Composition and exposure age of the Apollo 16 Cayley and Descartes regions from Clementine data: Normalizing the optical effects of space weathering

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Abstract. In order to quantitatively assess the composition of the lunar surface from reflectance spectroscopy, it is necessary to be able to differentiate between the optical effects due to composition and those due to exposure to space weathering processes. Laboratory analyses of returned lunar soils are used to show that limited quantitative compositional information and the exposure age of the lunar surface can be determined using straightforward calculations from remotely acquired reflectance data sampled with a small number of spectral channels. Exposure age, approximated by $I_{FeO}/I_s$ (where $I_s$ is the characteristic ferromagnetic signal from single-domain iron metal), is estimated using a ratio of the reflectance at a wavelength outside of the 1-μm ferrous iron absorption band to the reflectance at a wavelength within the band. The iron plus titanium content of a soil can then be calculated from its $I_{FeO}/I_s$ and reflectance. These combined techniques are applied to Clementine UVVIS multispectral data of the lunar highlands in the vicinity of the Apollo 16 landing site. The $I_{FeO}/I_s$ and FeO+TiO$_2$ contents are calculated for this region. Materials associated with recently formed impact craters and recent and/or ongoing downslope movement are easily detected as nonmature. The FeO+TiO$_2$ content of the Descartes Mountains is found to be 1-2 wt% less than the Cayley plains west of the Apollo 16 landing site. Localized areas of compositional heterogeneity associated with some small impact events are also revealed. A model for normalizing the optical contribution due to exposure to space weathering processes is applied to the Clementine UVVIS data in order to bring the data to an equivalent mature exposure state. This approach allows residual spectral differences between the observed materials to be confidently interpreted as being due to compositional differences alone rather than to differences both of composition and of exposure. The exposure-normalized data reveal that this region of the highlands is characterized by limited large-scale compositional heterogeneity that is detectable by a small number of spectral bandpasses. The Descartes Mountains are identified as being more anorthositic than the Cayley plains units. Most small impacts in the region excavated material compositionally similar to material surrounding them, with the notable exceptions of the impacts that created South Ray Crater and an unnamed crater on the floor of Abulfeda.

Introduction

Visible and near-infrared reflectance spectroscopy has proven to be an important tool for remote compositional analysis of planetary surfaces. Diagnostic absorption bands and the overall character of a spectrum yield important information concerning the mineralogy of a surface [e.g., Burns, 1993]. In the case of the Moon, a variety of principal rock types can be successfully identified with visible and near-infrared spectroscopy [e.g., Pieters, 1986, 1993]. However, compositional determination in terms of quantitative chemistry and mineral abundance has heretofore been limited. The two principal reasons for there being little quantitative compositional interpretation of lunar reflectance spectral data are (1) the difficulty of developing and testing mathematical techniques for deriving such quantitative information, and (2) the absence of a mathematical model for describing how the optical properties of lunar materials are altered by exposure to space weathering processes at the lunar surface such as micrometeorite bombardment.

The optical effects of space weathering include a reduction of reflectance, a reduction of absorption band strengths and the creation and steepening of a red-sloped continuum [Adams and McCord, 1973; Charette et al., 1976; Fischer and Pieters, 1994]. The compositional interpretation of lunar spectral data is thus greatly complicated by the optical effects of space weathering. For example, soils derived from identical lithological sources will exhibit different spectral properties if exposed at the lunar surface for different lengths of time. In order to derive quantitative compositional information from lunar spectroscopic data, it is critical to be able to differentiate between the optical effects due to exposure and those due to composition.

In this study, detailed spectroscopic analyses of returned lunar soils are used to show that limited quantitative compositional information (e.g., iron plus titanium content) and the degree of exposure of the lunar surface can be determined using straightforward calculations from multispectral data. Techniques for deriving this information are then applied to Clementine UVVIS multispectral data of a...
region of the south-central highlands in the vicinity of the Apollo 16 landing site; the exposure state and general compositional character of the region are determined. In addition, to detect more subtle compositional variation in the region, the optical alteration model developed by Fischer [Fischer, 1995; Fischer and Pieters, 1995a] is applied to the Clementine data to normalize the exposure degree of surface materials in the area. This approach allows residual spectral differences between the observed materials to be confidently interpreted as being due to compositional differences alone rather than to differences both of composition and of exposure. Each of the steps taken in this study depends upon data and analyses performed and reported elsewhere. Although these supporting analyses are not duplicated here, the results thereof are summarized and ample references are provided. The thrust of the research presented below is to focus on an important application which integrates these interrelated steps to understand the Apollo 16 region in detail.

Data

Laboratory Measurements of Returned Soils

In the present study, analyses of lunar soil spectral data are used to establish the techniques for deriving key compositional and exposure information from remote measurements. All soils analyzed in this study were measured in bulk form with the RELAB (reflectance experiment laboratory) bidirectional spectrometer at Brown University. Listed in Table 1 are the soils used for these analyses. A standard viewing geometry was employed: an incidence angle of 30° and an emergence angle of 0° with respect to the surface normal. Spectroscopic data were corrected for the non-Lambertian properties of the reflectance standard, Halon.

Clementine UVVIS Multispectral Data

The remotely acquired data used in this study were obtained by the five-channel Clementine UVVIS multispectral camera [Nozette et al., 1994]. The data are from orbit 295 and cover a 220-km (north-south) strip of 14 frame sets (seven sets of long and short exposures) extending from the crater Abulfeda in the south to the Cayley plains west of the Apollo 16 landing site in the north. The mosaicked image strip is shown in Figure 1. The average phase angle for these data is 27°. This region was chosen because it is a fairly homogeneous area thought to be characterized by subtle compositional variation, and is an area for which we have some ground truth in the form of lunar samples. The subtle compositional variations expected to exist within this area provide an excellent test for the spectroscopic techniques described in this paper.

The Apollo 16 landing site itself is just off of the eastern edge of the imagery from this orbit. A portion of South Ray Crater as well as the spectral standard site "Apollo 16B" [Pieters, 1986], however, are present within the data analyzed. The Cayley plains are well-represented in the northern portion of the study area. The Descartes Mountains and the Copernican-aged crater Descartes A fill the central portion of the data strip, whereas the plains deposit filling the large crater Abulfeda makes up the majority of the southern portion of the data analyzed.

The Clementine UVVIS five-color data require extensive processing to produce multispectral image mosaics and spectra for compositional analysis. The steps used to calibrate the UVVIS data are discussed by Pieters et al. [1994, 1995]. Due to improvements in the understanding of the in-flight behavior of the UVVIS instrument, residual filter-to-filter (spectroscopic) errors for the calibrated UVVIS mosaic analyzed here are estimated to be approximately 1%.

Quantitative Assessment of Composition and Exposure from Lunar Reflectance Spectroscopic Data

I$_{5}$/FeO

As noted above, in order to derive accurate compositional information from lunar reflectance spectral data, it is critical to be able to differentiate between the optical effects due to exposure and those due to composition. The first step to achieve this is to calculate the exposure age of an observed soil.

The exposure age of a lunar soil can be approximated by I$_{5}$/FeO [i.e., Morris, 1978]. I$_{5}$ is the characteristic ferromagnetic resonance from submicroscopic (single-domain) iron and FeO is the weight percent FeO of the soil. Submicroscopic iron is produced by space weathering processes such as implantation of solar wind particles and bombardment by micrometeorites. In agglutinates, the iron is dispersed preferentially in the glassy portions [Housley et al., 1973]. The longer a soil is exposed, the more single-domain iron is produced, and thus the higher the value of I$_{5}$/FeO.

Calculation from spectroscopic data. To derive the I$_{5}$/FeO value of a remotely observed soil, we use a modification of the method of Fischer and Pieters [1994]. Fischer and Pieters showed that because of the coupling of band strength and continuum slope in the soil evolution process, a ratio between the reflectance at a wavelength outside of the 1-μm ferrous iron absorption band to the reflectance at a point within the band can be used to distinguish between mature and nonmature highland soils. McEwen et al. [1993] and Fischer and Pieters [1994] discussed the potential for this type of ratio to estimate I$_{5}$/FeO values for nonmature soils as well. Laboratory bidirectional reflectance measurements of soils provide the "ground-truth" basis for such an I$_{5}$/FeO derivation. Shown in Figure 2 is a logarithmic function

Table 1. Soils Used for the I$_{5}$/FeO and FeO+TiO$_{2}$ Analyses

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a Used for FeO+TiO$_{2}$ analysis (Figure 4).
b Used for I$_{5}$/FeO analysis (Figure 2).
c Nonmare soil.
describing the relationship between $I_g/FeO$ (data from Morris et al. [1983] and Fischer [1995]) and the $0.75 \mu m/0.95 \mu m$ ratio for most nonmare lunar soils measured in RELAB (the soils used in this analysis are noted by "b" in Table 1). The $0.75$- and $0.95-\mu m$ values are derived from RELAB bidirectional spectra that have been convolved with the filter bandpasses of the Clementine UVVIS multispectral camera. The function shown by a dashed line in Figure 2 is

$$I_g/FeO = e^{\frac{(1.312-R_{ratio})}{0.093}}$$  \hspace{1cm} (1)

where $R_{ratio}$ is the reflectance at $0.75 \mu m$ divided by the reflectance at $0.95 \mu m$. The multiple correlation coefficient for this function for nonmature soils is 0.95. Because this function does not describe the plateau of ratio values reached by mature soils, we discriminate between mature and nonmature soils by a maximum ratio value for mature soils in Figure 2 (shown by the horizontal dashed line). Values less than 0.915 correspond to mature soils ($I_g/FeO \geq 70$). (Note that we use a value of $I_g/FeO \geq 70$ for optically mature soils [see Fischer, 1995].) Provided that remotely acquired spectra are properly calibrated to laboratory spectroscopic data (which are in this case obtained at an incidence angle of $30^\circ$ and an emergence angle of $0^\circ$), equation (1) and the mature soil cutoff value of 0.915 can be used to estimate $I_g/FeO$. It should be noted, however, that this technique cannot be confidently applied to spectral data for mare and pyroclastic materials [see Fischer and Pieters, 1994].

**Application to Clementine data.** $I_g/FeO$ is calculated for the strip of Clementine UVVIS data in the vicinity of the Apollo 16 landing site using equation (1). A map of $I_g/FeO$ values calculated for this strip is shown in Figure 3. This $I_g/FeO$ calculation technique clearly identifies nonmature material associated with recent impacts as well as with downslope movement. In some cases, the technique reveals small, fresh craters that are not visible as such at the resolution of the UVVIS reflectance (or albedo) data (i.e., the crater labelled A in Figures 1 and 3), and that are even difficult to observe in Apollo Metric photography. Flat-lying material such as the Cayley plains west of the Apollo 16 landing site is characterized generally by $I_g/FeO$ values indicative of mature material, as expected. The most immature crater observed in this area appears to be an unnamed crater on the floor of Abulfeda (location 7 in Figure 1). $I_g/FeO$ values for this crater and immediate surrounding ejecta are in the single digits. $I_g/FeO$ values for South Ray Crater and immediate surrounding ejecta are in the 20s and 30s at the resolution of the UVVIS data.

**Quantitative Compositional Determination**

**Calculation from spectroscopic data.** From a combined analysis of Galileo solid-state imaging system (SSI)
Figure 1. It is apparent that material associated with recent Is/FeO > 70; see Fischer [1995]). By comparing this figure to bar, all materials in black are mature soils (assumed to be calculated as described by equation (1). As shown by the scale used to estimate the aluminum and iron contents of the soil. be derived from remotely acquired data for both mature and/or ongoing downslope movement.

Here, we use spectroscopic and Is/FeO data of returned lunar soils to show that additional compositional information can be derived from remotely acquired data for both mature and nonmature soils. In Figure 4a, natural log of reflectance is plotted versus Is/FeO values for a wide range of lunar soils measured in the laboratory which have been grouped by iron plus titanium content (chemical and Is/FeO data are from Morris et al. [1983] and Fischer [1995]). Although the spectroscopic measurements used to construct Figure 4a (see Table 1) were not performed as a survey of lunar soils, the data set is fairly representative of returned soils. By analyzing the spectral data of both mature and nonmature soils, it is shown in Figure 4a that the reflectance of a soil is related to its iron plus titanium content and Is/FeO value, and thus that if the Is/FeO of a soil is known, the reflectance can be used to calculate composition for soils of any exposure age. The data shown in Figure 4a have been used to produce the general contours in Figure 4b, which describe the variation of reflectance as a function of Is/FeO and FeO+TiO₂ concentration. The function that describes the relationship shown in Figure 4b is

\[
\ln\left[\frac{R_{0.75\mu m} \times 100}{0.000001 \times (I_s/FeO)^2} - 0.000249 \times I_s/FeO - 0.051845\right] = \frac{3.9853 - (0.010266 \times I_s/FeO)}{\text{FeO} + \text{TiO}_2}
\]

(2)

Figure 2. I_s/FeO versus 0.75 μm/0.95 μm reflectance ratio values for most nonmare returned lunar soils measured in RELAB (the soils used in this analysis are noted by "b" in Table 1). From the relationship shown, it is clear that the 0.75 μm/0.95 μm ratio provides the means to estimate I_s/FeO from remotely acquired spectroscopic data. The logarithmic function shown by the dashed line is that used in this study to estimate I_s/FeO for nonmature soils (see equation (1)). The horizontal dashed line indicates the reflectance ratio value used to differentiate between mature and nonmature soils. I_s/FeO data are from Morris et al. [1983] and Fischer [1995].

and Apollo X ray spectrometer data, Fischer and Pieters [1995b] showed that the reflectance of a mature soil could be used to estimate the aluminum and iron contents of the soil. Here, we use spectroscopic and I_s/FeO data of returned lunar soils to show that additional compositional information can be derived from remotely acquired data for both mature and nonmature soils. In Figure 4a, natural log of reflectance is plotted versus I_s/FeO values for a wide range of lunar soils measured in the laboratory which have been grouped by iron plus titanium content (chemical and I_s/FeO data are from Morris et al. [1983] and Fischer [1995]). Although the spectroscopic measurements used to construct Figure 4a (see Table 1) were not performed as a survey of lunar soils, the data set is fairly representative of returned soils. By analyzing the spectral data of both mature and nonmature soils, it is shown in Figure 4a that the reflectance of a soil is related to its iron plus titanium content and I_s/FeO value, and thus that if the I_s/FeO of a soil is known, the reflectance can be used to calculate composition for soils of any exposure age. The data shown in Figure 4a have been used to produce the general contours in Figure 4b, which describe the variation of reflectance as a function of I_s/FeO and FeO+TiO₂ concentration. The function that describes the relationship shown in Figure 4b is

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\]

(2)

Figure 3. A map of I_s/FeO for the Clementine UVVIS strip calculated as described by equation (1). As shown by the scale bar, all materials in black are mature soils (assumed to be I_s/FeO > 70; see Fischer [1995]). By comparing this figure to Figure 1, it is apparent that material associated with recent impacts is clearly identified as nonmature by this method. Some slopes are also identified as nonmature because of recent and/or ongoing downslope movement.
Bidirectional reflectance calibrated as described by Pieters et al. [1994], Is/FeO is <_70 (the Is/FeO of mature soils is set to where R0.751_tm is the reflectance at 0.75 µm (absolute relationship between natural log reflectance and Is/FeO (a proxy for exposure age) is consistently describable at all ultraviolet to near-infrared wavelengths is an important feature of a model that attempts to describe the systematics of mathematical modeling of the effects of exposure on the spectroscopic properties of lunar soils has shown that the relationship between natural log reflectance and Is/FeO (a proxy for exposure age) is consistently describable at all wavelengths by a single type of mathematical function. The same is not necessarily true of reflectance versus Is/FeO. A mathematical function that is consistent over at least the wavelengths by a single type of mathematical function. The ultraviolet to near-infrared wavelengths is an important feature of a model that attempts to describe the systematics of exposure-related optical alteration. See Fischer [1995] for a more detailed discussion.

Using laboratory measurements of Is/FeO for the soils listed in Table 1, the multiple correlation coefficient for actual versus calculated values of FeO+TiO2 is 0.97. Iron plus titanium values are estimated to within ±1 to 2 wt% using equation (2). Note that the reflectance data used in equation (2) are for a phase angle of 30°. As for all reflectance-dependent parameters, changes in phase angle and/or surface topography may affect the calculated FeO+TiO2.

Application to Clementine data. The reflectance observed and the Is/FeO values calculated for the Clementine data strip (Figure 3) were used in conjunction with equation (2) to calculate the weight percent FeO+TiO2 for the study area, shown in Figure 5. The flat-lying Cayley plains including the material filling the large impact crater Abulfeda in the south are found to be more iron and titanium rich than the Descartes Mountains material. This is consistent with several reinterpretations of returned soils from the Apollo 16 site. Material collected at the Apollo 16 site that has been interpreted as Cayley plains is characterized by slightly higher iron plus titanium contents (by approximately 1 wt%) than the light, friable material thought to be derived from the Descartes Mountains [Adams and McCord, 1973; Ulrich and Reed, 1981; Wilshire et al., 1981; Housk, 1982a, 1982b; Morris et al., 1983]. The relatively feldspathic character of Descartes material observed in Clementine is also supported by results from the Apollo X ray and gamma ray spectrometers [e.g., Andre and El-Baz, 1981; Metzger et al., 1981]. Consistently higher iron plus titanium values for the Abulfeda-filling material in the south suggest that this material may be somewhat more mafic than the Cayley plains to the west of the Apollo 16 site. The material in Abulfeda may in fact be relatively mafic impact melt breccia.

Because this technique for calculating the iron plus titanium content relies upon reflectance, and because the effects of topography upon reflectance have not been removed from the data, sunlit and shadowed slopes appear to be less and more iron- and titanium-rich, respectively, than they actually are. For example, sunlit crater walls appear to have less iron and titanium because of their higher reflectance. These sunlit and shadowed regions result in calculated iron plus titanium concentrations that tend to cluster in the <2.0 and >6.0 wt% ranges, respectively. Material plotting in these concentration ranges in Figure 5 should thus be viewed with caution if associated with topographic features. On the other hand, there do appear to be small areas in these concentration ranges that are likely to be, in fact, characterized by material of these compositions. For example, the fresh crater in the plains filling Abulfeda (location 7 in Figure 1) appears to be more mafic relative to surrounding materials. Bright material immediately to the south of Descartes A appears to be somewhat more anorthositic than the bulk of the material comprising the Descartes Mountains.

In general, however, as expected there is not a great deal of large-scale compositional heterogeneity in this region. By using the optical alteration model described by Fischer [1995] and Fischer and Pieters [1995a], compositionally related color differences can be detected which may be indicative of more subtle compositional heterogeneity. This is discussed in the next section.

Lucey et al. [1995] presented a somewhat different method for estimating the iron content of lunar soils using similar optical data (0.75-µm reflectance and the 0.95 µm/0.75 µm
color ratio). The Lucey et al. approach derives an empirical optical parameter, $\theta$, which is then correlated with the iron content of lunar samples. In contrast, one major advantage of the approach taken here is the direct calculation of the easily recognized exposure parameter $I_g/FeO$. Iron abundance is then derived separately from soil maturity issues. Both approaches are limited by sample information available, of course, and neither is accurate for mare regions. Lucey et al. ignore the often dominating effect of widely varying amounts of opaque minerals (e.g., ilmenite) in mare soils on reflectance and spectral contrast -- spectral parameters which directly affect their calculation of $\theta$ and FeO. Thus the calculation of mare soil FeO content using both the Lucey et al. method and the method developed herein should be viewed with caution. Applying the Lucey et al. method to the Apollo 16 Clementine data (assuming proper calibration of reflectance) produces general results which agree with those found using the technique described here.

Normalizing the Exposure Age

In order to accurately assess the compositional variation of lunar materials using spectroscopic methods, the optical effects of exposure must be removed or normalized. Only for materials that have been exposed at the lunar surface for equivalent lengths of time is it possible to interpret spectral differences between the materials as due to compositional differences alone. For example, to compare the spectra of a fresh impact crater and mature surrounding material in terms of compositional differences, the two spectra must be brought to the same degree of exposure. Otherwise, the spectral differences between the two observed materials will be the result of a combination of compositional and exposure differences.

The optical alteration model. A mathematical model has been developed which provides the means to calculate the spectrum of a soil at any $I_g/FeO$ from an observed spectrum of a soil of any other exposure age (of equivalent composition) [Fischer, 1995; Fischer and Pieters, 1995a]. That is, compositionally related spectral properties of diverse soils can be directly compared by using the model to evolve the spectra to the same exposure state.

The model was derived by quantifying the spectral dependence upon exposure of four carefully selected suites of lunar soils. It was found that the spectral properties of all soil types are altered in the same fashion, but at different rates. The rate of optical alteration is a function of the iron plus titanium concentration of the soil. Given the spectrum of a soil and estimations of $I_g/FeO$ and the iron plus titanium concentration of that soil, the model can be employed to calculate the spectrum of the soil at any desired exposure age.

Figure 5. The weight percent FeO+TiO$_2$ for the Clementine UVVIS strip calculated using equation (2). The Descartes Mountains and Cayley plains are characterized by subtly different compositions. This is corroborated by Apollo X ray and gamma ray data as well as by several interpretations of samples returned from the Apollo 16 site. Most materials in the <2.0 and >6.0 wt% ranges plot in these ranges because of topographic effects (i.e., sunlit slopes of craters) and not due to true compositional differences. Nevertheless, there are small areas in these compositional ranges that likely do, in fact, reflect compositions unique for much of this region (see text).
Application to Clementine data. The optical alteration model of Fischer [1995] and Fischer and Pieters [1995a] was applied to the Clementine study area to calculate five-color spectra from the UVVIS camera as they would appear at a mature state. Shown in Plate 1a is a color ratio composite of the study area before the model was applied. In this color composite, the 0.75 μm/0.41 μm ratio is shown in red, the 0.75 μm/0.95 μm ratio is shown in green, and the 0.41 μm/0.75 μm ratio is shown in blue. This color-ratio scheme has commonly been used to illustrate general compositional variations in multispectral data [e.g., Belton et al., 1992, 1994; Pieters et al., 1994; McEwen et al., 1994]. In this color scheme, bright blue corresponds to nonmature feldspathic material, whereas duller blue indicates more heavily exposed, relatively anorthositic material. Bright green corresponds to freshly exposed, relatively more mafic material, whereas red indicates mature material that is slightly less feldspathic than the dull blue material.

Plate 1. (a) Color-ratio composite of the Clementine UVVIS strip before the optical alteration model was applied. The 0.75 μm/0.41 μm reflectance ratio is shown in red, the 0.75 μm/0.95 μm ratio in green, and the 0.41 μm/0.75 μm ratio in blue. In this color scheme, bright blue corresponds to nonmature feldspathic material, duller blue to more extensively exposed relatively anorthositic material, bright green to nonmature relatively mafic material, and red to mature material that is slightly less feldspathic than the dull blue material. (b) Color ratio composite after the optical alteration model was applied to normalize the data to a mature exposure state. The same image stretches are used here as for Plate 1a. The numbered boxes mark the locations of spectra shown in Figure 6.
Shown in Plate 1b is the color ratio composite (with the same red, green, and blue channel stretches) after the optical alteration model has been applied to bring all areas to an equivalent mature exposure state. The color differences in Plate 1b represent what residual color differences there would be if all of the soils in the region were at a mature state. In Figures 6a and 6b are shown seven representative spectra before and after, respectively, the model was applied to the UVVIS data. The locations of the spectra in Figure 6 are shown in Figure 1 and Plate 1 by the numbered boxes. The color information in Plate 1 and the associated five-channel spectra in Figure 6 together provide information for the compositional interpretation of this region.

The pervasively red unit of this portion of the south-central highlands revealed in Plate 1b indicates there is very little compositional heterogeneity on the whole (that is detectable by a limited number of spectral bandpasses), and also indicates that the overall composition of the region is feldspathic, as expected. Nevertheless, there are a few regions in which subtle compositional differences are noted. For example, the Descartes Mountains, on the whole, map as relatively bluer than the Cayley plains in the north and south. This suggests a relatively more anorthositic character for the Descartes region, consistent with the iron plus titanium concentrations calculated in the previous section (see Figure 5).

Spectrum 1 in Figure 6 is a typical spectrum for the Cayley plains and is also the telescopic standard area "Apollo 16B." (Mature Apollo 16 soil 62231 is used as the reference spectrum for this site.) Spectrum 3 is that of a submature crater in the Cayley plains. The exposure-normalized spectrum of this crater in Figure 6b is almost identical to that of spectrum 1, indicating this crater excavated only the Cayley plains material upon which it lies. Spectrum 4 is typical of the rough Descartes Mountains terrain. The exposure-normalized Descartes Mountains spectrum in Figure 6b is clearly brighter than the Apollo 16B Cayley plains spectrum 1 and may perhaps also be characterized by a slightly shallower 1-μm ferrous iron absorption band. The small number of spectral bandpasses of the UVVIS camera, however, does not allow detailed assessment of the character of the 1-μm band. The purplish region south of Descartes A (Plates 1a and 1b) is indicative of soils that are more anorthositic than the bulk of the Descartes Mountains, which is consistent with the FeO+TiO2 results illustrated in Figure 5. A spectrum of this region (spectrum 5 in Figure 6) supports this interpretation in the sense that it is brighter than the Descartes Mountains spectrum 4 and is characterized by a 1-μm band that is at least as shallow.

This region of the south-central highlands is generally uniform in color after the optical alteration model is applied. As indicated by the uniformity of color in the vicinity of (formerly) fresh craters in Plate 1b, most small fresh craters appear to have excavated material similar to the more mature material surrounding them (i.e., the crater labelled B in Plate 1). Possible exceptions include South Ray Crater, which, given its blue color in Plate 1b and the spectrum of its distal ejecta in Figure 6 (spectrum 2), appears perhaps to have excavated material more feldspathic than the typical Cayley plains in the immediate vicinity. The exposure-normalized spectrum of the distal ejecta (spectrum 2 in Figure 6b) is similar in brightness to the Descartes Mountains spectrum 4 and is characterized by a 1-μm band that appears to be slightly shallower than that of Apollo 16B spectrum 1. This observation of relatively anorthositic South Ray Crater ejecta may support the suggestion of an unusually aluminous source of the dimict breccias excavated by the South Ray impactor [e.g., Eugster et al., 1995].

The unnamed fresh crater on the floor of Abulfeda appears to have excavated material somewhat more mafic than the surrounding plains, given its yellow color in Plate 1b and

![Figure 6](image-url)
spectrum in Figure 6 (spectrum 7). Of all the exposure-normalized spectra in Figure 6b, the spectrum of this fresh crater is the most unique. The 1-µm band is clearly stronger than any other spectrum, even relative to the surrounding plains (spectrum 6). The spectrum of the unnamed fresh crater is also flatter and darker, consistent with a relatively more mafic character. The presence of craters such as that on the floor of Abulfeda indicate that although this region of the highlands is characterized by somewhat limited compositional heterogeneity on a large scale, there are nevertheless significant areas of localized compositional heterogeneity.

The walls of the two large craters in the Descartes Mountains, Descartes A and Dollond, appear bluer than the Descartes Mountains material in Plate 1b. This may indicate more feldspathic material on the walls or, more likely, may indicate an effect of the incidence angle and/or limitation of the UVVIS data calibration that are conspiring to make the crater walls appear blue. The weak blue "rings" around many of the small craters in Plate 1b are an artifact of the lower spatial resolution of the 0.41-µm data with respect to the other channels. They are not indicative of compositional variations.

Conclusions

A straightforward multispectral technique involving the ratio of the reflectance at a wavelength outside of the 1-µm ferrous iron absorption band to the reflectance at a wavelength within the band makes it possible to calculate the exposure age, as approximated by I_s/FeO, from remotely acquired data of material of nonmare compositions. Given I_s/FeO, reflectance data can be used to calculate the iron plus titanium content of the lunar surface. These techniques have been successfully employed to calculate I_s/FeO and the FeO+TiO_2 content from Clementine UVVIS data of a region of the south-central highlands in the vicinity of the Apollo 16 landing site. The Descartes Mountains are found to be characterized by approximately 1 to 2 wt% less iron plus titanium than Cayley plains material in the region. This is consistent with several interpretations of samples returned from the Apollo 16 landing site.

The optical alteration model developed by Fischer [Fischer, 1995; Fischer and Pieters, 1995a] has been used to normalize the exposure state of the materials in the Clementine UVVIS study area. This allows residual spectral differences to be confidently interpreted as due to compositional differences alone rather than to differences both of composition and of exposure. The exposure-normalized data of the Apollo 16 highlands region analyzed indicate that, on a large-scale, there is a small amount of compositional heterogeneity detectable by a limited number of spectral bandpasses. The Apollo 16 Cayley and Descartes materials are quite feldspathic, the Descartes Mountains being somewhat more anorthositic than the Cayley plains. Most small craters in the region excavated material compositionally similar to that surrounding them, with the most notable exceptions being South Ray Crater, which excavated relatively more anorthositic material, and an unnamed crater on the floor of Abulfeda, which excavated relatively more mafic material. The presence of diverse material at these craters indicates the existence of localized areas of compositional heterogeneity in this region of the highlands.

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