Lunar Regolith Analogues: Spectral Reflectance Properties of Compositional Variations

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The reflectance spectra of a number of glass and mafic silicate-bearing mineral mixtures designed to reproduce some of the spectral reflectance properties of lunar regoliths have been analyzed in order to assess how the reflectance spectra are altered by glass, end member abundance, and compositional variations. The reflectance spectra of glasses produced from different starting compositions show wide spectral variations attributable to differences in fusion times, techniques, and starting compositions. All the glasses show increasing reflectance toward longer wavelengths and very subdued or absent absorption bands. Olivine abundance and pyroxene compositional variations have the most dramatic effects on the spectra of mafic silicate-bearing mixtures in terms of changes in band positions, widths, depths, and areas and consequently are the easiest types of variations to recognize. Pyroxene, ilmenite, and plagioclase abundance variations cause less readily detectable changes in these spectral parameters. Plagioclase, being more weakly featured than mafic silicates, is difficult to unambiguously identify in mafic silicate-bearing mixture spectra unless its abundance exceeds ~50 wt%. Continuum removal was applied to glass-bearing mineral mixtures in attempts to reconstruct band positions, widths, depths, and areas of glass-free mineral mixtures by dividing glass-bearing mixture spectra by a straight line continuum or by the spectrum of the glass used in the mixture. The results suggest that straight line continuum division is generally more effective at reproducing most of the diagnostic spectral parameters of the corresponding glass-free mixtures and hence is more effective for isolating and subsequently analyzing mineral absorption bands.

INTRODUCTION

Reflectance spectroscopy is currently one of the most cost-effective means for obtaining geological information from remote or inaccessible targets. With very few exceptions "ground truth," in the form of actual samples from known localities, is unavailable for most bodies in the solar system. Even the samples available from the second most studied body after the Earth, the Moon, are representative of only a very limited portion of the lunar surface and remote sensing methods must be employed for more extensive regional or global geological surveys. Thus it is imperative that the amount of geological information derivable from remote sensing studies be maximized.

The goal of most lunar spectroscopic remote sensing studies is to isolate and analyze silicate mineral spectral features. Silicate absorption bands are useful for deriving information such as end member mineral abundances, compositions, and particle sizes from parameters such as band depths, positions, widths, and areas.

A number of lunar regolith analogues have been spectrally characterized in order to assess the effects of varying compositional parameters on reflectance spectra. Pure mineral mixtures are not the most suitable analogues for the interpretation of lunar sample and surface spectra because the latter commonly show a red slope (reflectance generally increasing toward longer wavelengths) not present in pure mineral mixture spectra (e.g., McCord et al. 1981, Pieters et al. 1985, Smrekar and Pieters 1985, Lucey et al. 1986, Pieters 1986). Mineral absorption bands become weaker, the slopes become increasingly red sloped and absolute reflectance decreases as surface exposure time increases. Lunar soils are also more red sloped and less strongly featured than whole rock spectra (Adams and Charette 1975a,b).

The red slope in the lunar spectra is attributable to the presence of glass formed as either a primary eruptive product (Heiken et al. 1974) or to glasses/aggelulates formed due to the vitrification of minerals exposed to the
space environment. This exposure causes a number of changes in the petrology and mineralogy of the surface assemblage which will have an effect on the optical properties of the regolith. These include differential comminution of minerals (Papke et al. 1982, Hörz et al. 1985, See et al. 1986, Laul et al. 1987), the formation of very fine-grained metal particles, and coatings, and other processes (Basu 1977, Bell and Mao 1977, Levin and McKay 1987), all of which serve to alter the optical properties of lunar surface materials (Conel and Nash 1970, Adams and McCord 1971a, Cassidy and Hapke 1975, Hapke et al. 1975, Gaffey 1976, Bell and Mao 1977, Pieters 1978). Vitriified materials may also form as impact melt glass, pyroclastic glass, and glass welded materials (agglutinates) (Adams et al. 1975, Rhodes et al. 1975, Rode and Csaika 1985, Simon et al. 1985, Boschelli and McKay 1987, See and Hörz 1988). The composition of the glasses/agglutinates may also change over time (Pillinger et al. 1978) and the presence of ilmenite will eventually lead to the formation of dark glasses (Adams and McCord 1971a).

It is not expected that glass will impart any resolvable absorption features to reflectance spectra of mixtures containing mafic silicates because whatever absorption bands glasses do possess are typically 10 to 20 times weaker than pyroxene absorption bands (Farr et al. 1980). Shifts in the wavelength positions of pyroxene absorption bands due to overlapping glass bands should therefore be minimal and only the displacements due to the red slope of the glass need be considered (Adams and McCord 1970, Farr et al. 1980).

Although ideally one would like to study glass welded particles in the laboratory, production of such materials introduces uncertainties in overall glass : mineral ratios and elemental partitioning. Consequently, glasses were produced in the laboratory and mixed with mineral grains in an attempt to simulate lunar regolith samples while retaining the ability to control phase abundances and compositions. Some of the characteristics of spectral modification were the subject of an earlier study (Cloutis et al. 1990).

Previous studies of lunar, mafic, and nonmafic silicate spectra indicate that the most useful spectral parameters for determining assemblage properties such as end member abundances and compositions involve band wavelength positions, band depths, band areas, and band widths (e.g., McFadden and Gaffey 1978, McCord et al. 1981, Singer 1981, Cloutis et al. 1986a,b, Lucey et al. 1986, Pieters 1986, Crown and Pieters 1987, King and Ridley 1987, Sunshine et al. 1990). Since thermal emissions from the lunar surface increase with increasing wavelength, shorter wavelength spectral features will be easier to interpret than those at longer wavelengths. Band wavelengths positions, depths, areas and widths have been determined for various mafic silicate and glass-bearing mixtures subjected to continuum removal designed to isolate specific absorption features relative to the values for corresponding glass-free mineral mixture spectra. This continuum removal involves division of a glass-bearing mineral mixture by a straight-line continuum tangent to the spectrum on either side of the main absorption feature present near 1 \( \mu \)m or division by the spectrum of the glass used in the particular mineral mixture.

The lunar surface is dominated by a few phases—plagioclase feldspar, pyroxene, olivine, ilmenite, and impact-generated glasses (Smith 1974, Smith and Steele 1976, Taylor 1982). Telescopic reflectance spectra for many areas of the Moon, both sampled and unsampled, exhibit spectral features in the 0.3–2.6-\( \mu \)m spectral region attributable to the silicate minerals (e.g., Bell and Hawke 1984, Lucey et al. 1986, Pieters 1986). These spectra are inevitably modified from those expected for silicate mineral mixtures due to the presence of impact-generated glasses and glass welded fragments (agglutinates) and opaque minerals, of which ilmenite is the most abundant.

The spectral reflectance properties of the major lunar minerals and the spectral changes accompanying compositional variations have been extensively documented. Reflectance spectra of olivine exhibit a major absorption feature near 1 \( \mu \)m (band I) which is composed of three overlapping bands attributable to crystal field transitions in ferrous iron. An additional weaker band is present near 0.65 \( \mu \)m likely due to the presence of Ni\(^{2+}\), although a number of alternative explanations have been offered (King and Ridley, 1987, and references therein). A reflectance decrease short of 0.5 \( \mu \)m is due to various charge transfer absorptions. The wavelength position of band I shifts to longer wavelengths with increasing iron content (Burns 1970a, Cloutis 1985, King and Ridley 1987).

Low calcium content pyroxene or orthopyroxene (OPX) spectra exhibit two major absorption bands near 1 \( \mu \)m (band I) and 2 \( \mu \)m (band II) both due to Fe\(^{2+}\) crystal field transitions. Both bands move to longer wavelengths with increasing calcium and ferrous iron contents (Burns 1970b, Adams and McCord 1972, Adams 1974, Cloutis 1985, Cloutis et al. 1986a,b, Cloutis and Gaffey 1991). OPX also exhibits a charge transfer related reflectance decrease short of 0.5 \( \mu \)m.

High-calcium-content pyroxene or clinopyroxene (CPX) spectra are of two main types. One type (type B) is similar in overall appearance to OPX spectra, whereas type A CPX spectra exhibit two absorption bands near 0.95 and 1.15 \( \mu \)m, respectively, and a very weak or nonexistent band near 2 \( \mu \)m (Adams 1975, Cloutis 1985, Cloutis and Gaffey 1991). The wavelength positions of the type B absorption bands are not simple linear functions of either calcium or ferrous iron content (Cloutis and Gaffey 1991). Type A spectra are generally confined to clino-
pyroxenes containing $>50\%$ CaSiO$_3$, whereas spectral type B generally contain $<50\%$ CaSiO$_3$ (Cloutis and Gaffey 1991). Both spectral types often exhibit an additional absorption band near 0.8 $\mu$m attributable to Fe$^{2+}$–Fe$^{3+}$ charge transfers as well as a charge-transfer-related reflectance decrease short of $\sim$0.5 $\mu$m (Hunt and Salisbury 1970, Adams 1975).

Plagioclase feldspar spectra are characterized by high overall reflectance, a weak ferrous iron absorption band near 1.25 $\mu$m, and a charge-transfer-related reflectance decrease toward shorter wavelengths (Hunt and Salisbury 1970, Adams and Goulaud 1978).

Ilmenite is the most common lunar opaque mineral and its reflectance spectrum exhibits a broad Fe–Ti charge transfer absorption feature near 0.5 $\mu$m and a broad, weak ferrous iron absorption feature between 1.2 and 1.5 $\mu$m (Hunt et al. 1971, Adams 1974, Nash and Conel 1974, Adams 1975, Pieters 1983, Cloutis et al. 1990).

Naturally occurring and artificially produced lunar glasses show nearly featureless, red-sloped reflectance spectra with a range of absolute reflectances and slopes (Conel and Nash 1970, Adams and McCord 1971a,b, Nash and Conel 1973, Adams et al. 1974, Adams 1975, Farr et al. 1980). These spectra are similar to the spectra of lunar regolith fines, indicating that the glassy agglutinates are a spectrally significant component of most lunar soils (Adams and Charette 1975a).

**EXPERIMENTAL PROCEDURE**

Analogues of lunar mineral assemblages have been prepared for this study using terrestrial minerals because of the quantities required. The minerals used are a high-iron-content orthopyroxene from Ekersund, Norway (PYX032), a spectral type B clinopyroxene from Val di Fassa, Italy (PYX036), a high-calcium-content plagioclase feldspar (bytownite) from the Stillwater complex, Montana (PLG180), an ilmenite from Telemark, Norway (ILM101), and an olivine from San Carlos, Arizona (OLV003). The minerals were analyzed at the University of Calgary SEMQ electron microprobe facility. The compositions of the various minerals (Table I) are an average of 4–8 point analyses or area scans. The data were reduced using Bence-Albee $\alpha$ and $\beta$ correction factors. Ferrous iron contents have been determined using wet chemical methods and ferric iron contents taken as the difference between total and ferrous iron.

Powdered samples (45–90 $\mu$m grain size) were used for the spectral measurements. The various minerals were ground in an alumina mortar and pestle and any impurities removed through a combination of magnetic separation and hand picking. Well constrained size ranges were acquired by repeated wet sieving with acetone. The reflectance spectra of the various minerals are shown in Fig. 1. The glasses used in the various mineral mixtures were produced from the same mineral proportions as the mixtures into which they were incorporated. These samples were placed in platinum crucibles and heated at 1000°C for 15–30 min to drive off any water. They were then transferred to a Deltech DT-31-VT furnace and held at 1400°C for 15 min in a CO–CO$_2$ atmosphere at a calculated oxygen fugacity of $10^{-6}$ atmospheres except for glass G4, which was fused for 90 min. The samples were quenched by immersing the lower half of the crucible in a water bath. This prevented the water from contacting the sample and solidification was generally completed within 5–10 sec after removal from the furnace. The glass powders were prepared in the same way as the mineral powders and were examined for homogeneity using both backscattered electron (BSE) imaging and X-ray diffractometry (XRD). Glass compositions were determined at the University of Alberta ARL SEMQ microprobe facility using a Tracer Northern 5402 energy dispersive detector system and the data were reduced using Bence-Albee $\alpha$ and $\beta$ correction factors. Ferrous and ferric iron abundances were determined in the same way as for the mineral samples.

The mineral and glass proportions incorporated into the various samples that have been spectrally characterized are listed in Table II. Four types of samples have been spectrally characterized. Glass-free samples are designated by a GF prefix, glass-bearing samples by a GB prefix, pure glass by a G prefix, and minerals by a three-letter prefix. Glass-free, glass-bearing, and pure glass samples, which are derived from the same initial proportions of minerals, have been assigned the same numerical suffix and the starting composition of a glass is the same as the glass-free equivalent sample with which it is paired. Thus, for example, the mineral abundances used in making glass G1 are the same as those listed for glass-free sample GF1. The only exceptions are GB5 and GB6, which are glass-bearing samples containing mineral proportions identical to GF1 and varying proportions of glass G1.

Reflectance spectra were measured at the NASA RELAB spectrometer facility at Brown University (Pieters 1983). Bidirectional reflectance spectra were measured ($\iota = 30^\circ$, $\varepsilon = 0^\circ$) at 5 nm resolution relative to halon, a near perfect diffuse reflector in the 0.3–2.7-$\mu$m region (Weidner and Hsia 1981). The spectra have been corrected for dark current offsets as well as for minor irregularities in the absolute reflectance of halon in the 2-$\mu$m region. The spectral data have been processed using the Gaffey Spectrum Processing System, a PC-compatible version of SPECPR (Clark 1980).

Band minima and band center wavelength positions have been determined by fitting a quadratic function to
### TABLE I

Chemical Composition of the Orthopyroxene (PYX032), Clinopyroxene (PYX036), Olivine (OLV003), Plagioclase Feldspar (PLG108), and Ilmenite (ILM101) Used in This Study

<table>
<thead>
<tr>
<th>Phase</th>
<th>OPX PYX032</th>
<th>CPX PYX036</th>
<th>OLV OLV003</th>
<th>PLG PLG108</th>
<th>ILM ILM101</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>50.21</td>
<td>50.54</td>
<td>40.64</td>
<td>46.55</td>
<td>0.20</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>1.24</td>
<td>2.99</td>
<td>tr.</td>
<td>32.70</td>
<td>0.11</td>
</tr>
<tr>
<td>FeO</td>
<td>23.65</td>
<td>8.18</td>
<td>9.25</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>5.11</td>
<td>1.71</td>
<td>0.59</td>
<td>0.64ᵇ</td>
<td>—</td>
</tr>
<tr>
<td>MgO</td>
<td>17.57</td>
<td>14.64</td>
<td>49.13</td>
<td>0.04</td>
<td>0.02</td>
</tr>
<tr>
<td>CaO</td>
<td>1.59</td>
<td>20.35</td>
<td>0.07</td>
<td>17.28</td>
<td>0.11</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.00</td>
<td>0.27</td>
<td>0.00</td>
<td>1.71</td>
<td>0.08</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.19</td>
<td>0.86</td>
<td>0.00</td>
<td>0.05</td>
<td>51.49</td>
</tr>
<tr>
<td>Cr₂O₃</td>
<td>0.04</td>
<td>0.07</td>
<td>0.01</td>
<td>0.03</td>
<td>0.01</td>
</tr>
<tr>
<td>V₂O₅</td>
<td>tr.</td>
<td>0.08</td>
<td>0.00</td>
<td>0.01</td>
<td>ND</td>
</tr>
<tr>
<td>CoO</td>
<td>0.06</td>
<td>0.04</td>
<td>0.04</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>NiO</td>
<td>0.01</td>
<td>0.02</td>
<td>0.33</td>
<td>0.09</td>
<td>0.00</td>
</tr>
<tr>
<td>MnO</td>
<td>0.53</td>
<td>0.25</td>
<td>0.09</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>K₂O</td>
<td>ND</td>
<td>ND</td>
<td>0.00</td>
<td>0.02</td>
<td>0.00</td>
</tr>
<tr>
<td>Total</td>
<td>100.20</td>
<td>100.00</td>
<td>100.15</td>
<td>99.16</td>
<td>97.25</td>
</tr>
</tbody>
</table>

*Note. tr., <0.01%. ND, not determined.
ᵃ All Fe reported as FeO (ferrous iron).
ᵇ All Fe reported as Fe₂O₃ (ferric iron).*

10–20 data points on either side of a visually determined approximate minimum or center. A series of curve-fitting trials have indicated that changing the number of data points used in the fit (over the range of 10 to 60 data points) may result in variations of, at most, 2 nm in the calculated position of a band minimum or center. Consequently, differences in band minima or centers are considered significant if they exceed 3 nm. Band depths ($D_b$) have been calculated using Eq. (32) in Clark and Roush (1984). Band depth accuracies are constrained by the accuracy of the data, in this case to better than ±1%. Band area ratios are often useful for deconvolving mafic silicate bearing mixture spectra (Cloutis et al. 1986b). The most useful band area ratio involves the areas of the two major absorption bands near band I and band II. The band I* area is the area enclosed by the reflectance spectrum at band I and a straight-line continuum tangent to the spectrum on either side of this band multiplied by the reflectance ratio of the interband peak (reflectance maximum between band I and band II near 1.4 μm) to the local reflectance maximum in the 0.5–0.8-μm region (Fig. 2). This reflectance ratio is included in the band area determination for utilitarian reasons—the band II*/I* ratio is found to be fairly constant (±10%) for all orthopyroxenes regardless of ferrous iron content (Cloutis et al. 1986b). The band II* area is the area enclosed by the reflectance spectrum near band II, a horizontal line tangent to the reflectance spectrum at the interband peak, and a vertical line intersecting the spectrum at the band II minimum (Fig. 2). The band area ratio used throughout this paper refers to band II*/band I*. Repeated determinations of band area ratios indicate that they are consistently repeatable to within ±2%. Overall spectral slope was quantified using the ratio of the reflectance at 2.5 μm to that at 0.5 μm. Bandwidths used in this study were measured as the difference in wavelength between the intercepts of an absorption band and a horizontal line located halfway between the point of lowest reflectance and a straight-line continuum tangent to the spectrum on

![Figure 1](image-url)
TABLE II
Mineral and Glass Weight Percentages in the Various Spectrally Characterized Glass-Bearing (GB) and Glass-Free (GF) Samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>OPX (PYX032)</th>
<th>CPX (PYX036)</th>
<th>OLV (OLV003)</th>
<th>PLG (PLG018)</th>
<th>ILM (ILM101)</th>
<th>GLA</th>
</tr>
</thead>
<tbody>
<tr>
<td>GB1</td>
<td>50.0</td>
<td>0.0</td>
<td>0.0</td>
<td>20.0</td>
<td>5.0</td>
<td>25.0</td>
</tr>
<tr>
<td>GB3</td>
<td>52.6</td>
<td>0.0</td>
<td>0.0</td>
<td>21.1</td>
<td>0.0</td>
<td>26.3</td>
</tr>
<tr>
<td>GB5</td>
<td>33.3</td>
<td>0.0</td>
<td>0.0</td>
<td>13.3</td>
<td>3.3</td>
<td>50.0</td>
</tr>
<tr>
<td>GB6</td>
<td>16.7</td>
<td>0.0</td>
<td>0.0</td>
<td>6.7</td>
<td>1.7</td>
<td>75.0</td>
</tr>
<tr>
<td>GB8</td>
<td>42.1</td>
<td>0.0</td>
<td>0.0</td>
<td>16.8</td>
<td>20.0</td>
<td>21.1</td>
</tr>
<tr>
<td>GB9</td>
<td>25.0</td>
<td>0.0</td>
<td>50.0</td>
<td>10.0</td>
<td>2.5</td>
<td>12.5</td>
</tr>
<tr>
<td>GB10</td>
<td>75.0</td>
<td>0.0</td>
<td>0.0</td>
<td>10.0</td>
<td>2.5</td>
<td>12.5</td>
</tr>
<tr>
<td>GB11</td>
<td>31.2</td>
<td>0.0</td>
<td>0.0</td>
<td>50.0</td>
<td>3.1</td>
<td>15.6</td>
</tr>
<tr>
<td>GB12</td>
<td>0.0</td>
<td>50.0</td>
<td>0.0</td>
<td>20.0</td>
<td>5.0</td>
<td>25.0</td>
</tr>
<tr>
<td>GF1</td>
<td>66.7</td>
<td>0.0</td>
<td>0.0</td>
<td>26.7</td>
<td>6.7</td>
<td>0.0</td>
</tr>
<tr>
<td>GF3</td>
<td>71.4</td>
<td>0.0</td>
<td>0.0</td>
<td>28.6</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>GF8</td>
<td>53.3</td>
<td>0.0</td>
<td>0.0</td>
<td>21.3</td>
<td>25.3</td>
<td>0.0</td>
</tr>
<tr>
<td>GF9</td>
<td>28.6</td>
<td>0.0</td>
<td>57.1</td>
<td>11.4</td>
<td>2.9</td>
<td>0.0</td>
</tr>
<tr>
<td>GF10</td>
<td>85.7</td>
<td>0.0</td>
<td>0.0</td>
<td>11.4</td>
<td>2.9</td>
<td>0.0</td>
</tr>
<tr>
<td>GF11</td>
<td>37.0</td>
<td>0.0</td>
<td>0.0</td>
<td>59.3</td>
<td>3.7</td>
<td>0.0</td>
</tr>
<tr>
<td>GF12</td>
<td>0.0</td>
<td>66.7</td>
<td>0.0</td>
<td>26.7</td>
<td>6.7</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Note. OPX, orthopyroxene (PYX032); CPX, clinopyroxene (PYX036); OLX, olivine (OLV003); PLG, plagioclase feldspar (PLG018); ILM, ilmenite (ILM101); GLA, glass. Particular sample descriptions are provided in the text. The abundances of minerals used to make the various glasses are identical to the GF samples with which they are paired; in this case the pairs are as follows: G1–GF1, G3–GF3, G4–GF1, G8–GF8, G9–GF9, G10–GF10, G11–GF11, G12–GF12. Samples GB5 and GB6 contain glass G1.

![Diagram](image)

FIG. 2. Spectrum of sample GB1 illustrating some of the spectral parameters measured in this study.

either side of the band (Lucey et al. 1986; Fig. 2). The accuracy of these values is limited by the spectral resolution of the data, in this case 5 nm; consequently, bandwidths are accurate to ± 10 nm.

The spectral effects of varying compositional parameters on mixtures containing more than three phases focus on sample groups in which the relative abundance of only one phase is varied, all other relative abundances remaining constant. This obviously involves tradeoffs in terms of how comparable the various samples are to each other. By holding constant the relative abundances of phases not under consideration, absolute abundances will vary. As an example, the spectral effects of varying ilmenite content has been evaluated for samples GB3, GB1, and GB8. The pyroxene : plagioclase : glass ratio is 10 : 4 : 5 in all three samples but the absolute abundances of pyroxene, plagioclase, and glass are different in each sample. This distinction between relative and absolute abundances should be noted. By comparing only those samples in which only one component is varied, the relative abundances of the other phases being kept constant, the spectrum altering effects of the phase of interest are largely isolated. For example, when examining ilmenite content spectral variations, samples GB3, GB1, and GB8 can be thought of as two-component mixtures, rather than four-component mixtures. Ilmenite is one of the two components; the other component is always 50 : 20 : 25 OPX : PLG : ILM (Table II). The only difference among samples GB3, GB1, and GB8 is the ratio of component 1 to component 2; i.e., the effects of ilmenite content variations on a multicomponent mixture are highlighted.

ANALYSIS OF LABORATORY PRODUCED GLASSES

The glasses produced from the various starting materials were examined with a variety of techniques, primarily
BSE and XRD. Because the glasses and minerals were analyzed at different facilities and at different times, only major element compositions have been made. In general it appears that the fusion technique employed has resulted in slight systematic enrichments of Al\(_2\)O\(_3\) and CaO and slight systematic depletions of SiO\(_2\) and MgO between the starting materials and the glasses (Table III). Ferric iron abundances are consistently higher in the glasses, indicating that attempts to control oxygen fugacity were not successful. This is important because ferric iron is virtually absent in lunar samples (Basaltic Volcanism Study Project 1981).

The wide range of absolute reflectances of the various glasses produced from the various starting materials (Table II) at various wavelengths are presented in Table IV and Fig. 3. The data suggest immediately that composition will have an effect on the resultant glass spectra. However, all the spectra exhibit certain common features—low overall reflectance in the visible region (1–6%) and no well-developed absorption bands such as those shown by the starting materials (Fig. 1). The large variations in overall spectral slope are more evident in the normalized spectra (Fig. 4).

Examination of the glasses suggests that their spectral variability can be attributed to both differences in composition and the degree of homogeneity and recrystallization. Glass G1 appears to be completely amorphous and homogeneous when examined by BSE and XRD.

Glass G3 is largely amorphous with a few (<1% by area in BSE images) scattered anhedral grains <5 \(\mu \text{m}\) in size. XRD and electron microprobe analyses corroborate the largely amorphous nature of this material with a few weak diffraction peaks, indicating a small amount of an Mg- and Fe-rich oxide similar to magnesioferrite (MgFe\(_2\)O\(_4\)).

Glass G4 was produced from the same initial mixture as G1 and is also largely amorphous and homogeneous but contains a greater amount (~5% by area in BSE images) of small (<10 \(\mu \text{m}\) size) anhedral grains composed largely of an Al–Fe–Ti–Mg oxide (Table V).

Glass G8 was produced from an ilmenite-rich starting material (Table II) and the quenching process seems to have been ineffective in producing a completely amorphous and homogeneous material. A substantial portion of the glass (~25% by area in BSE images) contains numerous acicular grains (~20 \(\mu \text{m} \times 1 \mu \text{m}\)) of an iron- and titanium-rich oxide as well as lesser amounts (~5% by area in BSE images) of <10-\(\mu \text{m}\)-sized anhedral, more iron- and titanium-rich oxide grains (Table V). XRD analysis corroborates the BSE observations, indicating a generally amorphous material with superimposed diffraction peaks attributable to a material similar to pseudobrookite (Fe\(_2\)TiO\(_4\)).

Glass G9 was produced from an olivine-rich starting material (Table II). Complete fusion and/or vitrification seems not to have been achieved in this case because BSE images show numerous (~50% by area) anhedral grains up to 20 \(\mu \text{m}\) in size whose composition (Table V)
closely resembles that of the original olivine (Table I). Also present are a few (~2% by area in BSE images) Fe–Al–Mg-rich anhedral grains (Table V). The XRD data indicate that the material is much less amorphous than the other glasses, with prominent diffraction peaks attributable to olivine and a pseudobrookite like material.

Glass G10 was produced from a pyroxene-rich starting material (Table II). Complete fusion was probably attained but quenching may not have been rapid enough to prevent some incipient recrystallization in the form of dendritic material (~5% by area in BSE images) more iron-rich than the starting composition (Table V). The recrystallized material is not a significant component and the XRD pattern indicates that the glass is largely amorphous with small superimposed peaks attributable to a metal-oxide-rich material.

Glass G11 was produced from a plagioclase-rich starting material (Table II). The BSE images show no evidence of heterogeneity but the XRD pattern exhibits a number of weak peaks attributable to a small amount of a calcium rich plagioclase.

Glass G12 was produced from a clinopyroxene bearing starting material (Table II). Fusion and quenching seem to have been effective because neither the BSE images nor the XRD data indicate any appreciable amounts of heterogeneous or recrystallized material.

### REFLECTANCE SPECTRA OF GLASSES

The effects of increasing titanium and iron contents on glass spectra can be evaluated by comparing spectra G1, G3, and G8 (Figs. 3 and 4). The Fe and Ti contents

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**TABLE IV**

Absolute Reflectance of Samples at Selected Wavelengths and 2.5/0.5 μm Reflectance Ratio

<table>
<thead>
<tr>
<th>Sample</th>
<th>0.5 μm</th>
<th>1.0 μm</th>
<th>1.5 μm</th>
<th>2.0 μm</th>
<th>2.5 μm</th>
<th>Ratio (2.5/0.5 μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GB1</td>
<td>0.099</td>
<td>0.096</td>
<td>0.188</td>
<td>0.122</td>
<td>0.255</td>
<td>2.58</td>
</tr>
<tr>
<td>GB3</td>
<td>0.096</td>
<td>0.091</td>
<td>0.191</td>
<td>0.125</td>
<td>0.264</td>
<td>2.75</td>
</tr>
<tr>
<td>GB5</td>
<td>0.063</td>
<td>0.062</td>
<td>0.114</td>
<td>0.093</td>
<td>0.175</td>
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<td>GB6</td>
<td>0.042</td>
<td>0.044</td>
<td>0.081</td>
<td>0.081</td>
<td>0.141</td>
<td>3.36</td>
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<tr>
<td>GB8</td>
<td>0.099</td>
<td>0.094</td>
<td>0.147</td>
<td>0.100</td>
<td>0.176</td>
<td>1.78</td>
</tr>
<tr>
<td>GB9</td>
<td>0.203</td>
<td>0.146</td>
<td>0.255</td>
<td>0.208</td>
<td>0.301</td>
<td>1.48</td>
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<tr>
<td>GB10</td>
<td>0.098</td>
<td>0.081</td>
<td>0.192</td>
<td>0.094</td>
<td>0.245</td>
<td>2.50</td>
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<tr>
<td>GB11</td>
<td>0.173</td>
<td>0.177</td>
<td>0.274</td>
<td>0.213</td>
<td>0.359</td>
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<td>GB12</td>
<td>0.101</td>
<td>0.116</td>
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<td>0.145</td>
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<td>0.154</td>
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<tr>
<td>GF8</td>
<td>0.121</td>
<td>0.120</td>
<td>0.207</td>
<td>0.124</td>
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<td>GF9</td>
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<td>0.413</td>
<td>0.304</td>
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<td>0.064</td>
<td>0.104</td>
<td>4.52</td>
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<tr>
<td>G3</td>
<td>0.026</td>
<td>0.033</td>
<td>0.067</td>
<td>0.087</td>
<td>0.124</td>
<td>4.77</td>
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<tr>
<td>G4</td>
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<td>0.027</td>
<td>0.049</td>
<td>0.061</td>
<td>0.097</td>
<td>4.22</td>
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<tr>
<td>G8</td>
<td>0.028</td>
<td>0.027</td>
<td>0.030</td>
<td>0.036</td>
<td>0.051</td>
<td>1.82</td>
</tr>
<tr>
<td>G9</td>
<td>0.031</td>
<td>0.031</td>
<td>0.031</td>
<td>0.034</td>
<td>0.041</td>
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<tr>
<td>G10</td>
<td>0.028</td>
<td>0.029</td>
<td>0.039</td>
<td>0.046</td>
<td>0.061</td>
<td>2.18</td>
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<tr>
<td>G11</td>
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<td>0.037</td>
<td>0.067</td>
<td>0.097</td>
<td>0.153</td>
<td>7.29</td>
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<tr>
<td>G12</td>
<td>0.037</td>
<td>0.069</td>
<td>0.144</td>
<td>0.172</td>
<td>0.243</td>
<td>6.57</td>
</tr>
</tbody>
</table>

Note. PYX032, orthopyroxene (OPX); PYX036, clinopyroxene (CPX); PLG108, plagioclase feldspar (PLG); OLV003, olivine (OLV); ILM101, ilmenite (ILM).
(TiO₂ + FeO + Fe₂O₃) increase in the series G3 (21.51%)–G1 (26.08%)–G8 (39.95%) (Table III). This increase manifests itself as progressive decreases in overall reflectance beyond 1 μm and overall slope (Table IV). These observations agree well with those of other investigators concerning transition series element variations on glass spectra (Adams and McCord 1971b, Pieters et al. 1973). Despite the incipient recrystallization observed for glass G8, it exhibits no well-defined absorption bands.

Fusion times and techniques have also been implicated in explaining the wide spectral variations in laboratory-produced glasses (Conel and Nash 1970, Nash and Conel 1973, Cassidy and Hapke 1975, Cloutis et al. 1990). Glasses G1 and G4 were produced from identical starting compositions with fusion times of 15 and 90 min, respectively. Their reflectance spectra are nearly identical (Figs. 3 and 4) as expected since BSE imaging, electron microprobe analysis, and XRD examination reveal no major
TABLE V

Major Element Abundances in Selected Nonmatrix Phases in Various Glasses

<table>
<thead>
<tr>
<th>Sample</th>
<th>SiO$_2$</th>
<th>Al$_2$O$_3$</th>
<th>CaO</th>
<th>FeO$^a$</th>
<th>TiO$_2$</th>
<th>MnO</th>
<th>MgO</th>
</tr>
</thead>
<tbody>
<tr>
<td>G4$^b$</td>
<td>0.55</td>
<td>9.55</td>
<td>0.29</td>
<td>69.06</td>
<td>8.02</td>
<td>0.41</td>
<td>7.96</td>
</tr>
<tr>
<td>G8$^b$</td>
<td>0.48</td>
<td>2.36</td>
<td>0.18</td>
<td>39.32</td>
<td>50.04</td>
<td>0.20</td>
<td>4.54</td>
</tr>
<tr>
<td>G8$^c$</td>
<td>14.85</td>
<td>4.44</td>
<td>1.77</td>
<td>30.19</td>
<td>41.81</td>
<td>0.25</td>
<td>6.31</td>
</tr>
<tr>
<td>G9$^d$</td>
<td>0.88</td>
<td>6.88</td>
<td>0.20</td>
<td>68.23</td>
<td>1.98</td>
<td>0.44</td>
<td>12.68</td>
</tr>
<tr>
<td>G9$^d$</td>
<td>40.48</td>
<td>0.00</td>
<td>0.18</td>
<td>11.42</td>
<td>0.06</td>
<td>0.22</td>
<td>49.68</td>
</tr>
<tr>
<td>G10$^e$</td>
<td>36.96</td>
<td>5.35</td>
<td>2.34</td>
<td>43.80</td>
<td>1.83</td>
<td>0.38</td>
<td>9.53</td>
</tr>
</tbody>
</table>

$^a$ All Fe reported as FeO.
$^b$ Bright anhedral grains in backscattered electron microprobe images.
$^c$ Bright acicular phases in backscattered electron microprobe images.
$^d$ Dark anhedral grains in backscattered electron microprobe images.
$^e$ Dendritic/acicular phases in backscattered electron microprobe images.

differences. Quick-melt (on the order of seconds) and slow-melt (on the order of minutes) glasses produced by Nash and Conel (1973) exhibit much more diverse spectra. Their quick-melt glass displays more resolvable absorption bands and higher overall reflectance than their slow-melt glass. When normalized the slow-melt glass has a much redder slope, opposite of the trend found here where the quick-melt glass (G1) is slightly redder than the slow-melt glass (G4) (Table IV). The results of Nash and Conel (1973) suggest that fusion techniques and times will strongly affect laboratory-produced glass spectra; increased fusion times will result in a decrease in overall reflectance and a more featureless reflectance spectrum. It has also been shown that oxidation conditions can affect glass spectra and the low overall reflectances of the glasses produced for this study are probably related to the high ferric iron contents. Cassidy and Hapke (1975) showed that glasses produced in a vacuum had a much higher overall reflectance than glasses produced in air, probably due to the oxidation of iron to Fe$^{3+}$ and the possibility that this oxidation may also occur in presumed inert atmospheres such as nitrogen. Given these observations and the aforementioned difficulties in controlling oxygen fugacity in the glasses produced for this study, it would appear that the more extensive results of Nash and Conel (1973) are valid concerning the importance of fusion time on the resultant glass spectra.

In addition to time, technique, and opaque abundances, other factors such as phase abundances and compositions can affect glass spectra. Sample G9 was produced from an olivine-rich starting composition. Its initial pyroxene : plagioclase : ilmenite ratio is identical to that of glass G1 (Table II). The higher initial olivine content in G9 results in a "glass" (containing ~50% recrystallized material) with a slightly lower total iron and titanium content than G1 (Table III). The G9 spectrum is shown in greater detail in Fig. 5. It exhibits the lowest overall reflectance beyond 1.5 μm and flattest slope of all the glasses (Table IV). This is unexpected for a material relatively depleted in iron and titanium. The appearance of the broad absorption feature between ~1.0 μm and 1.5 μm (reflectance minimum at 1.22 μm) is not unexpected given the semiamorphous nature of the sample. Some quick-melt glasses which may also have been incompletely fused show similarly featured spectra (Nash and Conel 1973). The G9 spectrum indicates that incompletely vitrified glass could conceivably contribute absorption features to a reflectance spectrum, although these features will likely be much weaker than absorption bands due to crystalline mafic silicates with which they may be associated (Farr et al. 1980).

The effect of increasing initial pyroxene abundance on glass spectra can be evaluated by comparing spectra G1 and G10 (Figs. 3 and 4). The initial plagioclase : ilmenite

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**FIG. 5.** Reflectance spectrum of glass G9 produced from an olivine-rich starting assemblage.
ratio is the same in both samples but the initial pyroxene contents were 66.7% in G1 and 85.7% in G10 (Table II). The higher transition series element content in G10 results in lower overall reflectance beyond ~1.2 μm and overall slope relative to G1 (Table IV) as expected (Adams and McCord 1971b). The expected visible-ultraviolet reflectance decrease toward shorter wavelengths is absent in the laboratory glass, again probably due to the inadvertent oxidation of the iron. The spectra suggest that initial mineral abundances will affect the spectra of the resultant glass although it is possible that long-term exposure of a glass to the space environment may lead to a convergence of spectral signatures due to increasing concentration of transition series elements (Nash and Conel 1973).

Glass made from a plagioclase-rich starting material also shows spectral variability. Glasses G1 and G11 have been prepared from mixtures with identical pyroxene: ilmenite ratios but different plagioclase abundances, 26.7% in G1 and 59.3% in G11 (Table II). The higher initial plagioclase abundance in G11 results in higher overall reflectance beyond ~0.7 μm and a redder overall slope (Table IV; Figs. 3 and 4). G11 also has a less strongly featured reflectance spectrum at longer wavelengths and there is little evidence for an absorption feature in the 1.8-μm region. This type of behavior is similar to that found by Adams and McCord (1971b), who produced glasses from a whole rock lunar sample (containing some opaques) and from a pyroxene–plagioclase separate. The latter exhibited higher overall reflectance and a redder slope. Spectrum G11 has the reddest slope of all the glasses and this is probably due to the low abundance of transition series elements. However, analysis of lunar surface and sample spectra indicates that very red sloped spectra are not necessarily diagnostic of plagioclase rich lithologies (Pieters 1986).

The effect of varying initial pyroxene composition on subsequently fused glass spectra has been investigated by preparing two glasses from identical initial mineral proportions but different pyroxene compositions. Glass G1 was prepared using an orthopyroxene (PYX032) and glass G12 using a clinopyroxene (PYX036). Both glasses are essentially amorphous and homogeneous. G12 has a higher overall reflectance and a redder slope than G1 (Table IV). These differences can probably be attributed to the lower iron abundance in G12. The steep red slope of G12 is reminiscent of glass G11, another low-iron-content sample. The weak absorption bands appear near 0.9 and 1.7 μm in both G1 and G12, irrespective of the fact that the pyroxenes used to make the glasses exhibit absorption bands at different wavelengths (Fig. 1). This indicates that precursor mineral compositions may not be derivable from the wavelength positions of absorption features of subsequently formed glass. In spite of the diversity in overall reflectance and slope of the various glasses, almost all the glass spectra exhibit weak absorption features near 0.9 and 1.7 μm.

Artificially produced and naturally occurring lunar glasses and fines also show a range of spectral features, although not nearly as extreme as the glasses produced for this study.

The spectral range of a number of artificial glasses produced in previous studies (Adams and McCord 1971b, Nash and Conel 1973) are shown along with the spectral extremes of the glasses of this study in Fig. 6. All spectra have been normalized at 0.56 μm in order to minimize the spectra effects due to grain size differences. The glasses produced by these investigators all exhibit higher overall reflectance than the current glasses, but when normalized generally fall between the extremes of this study (G9, G11, and G12) and may show distinct absorption bands depending on fusion conditions. A number of the current glasses (G1, G3, G4, G11, and G12) are more red sloped than previously measured glass spectra. The cause of this is unclear but may be a function of the high ferric : ferrous iron ratios. It should again be noted that ferric iron is virtually absent in lunar samples (Basaltic Volcanism Study Project 1981).

Lunar surface fines, especially from mature areas, may contain over 50% agglutinates (Adams and Charrette 1975a) and their reflectance spectra are only weakly featured if at all (Adams and McCord 1970, 1971b, Nash and Conel 1973, Adam and Charrette 1975b, Pieters and Mustard 1988). Once again their reflectance spectra are generally intermediate between the extremes of this study (Fig. 7) and their range generally matches that of the artificial glasses presented in Fig. 6.
SPECTRAL PROPERTIES OF LUNAR REGOLITH ANALOGUES

Naturally occurring terrestrial basaltic glasses (which normally contain some ferric iron), glasses produced by fusion of lunar material, lunar pyroclastic glasses, and the magnetic fraction of lunar soil are the most readily available analogues to compare with the spectra of lunar impact melt glasses and agglutinates. Terrestrial basaltic glass spectra (Adams 1975) generally fall in the same range occupied by lunar fines and exhibit the expected weak or nonexistent absorption features near 1 and 2 μm. Glasses produced by fusion of lunar samples (Adams and McCord 1971b, Nash and Conel 1973) also closely match the available spectra of naturally occurring lunar basaltic glasses. Lunar pyroclastic glasses and "black spheres" show extreme spectral variability (Adams et al. 1974) with generally resolvable absorption bands. These materials are generally not suitable analogues for impact-produced basaltic glasses but this dissimilarity can be exploited for spectral mapping of their distribution on the lunar surface (Adams et al. 1974). The magnetic fractions of lunar soils are enriched in glasses and agglutinates and they closely resemble the spectra of impact-produced glasses (Adams and McCord 1973). The spectral range of these materials are shown in Fig. 8 along with the spectral extremes of the glasses produced for this study.

The relative importance of each factor which can affect glass spectra, such as fusion time, technique, duration, and starting materials, to lunar spectroscopy is unclear. Lunar surface spectra show differences undoubtedly related to mineralogical variability (e.g., McCord et al. 1981, Pieters 1986). The amount of variability which can be attributed to spectral differences in the nonmineral components is unknown but is probably of secondary importance to mineralogical variations across the surface. The small range of variability seen in lunar soil spectra supports this conjecture and is probably related to the fact that all the soils have been subjected to the same processes of maturation and the same range of impact energies.

REFLECTANCE SPECTRA OF MULTICOMPONENT MINERAL MIXTURES

Most lunar surface spectra show weak absorption bands superimposed on a red continuum slope (e.g., McCord et al. 1981, Lucey et al. 1986, Pieters 1986). Estimates of these continuum slopes are routinely divided out of the spectra in order to isolate mineral absorption bands for analysis. A number of glass-bearing and glass-free mineral mixtures have been spectrally characterized in order to examine the spectrum-altering effects of glass and variations in mineral abundances and compositions and to evaluate two possible approaches to isolating the mineral absorption bands, division of the spectrum by a straight-line segment or by a glass spectrum. A standard mixture (GB1), its glass (G1), and the glass-free equivalent of GB1 (GF1) were produced to serve as a benchmark against which to evaluate the spectral effects of such variations (Table II, Fig. 9).

Ilmenite content variations. The spectral effect of increasing ilmenite content were initially examined in Cloutis et al. (1990). The series has now been expanded to three glass-bearing (GB3–GB1–GB8) and three glass-free (GF3–GF1–GF8) samples (Table II). The pyrox-
ene : plagioclase : glass ratios are the same in each series; ilmenite contents are variable. Sample series in which the absolute abundance of the spectrally dominant phase (OPX) has been kept constant have not been characterized. However, the GB3–GB1–GB8 and GF3–GF1–GF8 series exhibit the smallest variations in absolute orthopyroxene abundance of any three sample sets; consequently these series are best suited to illustrate the spectral changes accompanying ilmenite content variations, while minimizing the spectral changes accompanying orthopyroxene abundance variations. The reflectance spectra of the three glass-bearing samples are shown in Fig. 10 and the glass-free equivalents in Fig. 11. The most noticeable effect of increasing ilmenite content is the decrease in overall reflectance and overall slope for both the GB and GF spectra (Table IV). The spectra of the two lowest ilmenite content sample spectra pairs (GF3 vs GF1 and GB3 vs GB1) show only small differences in reflectance and overall slope probably because the large grain size of the ilmenite (45–90 μm) inhibits effective dispersal of this phase throughout the mixture. A 45–90-μm grain size was used in the mixtures because ilmenite is normally not enriched in the finest fraction (<10-μm grain size) of lunar soils (e.g., Stabin and Taylor 1979, Laul et al. 1987).

The effect of increasing ilmenite content on key spectral parameters can be assessed from the data for GF3, GF1, and GF8 presented in Tables VI and VII. The increase in ilmenite content for these samples (with identical OPX : PLG ratios) appears to have little effect on band minima positions (4 nm maximum variation) and causes a decrease in interband peak position (23 nm), band center positions (5 and 3 nm for bands I and II, respectively) and band depths (11 and 13% for bands I and II, respectively). Band I width is virtually unchanged and band area ratios, both uncorrected and after straight-line continuum division, exhibit small increases (up to 8 and 4%, respectively).

The glass-free samples GF3, GF1, and GF8 can be used to assess the spectral effects attributable to the addition of glass and the ability to recover silicate absorption features. The relative accuracy of dividing a glass-bearing spectrum by a straight-line continuum versus division by the corresponding glass spectrum can be assessed by determining which of these two approaches more accurately reproduces the various spectral parameters of the glass-

FIG. 9. Absolute reflectance spectra of a glass-free mixture (GF1), a glass-bearing mixture (GB1) containing the same proportions of pyroxene : plagioclase : ilmenite and 25 wt% glass, and the glass (G1) produced from a starting mixture identical to GF1. The various proportions of minerals and glass are provided in Table II.

FIG. 10. Absolute reflectance spectra of three glass-bearing mixtures containing identical pyroxene : plagioclase : glass ratios and increasing ilmenite contents: GB3 (0% ilmenite), GB1 (5% ilmenite), and GB8 (20% ilmenite).

FIG. 11. Reflectance spectra of three glass free mixtures containing identical pyroxene : plagioclase : glass ratios and increasing ilmenite contents: GF3 (0% ilmenite), GF1 (6.7% ilmenite) and GF8 (25.3% ilmenite).
### Table VI

<table>
<thead>
<tr>
<th>Sample</th>
<th>Band minima</th>
<th>Interband peak</th>
<th>Band centers</th>
<th>Band centers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I (µm)</td>
<td>II (µm)</td>
<td>I (µm)</td>
<td>II (µm)</td>
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<td>0.977</td>
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<td>2.254</td>
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**Glass-bearing (GB) samples**

<table>
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<th>Interband peak</th>
<th>Band centers</th>
<th>Band centers</th>
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</thead>
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<td>I (µm)</td>
<td>II (µm)</td>
<td>I (µm)</td>
<td>II (µm)</td>
</tr>
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<td>0.925</td>
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<td>0.935</td>
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<tr>
<td>GF3</td>
<td>0.923</td>
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<td>1.368</td>
<td>0.937</td>
</tr>
<tr>
<td>GF8</td>
<td>0.922</td>
<td>1.950</td>
<td>1.345</td>
<td>0.932</td>
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<tr>
<td>GF11</td>
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<td>1.947</td>
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<td>0.936</td>
</tr>
<tr>
<td>GF12</td>
<td>1.020</td>
<td>2.298</td>
<td>1.731</td>
<td>1.039</td>
</tr>
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</table>

**Glass-free (GF) samples**

**Minerals**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Band minima</th>
<th>Interband peak</th>
<th>Band centers</th>
<th>Band centers</th>
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<tbody>
<tr>
<td></td>
<td>I (µm)</td>
<td>II (µm)</td>
<td>I (µm)</td>
<td>II (µm)</td>
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<tr>
<td>PYX032</td>
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<td>PLG108</td>
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<td>—</td>
<td>—</td>
<td>1.264</td>
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<tr>
<td>OLV003</td>
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<td>—</td>
<td>—</td>
<td>1.059</td>
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</tbody>
</table>

*Note.* PYX032, orthopyroxene (OPX); PYX036, clinopyroxene (CPX); PLG108, plagioclase feldspar (PLG); OLV003, olivine (OLV).

*a* No continuum removed.

*b* After division by a straight-line continuum.

*c* After division by the corresponding glass spectrum.

The presence of glass in the GB3, GB1, and GB8 samples causes little change in the band I minimum wavelength positions compared to that seen in the glass-free equivalents; differences do not exceed 2 nm (Table VI). However, the band II minima positions of the glass-bearing samples are consistently lower than those of the corresponding glass-free samples (GB3–GF3, GB1–GF1, GB8–GF8) by up to 19 nm (Table VI). The widths of band I for the GB samples are generally slightly lower than those for the GF samples (Table VII). The presence of glass also leads to an increase in the wavelength position of the interband peak of up to 59 nm (Table VI).

The results of attempts to reproduce the spectral parameters of the glass-free samples through division of the glass-bearing samples by either a straight line continuum or the corresponding glass spectrum are shown in Figs. 12 and 13, respectively, and are tabulated in Tables VI and VII and summarized in Table VIII. Straight-line continuum division of the GB samples provides a better representation of the GF spectra in terms of band I and II center positions, band I depths, band depth ratios, band I widths, and band area ratios. Division of the GB spectra by the glass spectra more closely matches the GF spectra only in terms of band II depths (Table VIII). In general, straight-line continuum divided GB spectra, compared to the GF equivalents, exhibit band II centers at shorter than expected wavelengths and smaller than expected band depths, band depth ratios, band I widths, and band area ratios. The maximum differences for band I centers are small (1 nm maximum); band depths are underestimated by up to 11% (band I) and 19% (band II), and band area ratios by up to 33%. The corresponding maximum differences for the GB spectra after division by the corresponding glass spectra are 11 nm (band I center position), 16% (band I depth), 8% (band II depth), and 45% (band area Ratio). The implications of these differences are that division of a straight-line continuum is generally preferable to division by a glass spectrum although band II centers calculated after straight-line continuum removal will indicate a more iron- and calcium-poor pyroxene than is actu-
### Table VII
Selected Spectral Parameters for the Mineral Mixtures

<table>
<thead>
<tr>
<th>Sample</th>
<th>Band depths&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Band depths&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Band width FWHM (μm)&lt;sup&gt;c&lt;/sup&gt;</th>
<th>Band area ratios (I&lt;sub&gt;L&lt;/sub&gt;/I&lt;sub&gt;0&lt;/sub&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I (%)</td>
<td>II (%)</td>
<td>II/I</td>
<td>I (%)</td>
</tr>
<tr>
<td>GB1</td>
<td>45</td>
<td>53</td>
<td>1.18</td>
<td>41</td>
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<td>GB8</td>
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<td>PLG108</td>
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<tr>
<td>OLV003</td>
<td>39</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

Note. PYX032, orthopyroxene (OPX); PYX036, clinopyroxene (CPX); PLG108, plagioclase feldspar (PLG); OLV003, olivine (OLV).

<sup>a</sup> After division by a straight-line continuum (SL).

<sup>b</sup> After division by the corresponding glass spectrum (GL).

<sup>c</sup> Full width of band 1 at point halfway between the point of minimum reflectance and a straight-line continuum tangent to the reflectance spectrum on either side of the absorption feature (see Fig. 2 for details).

<sup>d</sup> No continuum removed (NC).

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**Fig. 12.** The spectra of glass-bearing samples GB3, GB1, and GB8 after division of each by a straight-line continuum tangent to the spectra on either side of the absorption feature near 1 μm. The spectra have been normalized to 1 at 0.56 μm.

**Fig. 13.** The spectra of glass bearing samples GB3, GB1, and GB8 after division of each spectrum by its corresponding glass (GB3/G3, GB1/G1, and GB8/G8). The spectra have been normalized to 1 at 0.56 μm.
### TABLE VIII
Comparisons of Glass-bearing to Glass-free Sample Spectral Parameters:
Straight-line Continuum Division Versus Glass Spectrum Division

<table>
<thead>
<tr>
<th>Sample pair</th>
<th>Band centers&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Band depths</th>
<th>Band depth</th>
<th>Band I width&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Band area ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td>GB1-GF1</td>
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</tr>
<tr>
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<td>SL</td>
<td>SL</td>
<td>SL</td>
<td>SL/GL</td>
<td>SL</td>
</tr>
<tr>
<td>GB5-GF1</td>
<td>SL</td>
<td>SL</td>
<td>SL</td>
<td>SL</td>
<td>SL</td>
</tr>
<tr>
<td>GB6-GF1</td>
<td>SL</td>
<td>SL/GL</td>
<td>SL</td>
<td>SL</td>
<td>SL</td>
</tr>
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<td>GB8-GF8</td>
<td>SL</td>
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<td>SL</td>
<td>SL/GL</td>
<td>SL</td>
</tr>
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<td>GB9-GF9</td>
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<td>GL</td>
<td>SL/GL</td>
<td>SL</td>
</tr>
<tr>
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<td>SL</td>
<td>SL</td>
<td>GL</td>
<td>SL</td>
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<td>GB11-GF11</td>
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<tr>
<td>GB12-GF12</td>
<td>SL</td>
<td>SL</td>
<td>SL</td>
<td>SL</td>
<td>SL</td>
</tr>
</tbody>
</table>

<sup>a</sup> Comparison to the GF samples with a straight-line continuum divided out.

<sup>b</sup> Full width of band I at point halfway between the point of minimum reflectance and a straight-line continuum tangent to the reflectance spectrum on either side of the absorption feature.

<sup>c</sup> No continuum removed from GF spectra.

<sup>d</sup> After division of GF and GB spectra by straight-line continua.

---

In a previous work (Cloutis and Gaffey 1991), the smaller than expected band depths after straight-line continuum removal were indicative of less mafic silicates or finer grain sizes than are actually present (Adams and Filice 1967).

**Olivine abundance variations.** Samples GF9 and GB9 contain 57.1 and 50% olivine, respectively, and can be compared to GF10 and GB10, respectively (0% olivine) as the two GF and two GB samples contain identical plagioclase : ilmenite : glass ratios (Table II). The spectra are shown in Fig. 14. The substitution of olivine for pyroxene results in a number of measurable spectral changes. The olivine-bearing sample spectra GF9 and GB9 exhibit higher overall reflectance and less red sloped spectra than GF10 and GB10 (Table IV).

The presence of olivine in GF9 and GB9 results in increases in band I minima and interband peak positions relative to GF10 and GB10 (up to 55 and 195 nm, respectively, Table VI). Because olivine possesses no absorption band in the 2 µm region and is more weakly absorbing than pyroxene, band depths, band depth ratios, and band area ratios are less for GF9 and GB9 than for GF10 and GB10 (Table VII). The presence of olivine also results in an increase of up to 0.09 µm in the width of band I in both the GB and the GF samples (Table VII).

The presence of 12.5% glass in GB9 compared to 0% in GF9 has no effect on the position of the band I minimum, whereas the band I1 minimum and the interband peak are shifted to shorter wavelengths due to the addition of glass (1.942 µm vs 1.947 µm and 1.493 µm vs. 1.499 µm, respectively). The difference between GB9 and GF9 is greater for the band I1 center (12 nm) than for the band I center position (1 nm) (Table VI). Band depths, band depth ratios, and band I width are also reduced due to the presence of the glass in GB9 compared to GF9 (Table VII).

Comparisons of straight-line continuum division to glass spectrum division for GB9 indicate that the former more accurately reproduces the GF9 values in terms of band center positions and band I depth and width. Glass spectrum division is more accurate for determining band II depth, band depth ratio, and straight-line continuum removed band area ratio of GF9 (Table VIII).

**Pyroxene abundance variations.** The spectral effects arising from changes in pyroxene abundance can be assessed by comparing spectra GF10 to GF1 and GB1 to GB1 (Fig. 15). Sample GF1 contains 66.7% orthopyroxene and GF10 contains 85.7% orthopyroxene; plagioclase : ilmenite ratios are the same in all four samples. The GF10 spectrum exhibits lower absolute reflectance than GF1 (Table IV) due to its higher abundance of orthopyroxene and lower plagioclase abundances (Table II). The GB1 spectrum has shallower bands I and II than GB10 (Table VII) and roughly the same overall reflectance (Fig. 15).

Comparisons of the GF10 spectrum to that of GB10 indicates that the presence of 12.5% glass in the latter causes small shifts in the band I (2 nm) and band II (6 nm) minima positions and an increase in the wavelength position of the interband peak by 79 nm. The band center wavelength positions of the two samples (after division by straight-line continua) results in band centers equal to
(band I) or displaced 6 nm from (band II) the GF10 values. Division of the GB10 spectrum by the G10 spectrum results in band positions which differ by 10 nm (band I) and 19 nm (band II) from GF10 (Table VI).

The presence of glass in the GB10 sample also causes small reductions (5–7%) in band depths relative to GF10 after straight-line continuum removal although band depth ratios are similar (1.17 vs 1.19; Table VII). Division of GB10 by G10 results in a slightly greater reduction in band depths relative to GF10 (7–8%). Straight-line continuum removal from GB10 also results in a closer match to the band I width of GF10 than does glass spectrum division (Table VII). Straight-line continuum division from GB10 provides a better match to the GF10 values for band center positions, band depths, and band I width than does division of GB10 by G10 (Table VIII).

**Plagioclase abundance variations.** The effect of increasing plagioclase content (and decreasing absolute orthopyroxene abundance) can be seen by comparing spectra GF1 to GF11 and GB1 to GB11 (Fig. 16). Pyroxene : ilmenite : glass ratios are identical for each pair (Table II). The increase in plagioclase abundance does not dramatically affect the overall shape of the spectra which is dominated by pyroxene as expected (Nash and Conel 1974, McFadden and Gaffey 1978, Crown and Pieters 1987). Overall reflectance of the plagioclase-rich mixture spectra (GF11 and GB11) are higher and they are less red sloped than GF1 and GB1 (Table IV). Comparisons of GF11 to GF1 and GB11 to GB1 indicate that the addition of plagioclase has a greater effect on the band I and band II minima positions of the GB spectra (differences of 2 and 7 nm, respectively) than the GF spectra (differences of 0 and 1 nm, respectively, Table VI). Since band position differences of 3 nm or greater are considered significant, only the band II minimum wavelength positions of the

![Figure 14](image14.png)  
**Figure 14.** Reflectance spectra of glass-bearing samples GB9 and GB10 and glass-free samples GF9 and GF10 illustrating the spectral variations arising due to increasing olivine content at the expense of orthopyroxene. Plagioclase : ilmenite : glass contents are identical between GB9–GB10 and GF9–GF10. See Table II for the phase abundances in each sample.

![Figure 15](image15.png)  
**Figure 15.** Reflectance spectra of glass-bearing samples GB1 and GB10 and glass-free samples GF1 and GF10 illustrating the spectral variations arising due to increasing orthopyroxene content. Plagioclase : ilmenite : glass contents are identical between GB1–GB10 and GF1–GF10. See Table II for the phase abundances in each sample.
GB spectra appear to have been significantly affected. Interband peak positions also shift to higher wavelengths by up to 33 nm with the increase in plagioclase content. Band centers show greater variation between GB1 and GB11 than between GF1 and GF11, probably due to the spectral differences of the respective glasses.

The spectral effects of glass on the plagioclase-rich mixtures can be assessed by comparing GB11 to GF11. The position of the band I minimum is not significantly changed (0.924 μm vs 0.925 μm), the band II minimum is shifted to shorter wavelengths (1.920 μm vs 1.947 μm) and the interband peak is shifted to longer wavelengths (1.428 μm vs 1.384 μm). Band depths, band depth ratio, band I width, and band area ratio are greater for GF11 than GB11 (Tables VI and VII).

The effect of straight-line continuum division from GB11 versus division of GB11 by the glass spectrum G11 indicates that the former provides a more accurate match to the GF11 spectrum in terms of band II center position, band depth ratio, and band area ratio. Glass spectrum division provides more accurate values for band depths (Table VIII). Both approaches show little difference in terms of reproducing the band I center position and width although the glass spectrum division method provides slightly more accurate values for these parameters (Tables VI and VII).

**Pyroxene compositional variations.** Examining the substitution of clinopyroxene for orthopyroxene is relevant to remote sensing mapping of mafic silicate variations on the lunar surface. The reflectance spectra of two glass-free and glass-bearing mixtures containing identical amounts of either an orthopyroxene (GF1 and GB1) or a clinopyroxene (GF12 and GB12) are shown in Fig. 17. The effect of the pyroxene substitution is to alter key spectral parameters such as band positions, depths, areas, widths, and overall reflectance (Tables IV, VI, and VII). These variations are readily apparent in Fig. 17 and are useful for deriving compositional information.
The glass present in GB12 results in both band minima being shifted to shorter wavelengths relative to GF12 (Table VI). The interband peak position is shifted to a longer wavelength by the addition of glass (1.739 μm vs 1.731 μm). The GB12 and GF12 band centers, after straight-line continuum removal, differ by 3 nm (band I) and 9 nm (band II). The addition of glass also results in a reduction in band depths, band depth ratio, and band area ratio and an increase in band I width (Table VII).

After division of the GB12 spectrum by a straight-line continuum or the corresponding glass spectrum (G12), the straight-line continuum divided GB12 spectrum more closely resembles GF12 in terms of band center positions, band I depth, band depth ratio, band I width, and band area ratio. The glass spectrum divided GB12 spectrum more closely resembles the GF12 spectrum only as measured by band II depth (Table VIII).

Glass abundance variations. The spectrum-altering effects of glass abundance variations were briefly examined in an earlier study (Cloutis et al. 1990). Here the analysis is extended to include the various spectral parameters presented in Tables VI and VII. The effects of increasing glass contents on the spectra of a mafic silicate-bearing mixture are examined in the spectral series GF1 (0% glass), GB1 (25% glass), GB5 (50% glass), GB6 (75% glass), and G1 (100% glass) (Fig. 18). Pyroxene : plagioclase : ilmenite ratios are identical for the first four of these samples (Table II). All the glass-bearing samples contain G1 glass. The result of the increasing glass content is a gradual decrease in overall reflectance and increase in overall slope (Table IV), an overall decrease in band I and band II minima positions (up to 8 and 125 nm, respectively, Table VI), and an increase in interband peak position (up to 208 nm, Table VI) relative to the GF1 spectrum. Some of the decrease in overall reflectance is undoubtedly due to the decrease in plagioclase content which accompanies the increasing glass content. The increase in overall slope cannot be attributed to plagioclase content variations since the 2.5 : 0.5-μm reflectance ratio of plagioclase is 1.08 (Table IV). After division of the spectra (including GF1) by straight-line continua, increasing glass content results in an increase in band I center wavelength position (up to 10 nm) and decreases in band II center wavelength position (up to 62 nm), band I and II depths (up to 24 and 49%, respectively), band depth ratio (up to 50%) and band area ratio (up to 87%) relative to GF1.

Comparison of the most glass-rich sample spectrum (GB6) to GF1 indicates that after division of GB6 by a straight-line continuum, use of the derived band center positions for determining pyroxene composition would result in an overestimation of the combined iron and calcium contents by approximately 5% (band I) and 10% (band II) (Cloutis and Gaffey 1991).

Comparisons of straight-line division to glass spectrum (G1) division from GB1, GB5, and GB6 indicate that straight-line continuum removal better reproduces the band I and band II center positions, band I depth, and band area ratio of GF1 than does glass spectrum division which better reproduces the GF1 band II depth (Table VIII). The results for reproducing the GF1 band depth ratio and band I width favor straight-line continuum removal with the exception of the most glass-rich sample GB6, where glass spectrum division provides a better match to the GF1 values. Overall the results indicate that straight-line continuum removal generally exceeds the accuracy obtained by dividing out the corresponding glass spectrum for almost all of the shorter wavelength (<1.5 μm) spectral parameters listed in Tables VI and VII.

DISCUSSION

The successful production in the laboratory of mafic silicate glasses which possess spectral properties analogous to those of naturally occurring impact-derived lunar glasses and agglutinates depends on a number of factors. The choice of starting materials has a large effect on the spectral properties of the final product when other factors such as fusion time and oxygen fugacity are held constant (Adams and McCord 1971b). Clinopyroxene and plagioclase-rich starting assemblages yield the most red-sloped glasses (Table IV). Ilmenite-, olivine-, and orthopyroxene-rich starting materials yield less red-sloped glasses. The reasons for the wide spectral variability seen in the
glasses are not completely understood at present but are probably related in part to the content of transition series elements. The spectrum of glass G9 produced from an olivine-rich material shows a broad absorption band in the 1-μm region (Fig. 5), suggesting that some glass spectra may indeed exhibit resolvable absorption bands depending on the composition of the precursor materials and particularly fusion techniques.

Spectrally ilmenite is weakly featured compared to mafic silicates such as pyroxene and olivine. Consequently the presence of ilmenite in a mixture containing mafic silicates will not be readily apparent from examination of absorption bands in the 0.3–2.6-μm region. This is evident from the data presented in Tables IV, VI, and VII for the GB3–GB1–GB8 and GF3–GF1–GF8 series. Increasing ilmenite content very effectively reduces overall reflectance (Table IV) but affects band minima and band centers by at most 12 nm, small compared to the variations due to changes in abundances of other minerals. Similarly the band depth and band area ratio variations are not particularly diagnostic of ilmenite content variations. Other techniques such as multivariate spectral analysis and reflectance ratios have been developed which can be used to quantify ilmenite and titanium abundance variations (Charette et al. 1974, Jaumann 1991, Johnson et al. 1991a,b).

The addition of olivine to a pyroxene-bearing mixture produces a number of spectral changes. The most diagnostic are increases in the wavelength positions of the band I minimum and center and interband peak positions, decreases in band depth ratio and band area ratio and an increase in the width of band I. All of these spectral parameters may be potentially useful for developing quantitative relationships to olivine content. Based on previous spectral studies of pyroxene–olivine mixtures (Singer 1981, Cloutis et al. 1986b) the most fruitful shorter wavelength spectral parameters for analyzing olivine content variations involve some combination of band 1 center wavelength positions, band 1 widths, and interband peak positions.

Pyroxene abundance variations measured in the spectral pairs GB1–GB10 and GF1–GF10 indicate that increasing pyroxene content has little effect on band center positions, band 1 width, and band area ratio. The most diagnostic spectral parameter appears to be band depths (Table VII). However, development of this parameter as a quantitative tool will be hampered by the fact that pyroxene grain size variations and glass abundance variations can also affect band depths (e.g., Adams and Filice 1967, Hunt and Salisbury 1970; Table VII). The latter can be identified by its effect on other spectral parameters such as band area ratio and interband peak position. If grain size variations can be independently determined or otherwise compensated for, quantitative determinations of pyroxene abundance variations may be possible.

Detecting the presence of plagioclase in a mafic silicate bearing assemblage in the 0.3–2.6-μm region is difficult when plagioclase abundance is less than ~50% (Adams 1974, Nash and Conel 1974, McFadden and Gaffey 1978, Crown and Pieters 1987). Plagioclase detection is further hampered if the mineral has been subjected to shock, which leads to a reduction in band depth (Adams et al. 1979, Bruckenthal and Pieters 1985) or if its grain size is reduced (Crown and Pieters 1987; Cloutis et al. 1990). Plagioclase mixed with pyroxene most noticeably affects the reflectance spectrum in the region of the interband peak, or reflectance maximum, near 1.4 μm (Table VI). Significant amounts of plagioclase (tens of percent) cause this peak to appear decidedly asymmetric and/or to be shifted to longer or shorter wavelengths. However, these effects can also be associated with the presence of small amounts of olivine. The presence of glass can also cause shifts in the wavelength position of the peak (Adams and McCord 1971b, Cloutis et al. 1990; Table VI). Comparison of the GF1 to the GF11 spectrum (Fig. 16) shows that both exhibit roughly the same amount of asymmetry at the interband peak in spite of the presence of more plagioclase in the latter (26.7% vs 59.3%, Table II). The GB1 sample contains glass as well as less plagioclase than GF11 but its interband peak appears more asymmetric, suggesting more rather than less plagioclase. Band depths and overall slope are generally reduced and overall reflectance increases with increasing plagioclase content (Tables IV and VII); band depth ratios are relatively constant. However, these variations are not uniquely diagnostic of plagioclase content variations. Band depth and overall slope reductions are also characteristic of increasing ilmenite content, whereas overall reflectance increases can be associated with decreasing grain size (Adams and Filice 1967). These observations all serve to illustrate the difficulties associated with reliably identifying plagioclase in lunar spectra in the 0.3–2.6-μm region. Detection and quantification of plagioclase abundances can more successfully be pursued at longer wavelengths (Nash and Salisbury 1991).

Pyroxene compositional variations are best quantified by use of band center wavelength position criteria (Adams 1974, Cloutis and Gaffey 1991) and this approach has been successfully applied to the analysis of lunar surface and sample spectra (e.g., Adams and McCord 1972, McCord et al. 1981, Lucey et al. 1986). The results of this study indicate that of the various spectral parameters examined, band positions are the most diagnostic for assessing pyroxene compositional variations. Band 1 width criteria should also be employed for reducing uncertainties in pyroxene compositional analysis.

The addition of increasing amounts of glass to a mineral mixture (series GF1–GB1–GB5–GB6) affects all the spectral parameters listed in Tables IV, VI, and VII, most
notably band minima and interband peak positions. Since
the goal of most lunar remote sensing programs is to
map compositional and abundance variations of various
minerals, the spectrum-altering effects of the nonmineral
components must be compensated for in order to facilitate
the analysis of the spectral features due to the minerals.
The results of the two approaches used for continuum
removal in this study, division of a glass-bearing mineral
mixture spectrum by a straight-line continuum or by the
spectrum of the glass used in the mixture, have been
summarized in Table VIII. From the data it can be seen
that straight-line continuum division is superior to glass
spectrum division in the majority of the sample pairs for
more accurately reproducing the corresponding glass-free
spectra in terms of band I and band II center wavelength
positions, band I depths, band depth ratios, band I widths,
and band area ratios. Glass spectrum division provides
an overall better match to the glass-free spectra only for
band II depths. Consequently division by a straight-line
continuum can be fruitfully employed for isolating specific
spectral features without recourse to, or knowledge of,
the spectral signature of the nonmineral component(s).
This result generally holds for mixtures with widely varying
end-member abundances and chemistries, glass contents,
and glass spectra.

CONCLUSIONS

The spectral properties of laboratory-produced glasses
seem to be sensitive to parameters such as fusion tech-
niques and initial composition. Variations in these para-
eters can yield glasses which show spectral variations far
in excess of those found for naturally occurring lunar
impact-derived glasses and surface fines. The addition of
glass to a mafic silicate-bearing assemblage results in a
reduction in overall reflectance, band depths, and band
area ratios and a general decrease in band II minimum
wavelength position and increase in interband peak posi-
tion.

The significance of the spectral differences found be-
tween these glasses and naturally occurring samples is
uncertain at present. Laboratory fusion techniques cannot
accurately reproduce the conditions present on the lunar
surface. Prolonged exposure of materials on the lunar
surface may serve to reduce spectral variability through
a number of processes such as selective depletion of more
volatile elements, resulting in materials with much less
spectral variability than the laboratory samples.

Variations in abundances of end members such as py-
roxene and olivine in multicomponent mineral mixtures
can be detected by their effect on spectral parameters such
as band positions, depths, widths, and areas. Variations in
ilmenite and plagioclase abundances are more difficult to
unambiguously identify in the 0.3–2.6-μm region using
these parameters. Consequently other spectral para-
metric, analytical techniques, and/or different wavelength
regions must be employed to reduce uncertainties in these
end member abundances (e.g., Charette et al. 1974, Jau-
mann 1991, Johnson et al. 1991a, b, Nash and Salisbury

The addition of glass to a mafic silicate-bearing mixture
affects all of the spectral parameters presented in Tables
VI and VII (band positions, depths, widths, and areas).
Since most spectral remote sensing studies are concerned
with compositional and abundance variations in the min-
eral phases present, the spectrum-altering effects of the
glass should be compensated for before the mineral ab-
sorption features are analyzed. The data in Table VIII
suggest that even when the spectral signature of the non-
mineral component of a mixture is known, simple division
of a straight-line continuum is better able to reproduce
most of the diagnostic spectral parameters of the mafic
silicates such as band positions, depths, widths, and areas.

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