References and Notes

1. For original location of the samples at Tranquillity Base, see Fig. 3-16 of E. M. Shoemaker *et al.*, in *Apollo 11 Preliminary Science Report*, NASA, SP-214 (1969), p. 52.
2. Color notations follow the system of *Munsell Soil Color Charts* (Munsell Color Co., Baltimore, 1954).
3. The Lunar Sample Preliminary Examination Team, *Science* **165**, 1211 (1969).
4. E. C. T. Chao, C. Frondel, R. E. Wilcox, personal communication (1969).
5. Geology Group Report, in *NASA 1965 Summer Conference on Lunar Exploration and Science*, NASA SP-88 (1965), pp. 95–98.
6. H. Jenny, *Factors of Soil Formation* (McGraw-Hill, New York, 1941), pp. 1–19, especially p. 16.
7. The Lunar Sample Preliminary Examination Team, *Science*, in press.
8. We thank T. H. Foss, C. Frondel, J. Lindsay, and R. E. Wilcox for helpful discussions or for critical review of the manuscript.

4 January 1970

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.

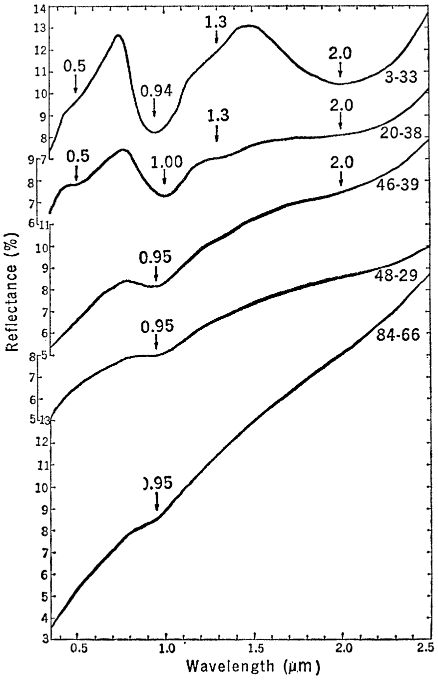

Fig. 1. Spectral reflectance curves of Apollo-11 lunar samples. The reference is MgO. Samples 3-33 and 20-38 are crystalline rocks; 46-39 and 48-29 are breccias; 84-66 is surface fines.

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 requires an adjustment of Fe-O bond distances on the octahedral sites.

The reflectivity curve for sample 3-33 also shows a faint (<5 percent) band at 0.5 μm and a flattening of the curve at 1.3 μm. These structures occur at frequencies that correspond to titanium in the pyroxene. The shallowness of the bands suggests that TiO_2 comprises less than 1 percent of the pyroxene. The curve shows no evidence for chromium.

Sample 3-33 is a useful reference for the interpretation of bands in other lunar materials because it contains essentially no olivine or glass. The other major minerals present, plagioclase and ilmenite, do not contribute any measurable band structure to the rock curve.

Sample 20-38 differs mineralogically from sample 3-33 in that the pyroxene appears to be richer in Ca and minor olivine is present. Olivine alone has a single strong absorption band at 1.03 μm that arises from Fe^{2+} in sixfold coordination. In the curve for sample 20-38 (Fig. 1) the band at 1.00 μm is attributed to a combination band representing the unresolved pyroxene and olivine bands. The band at 2.0 μm is assigned to the pyroxene, because olivine has no selective absorption in this wavelength region. The clinopyroxene alone may have a band between 0.94 and 1.00 μm due to the increased Ca; however, it has not been possible to verify this band frequency without access to a separate pyroxene concentrate. A more calcic pyroxene would also explain the weaker band at 2.0 μm in this sample. The curves for sample 20-38 also show an enhancement of the titanium bands at 0.5 and 1.3 μm, implying a higher TiO_2 content in the pyroxene.

The samples of fines and breccias also contain pyroxene and traces of olivine, but less olivine than sample 20-38. The fines and breccias show a weak (<5 percent) band at approximately 0.95 μm and only a faint suggestion of a dip near 2 μm (Fig. 1). The band at 0.95 μm is consistent with the observed proportions of pyroxene and olivine and does not require the presence of other minerals. The virtual disappearance of the 2.0-μm band in the fines and breccias is related to the overall darkness of these materials and to a smaller pyroxene content.

The fines and breccias are darker, have shallower absorption bands, and have steeper overall curves than the crystalline rocks. We attribute these features to the presence of the dark red-brown glass. Although the glass selectively absorbs shorter wavelengths, it does not contribute measurable band structure in the lunar materials. We suggest that the pigmentation in the glass is iron and titanium that was derived largely from ilmenite through melting, probably by impact, of the crystalline rock. The decrease in reflectivity from crystalline rock to glass-rich rock or fines can be explained by more efficient use of the available metal ions as light absorbers. In the oxide form, ferrous iron absorbs nearly all incident light in the outer 5 μm of a mineral grain; hence the interior portion of an ilmenite grain does not further attenuate light. If, however, the ilmenite grain is dissolved in a silicate melt, there is greater opportunity for light absorption by each iron or titanium ion.

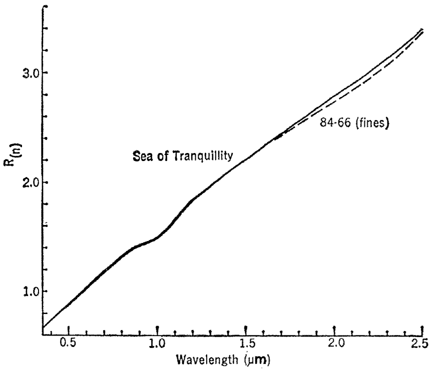

Fig. 2. Comparison of McCord's telescopic curve for an 18-km area that includes the Apollo-11 site with the curve for sample 84-66, surface fines. $R_{(n)}$, normalized reflectance.

Microbrecciation of mineral grains (presumably by impact shock) is observed on the surfaces of many of the Apollo-11 rocks. Microfractured silicate minerals reflect more light than undisturbed grains. Each fracture is an optical discontinuity with the potential of reflecting incident light. The effects of microbrecciation are closely analogous to the increase in reflectivity that results from grinding silicate minerals to smaller particle sizes (*9*). Comparison of reflectivity measurements of outside and of interior surfaces of the lunar samples shows that, although microbrecciated surfaces have up to a 30 percent higher reflectivity, there is no change in the frequency of any of the absorption bands. This observation is in agreement with theory, because the band frequencies are determined by Fe-O bond distances which in turn are little affected by mechanical deformation on a scale larger than the unit cell.

More extreme shock leads to vitrification of mineral grains, and it is expected that absorption bands will shift in frequency when new metal-oxygen bonds are formed. In the samples observed glass-lined pits covered too small an area and the glass was too dark to yield a definitive measurement of any new absorption bands. We observed that absorption-band frequencies are unaffected by the presence of glass-lined pits or microbrecciated zones on the surfaces of the Apollo-11 rocks.

We have found no evidence for metal coatings or other deposits (other than glass) on the surfaces of mineral grains. If such coatings are present, they are not thick enough to cause a measurable attenuation of light and can be disregarded for purposes of interpreting mineral absorption bands.

Reflectivity measurements also were made of surface fines in vacuum, in N_2, and in air to test for possible changes arising from removal of the samples from the lunar environment. No differences in reflectivity were observed between 87-13 in vacuum and 84-66 which had been exposed to dry nitrogen. In addition, 0.5 g of 84-66 was exposed to air for 3 hours at 25°C. No departures from the previous reflectivity measurements were noted.

We have compared the laboratory reflectivity curves of the Apollo-11 rocks with earth-based telescopic measurements of the landing site (*10*). The reflectivity curve for an 18-km area that includes the Apollo-11 site agrees very closely with the laboratory curve for the bulk surface fines (Fig. 2). We conclude that: (i) Sample 84-66 (fines) appears to be representative of the main lunar surface material for at least tens of kilometers around the Apollo-11 site. (ii) Crystalline rocks are not abundant enough at and around this site to impose the pyroxene double-band structures on the telescopic reflectivity curves. (iii) The single weak band at 0.95 μm in the telescopic curve is the clinopyroxene-olivine combination band. The telescopic curves, therefore, are recording mineralogical information. Earlier predictions (*3*) of mineralogy based on a reported band near 1 μm for the Sea of Tranquillity are generally substantiated. (iv) The low albedo of the Sea of Tranquillity, the steepness of the reflectivity curve, and the weakness of the absorption-band structure can now be accounted for by the presence of glass rich in iron and titanium. (v) Interpretation of telescopic curves for other parts of the moon can be expected to yield information on areal differences in mineralogy and in glass content.

JOHN B. ADAMS
Caribbean Research Institute,
College of the Virgin Islands,
St. Croix 00820

ROBERT L. JONES
Manned Spacecraft Center,
Houston, Texas 77058

References and Notes

1. W. B. White and K. L. Keester, *Amer. Mineralogist* **51**, 774 (1966); R. G. Burns and W. S. Fyfe, in *Researches in Geochemistry*, P. H. Abelson, Ed. (Wiley, New York, 1967), vol. 2, p. 259.
2. G. M. Bancroft and R. G. Burns, *Amer. Minerologist* **52**, 1278 (1967); W. B. White and K. L. Keester, *ibid.*, p. 1508.
3. J. B. Adams, *Science* **159**, 1453 (1968).
4. T. B. McCord and J. B. Adams, *ibid.* **163**, 1058 (1969); J. B. Adams and T. B. McCord, *J. Geophys. Res.* **74**, 4851 (1969); D. P. Cruikshank, *Science* **166**, 215 (1969).
5. Lunar Sample Preliminary Examination Team, *Science* **165**, 1211 (1969).
6. J. B. Adams and R. L. Jones, *Geochim. Cosmochim. Acta*, in press.
7. J. B. Adams and L. T. Silver, in preparation.
8. J. B. Adams, in preparation.
9. J. B. Adams and A. L. Filice, *J. Geophys. Res.* **72**, 5705 (1967).
10. See also T. B. McCord, T. V. Johnson, H. H. Kieffer, *ibid.* **74**, 4385 (1969).
11. Supported by NASA (NAS 9-9578). We thank J. Larsen for his assistance, and Dr. T. McCord for new telescopic data in advance of publication.

5 January 1970

Apollo 11 Soil Mechanics Investigation

Abstract. *The fine-grained surface material at the Apollo 11 landing site is a brownish, medium-gray, slightly cohesive granular soil, with bulky grains in the silt-to-fine-sand range, having a specific gravity of 3.1 and exhibiting adhesive characteristics. Within the upper few centimeters, the lunar soil has an average density of about 1.6 grams per cubic centimeter and is similar in appearance and behavior to the soils studied at the Surveyor equatorial landing sites. Although considerably different in composition and in range of particle shapes, it is similar in its mechanical behavior to terrestrial soils of the same grain size distribution.*

The upper few centimeters of surface material in the vicinity of Tranquillity Base consist of a brownish, medium-gray, slightly cohesive granular soil largely composed of bulky grains in the silt-to-fine sand size range. Angular-to-subrounded rock fragments ranging up to 1 m in size are distributed throughout the area. Some of these fragments are lying on the surface, some are partly buried, and others are barely exposed.

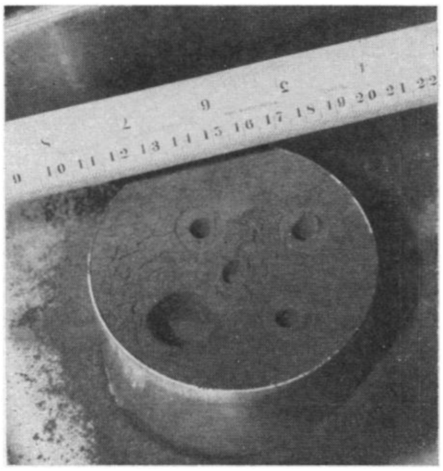

Fig. 1. Penetration of loosely placed lunar soil sample at the nitrogen cabinets of the LRL Biological Preparation Laboratory. [LRL photo S-69-47484]

The soil grains vary in shape from blocky angular with smooth plane surfaces to completely spherical; some of the larger particles are vesicular. No shards, needles, or filaments have been observed. A large portion of the soil grains consists primarily of glasses, with chemical composition covering a wide range. The color of these particles varies from clear, to dark reddish-brown, to dark gray.

The grain size distribution of fine-grained material collected with the documented sample, the core tubes, and the bulk sample was found, in all cases, to be that of a silty fine sand. However, aggregation of individual particles may have biased the analyses toward the large size range.

The following observations and measurements were made (*1*, *2*) on lunar soil samples placed in the nitrogen cabinets of the Lunar Receiving Laboratory's Biological Preparation Laboratory at room temperature and at normal atmospheric pressure.

1) Visual examination of core-tube soil samples 10004 and 10005 revealed that the soil was remarkably uniform in color and texture; fine reflecting surfaces over about 10 percent of the area produced a sparkling appearance. There was no variation in structure with length along the samples, although there was a very slight color difference between the upper and lower halves of sample 10004; however, probing indicated no discernible differences in mechanical properties. Sample 10005 contained numerous small cracks and voids. Its average bulk density, not taking into account the voids and cracks, was about 1.66 g/cm^3, as compared with 1.54 g/cm^3 for sample 10004.

2) The specific gravity of the soil in the core tubes was found to be 3.1, as measured by a gas comparison pycnometer. This is considerably higher than the typical value of 2.7 for terrestrial soils and may be attributable to the fact that the lunar soil is composed mainly of the basic igneous minerals (for example, plagioclase, olivine, and pyroxene), as well as relatively large amounts of titanium and iron oxides.

3) On the basis of the specific gravity and bulk-density measurements, the void ratios of the core-tube samples were found to be 1.01 and 0.87. The respective porosities are 50.1 and 46.5 percent. It should be noted that the core bit of both core samplers was flared inward at 15°, the reverse of the direction for most terrestrial samplers. Thus, the soil was probably deformed considerably during sampling, and the measured bulk densities and porosities may not necessarily be indicative of the bulk density and porosity of the undisturbed lunar soil.

4) The bulk density of bulk sample material finer than 1 mm, placed as loosely as possible in a container, was determined to be 1.36 g/cm^3, corresponding to a void ratio of 1.28 and a porosity of 56 percent. Under the 1/6-*g* lunar gravity, the adhesive forces between the particles would probably

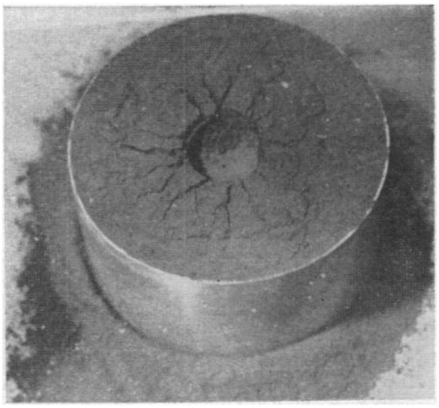

Fig. 2. Penetration of compacted lunar soil sample at the nitrogen cabinets of the LRL Biological Preparation Laboratory. [LRL photo S-69-47489]