equant pores. This is evidenced by the facts that: (i) the velocity at P=0 changed from an initial value of 1.2 to 2.2 km/sec, with little change in density; (ii) the final V_P-P curve is similar to that of rock 10017. Because of the presence of many equant pores, it is unlikely that V_P of about 6 km/sec represents the intrinsic values for these rocks. The idealized rock should have a higher value, perhaps closer to that of the glass spheres.

V_P of Lunar Fines. Compressional sound velocities were measured at various pressures and compactness on the soil, by a technique (*12*) that incorporates the pulse transmission method (*11*). Sample length and density were determined throughout the experiment.

Behavior of V_P, as a function of compaction (density), is shown schematically in Fig. 3. The soil compacts inelastically, along the locus P_1-P_4. If at point 2 pressure is released, the density changes very little, but V_P drops elastically (point 2, to point 3 at P=0).

The line marked "P=0" represents the locus of values of V_P (ρ, P=0) generated by a series of elastic and inelastic pressure cycles. Curves of constant pressure ($P > 0$) have the general shape shown by the dashed line. For the soil along an elastic curve V_P drops from 2.23 (ρ=2.08, P=430 bars) to 0.67 km/sec (ρ=2.03, P=0).

For P=0, V_P increases with ρ along the zero isobar, and importantly, has a value of 1.1 km/sec at ρ=2.2 comparable to the zero pressure values of the microbreccia rock 10046 (V_P=1.2, ρ=2.2). From the observed $\triangle P/\triangle \rho$ along the elastic curve, the bulk modulus, K, of the lunar soil is found. Significantly at P=0, the value of K for the soil and 10046 are close (12 kbar and 19 kbar, respectively). The soil and microbreccia are mechanically similar.

The Velocity Profile in the Lunar Surface. Three simple models were calculated from our data giving velocity versus pressure at shallow lunar depth (Table 1). Model 1 assumes a soil-microbreccia mixture under self-compaction. Model 2 assumes a breccia of "igneous" rock 10017 under self-compaction. The variation of K with P as measured for the soil and 10046 (first pressure run) is used. However zero pressure values of V_P, ρ, and K are taken from 10017. This "igneous heterogeneous" model corresponds to a regolith of brecciated and broken up rock blocks.

Model 3 is derived from V_P and β of the rock 10017 and represents the case of a homogenous half space, in which cracks simply close under pressure. All three are dry models, that is, there are no pore fluids.

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Apollo 11 Drive-Tube Core Samples: An Initial Physical Analysis of Lunar Surface Sediment

Abstract. *Two drive-tube core samples were obtained at Tranquillity Base. Fines include much glass, are unweathered, medium gray, loose, nonstructured, very weakly coherent, and demonstrate both accumulation and mixing in a waterless vacuum environment. In contrast to chemical weathering characteristic on the earth, lunar alteration processes are primarily mechanical. We infer that environmental processes of the lunar surface may be expressed as follows:* R *(regolith)* = f(cl, p, r, t, b, a, . . .), *in which climate* (cl) *is constant and the time* (t)*-dependent processes of bombardment* (b) *and accumulation* (a) *assume significance unparalleled on the earth because of their effects on parent material* (p) *and relief* (r).

Two drive-tube core samples were collected successfully late during Apollo 11 exploration on the surface of the moon by Neil A. Armstrong and Edwin E. Aldrin, 20 July 1969. These cores thus provide the first samples of unconsolidated lunar surficial deposits and their subsurface characteristics.

During sampling, both drive tubes penetrated the first few inches easily, but required hammering to penetrate more deeply (Fig. 1) (*1*). The drive-tube samplers consist of an aluminum outer barrel, or tube, equipped with a disposable steel bit with inward taper at one end and a disposable aluminum handle at the other; the bit was replaced after use with a cap to protect and to retain the collected sample. An extractable aluminum split-tube assembly was housed inside the barrel to receive the sample as the tube was driven, and to permit later removal of the sample in undisturbed condition. This assembly consists of an anodized aluminum tube split lengthwise, surrounded by a Teflon sheath previously heat-shrunk into place to bind halves of the split-tube in position. A Teflon follower and steel spring are driven back inside the tube as the sample enters, and remain in place at the top of the sample to support it during trans-

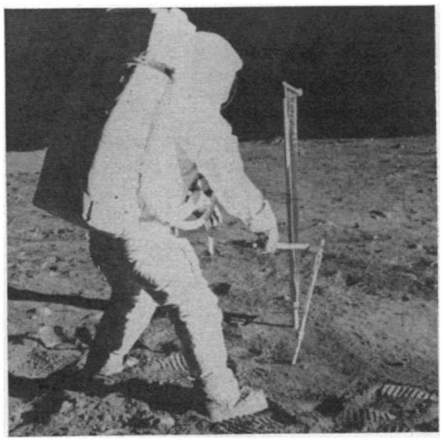

Fig. 1. Collection of Core Tube No. 1, approximately 3.5 m NNW of LEM, showing position relative to solar wind composition experiment in background. Note slant of tube and use of hammer required by Aldrin to drive it. [NASA photo AS11-40-5964 by Neil A. Armstrong]

port. Maximum possible sample size is determined by inner dimensions of the split aluminum tube, 31.75 cm in length and 1.95 cm in diameter. Both drive tubes were opened in the Biological Preparations Laboratory of the Lunar Receiving Laboratory on 28 July, in a sterile dry nitrogen environment. After preliminary sketching, description, and photography of each core, the cores were split lengthwise by removing half of each core by trowelling. The material, consisting of 22.39 g from Core No. 1, and 26.73 g from Core No. 2, comprised the prime biological sample. Particle size distribution of each half-core removed was obtained by sieving; bulk densities were estimated by calculation; and the remaining core halves were stored.

Core No. 1 (sample 05,0) is 10 cm long (Fig. 2); Core No. 2 (sample 04,0) is 13.5 cm long. Both appeared to be essentially undisturbed in regard to their primary characteristics. Core No. 2 is faintly stratified; the other is not. Both cores include very small particles with highly reflective surfaces, and the matrix of both cores is nearly uniform medium gray (N3 to N4) (*2*) with a low-chroma brownish hue (10YR 3/1 to 4/1) that is most evident under tungsten light. Texturally, the cores appeared to be a silty fine sand or loam with admixed angular rock fragments, glass spherules, and aggregates of glass up to 3 or more millimeters in diameter; average grain size is about 0.11 mm. Core No. 2 included a large subrounded glass aggregate of 1.2 cm maximum diameter (Fig. 3). The core material is loose, weakly cohesive, and consists of single grains except for minor aggregates of glass. When exposed in the opened core-tube liner, the material clearly had bearing strength insufficient to support available soil penetrometers.

When probed with a small spatula, the material disintegrated particle by particle or formed extremely fragile units of subangular blocky shapes (in the case of tiny slump blocks 2 to 4 mm across) or crumb-like shapes (when less than 2 mm in diameter). Because similar ephemeral units could be reproduced experimentally, it is not demonstrable whether these shapes (Fig. 2) were original structures comparable to the peds of terrestrial soils. A single band or layer of slightly higher value and chroma about 0.5 cm thick was observed in Core No. 2, 6.2 to 6.5 cm below its original surface. Upper and lower boundaries of this band were sharply defined, but it was not macroscopically different in texture. No systematic distribution of coarse particles (> 1 mm) was observed.

Data from Surveyor experiments, and observations and photographs made by Aldrin and Armstrong, record a surface veneer of material with high albedo, visibly disturbed by the astronauts' footprints. No trace of light-colored material was found at the top of either core sample (note Fig. 2), although scattered small ellipsoidal patches of fine incoherent material of lighter gray color (N7) and dimensions up to slightly more than 1 mm were found in both cores. These light patches may be fragments of a disrupted layer, now mixed with glass spherules and rock fragments in the fine matrix of the cores.

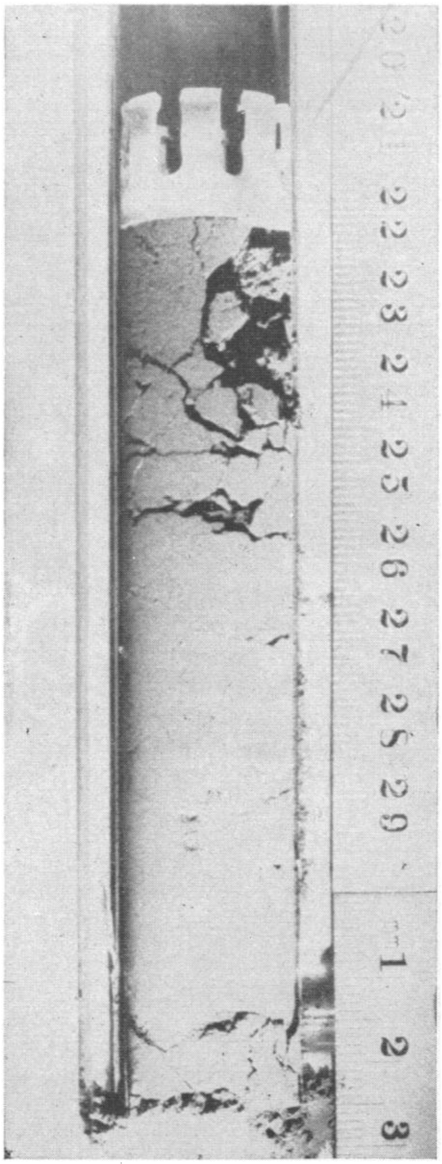

Fig. 2. Contents of Core Tube No. 1 (sample 05,0) before dissection. Note (i) void space near top beneath Teflon follower, possibly resulting from irregular lunar surface, (ii) lack of light-colored surface veneer, and (iii) fracture pattern of core material, showing weak coherence despite otherwise loose consistence and single-grain structure except for weak aggregates of glass. Scale is in centimeters. [NASA photo S-69-45049]

Quantitative measurements of grain size distribution and bulk densities of the core samples were limited in their accuracy by restricted working conditions in the environmental cabinets in which the samples were handled. Bulk densities of 1.66 ± 0.03 g/cm^3 and 1.54 ± 0.03 g/cm^3 (*3*, p. 1219) were calculated by using a nominal diameter of 2.00 cm, whereas blueprint specifications call for an interior diameter of 1.95 cm.

Assuming that the diameter may range from 1.95 to 2.00 cm, the calculated densities would be 1.70 ± 0.04 g/cm^3 and 1.58 ± 0.04 g/cm^3, respectively. More precise calculation is impossible because of undetermined compression by the funnel-shaped bit of the core tubes, and because halves of the split-tube liners of both core tubes had slipped out of register. Whether this occurred during or after sampling is not known, and effective diameter of the core tube during sample collection cannot, therefore, be established.

Similarly, difficulties limit the size range for which sieve analyses made in the nitrogen cabinets (*3*, figure 11, p. 1219) are reliable. The small sample size limits accuracy of any percentage determined for particles coarser than 1 mm, and mechanical difficulties beset sieve measurements in the range below about 65 μ.

Mechanical analyses made outside the LRL cabinets consistently have been different from those made inside them during the quarantine period of Apollo 11. Subsequent analyses show both a larger concentration of fines than was found earlier, and a range of material to diameters far smaller than was first estimated.

Two possibilities for these discrepancies are evident: (i) material sieved inside the cabinets may have failed to pass meshes larger than actual particle diameters because of static electricity; and (ii) weak aggregates of lunar material may continue to break down with continued sieving. The first possibility is probable; the second is supported by much evidence. During microscopic examination, other members of the Lunar Sample Preliminary Examination Team repeatedly observed and measured fine aggregates, especially of glass, including fragments only a few microns or even less than a micron in diameter (*4*). Such fragments not only demonstrate the presence of a very finely comminuted fraction, highly glassy in composition, but also make clear the great difficulty of obtaining reliable sieve analyses on any consistently reproducible basis which does not break down all aggregates. Unfortunately, the actual mechanical properties of lunar surficial deposits are determined by sediment in aggregated rather than disaggregated form.

Microscopically, Apollo-11 fines are about half glass, with plagioclase, clinopyroxene, ilmenite, and olivine. Freshness (except for shock metamorphism), limited devitrification, lack of hydration of even the finest glass fragments, and unoxidized free iron particles and spheres (*3*, p. 1220) indicate a waterless vacuum environment for the samples throughout their history. This lack of chemical weathering is reflected by the almost neutral colors of the cores. The near absence of any effective chemical alteration processes on the lunar surface is further illustrated by the similarity in initial chemical analyses of 23 Apollo-11 samples, including fines (*3*, p. 1221 and table 1, p. 1222), which suggest that the surficial debris are simply fragmented or remelted versions of the three major rock types collected there.

In almost all terrestrial weathering environments, physical and chemical weathering not only proceed concurrently, but generally shift toward dominance of chemical weathering as decrease in particle size results in greater surface-to-volume ratios and thus in greater reactivity per unit volume. Clearly this is of little importance in the case of Apollo-11 fines, which lack clay minerals but instead have anhydrous glass in even the finest size fractions.

The influence of mechanical processes, however, appears to control features of the cores, which demonstrate both accumulation and mixing. Accumulation is recorded by the subtle layering of Core No. 2; mixing, by the variation in composition and morphology of glass, presence of rock fragments of mixed lithology, and the incoherent gray inclusions of both cores. Thus, the lunar regolith at Tranquillity Base is not homogeneous, but varies three-dimensionally as shown by the cores and by photographs of the surface. Obviously, the dominant mechanical process responsible for both mixing and accumulation of regolith debris on the unprotected lunar surface is bombardment. Apollo-11 data unquestionably show evidence of shock metamorphism to be abundant in the fines, and bombardment has resulted in development of craters, minute pitted rock surfaces, shattering and mixing of the regolith, scattering of materials, shock metamorphism, melting, vaporization, condensation, and addition of glass and extralunar material to surficial deposits (*3*, pp. 1226–1227).

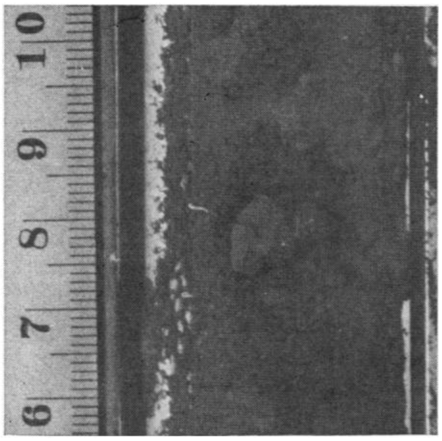

Fig. 3. Large subrounded aggregate of glass, found during dissection of Core Tube No. 2 (sample 04,0). Scale in centimeters indicates approximate depth below lunar surface. Note contrast in size with fine texture of matrix. [NASA photo S-69-45536]

The contrast between lunar and terrestrial surface environments and resulting characteristics of surficial deposits may be expressed through comparison of the Apollo-11 cores with analogous terrestrial materials, especially soil profiles.

Geologically, weathering profiles are a primary criterion for establishing relative chronologies in Quaternary deposits, and—if recognizable—eventually could be of similar use on the moon (*5*). Absence of such profiles is as important as their presence, for macroscopic comparison of morphology of the cores with terrestrial soil profiles permits a qualitative estimate of the relative importance and nature of weathering or alteration processes affecting lunar surficial deposits.

Pedologically, the terrestrial weathering environment has been summarized by Jenny's (*6*) classic formula expressing the relationship between the solum and soil-forming factors acting upon it:

$$S = f\ (cl, o, r, p, t, \ldots)$$

where S = soil and the independent variables recognized are climate (cl), organisms (o), relief (r), parent material (p), and time (t). Absence of any trace of organic life in Apollo-11 samples eliminates organic influence as a factor in the lunar surficial environment. Similarly, the lack of an effective atmosphere to serve as a variable dispersing medium for insolation and moisture reduces climate for any particular spot on the lunar surface to a constant range of diurnal temperature extremes. Thus relief, parent material and time clearly are the factors in the terrestrial equation having effective variability on the lunar surface.

Even lacking the terrestrial influences of climate and organisms, development of alteration profiles or zonation of sediments on the lunar surface is expectable as a result of at least the following agencies: (i) mixing, with other lunar or extralunar materials; (ii) bombardment by radiation and by atomic particles as well as by meteorites; and (iii) gravity movement. Cosmic ray and atomic bombardment may provide alteration profiles not macroscopically evident (none were recognized in these cores), and gravity movement probably is a dependent rather than independent process. But because Apollo-11 cores (and, more recently, those of Apollo 12) (*7*) display layering, mixing, and evidence of bombardment, recognition of these characteristics permits construction of a revised formula to express environmental factors which influence lunar surficial debris:

$$R = f\ (cl, p, r, t, a, b, \ldots)$$

in which R = regolith and the new variables introduced are accumulation (a) and bombardment (b). Because climate (cl) is essentially constant, the time (t)-dependent, mechanical processes of bombardment and accumulation assume significance unparalleled on earth because of their effects on parent material (p) and relief (r). Thus, in contrast to earth, lunar alteration processes are primarily mechanical rather than chemical.

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Spectral Reflectivity of Lunar Samples

Abstract. *Twelve rock chips and two samples of fines all have electronic absorption bands in diffuse reflected light between 0.32 and 2.5 micrometers. Major bands occur between 0.94 and 1.00 micrometer and at 2.0 micrometers, and arise from Fe^{2+} in clinopyroxene and to a lesser extent in olivine. A band at 0.95 micrometer and other details of curve slope and shape for the lunar surface fines match McCord's telescopic curve for an 18-kilometer area that includes the Apollo-11 site. Results confirm mineralogical predictions based on telescopic data and support the feasibility of obtaining mineralogical information by remote reflectivity measurements.*

Our investigation had the following objectives: (i) To search for electronic or other absorption bands in the visible and near-infrared portions of the spectrum and to relate any bands to the mineralogy of the samples; (ii) to investigate parameters other than mineralogy that might affect the frequencies or depths of bands; and (iii) to relate laboratory spectra and sample mineralogy to earth-based telescopic spectra of the moon and to evaluate the feasibility of obtaining mineralogical information by remote reflectivity measurements.

The basis for interpretation of absorption bands in silicates between 0.3 and 2.5 μm was developed through the application of crystal field theory to mineralogy (*1*). Transmission spectra of single oriented crystals, with polarized light, have led to further refinements in band assignments (*2*). Electronic bands are produced by transition elements, notably iron, in various valence and coordination states. Band frequencies are sensitive to distortion of *d*-orbital shells of transition metals by neighboring anions. Because metal-oxygen distances differ for most minerals, the absorption band frequencies can be used for identification of minerals that exhibit bands.

Absorption bands also appear in diffuse reflectance spectra of minerals and their powders. The feasibility of making mineral identifications based on reflectivity curves of minerals and rocks has been discussed (*3*). Interpretations of bands in lunar and planetary reflectivity curves have been made on the basis of the above arguments (*3, 4*). The reflectivity measurements of the lunar samples provide the first opportunity to test the validity of mineralogical interpretations that were based on reported absorption bands in the telescopic curves. Major uncertainties have been whether the lunar surface has been altered in an unknown way and whether the lunar reflectivity curves can be correctly interpreted in terms of terrestrial mineral and rock curves.

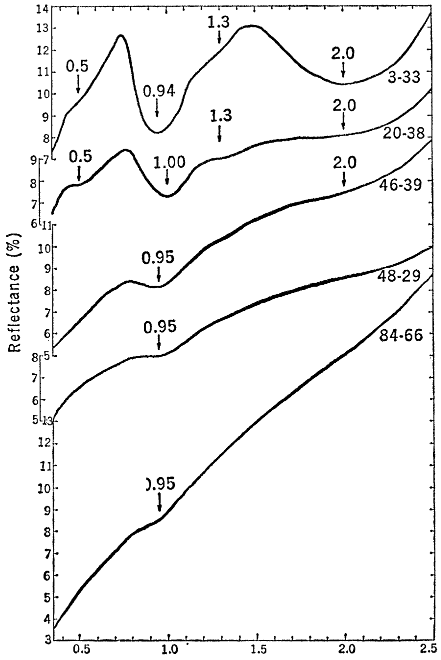

Fig. 1. Spectral reflectance curves of Apollo-11 lunar samples. The reference is MgO. Samples 3-33 and 20-38 are crystalline rocks; 46-39 and 48-29 are breccias; 84-66 is surface fines.

We made reflectivity measurements of type A, crystalline rock containing olivine; type B, crystalline rock without olivine; type C, breccia (two samples); and type D, surface fines (two samples) (*5*). Each sample of rock and of breccia consisted of three chips taken from the top, interior, and bottom parts. One sample of fines was packaged in a vacuum container. All other samples were kept in an N_2 atmosphere except for a small fraction of fines that was deliberately exposed to air.

Two spectroreflectometers were used, a Cary-14 RI and a Beckman DK-2A. The instruments and the measurement procedures will be discussed elsewhere (*6*). Both instruments employ MgO-lined integrating spheres. Freshly smoked MgO and sandblasted gold were used as reflectivity standards.

Broad absorption bands occur in the diffuse reflectance spectra of all of the lunar samples investigated. There are significant differences in band frequencies and band depths among the samples. All observed bands are attributed to electronic transitions in iron and titanium. No vibrational bands were observed. Conspicuously absent are the OH^- or H_2O bands at 1.4 and 1.9 μm that occur in many terrestrial minerals and rocks.

Sample 3-33 illustrates the simplest type of curve (Fig. 1) in which the two main bands, one at 0.94 μm and the other at 2.0 μm, are contributed by Fe^{2+} in the clinopyroxene. The curve is generally similar to published polarized absorption spectra and diffuse reflectance spectra of orthopyroxenes (*2*). However, the band positions and the detailed shape of the curve are virtually identical with unpublished curves (*7*) of pigeonite concentrates from some basaltic achondrites, Pasamonte, for example.

The Pasamonte sample and other achondrites have the two absorption bands shifted to slightly longer wavelengths from the orthopyroxenes. Adams (*8*) found that there is a progressive shift to longer wavelengths of the two orthopyroxene bands as composition changes toward pigeonite and diopside. The lunar sample bands at 0.94 and 2.0 μm are here assigned to Fe^{2+} in sixfold coordination, with the splitting resulting from the distorted octahedral site, as occurs in orthopyroxenes. The shift of the bands to slightly longer wavelengths relative to orthopyroxene is ascribed to minor Ca^{2+} in the pyroxene lattice, which re-