Results of Special Mechanical Analyses of Luna 16 Material[1]

H. Stiller, H. Vollstädt, R. Wasch, P. Bankwitz,
E. Bankwitz, and F. C. Wagner
Akademie der Wissenschaften der DDR,
Zentralinstitut für Physik der Erde,
Potsdam, East Germany

J. Schön
Bergakademie Freiberg
Sektion Geowissenschaften
Freiberg (Sa), East Germany

For the analysis of lunar soil samples in the GDR, under the direction of the GDR Academy of Sciences, a special methodological system for the examination of the regolith has been developed by selected scientific institutions of the Academy of Sciences and some universities. This system consists of the following complex branches:

1. Examination of fractured or split structures for mineral grains or glass grains
2. Consideration of the pressure-dependence of the propagation velocity of elastic waves in lunar rock samples
3. Investigation of the structural behavior of lunar minerals and glasses under normal thermodynamic conditions and at high pressures
4. Electron-optical study of the regolith to clarify mineralogical and crystallographic properties of selected materials
5. Studies into the mineralogy and crystallography of the rock-forming minerals and the petrochemistry of the lunar soil samples
6. Determination of main and trace elements by means of a methodology oriented to very small samples (plus determination of isotopes, isotopic abundances, and isotopic ratios)
7. Gamma-ray spectroscopic analyses of the radioactivity of the Luna 16 regolith

This methodological system forms the basis of a general scheme consisting mainly of comparative studies of lunar and terrestrial rocks: lunar materials and corresponding analogous terrestrial materials are analyzed in the same way and with the same objective, and the results obtained are brought into the discussion and interpretation of geophysical, physical, chemical, and mineralogical problems of the Earth and the Moon.

For comparative studies of the physico-mechanical behavior of lunar and terrestrial rocks, it is essential that the chemical and mineralogical parameters be known. The studies carried out on the Luna 16 regolith to find these have confirmed the data that were already published internationally. For example, by means of activation analysis under irradiation in the reactor, activation analysis with a 14 MeV U-generator, and mass spectroscopy on samples of 10 or 20 mg, six main and 63 trace elements were quantitatively determined and compared with known data (ref. 1).

[1] Central Earth Physics Institute report No. 409.

Mineralogical and crystallographic studies confirmed that in addition to glass of the most varied composition, mainly olivine, pyroxene, and plagioclase occur (ref. 2). The results of the chemical and mineralogical-crystallographic studies show that the properties and behavior of lithogenetic minerals found on the Moon basically correspond to those of analogous minerals on the Earth (refs. 3 and 4). Nevertheless, the thermodynamic conditions peculiar to the Moon, i.e., absence of free water, vacuum, and mechanical stress through meteorite impacts, etc., ought to have an effect on the rocks forming the upper strata of the Moon. The mechanical-elastic behavior in particular can be affected by these parameters. The extent to which this applies to minerals and glasses can be shown in part by the following studies (ref. 5).

Analysis of Fracture and Cleavage Surfaces of Lunar Mineral and Glass Fragments

The mineral and glass fragments used for these studies are between 0.02 and 0.2 mm in diameter and correspond, "terrestrially" speaking, to the fine sand fraction. The examination of structures for fracture surfaces is justified in that they are a documentation of (1) the course of events in processes of rupture; (2) surface formations differing in age; and (3) the nature of rupture processes (especially their speed) from which, to a certain extent, further information can be obtained as to the causes of rupture.

These experiments are therefore very suitable for the examination of fracture concepts developed on terrestrial material—and in this case on rocks as well—which we have been studying for a long time. Particular features of the fracture surfaces (in rock ruptures the so-called joint structures) give an indication as to the nature of the process of rupture: surface steps radiate from the starting point of the crack, their divergence indicating the direction of propagation. These surface steps can also turn into independent secondary fracture surfaces. They are evidence of the propagation of a fracture at different levels.

A conclusion can also be drawn as to the fracture propagation velocity. It is known from fracture physics that the propagation of a fracture usually occurs rapidly (slow fatigue fractures are clearly distinguishable). It can also be deduced from the physical nature of the rupture process that certain surface structures, as well as a rupture process itself, are genetically related to the propagation, refraction, etc., of elastic waves, and that the fracture propagation velocity, being about half the transverse wave velocity, is relatively high. Interruptions in fissuration are marked in particular by initial fields lying in series.

Following is an example to explain the method of work and the object of the investigation. Figure 1 shows a regolith grain (a),

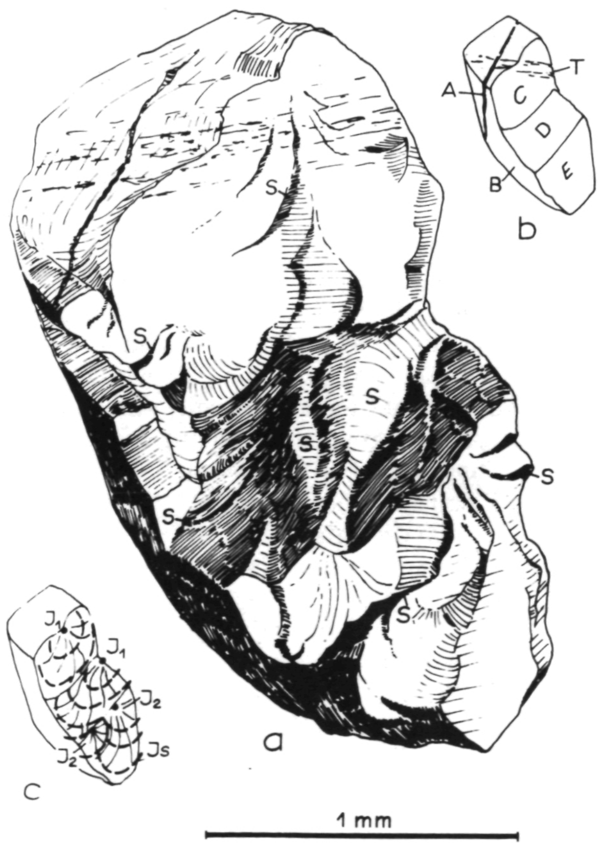

Figure 1.—*Analysis of fracture of a regolith-grain.*

with two detailed sketches (b + c). Owing to the coarse internal structure, the individual surfaces are unevenly formed, while (b) shows the interrelationship of the ages of the fracture surfaces, (c) shows the centers of cracking and the directions of cracking of the surface portions.

(1) I_1 and I_2 are initial points that have occurred simultaneously because their structures of rupture interlock at their line of intersection.

(2) Since C and D on surface B form steep steps, it can be assumed that B is older than C and D. The structures of E develop from D, i.e., E developed after D.

(3) From two secondary initial points, I_2, the process of fracture propagation from D to E can be seen (in b). A is a mineralized rupture. One suspects that A and B belong to older surface systems while C, D, and E represent a younger system. Figures 2 and 3 show further examples of fracture surface analysis.

Unlike geologically comparable material, the regolith from Luna 16 is very finely divided. On the surface of the Earth, this occurs only in areas of mylonite. In addition, despite the fineness, the regularity of the larger particles is remarkable. This indicates fracture-producing impacts at fairly large distances. Finally, such a fine disintegration is bound to absorb considerably all continuous elastic waves. The materials under review can reliably be said to have low wave velocities. From the first results obtained up to now the following can be stated: the fracture structures formed on the Moon correspond in all respects to those that have developed on the Earth. The rupture processes must therefore also be the same. It can be assumed that the formation of fractures in crystals, glasses, breccias, etc., took place in a vacuum and in the absence of free water. Both factors clearly have no decisive primary importance for the rupture process itself.

Fracture surface structures are a result

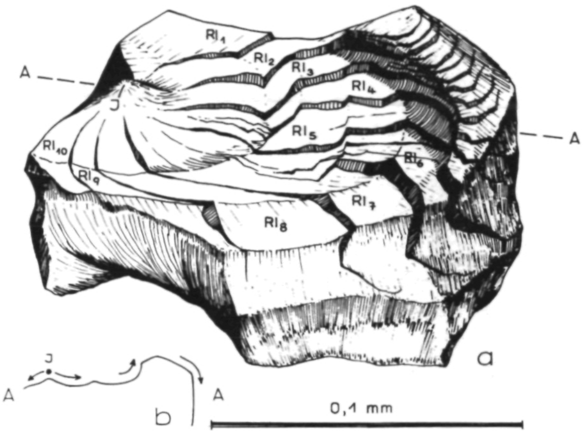

Figure 2.—*Example 2 of fracture surface analysis.*

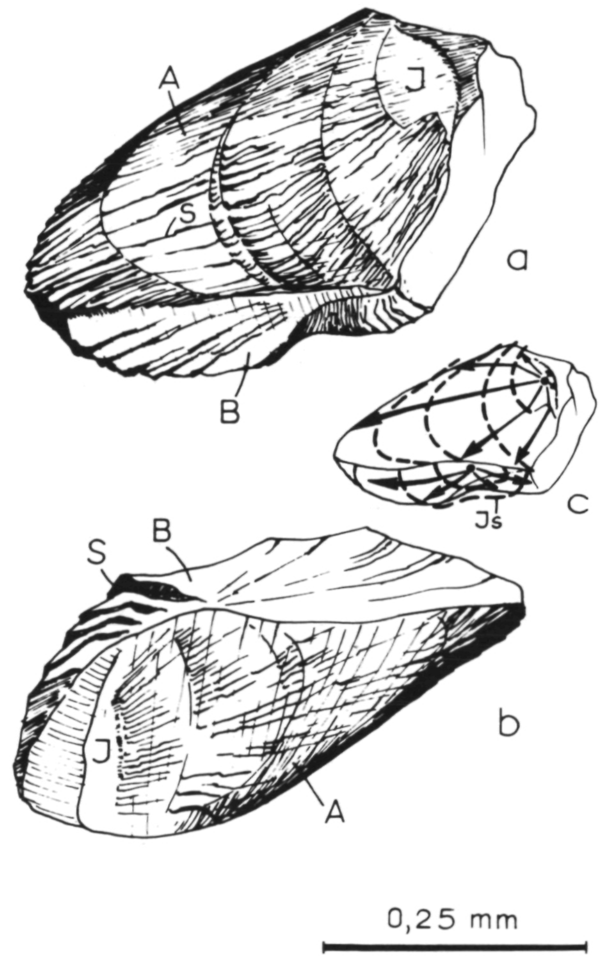

Figure 3.—*Example 3 of fracture surface analysis.*

of the dissipation of energy in the form of waves. The formation of every microcrack and of every fissure represents a tremor of the very smallest magnitude. In the Luna 16 regolith, the final forms that predominate suggest a highly intense or explosive rupture.

It still remains to be investigated to what extent changes in the internal structure of a material are manifested in different changes in the form of the fracture structures typical for the particular case; to what extent one can infer internal structural features—for rocks as well—from small differences in the formation of the fracture structure; and how these structural features affect the rupture process of individual rock constituents.

Examination of the Pressure-Dependence of the Propagation Velocity of Elastic Waves in Lunar and Terrestrial Rocks

The behavior of the propagation velocity of elastic waves particularly longitudinal waves in this case under increasing pressure found through examination of dense Moon rock samples can be compared with that found for terrestrial rocks. Such comparison shows that (1) lunar rock samples demonstrate a far greater pressure-dependence than terrestrial rock samples of comparable density and chemistry and (2) at low pressures in particular, the velocities of the lunar samples are far below those of the comparable terrestrial samples. Possible causes of the pressure-dependence are changes in the elastic properties of the minerals themselves and changes in pore or fissure volume.

Even with the high density of the material of $\rho = 3.1$ g/cm^3, neither of these causes can explain the considerable changes in velocity with increasing pressure. It is more likely that the reason for this dependence is to be found in the occurrence of "imperfectly elastic bonds between the rock constituents." These defects, e.g., in grain or mineral contacts, are not necessarily tied to a "fissure volume" worth mentioning. The theoretical treatment of this problem leads to the following considerations.

A quantity K_0 can be taken as a coefficient of measure for the cracks in the rocks described. K_0 characterizes the imperfect bond between the rock constituents caused by cracks. K_0 can be expressed by analytical formula corresponding to Stiller et al. (ref. 7). Taking into account this K_0 parameter, a velocity-pressure relation of the following can be obtained:

$$V_P = V_F(1 - K_0 e^{-A\sigma})^{1/2}$$

where V_P = velocity of longitudinal waves of the sample under pressure

V_F = velocity of the flawless compact substance

K_0 = initial value of quantity K, i.e., K at a pressure of $\sigma = 0$ kg/cm^2

A = coefficient for the deformability of the sample

Figure 4 shows the dependence

$$\frac{V_P}{V_F} = (1 - K_0 e^{-A\sigma})^{1/2}$$

on a double logarithmic scale. The double logarithmic representation makes it possible to use the curves as "master curves" for the interpretation of experimental results. The measured values are drawn on paper of the same scale as that of the master curve; this is then placed over the master curve, and an attempt is made, by moving the paper and keeping the axes parallel, to bring the measured values into coincidence with the master curve.

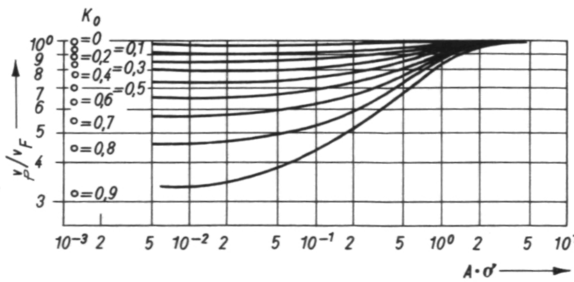

Figure 4.—*Function* $V_P/V_F = (1 - K_0e^{-A\sigma})^{1/2}$ *in double logarithmic scale.*

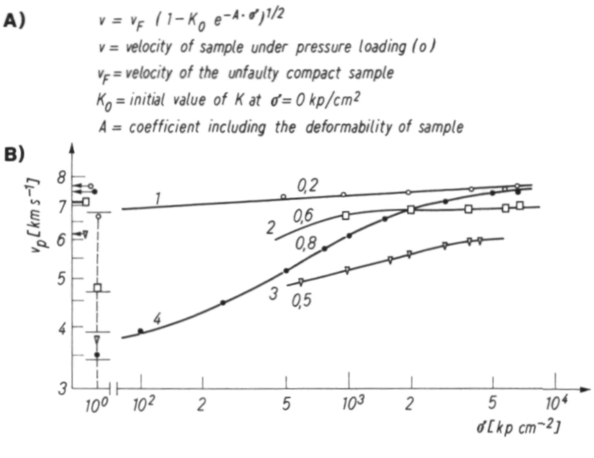

Figure 5.—*Experimental results of terrestrial and lunar rocks, evaluated from the relation under A: curve 1 dunite (terrestrial) = 2.31 gcm*$^{-3}$*; 2 chloritic schists (terrestrial) = 2.84 gcm*$^{-3}$*; 3 gneiss (terrestrial) = 2.72 gcm*$^{-3}$*; 4 basalt (lunar) = 3.32 gcm*$^{-3}$.

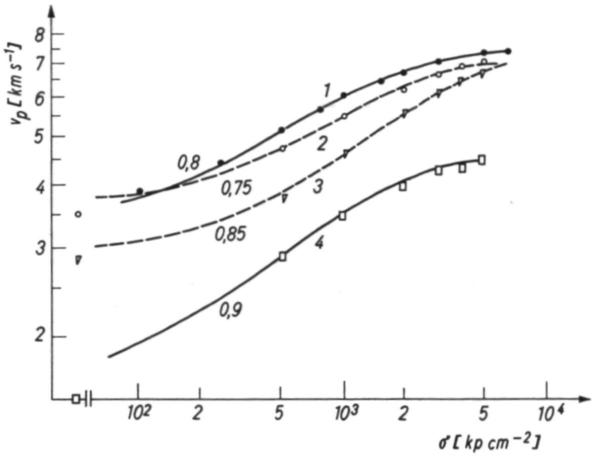

Figure 6.—*Experimental results of lunar rocks: curve 1 basalt = 3.32 gcm*$^{-3}$*; curve 2 basalt = 3.18 gcm*$^{-3}$*; curve 3 basalt = 2.88 . . . 3.38 gcm*$^{-3}$*; curve 4 breccia = 2.35 gcm*$^{-3}$

Figure 5 shows this velocity relation (A) and the results of such an interpretation, obtained from lunar and terrestrial samples (B). In part (B), curves 1, 2, and 3 for terrestrial rocks show K_0 values up to 0.6 (for a gneiss with density $\rho = 2.72$ g/cm^{-3}). The results for a lunar sample much denser in comparison (curve 4) show an even higher value for $K_0 = 0.8$, and therefore indicate extreme internal crushing of the rock.

Apart from the curve parameter K_0, the comparison of the calculated and the measured value at $\sigma = 1$ kg/cm^{-2} and the value for V_F marked by an arrow on the velocity axis are also given. This value V_F is the ordinate value on the experimental curve, corresponding to the ordinate value $V_P/V_F = 1$ on the calculated curves. Of particular interest here is the good agreement in the V_F values between the terrestrial dunite (curve 1) and the lunar "basalt" (curve 4). This underlines the fact that the differences in elastic behavior do not result primarily from the mineralogical composition, but from the nature and degree of the internal bonds. In figure 6, the evaluations of experimental results for lunar rocks are shown. They confirm the assumptions made so far. The considerable internal disturbance in the bonds between the constituents of the lunar rocks will most probably have been mainly caused by a heavy alternating thermal stress and also a very heavy mechanical stress (meteorite impacts—shock waves). Berzov et al. (ref. 6) brings these last influences together under the heading "impact metamorphosis."

Conclusions

The following conclusions can be drawn from the studies carried out so far:

1. The lithogenetic minerals on the surface of the Moon correspond in most respects to their terrestrial counterparts, as can be deduced from chemical, mineralogical, radiographic, and electronoptical examinations.
2. The mechanical short-term behavior also conforms to this trend.
3. From this it can be deduced that the special thermodynamic conditions on the Moon have no appreciable influence on the physico-mechanical behavior of lunar *minerals*, although there are some significant differences

in the distribution of elements.

4. This influence, however, makes itself felt more in the behavior of the lunar *rocks,* since in contrast to terrestrial conditions lunar rock has been subject to extreme dynamic influence. This is manifest in, among other things, a considerably greater pressure-dependence —above all at low pressures—of the velocity of longitudinal waves. The causes for this can be found in the relatively high degree of crushing in lunar rocks caused by meteorite impacts and other types of mechanical stress; this was substantiated quantitatively.
5. This mechanical influence has meant that the grain contacts and all other possibilities of connection between the rock constituents (minerals, glass) have not attained the "perfection" which predominates, for example, in most terrestrial rocks.
6. The results have shown that the physico-mechanical state of lunar rocks can be expressed as a formula on the basis of known dependences.
7. The velocity-pressure dependences of lunar rocks, corrected with regard to the crushing factor, behave quantitatively and qualitatively like the corresponding terrestrial rocks. Consequently, the velocity-depth dependences in the Moon at sufficient depth must be analogous to the corresponding depth dependences in the Earth, as can also be seen from the results of lunar seismology (see ref. 8).
8. The analogies of physico-mechanical behavior mentioned above make it possible to use adequate equations of state for the Moon as well.

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