benzene (0·020–0·010 mm, 0·010–0·004 mm, <0·004 mm). The density of the <0·020 mm fraction has been measured by the pycnometer method in octane.

From the 0·1–1 cm fraction different types of minerals, rocks and glasses have been separated by hand under the stereo-microscope. Polished thin sections have been made of about 90 selected specimens from separated fractions.

Optical examination of all thin sections and of the sieve fractions has been carried out with a petrographic microscope. Universal stage methods have been used to determine the orientation of deformation structures in shocked minerals.

The refraction index of glasses has been measured using the Becke test with sodium light. The immersion liquids were butylcarbitol—α-monobromonaphthalene and methylene iodide—α-monobromonaphthalene mixtures. The refractive index of the liquids was changed by temperature variation. The accuracy was ±0·0002.

The density of glass pieces has been measured by suspension in mixtures of bromoform and N,N-dimethylformamide. The accuracy was ±0·0004 g/cm$^3$,

Some plagioclase glasses have been annealed at different temperatures in an electric furnace in air. Each specimen was wrapped in platinum foil and air quenched.

Some single-crystal X-ray photographs have been taken of plagioclase glass and olivine grains.

Electron microscopy has been used to examine the minimum size of spherules.

Chemical analyses of feldspars, pyroxenes, plagioclase and alkali feldspar glasses and of fused glasses of different color and shape have been made with an ARL-EMX-SM-microprobe.

In the case of feldspars and feldspar glasses Ca, Na, and K only have been determined. The X-ray intensities have been corrected in accordance with the method described by Smith (1965).

From all other specimens total analyses have been made (Si, Al, Ti, Fe, Mg, Mn, Ca, Na, K). Cr, Ni, P, S have been examined from only a few selected samples.

All quantitative determinations have been obtained by 5–20 point analyses set at random on each grain. Normally a spot size of 10–20 μm dia. has been used. Iron spherules and alkali feldspar inclusions have been analyzed with a fully focused electron beam. Measurement conditions were as follows: 15 kV acceleration voltage, 10 nA sample current, 20 sec counting rate. Correction has been made for background, drift, mass absorption, secondary fluorescence and atomic number effect, using a computer program written by Goldstein and Comella (1969).

With some colored glasses a systematic deviation of up to 5 per cent from the total sum of 100 per cent has been observed. The error increases with increasing Fe-content and decreasing Si-content. We could not as yet check all possible sources of error. We assume that the glasses rich in Fe and low in Si are more instable against electron bombardment than those low in Fe and Si, so that partial volatilization of probably Si, alkalis or other elements may cause the deviations.