Millimeter Petrology and Kilometer Mineralogical Exploration of the Moon

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Coordinated petrologic and spectroscopic analyses were undertaken for a specially prepared 1-cm chip of regolith breccia 60019. The mineralogy of several large clasts (>1 mm) and matrix areas of this sample were analyzed in thin section. The mafic minerals of each large clast were readily identified from spectral reflectance measurements of the same clasts, and mineral abundance was shown to be directly related to absorption strength. Although most clasts of 60019 are noritic in composition, the presence of abundant olivine and/or high-Ca pyroxene in several clasts is easily noted spectroscopically, based on the wavelength and strength of absorption bands near 1 and 2 µm. The origin of an unusual absorption feature near 0.6 µm in an anorthositic clast was determined by petrographic analysis to be due to very fine-grained translucent ilmenite. The 60019 matrix is dark and glassy, and although a variety of clasts occur on all scales, particulate powders of 60019 are all very similar and have spectral properties that indicate a noritic breccia bulk composition. The spectral homogeneity of different powders from this complex regolith breccia indicates that the variety of distinct lithologies inferred from remote spectroscopic measurement of unsampled sites across the Moon must reflect basic variations in local rock types.

INTRODUCTION

Although a great deal of progress has been made over the last decade using remote sensors to identify the mineral composition of unexplored lunar areas, no global assessment of the composition of the Moon and its resources has yet been undertaken. Furthermore, it is becoming increasingly apparent from both the remote measurements (e.g., Pieters, 1978, 1986; Lucey et al., 1986; Lucey and Hauke, 1988) and analysis of the "pristine" lunar samples (e.g., Warren, 1985) that the bulk of returned lunar samples do not necessarily represent the lunar crust as a whole and that lunar crustal evolution is far more complex than originally envisioned at the close of the Apollo program. In a new era of exploration anticipated over the next decade, an accurate assessment of surface composition is a top priority for global exploration of the Moon (Phillips et al., 1986). Such information is crucial for understanding the evolution of the Moon, and ultimately bears on such questions as the origin of the Moon and its early relation to Earth.

Reflectance spectroscopy is a primary tool for remote analysis of surface mineralogy. Its success depends on the accurate interpretation of absorption features at visible and near-infrared wavelengths observed in spectra of (solar) radiation reflected from the surface. Most diagnostic absorption bands observed in lunar spectra are due to the splitting of d-orbital energy levels of transition metal ions in a crystal structure (Burns, 1970; White and Koester, 1966, 1967). The energy (wavelength) of an absorption is determined by the type of ions involved and the specific crystal structure. For common rock-forming minerals the combination of a well-defined crystal structure and possible compositions result in unique absorptions, whose wavelength positions exhibit observed and predictable trends. Since spectral properties of many minerals have also been empirically determined through laboratory measurements (e.g., Adams, 1975), absorption features observed in a reflectance spectrum of an unknown material often provide direct information on its constituent minerals.

Most near-infrared absorption bands for lunar minerals are broad, and a spectrum of a rock or soil usually contains several superimposed features. Interpretation is complicated by the fact that both physical and chemical alteration processes of surface material superimpose additional scattering or absorption characteristics on the resulting spectrum of reflected radiation. These additional characteristics not only make it more difficult to detect individual absorption features, but they also strongly affect estimations of modal mineral abundance. The combination of spectral properties of minerals in a mixture is a nonlinear process, and the desired deconvolution of individual mineral components from a spectrum of a mixture requires analytical modeling and testing with controlled laboratory data (e.g., Johnson et al., 1983; Cloutis et al., 1986; Clark and Roush, 1984; Smith et al., 1985; Mustard and Pieters, 1987a; Crown and Pieters, 1988; J. F. Mustard and C. M. Pieters, in preparation; R. N. Clark, K. S. Kiefer, and G. A. Swayze, in preparation).

Since the physical properties and alteration products of a planetary surface are strongly a function of surface evolution determined by the local space environment, some aspects of interpretative analysis must be tailored to the specific planetary environment. This is particularly true for mixtures of lunar materials. Lunar materials are unique in several important ways:
They are anhydrous and very reduced (e.g., no Fe$^{3+}$), and they are continually exposed to a space-weathering environment. Some of the more easily identified lunar alteration products are the complex glass welded aggregates, called agglutinates, which occur in lunar regoliths and contain the cumulative effects of comminution, brecciation, shock, radiation, sputtering, melting, recrystallization, reduction, mixing, etc. Dark agglutinates strongly influence the spectral character of a well-developed lunar soil (Adams and McCord, 1971, 1973), but the dominant effects from individual space-weathering processes have not been clearly separated (see overview in Pieters, 1978, 1986). The most prominent mineral absorption bands are observed in spectra of freshly exposed lunar surfaces, such as at craters or steeply sloped mountains.

Although the application of reflectance spectroscopy has been successful for targeted areas on the Moon, to achieve the more ambitious goals of global assessment of modal mineralogy of the surface at high spatial resolution using reflectance spectroscopy, there are several requirements for a solid interpretative base. First, the nature and variety of lunar materials must be well documented (spectroscopically and petrographically). Soils have been relatively well studied, but only minor amounts of spectral information has been obtained for well-characterized lunar mineral separates (Adams and McCord, 1971, 1973) and scant coordination between petrographic analyses and spectroscopy of multicomponent lunar rocks. Second, the manner in which lunar rocks, minerals, and alteration products mix to form natural lunar surfaces needs to be modeled and tested for accuracy in spectral deconvolution. This is the more difficult task, particularly because of the physically and compositionally complex lunar alteration products.

In order to develop the foundation necessary for quantitative interpretation of reflectance spectra of the unexplored lunar surface, an analysis program has been instigated to coordinate petrologic and spectroscopic studies of lunar materials. Reported here are results of an initial study of a complex lunar regolith breccia (60019) that has been specially prepared to allow individual clasts as well as the matrix to be analyzed spectroscopically and petrologically. This sample was chosen because it displayed a variety of different clasts, and as a regolith breccia it might provide insight into the relation between local rock types and regoliths observed remotely.

### LUNAR SPECTROSCOPY (BACKGROUND)

Pyroxenes (both high- and low-Ca), olivine, and plagioclase have been identified from spectral analysis of lunar materials both in the laboratory (e.g., Adams and McCord, 1971) and remotely (e.g., McCord et al., 1981). A brief sampling of laboratory and remote spectroscopic measurements of lunar materials is presented here in order to provide a context for the data from 60019. Laboratory spectra of particulate lunar mineral separates, rocks and soils are shown in Fig. 1. These spectra illustrate several characteristic aspects of lunar spectroscopy. First, spectra for both highland and mare materials are dominated by absorption features due to the presence of mafic minerals such as pyroxene. The composition of these pyroxenes can be identified by wavelength of their absorption bands (Adams, 1974; Hazen et al., 1978). Low-Ca orthopyroxene exhibits bands at wavelengths between 0.9 and 0.93 μm (e.g., the orthopyroxene separate of 78235) and is the dominant mafic mineral of most highland rock types (such as 67455), whereas high-Ca pyroxene (e.g., clinopyroxene separate from 12063) exhibits bands at longer wavelengths (0.97-1.00 μm) and is the major mafic mineral in mare basalts (such as 12063 whole rock). Second, even though the regolith formation process darkens and substantially reduces the absorption bands of soils (both 12070 and 62231 contain >50% agglutinates), the weak residual absorption bands nevertheless reflect the composition of the major mafic mineral present (Fig. 1c). Trace amounts of a strongly absorbing mineral species can affect the spectral character of more transparent material disproportionately. For example, the broad three-component multiple-absorption band near 1.05 μm for olivine (72415 separate) is characteristic of olivine (Adams, 1975), but the weak broad band observed near 2 μm in the same spectrum is not due to the olivine but to tiny trace amounts of translucent chrome spinel (C. M. Pieters, unpublished spectra, 1988), which occurs throughout this pristine rock (Bell et al., 1975; Dymek, 1975).
Fig. 1. Laboratory reflectance measurements of lunar materials. (a) Lunar mineral separates: anorthosite (from 15415), olivine (from 72415), orthopyroxene (from 78235), and clinopyroxene (from 12063). Vertical lines are drawn at 0.9 and 1.1 \( \mu \text{m} \) to allow easy comparison of absorption band centers in subsequent figures. (b) Typical lunar rock powders (67455 and 12063) and mature soils (62231 and 12070) from Apollo 16 (highland) and Apollo 12 (mare). Lunar soils are darker than local rock types and exhibit weaker absorption bands. (c) Residual absorption features near 1 \( \mu \text{m} \) for mature lunar soils 12070 and 62231. A continuum was estimated as a straight line tangent to the reflectance spectra of (b); the reflectance spectrum was divided by the continuum to produce these residual absorption spectra. The character of the absorption features are similar to, but weaker than, the local rock type, implying the type of mafic minerals are the same.

The laboratory measurements (both spectroscopic and petrologic) are of course made on millimeter-to-centimeter scale samples, whereas remote measurements of the lunar surface are made on the scale of a few kilometers. Shown in Figs. 2 and 3 are reflectance spectra obtained using earth-based telescopes (from Pieters, 1986) presented as examples of what is observed over large regions of unexplored lunar areas. The spectra in Fig. 2 are typical of small fresh highland craters (<10 km) or mountains and are representative of the upper 1-2 km of lunar highland crust, or the megaregolith. Pyroxene abundance clearly varies from area to area (strength of 0.9-1.1 \( \mu \text{m} \) band), but the dominant lithology is inferred to be noritic (low-Ca pyroxene + plagioclase) in composition from these spectra. Examples of material excavated from deeper within the highland crust are shown in Fig. 3. These spectra are for several central peaks of large impact craters and represent crustal material uplifted from 5-10 km in depth. The inferred composition of the dominant lithology forming these mountains (see Pieters, 1986) is as follows: Petavius = shocked anorthosite (plagioclase with no mafics); Arzachel = noritic anorthosite (plagioclase with low-Ca pyroxene); Copernicus = troctolite (plagioclase with olivine, no pyroxene); Tycho = gabbronorite (plagioclase with only high-Ca pyroxene). The diversity of these deep-seated crustal materials provides a glimpse of the range of rock types that make up large portions of the Moon. A long-term objective in lunar exploration, however, is to not only identify minerals present at such unexplored lunar areas, but ultimately to access the global composition and resources of the Moon.

**SAMPLE DESCRIPTION**

Three contiguous samples were prepared from a small 1-cm chip of 60019: a potted butt (60019.1914), a central thin section (60019.219), and a slab 1 mm thick (60019.215). The two sides (E2 and W2) of the slab are shown in Fig. 4. Direct coordination of thin-section petrology could be made with spectra of the (E2) slab face. Transmitted light images of thin section 60019.219 are shown in Fig. 5a. The scale bar on all figures is 1 mm.) Clasts and areas analyzed by both techniques are indicated on these figures. After spectroscopic measurements, a large section of the W2 face was polished for petrologic studies and two small subsections (indicated with dashed lines in Fig. 6) were later also prepared for thin-section
analyses, the larger of which is shown in transmitted light in Fig. 5b. Four separate small chips (#2, 8, 37, 312) were broken from the slab and prepared as a bulk powder (≤500 µm) for spectroscopic analysis. A sketch map of 60019,215 showing the locations of these samples is shown in Fig. 6.

**TECHNIQUES**

**Petrology**

Electron microprobe analyses were made with an ARLEMX microprobe using crystal spectrometers. Focused beam analyses were used for mafic silicates and plagioclase. Data were corrected by the Bence-Albee technique. Standards for olivine and pyroxenes were an aluminous augite (A209) for Si, Ti, Al, Fe, Mg, and Ca; and a synthetic diopside for Mn and Cr. Standards for plagioclase analyses were a synthetic anorthite for Si, Al, and Ca; orthoclase for K; albite for Na; and A209

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**Fig. 3.** Reflectance spectra of the deep-seated material forming central peaks of large impact craters (50-100 km in diameter) obtained using earth-based telescopes (from Pieters, 1986). Spectra on the top are scaled to unity at 1.02 µm and offset vertically for clarity. Spectra on the bottom are residual absorption spectra obtained by dividing the spectrum by a straight line continuum and offset vertically for clarity. These spectra indicate an unexpected variety of rock types exist at 5-10 km depth within the lunar crust (see text).

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**Fig. 4.** The cut surfaces of slab 60019,215. Clasts for which spectroscopic measurements were obtained are indicated with arrows. Spectra were obtained for circular areas approximately 1 mm in diameter centered on the clast indicated. Individual matrix areas measured are indicated with a circle on the surface of the slab and labeled on the side. Areas measured within clast G5 are shown in a similar fashion. The scale bar is 1 mm. (a) The E2 face. (b) The W2 face. Breccia clasts G5 and R3 are outlined with a heavy line.
all lunar materials were obtained using the Reflectance Experiment Laboratory (RELAB), a multisizer facility supported by NASA at Brown University. Viewing geometry for these bidirectional measurements was set at \( i = 30^\circ, e = 0^\circ \). Sampling resolution was 5 nm from 0.35 to 2.60 \( \mu \)m. The area for which each spectrum was obtained was chosen using spectrometer optics that provide direct viewing of the sample; the measured area extends approximately 1 mm in diameter. All spectra were obtained relative to Halon and corrected using NBS calibrations (Weidner and Hsia, 1981). Spectra were obtained for three forms of samples, all areas of which were \( \sim \)1 mm in diameter: spectra for cut surfaces on slab .215 (indicated with an s on figures), spectra for edges or broken surfaces of .215 (indicated with a b on figures), and particulate samples (<500 \( \mu \)m) prepared from individual chips of .215 after slab spectra were obtained.

**PETROLOGY**

Clasts A, B, D, and G were studied in thin section .219, which is coordinated with the E2 face of .215. Clasts G1, G2, G3, and G5 were studied on the W2 face of slab .215 after it was polished for petrologic study. The limitations of using reflected light only for petrologic analyses originally led to erroneous estimates of mineral abundances for clasts G2 and G5 and prompted the preparation of additional thin sections. The section containing the upper part of clast G5 also contains areas R1, R2, and S3 matrix and R3 clast (see Fig. 5b).

Petrologic data are summarized in Table 1. Although the concentrations of minor elements in all mafic silicate phases were measured, only the abundances of the end members are reported, because there was little variation from clast to clast in the abundances of Al, Ti, Cr, or Mn in a given mineral.

**Spectroscopy**

Except for the two soil measurements (62231 and 12070) obtained by J. B. Adams using a Beckman directional hemispheric diffusing sphere, spectral reflectance measurements of augite for Fe. We analyzed 5-10 grains of each mineral in each clast to obtain average compositions. Bulk compositions were done using a broad beam (100 microns) and the technique described by Lux et al. (1980).

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**Fig. 5.** Transmitted light images of 60019 thin sections. (a) Section .219. This section is coordinated with the E2 face of .215. (b) Special section prepared from a chip of the W2 face of .215 containing areas r1, r2, S2, S3, and clast R3 (see Fig. 6 for location).

**Fig. 6.** Sketch map of 60019.215 showing the location of chips analyzed as powder or special thin section.
TABLE 1. Modal and mineral data for clasts in 60019.

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>D</th>
<th>G</th>
<th>G1</th>
<th>G2</th>
<th>G3</th>
<th>R3</th>
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<td>15.2</td>
<td>4.3</td>
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<td>3.2</td>
<td>3.2</td>
<td>3.2</td>
<td>3.2</td>
<td>3.2</td>
<td>3.2</td>
<td>3.2</td>
</tr>
<tr>
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<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
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<td>3.2</td>
<td>3.2</td>
<td>3.2</td>
<td>3.2</td>
<td>3.2</td>
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Olive compositions (mol.%)  

<table>
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<th>Fa</th>
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<tr>
<td>Augite</td>
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<tr>
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<td>11.2</td>
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Ca pyroxene compositions (mol.%)  

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<th></th>
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<th>En</th>
<th>Fs</th>
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<td>11.9</td>
</tr>
<tr>
<td>Olig.</td>
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<td>44.8</td>
<td>11.9</td>
</tr>
<tr>
<td>Augite</td>
<td>43.2</td>
<td>44.8</td>
<td>11.9</td>
</tr>
<tr>
<td>Other</td>
<td>43.2</td>
<td>44.8</td>
<td>11.9</td>
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</table>

TABLE 2. Broad beam electron microprobe analyses of pinkish clasts and matrix in 60019.

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<tr>
<th></th>
<th>R3</th>
<th>R1</th>
<th>R2</th>
<th>S3</th>
<th>Matrix*</th>
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<tr>
<td>SiO₂</td>
<td>43.5</td>
<td>45.0</td>
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<tr>
<td>TiO₂</td>
<td>0.4</td>
<td>0.54</td>
<td>0.69</td>
<td>0.72</td>
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<tr>
<td>Al₂O₃</td>
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<td>25.2</td>
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<td>Cr₂O₃</td>
<td>0.09</td>
<td>0.13</td>
<td>0.11</td>
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<td>4.8</td>
<td>4.1</td>
<td>5.3</td>
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<tr>
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<td>0.04</td>
<td>0.03</td>
<td>0.04</td>
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</tr>
<tr>
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<td>7.0</td>
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<td>6.7</td>
</tr>
<tr>
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<td>0.10</td>
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</tr>
<tr>
<td>Na₂O</td>
<td>0.44</td>
<td>0.43</td>
<td>0.33</td>
<td>0.51</td>
<td>0.46</td>
</tr>
<tr>
<td>Total</td>
<td>95.98</td>
<td>96.54</td>
<td>97.26</td>
<td>98.50</td>
<td>99.61</td>
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</table>

Matrix analysis (Rose et al., 1975).

TABLE 3. Mass of 215 chips prepared as powdered samples.

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<tr>
<th>Chip #</th>
<th>Mass (mg)</th>
<th>Large Clasts</th>
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<tbody>
<tr>
<td>2</td>
<td>312</td>
<td>G</td>
</tr>
<tr>
<td>8</td>
<td>37</td>
<td>G1, G2, G3, B</td>
</tr>
<tr>
<td>312</td>
<td>5</td>
<td>G5</td>
</tr>
</tbody>
</table>

Consequently, differences in clast spectra are probably not caused by these elements and are more directly linked to modal abundance of mafic minerals. Bulk compositions of areas R1 and R2 (in clast G5), clast R3, matrix area S3, and typical 60019 matrix are listed in Table 2; slightly low totals are due to the presence of voids in the thin section.

Clast A

Clast A appears to be a troctolite impact melt. It has a subophitic texture and consists mostly of blocky olivine (0.15 mm across) and lath-shaped plagioclase (most 0.05-0.1 mm in size). Small amounts of chromite occur inside olivine and MgAl spinel inside plagioclase. The mesostasis contains submicron-sized droplets of metal and sulfides.

Plagioclase compositions (mol.%)  

<table>
<thead>
<tr>
<th></th>
<th>Or</th>
<th>Ab</th>
<th>An</th>
<th>FeO (wt.%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plagi</td>
<td>0.3</td>
<td>3.8</td>
<td>95.9</td>
<td>0.21</td>
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<tr>
<td>Olig.</td>
<td>0.3</td>
<td>3.8</td>
<td>95.9</td>
<td>0.21</td>
</tr>
<tr>
<td>Augite</td>
<td>0.3</td>
<td>3.8</td>
<td>95.9</td>
<td>0.21</td>
</tr>
<tr>
<td>Other</td>
<td>0.3</td>
<td>3.8</td>
<td>95.9</td>
<td>0.21</td>
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</table>

Clast G

Clast G is a poikilitic impact melt breccia. Blocky plagioclase clasts occur in a groundmass of low-Ca pyroxene, lath-shaped plagioclase, and a small amount of mesostasis. The low-Ca pyroxene encloses much of the plagioclase.

Clast G1

Clast G1 has a fine-grained (crystals 25-50 µm across) granular texture. Besides plagioclase and mafic silicates, small amounts of ilmenite and metal are also present.

Clast G2

Clast G2 is a poikilitic impact melt. Clasts of olivine and both clasts and lath-shaped plagioclase are enclosed by low-Ca pyroxene. Plagioclase laths and mesostasis also occur between poikilitic pyroxene crystals.

Clast G3

Clast G3 appears to be an impact melt. Plagioclase and low-Ca pyroxene are equiaangular and 50-100 µm across. Some ilmenite and metal are also present.

Clasts G5 and R3

Clast G5 is itself a breccia and appears slightly pink on the slab face. It differs from typical 60019 matrix areas in having a substantial amount of impact-melt rock clasts that consists of quench-crystallized or devitrified feldspathic material (37 vol. % vs. <5 vol. % in other areas of 60019). In many areas,
including those designated r1, r2, and clast R3, fine-grained, lath-shaped plagioclase grains make up the matrix. A reddish glass occurs between the plagioclase laths, and small, brownish grains of another phase occur. The glass and the brownish phase are too small to analyze (micron-sized areas), though enrichments of Ti near the brownish grains suggest that they might be ilmenite or another titaniferous phase. Clast R3 also contains olivine fragments and small (a few microns across) grains of either olivine or another mafic silicate; these grains are too small to analyze quantitatively. The bulk compositions of clast R3 and areas r1 and r2 in clast G5 are similar to matrix 60019, although perhaps slightly richer in Al on average.

Matrix Areas

Typical matrix areas, such as M3, M4, and S3 contain mineral fragments (25-50%), rock clasts (25-50%), and brownish glass (15-25%). Some matrix areas such as M5 contain much greater abundances of rock clasts (75%). Our broad beam analysis of areas S3 is similar to an analysis of the 60019 matrix reported by Rose et al. (1975).

SPECTROSCOPY

Spectra for clasts, matrix, and powders of 60019.215 are shown in Figs. 7-12. The negatively sloped continuum (decrease of reflectance with wavelength) is typical for spectra of cut surfaces and is due to the physical form of the sample rather than any compositional property (e.g., Yon and Pieters, 1988). In the residual absorption spectra of Fig. 13, albedo and continuum effects have been removed from these clast spectra to allow the character of mineral absorption bands (center wavelength, strength, symmetry) to be examined and directly compared with known variations in their petrology. In most cases a clast filled the field of view of the spectrometer optics and no matrix material was included in the spectroscopic measurements of individual clasts, except for measurements of clasts D and F which contained small amounts of matrix (15-30%). The mass of chips made into particulate samples are presented in Table 3. The mass contributed by the large clasts to the powder is estimated to be ≤10 vol.% from a visual estimate of the chip in three dimensions.

Clast A

This clast was measured both as a cut surface on the slab (A in Fig. 7) as well as a broken surface on the side of .215 (G7 in Fig. 7). The large abundance of olivine is clearly evident in the spectrum as broad multiple absorption centered beyond 1.0 μm. The effects of minor amount of low-Ca pyroxene can be seen by the weak absorption near 1.9 μm and the distortion of the olivine band near 0.9 μm due to the presence of an additional pyroxene band.

Clast B

This clast (Fig. 8) exhibits a very weak feature near 1.0 μm, due to the small amount of high-Ca pyroxene present in this predominantly anorthositic clast. The broad feature near
0.6 µm is unusual and is thought to be due to the very fine-grained ilmenite of this clast. [For comparison, a small fine-grained feldspathic clast on a broken surface (G6 in Fig. 8) does not exhibit the 0.6-µm feature but contains features of low-Ca pyroxene in minor amounts.] Although ilmenite is normally opaque and does thus not impart absorption features in a silicate matrix, if it is sufficiently fine-grained to be translucent, it can produce features disproportionate to its abundance. The 0.6-µm feature in clast B is similar to an ilmenite feature observed for the black spheres (recrystallized orange glass) of Apollo 17 (Adams et al., 1975), which had similar translucent properties due to its unusual form of occurrence as thin plates within the spheres. The form of ilmenite in other samples is opaque and does not allow a detectable 0.6-µm band.

Clast D

When two pyroxenes are present in a sample, the bands cannot be visibly resolved in the spectrum and the resulting composite feature is indicative of the average pyroxene composition. Although the spectrum for clast D (Fig. 9) contains a small amount of surrounding matrix material, the weak pyroxene feature near 0.96 is a composite of features from the orthopyroxene, augite, and olivine components.

Clast G

Since the spectrum of this clast (Fig. 10) was obtained for a broken edge that may not have filled the full field of view, the absolute value of the reflectance is uncertain. The low-Ca orthopyroxene is nevertheless evident as the dominant mafic mineral from the short wavelengths of the pyroxene absorption bands (near 0.93 and 1.9 µm).

Clasts G1, G2, and G3

These three noritic clasts measured from the cut surface of the slab (Fig. 11) all exhibit the characteristic absorption bands of low-Ca pyroxene. Except when olivine is present, the strength of the absorption bands is a general indication of the pyroxene abundance (see Table 1). For G1 the weak 2-µm pyroxene band relative to the 1-µm band (e.g., Cloutis et al., 1986) and the long wavelength distortion of the 1-µm band is an indication of the significant amount of olivine also present.
in this clast with orthopyroxene. For G1, the strength and wavelength of the 1-μm absorption band results from a combination of the olivine and pyroxene grains present in the clast. The smaller olivine component present in clast G2 is not readily apparent in its spectrum, perhaps because in this case the olivine grains were seen to be enclosed by the more absorbing pyroxene. These diagnostic characteristics of the 1-μm band for the noritic clasts G, G1, G2, and G3 are easily compared in the residual absorption spectra shown in Fig. 13.

**Matrix**

Several areas of matrix were measured on both the E2 and W2 surfaces of the slab (M5, M4, M5 on chip #2 in Fig. 10, and S2 and S3 in Fig. 12). Except when there are obvious clasts embedded in the matrix (e.g., M5, S2), these spectra are generally very dark and absorption features are quite subdued since light cannot easily penetrate into the surface.

**DISCUSSION**

A large variety of clasts in this regolith breccia were identified and documented both petrographically and spectroscopically. Although most clasts are clearly noritic in composition, the relative abundance of orthopyroxene with other mafic minerals (olivine and clinopyroxene) can be easily discerned based on strength, wavelength, and symmetry of absorptions (Fig. 13). For example, even though variations in grain size of individual clasts cannot be readily modeled for these slab spectra, the relative strength of pyroxene absorptions can be seen to increase with pyroxene abundance from noritic clasts G, G2, to G3. The combined petrologic and spectroscopic data presented here provides an excellent beginning for a spectroscopy database of well-characterized lunar materials.

Equally important are the unusual or enigmatic clasts that defy analysis by either or both techniques. Identification of the surprising ilmenite feature for feldspathic clast B could not have been resolved without the close coordination between spectroscopy and petrography afforded by this experiment. On the other hand, the unusual features of breccia clasts G5 and R3 are difficult to identify even with a carefully prepared thin section. For these complex clasts the presence of minor clinopyroxene could only be identified spectroscopically, but the origin of the pervasive feature near 0.6 μm is still somewhat unresolved.

In spite of the large variety of clasts in this regolith breccia, the reflectance spectra of powders prepared from chips of 60019,215 all look quite similar (Figs. 7, 10, and 11). The spectra of these particulate samples of 60019 exhibit a red sloped continuum with very weak absorption features near 0.93 and 1.9 μm. Although the volume contributed by the large clasts to each powder has been visually estimated as ~10%, the petrologic studies show that clasts exist at all scales within the matrix. The dark glassy matrix has a major effect on the spectral character of the powders by lowering the albedo and subduing absorption features of the clasts. The wavelength of the residual absorptions in the breccia powders indicates low-Ca pyroxene is the major mafic mineral and the bulk sample is still clearly a noritic breccia. The apparent homogeneity of 60019 illustrated by the spectra of the particulate samples is due to the inherent lithology of the average Apollo 16 parent material, rather than the process that created this regolith breccia. This lends credence to interpretations that require extrapolation to larger scales. On a similar vein, the variety of distinct lithologies observed with remote spectroscopic techniques at unsampled sites across the Moon (Figs. 2 and 3) must reflect basic variations in the dominant local rock types.
It is important to note, however, that none of the spectra for particulate samples of 60019 regolith breccia are comparable to spectra for mature Apollo 16 soil shown in Fig. 1. Compared to mature soils, the 60019 breccia powders are darker and exhibit a less steep continuum and stronger absorption bands. Furthermore, as discussed by McKay et al. (1986) the maturity indices for 60019 are lower than what is found for Apollo 16 soils and the breccia itself may have been formed from an ancient regolith. Sample 60019 is thus, unfortunately, not an appropriate regolith breccia to be used to model optical properties of current regolith processes.

Results from the petrologic and spectroscopic analysis for 60019 presented here underline the importance of coordinated data for lunar samples. These data are nevertheless only a fraction of what is desired as an interpretative base to assess the global composition and resources of the Moon. Additional information for a larger variety of lunar mineral separates and range of lunar rock types would provide a stronger foundation to confidently assess the uniqueness of compositional interpretations for the lunar case. Analyses on other regolith breccias of different maturity will certainly help better define the relation between rock types and surface regoliths, but considerable insight could also be gained through more complete documentation of the spectral and petrographic properties of important lunar rock types that have been involved in different surface processes (shock, brecciation, mixing, melting, recrystallization, metamorphism).

Primary goals of remote reflectance spectroscopy are identification of mineral composition and the quantitative analysis of modal mineralogy for an unsampled surface. Since lunar surface materials are very complex, analytical models must be refined to accurately portray individual lunar components, how they mix with other components, and how lunar surface processes alter observed properties. The inverse problem, deconvolution or unmixing of spectral features, is of course required to quantify mineral abundances from a remotely acquired spectrum. Models that address the deconvolution of spectra for complex mixtures have been used successfully to address terrestrial problems with imaging spectrometer data (Mustard and Pieters, 1987b), and as appropriate models are developed for mixtures of lunar materials, they must be tested (and revised) using data from naturally occurring lunar materials that have been involved in a variety of surface processes. Although the data for 60019 discussed here contributed additional examples of how reflectance spectroscopy is readily used to successfully identify the type of minerals present in a sample and their general abundance, the quantitative analysis of modal mineralogy preferred for global exploration of the Moon would benefit from more complete information on lunar materials and the further development of analytical mixing models explicitly designed for lunar materials.

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