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Discrimination between maturity and composition of lunar soils from integrated Clementine UV-visible/near-infrared data: Application to the Aristarchus Plateau

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Abstract. The reflectance spectrum of a lunar soil is mainly dominated by the composition and the degree of exposure to space weathering processes such as micrometeorite bombardment and solar wind implantation. The spectral alteration effects of space weathering should be removed for accurately investigating the composition of the lunar surface using remote sensing data. In this paper we show that the integration of the Clementine UV-visible (UVVIS) and near-infrared (NIR) channels provides an improved evaluation of the spectral alteration. The depth of the mafic absorption feature at 0.95 μ m is also better defined by combining the UVVIS and NIR data. Laboratory spectra of lunar soil samples indicate that the continuum slope derived from the 1500/750 nm ratio is closely related to the concentration of fine-grained submicroscopic iron (Is). The continuum slope therefore provides an evaluation of the spectral alteration of the surface, which can be subtracted from the 1 or 2 μ m absorption band depths to retrieve compositional information. This method has been applied to the Aristarchus plateau, which exhibits a broad range of mineralogical composition and maturity. A nine-channel multispectral mosaic of 680 Clementine images of the Aristarchus plateau has been processed. Eight telescopic spectra have been used to check the validity of the reduction process for the near infrared bands. The 1 μ m absorption band, once corrected for spectral alteration, provides an evaluation of the initial FeO content in mafic silicates (mafic iron). Lunar soil samples show that it is possible to quantitatively map mafic iron with this technique. Our results are in good agreement with those obtained using the algorithm of Lucey et al. [1995, 1998a], which is based on UVVIS bands alone. The mafic iron content and total iron content which can be derived from the combined UVVIS and NIR data sets are less sensitive to local slopes than that derived from Lucey et al.'s method. This new method could therefore be useful for investigating areas at middle to high latitudes. Removing spectral alteration from the 2000/1500 nm ratio also makes possible a better discrimination between olivine and pyroxene within identified mare basalts on the Aristarchus plateau.

1. Introduction

The Clementine spacecraft has provided an almost global coverage of the lunar surface in 11 wavelengths, which were chosen for their mineralogical interest. The UV-visible (UV-VIS) camera had five filters from 415 nm to 1000 nm, which are calibrated at the 1% level [Nozette et al., 1994; McEwen et al., 1998]. The scientific exploitation of UVVIS data has led to several important steps toward the comprehension of the lunar mineralogy. For instance, empirical methods using

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Paper number 1999JE001196. 0148-0227/00/1999JE001196\$09.00 UVVIS bands at 415, 750, and 950 nm have been developed to derive compositional global maps of the lunar surface for FeO and TiO₂ [*Lucey et al.*, 1995, 1998a]. The near-infrared (NIR) camera had been designed to complement the spectral coverage of the UVVIS camera. NIR bands at 1100 nm and 1250 nm provide the long-wavelength side of the ferrous 1 μ m feature (mafic minerals). Plagioclase, which is a major constituent in the lunar crust, has a weak absorption feature at 1250 nm if it has a little iron and is unshocked. The NIR band at 1500 nm represents the best estimate for the continuum of the spectra in the infrared domain. The 2000 nm band is useful to discriminate between olivine and pyroxene within identified mare basalts.

Unfortunately, calibration problems have delayed the scientific interpretation of the NIR data set. They are mainly due to a large varying dark frame signal and to uncertainties on gain and offset values [*Lucey et al.*, 1997, 1998b; *Priest et al.*, 1995]. Independently of the calibration effort for the full NIR data set, we developed a heuristic method to reduce NIR data in restricted areas of the Moon [*Le Mouélic et al.*, 1999a]. This method relies on the high correlation between well-calibrated UVVIS bands and NIR bands.

In this study we focus our analysis on the Aristarchus plateau. This area has been selected for its relevance to lunar surface composition and evolution. Several previous studies have revealed the heterogeneity of this part of the Moon [Zisk et al., 1977; Lucey et al., 1986; McEwen et al., 1994; Hawke et al., 1995; Pinet et al., 1996]. The Aristarchus plateau presents a wide range of typical lunar terrains such as mare basalts, highland type materials, and dark mantle deposits. Its high diversity makes it a very interesting area for testing new multispectral approaches to composition issues.

In this paper we show that the integration of UVVIS and NIR data gives the opportunity to investigate spectral parameters such as the continuum slope and the mafic absorption band depths at 1 μ m and 2 μ m. These spectral parameters are directly related to the mineralogy and the physical state of the surface materials [e.g., Adams, 1974]. After presenting the reduction of the data, we show the effects of maturity on extracted spectra. Then we discuss the improved evaluation of the 1 μ m absorption band depth provided by the integration of NIR channels and the new opportunity to investigate the continuum slope of the spectra with Clementine data. We then use spectra of laboratory samples to show the close relationship between the continuum slope and the concentration of fine grained iron (Is) already noticed by Hiroi et al. [1997]. The continuum slope can be used to correct the 1 μ m band depth from spectral alteration effects. We then assess the relationship of the corrected 1 μ m band depth with the FeO content. These results are compared with the algorithm of Lucey et al. [1998a]. Laboratory spectra of lunar soil samples are used to demonstrate that it is possible to quantitatively map iron with this method. Finally, the 2000/1500 nm ratio is corrected for spectral alteration effects to investigate the presence of olivine-rich areas.

2. Integration of UVVIS and NIR Data on the Aristarchus Plateau

We selected 680 Clementine UVVIS and NIR images from orbits 53 to 56 and 186 to 188 to compute a multispectral data cube covering the Aristarchus Plateau. UVVIS images at 415, 750, 900, 950, and 1000 nm were calibrated using the U.S.Geological Survey ISIS software [*McEwen et al.*, 1998]. We applied the reduction method described by *Le Mouélic et al.* [1999a] to reduce the NIR data. NIR images at 1100, 1250, 1500, and 2000 nm were selected according to their mineralogical interest. NIR images at 2600 nm and 2780 nm were not processed because they are suspected to be affected by thermal-emitted light and because the telescopic spectra used for calibration can not extend beyond 2.5 μ m. NIR instrumental modes (offset, gain, and exposure time) remain constant for each of the bands within the

two sets of orbits. NIR images were coregistrered to the UVVIS 750 nm image by using a rotation of 1.7° and by applying a dilatation factor. The UVVIS image at 1000 nm was used as a reference for a first order evaluation of the NIR offsets. As explained by Le Mouélic et al. [1999a], the offset evaluation exploits the high degree of correlation between UVVIS and NIR images. This method is valid when topographic shading dominates the signal variations. However, P. G. Lucey (personal communication, 1999) pointed out that the offset evaluation is systematically drifted toward high values at low phase angles when maturity variations dominate variations due to the topography, which is the case for the Aristarchus plateau. Indeed, a correlation exists between lunar reflectance and color, with mature soils being dark and also red. We used eight telescopic spectra acquired by Lucey et al. [1986] to calibrate gain values and to refine the first-order offset evaluation of the NIR images. Gain and offset values are optimized to match four telescopic spectra extracted from very different areas (spectra labeled 2c, 5a, 4a, and 4c from Lucey et al. [1986]). To account for the error on the location of the footprint of the telescopic aperture on the lunar surface, the location of telescopic spectra is optimized within a $10 \times 10 \text{ km}^2$ box, following the technique described by Pinet et al. [1999]. The accuracy of the set of gains and offsets is then tested on four other telescopic spectra (spectra 2b, 4b, 5c, and 2a from Lucev et al. [1986]). With this calibration test we were able to reproduce the eight telescopic spectra with a maximum error of 1.8%. Offset adjustements to the first-order evaluation are respectively 1, 10, 25, and 41 digital numbers (DN) for the 1100, 1250, 1500, and 2000 nm filters. A conservative estimate for the residual relative uncertainty on the final multispectral cube is 2%.

The mosaic represents a set of $\sim 270,000$ nine-channel spectra of the Aristarchus plateau. Figure 1 displays the reflectance at 1500 nm. The main variations in the image are due to compositional variations (highland-type material is brighter than mare-type material), maturity variations (immature areas are brighter than mature areas), and variations



Figure 1. Reflectance at 1500 nm on the Aristachus plateau. The arrow shows the fresh mare crater from which the spectra displayed in Figure 2 are extracted.

of the local slopes which induce photometric effects (Sunfacing slopes are brighter than shaded areas). In the next section we illustrate the spectral effects of space weathering processes on spectra extracted from the small fresh mare crater located in the lower left corner in Figure 1.

3. Spectral Effects of Maturity on Clementine Spectra

The interpretation of the spectral features in lunar soil spectra in terms of mineralogical and chemical composition is hampered by the optical effects of space weathering processes [Hapke et al., 1975; McKay et al., 1991; Fischer and Pieters, 1994, 1996]. The space weathering processes, which control the degree of maturity of the soil, result from the bombardment of the surface by micrometeorites, solar wind ions and cosmic rays. These highly energetic events modify the chemistry and the physical state of the surface minerals by reducing the mean grain size and by producing agglutinates [McKay et al., 1974], by producing submicroscopic single-domain iron [Hapke et al., 1975; Morris, 1976], and by creating amorphous coatings on individual grains [Borg et al., 1980; Keller and McKay, 1993]. Laboratory studies of lunar samples have shown that these physical processes have mainly three consequences on lunar soil spectra, which are an overall reduction of the reflectance, a reduction of the absorption band depth, and an increase of the continuum slope toward red wavelengths. These effects have been identified on spectra of lunar samples with similar major element oxide chemistry, but different exposure indices Is/FeO [e.g., Fischer and Pieters, 1994].

The integration of Clementine NIR data with the already available UVVIS data is extremely useful for investigating the spectral effects of the space weathering processes. This can be demonstrated by extracting spectra on a small fresh mare crater and its immediate surroundings (arrow in Figure 1). Given the small size of this crater (~ 2 km) and its location on a homogeneous mare area [McEwen et al., 1994], we assume that the content in FeO is homogeneous. This impact has induced variations in the soil maturity by excavating fresh material. Figure 2a displays five absolute reflectance spectra extracted from the crater area. Figure 2b shows the same spectra divided by a continuum line in order to emphasize the absorption features. Spectrum 1 is extracted from the brightest part of the crater interior, and spectrum 5 is extracted from the surrounding mare material. Spectra 2, 3, and 4 are extracted from intermediate distances between the two extreme areas. The 1 μ m and 2 μ m absorption band depths and the overall reflectance increase from spectrum 5 (corresponding to a mature area) to spectrum 1 (the most immature area). Conversely, the continuum slope increases with increasing maturity.

As a consequence, a given absorption depth near 1 μ m can result from various combinations of FeO content and maturity degree. An important step toward quantitative remote sensing spectroscopy would consist in separating the spectral alteration effects from the mineralogical and chemical composition. An extensively used method has been

Figure 2. (a) Absolute reflectance spectra extracted from the crater located in Figure 1. (b) Spectra divided by a continuum line. The overall reflectance and band depths decrease with increasing maturity (from spectrum 1 in the immature crater interior to spectrum 5 on the surrounding mature mare), whereas the continuum slope increases with maturity.

proposed by *Lucey et al.* [1995, 1998a] and *Blewett et al.* [1997]. This technique, which uses UVVIS bands only, is based on the uncorrelated effects of maturity and FeO content on a plot of the 950/750 nm ratio versus the 750 nm reflectance. This algorithm will be used as a comparison with our results. In the next section we present the spectral parameters which have been used in our study to discriminate between spectral alterations due to the space weathering and absorption features linked to FeO.

4. Spectral Parameters

4.1. Depth of the 1 μ m Absorption Feature

The depth of the 0.9 - 1 μ m absorption feature is directly linked to the concentration of ferrous iron and Fe-bearing silicate materials [*Charette and Adams*, 1977]. The depth of the 1 μ m feature, which was evaluated by the 950/750 nm





Figure 3. Depth of the 1 μ m absorption feature displayed from 0.02 (black) to 0.25 (white). Fresh exposures of pyroxene-rich materials appear in high values (small mare craters, and walls of Vallis Schroteri). This depth image is controlled by both the Fe²⁺ content and the degree of maturity of the surface. The high content of absorbing glass for dark mantle deposits reduces the spectral contrast and therefore the depth of the Fe²⁺ feature.

ratio from UVVIS data, can be better evaluated by using the long-wavelength side of the band provided by NIR filters at 1100 nm, 1250 nm, and 1500 nm (see spectra in Figure 2). Laboratory spectra of lunar samples show that the 750 nm and 1500 nm filters provide a reliable estimate of the continuum slope [*Pieters*, 1986]. Figure 3 displays the 1 μ m absorption band depth calculated on Aristarchus plateau by dividing the reflectance at 950 nm by the interpolated level of the continuum at 950 nm:

depth 1 = 1 -
$$\frac{R_{950}}{(2.2/3)R_{750} + (0.8/3)R_{1500}}$$
, (1)

where R_{750} , R_{950} , and R_{1500} are the reflectances at 750, 950, and 1500 nm. A difference up to 10% in relative terms is obtained with the depth calculated by the UVVIS 950/ 750 nm ratio. The 1 μ m absorption band depth is, as expected, maximum for the small fresh craters on the mare material (lower left corner in Figure 3). This corresponds to exposure of mafic-rich immature material. Conversely, the absorption band depth is minimum on the dark mantle deposits, where the presence of volcanic glass reduces the spectral contrast [Zisk et al., 1977]. The walls of the sinuous rille Vallis Schroteri (in the center of Figure 3) also appear as deeply absorbing at 1 μ m compared to the surrounding materials. As described previously, the band depth is controlled by both the content in absorbing Fe^{2+} and spectral alterations due to space weathering. Any interpretation in terms of composition alone therefore requires an evaluation of the spectral alteration of the soil.

4.2. Continuum Slope

The integration of Clementine UVVIS and NIR data gives a first opportunity to investigate the continuum slope of the spectra with remote sensing data. The bands at 750 nm (UVVIS) and 1500 nm (NIR) are outside the main absorption features found in common lunar soil spectra [*Pieters*, 1986]. The continuum slope is defined here by the slope of a straight line fitting the spectrum at 0.75 μ m and 1.5 μ m, and scaled to the 0.75 μ m point of tangency:

slope =
$$(1/R_{750}) \frac{R_{1500} - R_{750}}{(1.5 - 0.75)}$$
 $\mu \text{ m}^{-1}$. (2)

The continuum slope becomes increasingly red as surface exposure time increases. Pieters et al. [1993] showed that the red slope could not be explained solely by the presence of agglutinates formed during micrometeoritic and cosmic rays impacts. Laboratory studies suggest that the decrease in reflectance and spectral contrast and the increase in continuum slope can be attributed to the increase in nanophase metallic iron particles, which are produced by the reduction of Fe²⁺ during micrometeorite impacts [Hapke et al., 1975; Hapke, 1977; Allen et al., 1993, 1996; Pieters et al., 1993]. The amount of nanophase metallic iron particles can be evaluated by the intensity of the ferromagnetic resonance Is [Morris, 1978]. Hapke [1998] suggested that these submicroscopic metallic iron particles result from the deposition of silicate vapor produced by both solar wind sputtering and micrometeorite impacts.

Hiroi et al. [1997] have observed a good linear correlation between continuum slope parameters and Is. We have tested this correlation between the continuum slope computed from equation (2) and Is on a broader set of lunar sample spectra (which are taken from the J. B. Adams collection, available at the Planetary Data System (PDS) node at http://www.planetary.brown.edu/PDS). We restricted our analysis to 50 spectra of bulk soils, which are listed in Table 1. Of these, 35 samples are referred to as highland or highland boundary soils, and 15 samples are referred to as mare or mare/mantle type soils. All laboratory spectra have been convolved through Clementine filters. Is/FeO and FeO values for the selected bulk soil samples are taken from Morris [1978]. FeO ranges from 4 to 18 wt% and Is/FeO ranges from 6 (immature) to 92 (mature). Figure 4a displays the plot of the continuum slope versus the concentration of finegrained submicroscopic iron Is. The continuum slope is correlated with Is for both highland-type materials and maretype materials, with a saturation effect for the highest Is values. This plot shows that if the submicroscopic metallic iron is responsible for the spectral alteration due to the space weathering, which seems to be accepted by most authors, then the continuum slope provides a reliable evaluation of this spectral alteration. It is important to notice that for retrieving compositional information from lunar spectra, a spectral alteration index is more useful than a maturity parameter such as Is/FeO, which is linked to the time a sample has been exposed at the surface. The specific production processes of metallic iron and their relationship to exposure time or composition are not relevant for spectral interpretation. As a comparison, we have tested the correlation between the slope of the continuum and the optical maturity parameter (OMAT) proposed by Lucey et al. [1998c]

Sample	FeO	TiO ₂	Is/FeO	415 nm	750 nm	950 nm	1500 nm
10084	15.8	7.5	78	0.045	0.071	0.080	0.123
12042	15.4	3.1	61	0.080	0.113	0.120	0.178
12070	15.4	3.1	47	0.054	0.099	0.106	0.168
14003	10.4	1.7	66	0.081	0.139	0.153	0.232
14141	10.4	1.7	6	0.197	0.277	0.262	0.355
14148	10.4	1.7	74	0.084	0.139	0.153	0.229
14259	10.4	1.7	85	0.068	0.124	0.138	0.208
15081	16.8	1.6	68	0.063	0.114	0.121	0.198
15081	16.8	1.6	68	0.057	0.112	0.120	0.193
15101	11.5	1.3	70	0.065	0.134	0.149	0.236
15211	11.5	1.3	60	0.076	0.148	0.160	0.243
15231	11.5	1.3	71	0.078	0.147	0.162	0.240
15471	16.6	1.2	34	0.082	0.144	0.146	0.227
15271	12.1	1.5	63	0.069	0.136	0.148	0.227
15501	16.9	1.8	51	0.067	0.120	0.126	0.203
60601	5.6	0.6	85	0.114	0.203	0.229	0.318
61141	5.4	0.6	56	0.128	0.219	0.242	0.332
61161	5.4	0.6	82	0.141	0.229	0.249	0.329
61241	5.4	0.6	47	0.178	0.260	0.277	0.349
61241	5.4	0.6	47	0.167	0.253	0.274	0.359
61281	5.4	0.6	69	0.134	0.225	0.248	0.334
64421	4.6	0.5	83	0.125	0.205	0.228	0.298
64421	4.6	0.5	83	0.120	0.201	0.226	0.311
64501	4.6	0.5	61	0.173	0.262	0.283	0.359
65501	5.9	0.7	38	0.195	0.291	0.303	0.382
68501	5.6	0.6	85	0.108	0.191	0.214	0.306
69921	5.6	0.6	90	0.109	0.186	0.208	0.291
69961	5.6	0.6	92	0.117	0.203	0.227	0.309
6746 1	4.2	0.4	25	0.272	0.384	0.389	0.499
67481	4.2	0.4	31	0.243	0.357	0.373	0.480
67601	4.2	0.4	45	0.196	0.298	0.321	0.422
67701	4.2	0.4	39	0.237	0.335	0.351	0.440
63321	4.8	0.5	47	0.177	0.270	0.289	0.378
63341	4.8	0.5	54	0.178	0.268	0.287	0.370
63501	4.8	0.5	46	0.177	0.283	0.305	0.398
70181	16.6	8.5	47	0.085	0.126	0.140	0.188
71501	17.8	9.6	35	0.063	0.095	0.103	0.150
72701	8.7	1.5	61	0.107	0.177	0.196	0.274
73221	8.7	1.8	43	0.177	0.251	0.263	0.341
73281	8.7	1.8	34	0.194	0.273	0.286	0.366
75081	17.7	9.9	40	0.064	0.100	0.109	0.159
75081	17.7	9.9	40	0.064	0.103	0.111	0.167
7 626 1	10.7	3.4	58	0.096	0.160	0.177	0.249
78121	12.5	4.4	68	0.079	0.134	0.149	0.210
79221	15.4	6.4	81	0.062	0.101	0.113	0.164
79511	15.4	6.4	61	0.063	0.102	0.115	0.173
72141	13.4	4.4	81	0.077	0.123	0.140	0.202
72161	14.8	5.5	87	0.061	0.105	0.120	0.181
75111	15.9	6.7	54	0.059	0.098	0.114	0.170
75121	15.9	6.7	67	0.060	0.100	0.113	0.169

Table 1. List of the Soils Used in This Study

References for the TiO_2 and FeO content values are given by *Blewett et al.* [1997]. Is/FeO values are taken from *Morris* [1978]. Reflectance values of bulk soils are from the J. B. Adams spectra collection.

on our set of lunar samples (Figure 4b). The good correlation between these two parameters for both highland and mare samples confirms that the continuum slope is at first order representative of the spectral alterations due to the space weathering. This good correlation could provide a handle to improve offset determinations for the 1500 nm NIR filter. Figure 5 displays the continuum slope image on the Aristarchus plateau. The continuum slope is maximum on the dark mantle deposits. These dark mantle deposits have been interpreted as volatile-rich pyroclastic glass [Lucey et al., 1986; Gaddis et al., 1985; Weitz et al., 1998]. It should be noted that these glasses may cause changes in spectra



Figure 4. (a) Correlation of the continuum slope with the concentration of fine grain submicroscopic iron (Is) for the 50 highland and mare bulk soils listed in Table 1. (b) The continuum slope is also anticorrelated with the optical maturity parameter OMAT computed from *Lucey et al.* [1998c] on the corresponding spectra.

shapes which are similar to those induced by maturation processes [Gaddis et al.., 1985]. The continuum slope is therefore controlled by both maturity variations and the content of pyroclastic glass. The Aristarchus crater and the smaller impact craters have a symmetrical aspect with low values in the continuum slope image. The walls of Vallis Schroteri appear also symmetrical, with a lower slope compared to the surrounding plateau. This results from fresh material being brought to the surface either by impacts or by downslope movements on steep slopes.

5. Discrimination Between Maturity and Composition

The next step in our analysis is aimed at removing the spectral alteration effects evaluated by the continuum slope from the 1 μ m absorption band depth to retrieve information on the FeO content. The most widely used technique for se-

parating the influence of composition and maturity on spectral properties of the lunar surface is that proposed by *Lucey et al.* [1995, 1998a, c] and *Blewett et al.* [1997]. The results of this method will be used as a comparison with what can be inferred from our method. The optical maturity parameter (OMAT) image derived from *Lucey et al.* [1998c] and the FeO content image derived from *Blewett et al.* [1997] are shown in Figures 6a and 6b. As was the case for the laboratory samples spectra, the continuum slope (Figure 5) and the OMAT parameter (Figure 6a) are clearly correlated (correlation factor of 0.93). According to *Lucey et al.* [1998a], some care has to be taken concerning the absolute FeO values computed on pyroclastic deposits.

5.1. Correction of the 1 μm Band Depth From Spectral Alteration

Spectra obtained close to the small fresh mare crater (arrow in Figure 1) exhibited a relatively straightforward spectral evolution with maturity. The depth of the band as evaluated by equation (1) presents a good linear relationship with the continuum slope, which we use to evaluate spectral alteration (Figure 7a). In mare material it is therefore possible to remove the spectral alteration by substracting the local continuum slope from the band depth using the observed coefficient (0.286) of this linear correlation. From the similar behavior of mare and highland samples in the correlation plot between the continuum slope and Is (Figure 4a), we assume that the linear correlation between continuum slope and band depth is also valid for highland material.

Figure 7b shows the image corresponding to depth $1 + 0.286 \times (slope)$. As expected from the procedure and the good correlation of Figure 7a, the small mare craters now exhibit a homogeneous composition. This image is at first order consistent with the FeO map provided by the algorithm of Lucey and coworkers (Figure 6b). However, the



Figure 5. Continuum slope as defined by equation (2) in gray scale ranging from 0 (black) to 1.08 (white). The craters appear symmetrical, as do the walls of Vallis Schroteri. This is consistent with the interpretation of the continuum slope as a spectral alteration image.



Figure 6. (a) Negative image of the optical maturity parameter (OMAT) derived from *Lucey et al.* [1998c]. (b) FeO content computed using the algorithm described by *Blewett et al.* [1997]. Arrows a and b indicate artifacts due to local slopes in Vallis Schroteri and close to the crater Krieger.

1 µm band depth image corrected for spectral alteration is less affected by the local topography than the FeO image shown in Figure 6b. In the case of the Lucey et al. algorithm, the use of the 750 nm filter level introduces systematic artifacts due to the topography at high phase angles: Sun-facing slopes appear brighter than flat areas at 750 nm, which leads to an overestimation of the FeO content in these areas. This effect is particularly obvious on the walls of Vallis Schroteri (arrow a in Figure 6b) and on the walls of the medium-size craters (arrow b). The corresponding areas in our corrected band depth image are not affected by the local topography because this image is produced from band ratios only. The asymmetry of the Aristarchus ejecta blanket appears clearly in Figure 7b. Fe-poor highland-type material is distributed on the southern part of the ejecta. Similarly, Fepoor highland-type material is detected in the vicinity of the Cobra Head (arrow a in Figure 7b) and on Herodotus χ , a 1 km high bright hill in the northwest of the plateau (arrow b). These structures correlate well with the high-albedo patterns in Figure 1, and can therefore be confidently interpreted as highland-type material.

The 1 μ m band depth corrected from spectral alteration is linked to the Fe^{2+} content of unweathered silicates. We define as the "mafic iron" content of a soil the iron which was contained in mafic silicates before the onset of maturity processes. It therefore includes the iron in glassy particles (agglutinates and nanophase iron) which was originally in silicates. This parameter is not sensitive to iron contained in oxides, which does not contribute to the strength of the 1 μ m band. On the Moon, ilmenite (FeTiO₃) is the major iron-bearing oxide. Lucey et al.'s method is an evaluation of the total iron content. We therefore expect the qualitative difference between the two methods to be linked to the content in ilmenite, and hence to the content in titanium. Figure 8a shows the difference between the scaled mafic FeO map obtained by our spectral alteration correction method and the FeO map we obtained using the method of Lucey and coworkers. As expected, the observed differences show a significant correlation with the map of the titanium content derived from the method described by Lucey et al. [1998a].



Figure 7. (a) Correlation plot of the continuum slope versus the 1 μ m absorption band depth on the fresh mare crater (arrow in Figure 1) and its surroundings. (b) The 1 μ m absorption band depth corrected from spectral alteration. This image is controlled by the mafic iron content of the soil (see the correlation with Figure 6b).

Figure 8. (a) Difference of the FeO map derived from Lucey et al. [1998a] and the mafic iron image displayed in Figure 7b. (b) TiO₂ content in weight percent computed using the algorithm described by Lucey et al. [1998a]. The correlation between the images of Figures 8a and 8b shows that the difference between the two maps is controlled by local slopes and titanium content.

A second difference is obtained in areas with significant local slopes (walls of the sinuous rille and craters). Our method is less sensitive to the topography due to the use of band ratios only. In the next section the same analysis is performed on lunar soil samples spectra to define a quantitative evaluation method for mafic iron.

5.2. A Quantitative Method to Evaluate Mafic Iron in Lunar Soils

We used the set of 50 bulk soil samples described in section 4.2 to calibrate the mafic iron evaluation method. Compositional and relevant reflectance data for the soils used are listed in Table 1. Figure 9a shows the correlation of the mafic-iron-sensitive parameter computed from depth1 + $0.286 \times$ (slope) with the bulk FeO content measured in the laboratory. From the above analysis the low correlation can be attributed to iron contained in ilmenite. This is demonstrated by Figure 9b, which shows that the difference between measured FeO and evaluated mafic FeO values is correlated to the TiO₂ content. We can recover the total FeO content by adding one iron for each titanium to our mafic iron evaluation, hence adding 0.9 TiO₂ (wt%) to the weight percent of mafic FeO. Figure 9c displays the total FeO content evaluated by adding the mafic FeO and FeO from ilmenite:

$$FeO_{total} (wt\%) = FeO_{mafic} + FeO_{ilmenite}$$
$$= 45.6 \times (depth1 + 0.286 \times slope) - 3.8 + 0.9 \text{ Ti}O_2. \quad (3)$$

The good correlation (0.944) demonstrates that it is possible to quantitatively evaluate mafic iron in lunar samples from their spectra with this method. The difference between FeO predicted and FeO measured has a standard deviation of 1.6 wt%. Figure 9d shows the FeO content we derived from Lucey et al.'s algorithm on the same set of samples for comparison (1 σ of 1.5 wt%). Our method has a larger spread than Lucey et al.'s method for highland soils (FeO < 6wt%), which was expected as the inversion technique was calibrated on the Fe²⁺ absorption feature in mare regions. The coefficients of the linear regression shown in equation (3) are optimized for the directional-hemispherical spectra of lunar soils obtained by Adams and coworkers. This set of coefficients could be refined for Clementine bidirectional reflectance data by using images of the lunar sample-return stations as was done by Blewett et al. [1997] for Lucey et al.'s method.

This method and Lucey et al.'s method provide two different types of information on lunar soils: mafic iron content and total iron content. Our method is not dependent on local slopes as it is based on band ratios only. In order to obtain the total iron content with our method on Clementine remote sensing data, we have to independently evaluate the titanium content. This can be done with the TiO₂ mapping technique proposed by Lucey et al. [1998a]. This introduces a second-order dependence of the total iron content on local slopes when titanium is abundant. The volume percentages of ilmenite in lunar soils vary widely across the Moon, with titanium appearing mostly in mare basalts. A quantitative mafic iron evaluation method which is independent of local slopes, and which can be extended to total iron by evaluating the ilmenite contribution, can be very useful to investigate middle to high latitudes where local slopes play a major role. It can be noted that these regions are predominantly highlands, where mafic iron and total iron should be closely related.

6. Discrimination Between Olivine and **Pyroxene**

UVVIS bands have been used to discriminate between gabbroic highland-type materials, dark mantle deposits, and mafic mare materials [McEwen et al., 1994]. The 2000/1500 nm ratio, compared to the albedo and maturity images, provides the discrimination between olivine and pyroxene within





Figure 9. Test of our mafic iron mapping technique on the Adams soil samples spectra listed in Table 1. (a) Correlation of our mafic iron parameter with measured FeO values. (b) Difference between FeO measured in the laboratory and the mafic iron inferred from Figure 9a versus titanium content. (c) Total FeO content predicted from our method when including the contribution of ilmenite versus measured FeO content. (d) FeO content predicted from Lucey et al.'s method versus measured FeO content.

identified mare basalts [Le Mouélic et al., 1999b]. Pyroxene spectra exhibit two absorptions at 1 μ m and 2 μ m, whereas olivine has a single broad composite absorption near 1 μ m and has no absorption at 2 μ m. Olivine is present in mare materials. It is considered to be associated either with the lunar mantle or with Mg-rich plutons. The distribution of olivine on the lunar surface provides clues on the processes involving the lunar mantle and crust [Pieters and Wilhelms, 1985; Pinet et al., 1993; Tompkins and Pieters, 1999].

Figure 10a displays the 2000/1500 nm ratio, which is related to the depth of the 2 μ m absorption band. Olivinedominated areas are expected to show a high value in this ratio compared to pyroxene-rich areas. Fresh mare craters appear as low values, as is expected for a fresh exposure of pyroxene-rich materials. The dark mantle deposits appear as high values, and so do several areas on the southeastern rim of the Aristarchus crater. As was the case for the 1 μ m absorption band depth, the 2 μ m absorption band depth is controlled by both the composition and the spectral alteration due to the space weathering. Immature soils dominated by pyroxene have a deeper absorption at 2 μ m than mature soils. Therefore one must remove spectral alteration effects from the depth of the 2 μ m band to accurately interpret the 2 μ m absorption feature on a 2000/1500 nm ratio.



Figure 10. (a) Normalized 2000/ 1500 nm ratio from 0.8 (black) to 1.1 (white). This ratio is controlled by composition and maturity. Fresh exposures of pyroxene appear as low values in this ratio. (b) The 2000/1500 nm ratio corrected for maturity effects. Arrow a indicates the olivine-rich region previously mentioned by *Le Mouélic et al.* [1999b]. Arrow b indicates another possible olivine-rich region within the crater Krieger.

We performed the same correlation plot as shown in Figure 7a between the 2000/1500 nm ratio and the continuum slope on the small fresh mare crater to derive the linear coefficient (0.32) between the two parameters. From the high correlation index, it is then possible to remove spectral alteration from the 2000/1500 nm ratio (Figure 10b). As expected, the small fresh mare craters do not show variations in the corrected ratio. The major remaining variations (high values of the ratio) are observed on the southeastern rim of the crater (arrow a), where the presence of olivine has already been mentioned [*Lucey et al.*, 1986; *Le Mouélic et al.*, 1999b]. A small area in the crater Krieger (arrow b in Figure 10b) also exhibits a signature of olivine.

7. Conclusion

Clementine NIR data were used for the first time on a wide area covering the Aristarchus plateau. The integra-

tion of UVVIS and NIR data sets was performed on ninechannel spectra from 0.415 μ m to 2 μ m. Spectral effects of space weathering processes have been identified on spectra extracted from a small fresh mare crater and its immediate surroundings. A better investigation of the 1 μ m Fe²⁺ crystal field absorption band, which is related to the FeO content of the soil, is achieved by the knowledge of the continuum in the vicinity of the band. The integration of UVVIS and NIR data provides a better understanding of the spectral properties of the lunar surface by giving the new opportunity to investigate the continuum slope, which can be derived from the spectral reflectances at 750 nm (UVVIS) and 1500 nm (NIR). From laboratory samples spectra we have confirmed that the continuum slope is closely related to the concentration of fine-grained submicroscopic iron (Is) for highland-type and mare-type soils. Is is a major parameter for maturity-related evolution of lunar spectra. The continuum slope is therefore at first order representative of the spectral alteration due to the space weathering. We have used the continuum slope to correct the 1 μ m absorption band depth for spectral alteration to retrieve the iron initially contained in mafic silicates (mafic iron). Our mafic iron map is in general agreement with the FeO map we obtained with the algorithm of Lucey et al. [1998a] on the same data set. The differences are controlled by local slopes and titanium content, which was expected due to the contribution of ilmenite to the total iron. The analysis performed on lunar soil spectra showed that it is quantitatively possible to map mafic iron with this method, which is expected to be less sensitive to the local topography than Lucey et al.'s method due to the use of band ratios only. It could therefore be very useful for investigating areas at middle to high latitudes. With our method we can also derive the total iron content by adding the contribution of opaque minerals (mainly ilmenite) evaluated from the titanium content.

The removal of the spectral alteration contribution to the depth of the 2 μ m absorption feature, which is evaluated by the 2000/1500 nm ratio improves the reliability of the discrimination between pyroxene and olivine. Our results confirm the presence of olivine-rich areas on the southeastern rim of Aristarchus crater and indicate a new olivine-dominated area within the crater Krieger. These results demonstrate the interest of a comprehensive calibration of the Clementine NIR data set to investigate the mineralogy of the lunar crust. This is likely to require combining the house-keeping information with comparisons to the well-calibrated UVVIS data set as well as telescopic spectra when available, as we have done for the Aristarchus plateau.

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