

# MEASURING AND DISTINGUISHING COMPOSITIONAL AND MATURITY PROPERTIES OF LUNAR SOILS BY REMOTE VIS-NIR SPECTROSCOPY; Erich M. Fischer and Carle M. Pieters; Dept. of Geol. Sci., Brown Univ., Providence, RI.

**Introduction:** Space weathering on the lunar surface affects the spectral/optical character of an exposed lunar soil in three ways: the reflectance is reduced, absorption band depths are reduced, and a red-sloped continuum is created and increased with exposure. As a result, the spectrum of a lunar soil is dependent upon both the degree of exposure at the lunar surface and the original composition. It is critical to the remote analysis of lunar soils to differentiate between the optical effects of maturity and the effects of composition. In the laboratory, it is possible to determine and consequently distinguish the degree of exposure, or soil maturity, as measured by parameters such as  $I_s/\text{FeO}$  (e.g., 1; mature defined as  $I_s/\text{FeO} \geq 60$ ), and the composition, as measured by various chemical and petrographical techniques. Lunar soils returned by the Apollo missions provide important ground truth for developing methods for *remotely* measuring the maturity and the concentration of Fe-bearing minerals in lunar soil. The ground truth spectral data analyzed here are from the John Adams lunar soil spectra collection. Soils collected from or near highland terrains are emphasized in the present discussion. The mineralogical makeup of mare soils results in behavior somewhat different from highland soils.

**Concentration of Fe-bearing minerals:** One method of estimating the concentration of Fe-bearing minerals in a soil (approximated by wt.% FeO) from reflectance spectra, is to measure the band depth of the one micron  $\text{Fe}^{2+}$  crystal field absorption. In the case of lunar soils, however, the one micron band is superimposed upon a distinct red-sloped continuum. Band depth is determined by measuring the depth after removing a continuum. This is normally accomplished by fitting a tangent to both shoulders of the one micron band. This method effectively normalizes the continuum created in the optical alteration process and allows the band depth of soils to be compared directly. However, as illustrated in Fig. 1, this method of estimating relative iron content is accurate only for mature lunar highland soils. Similar relations were noted by Charette et al. (2). That is, the measurement of band depth is an accurate measurement of Fe-bearing mineral concentration only for highland soils that have been exposed long enough at the lunar surface to have reached a steady state in terms of space weathering. For mature soils, the band depth is no longer changed by the optical alteration process, and is thus a function only of composition. Therefore, in order to obtain an accurate compositional measurement, it is necessary to be able to distinguish between mature and non-mature lunar soils.

**Determination of maturity:** As mentioned above, the albedo of lunar soils decreases and the red-sloped continuum increases with increasing maturity. Thus, both albedo and the slope of the straight line continuum scaled to albedo can be used to roughly distinguish between mature and non-mature highland soils. However, because the albedo of a highland soil is sensitive to the compositional properties of the soil (principally the abundance of plagioclase), the relationship between albedo and maturity is also dependent upon composition. The relationship between scaled slope and maturity is similarly offset along compositional lines.

A useful method of distinguishing between mature and non-mature highland soils incorporates a ratio between the reflectance at a wavelength outside of the one micron band and the reflectance at a point inside the band, for example  $0.76\mu\text{m}/0.99\mu\text{m}$ . The relationship between this ratio and maturity as measured by  $I_s/\text{FeO}$  is shown in Fig. 2. The  $0.76\mu\text{m}/0.99\mu\text{m}$  (or similar) ratio combines information concerning the steepness of the continuum and the depth of the one micron band. Although there is some scatter, the linear nature of the relationship in Fig. 2 for submature and immature soils ( $I_s/\text{FeO} < 60$ ) indicates that it may be possible to distinguish between different degrees of immaturity for highland soils. McEwen et al. (3) discuss the dating of Copernican craters using similar spectral properties. Thus, given the  $0.76\mu\text{m}/0.99\mu\text{m}$  (or related) ratio, in order to remotely differentiate between mature and non-mature highland soils a cutoff value can be defined below which soils can be considered mature. For the data in Fig. 2, it is estimated that soils with  $0.76\mu\text{m}/0.99\mu\text{m}$  less than approximately 0.90 can be considered mature. Although this method is not a perfectly accurate way of distinguishing between mature and non-mature highland soils, there appears to be little scatter introduced as a result of calculating the Fe-bearing concentration for soils determined to be mature using the  $0.76\mu\text{m}/0.99\mu\text{m}$  ratio rather than by determining maturity based upon  $I_s/\text{FeO}$ .

**Limited spectral data:** In the above case, the lunar sample spectra are of large enough spectral range and high enough spectral resolution for a straight line continuum to be fit tangent to both shoulders of the one micron band; thus the band depth was accurately measured. But consider the case in which the data do not include both sides of the one micron band. An example of this are the Galileo SSI data, which consist of seven channels extending from  $0.40\mu\text{m}$  to  $0.99\mu\text{m}$ . Because the true band depth cannot be measured with these type of data, several approximations for calculating the concentration of Fe-bearing minerals from this type of data have been utilized in the past. Examples of these include 1) measuring an approximate band depth after removing a straight line continuum extrapolated from the short wavelength side of the band, and 2) calculating an approximate band depth using a ratio of the reflectance on one side of the band to the reflectance near the center of the band

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(0.76 $\mu$ m/0.99 $\mu$ m in the case of the SSI data). Neither of these methods results in an accurate measurement of band depth and Fe-bearing mineral concentration among highland soils. The poor correlation between 0.76 $\mu$ m/0.99 $\mu$ m and wt.% FeO for mature highland soils is shown in Fig. 3. Indeed, it was shown in the previous section that 0.76 $\mu$ m/0.99 $\mu$ m is extremely sensitive to the slope of the alteration continuum. It is clear that data on both sides of the one micron band are required to define a slope that effectively normalizes the alteration continuum.

Although band depth of mature soils cannot be utilized in order to measure Fe-bearing mineral concentration for the SSI type of limited spectral data, reflectance can be employed as a useful substitute. Figure 4 illustrates the good correlation between the reflectance at 0.56  $\mu$ m and wt.% FeO for mature highland soils. This correlation exists because the albedo of a highland soil that has reached a steady state in terms of alteration products is controlled primarily by the amount of the two most common lunar minerals -- bright plagioclase (high Al<sub>2</sub>O<sub>3</sub>), and the more absorbing Fe-bearing mafic minerals (high FeO). Because the concentrations of plagioclase and Fe-bearing minerals are inversely correlated, the albedo of a mature highland soil provides an estimate of the amount of both the Fe-bearing mineral concentration, and the amount of plagioclase. The 0.76 $\mu$ m/0.99 $\mu$ m (or similar) ratio can be used to distinguish mature from non-mature highland soils for this limited spectral range data as well.

**Conclusion:** Comparison of lunar soil optical properties and the maturity index  $I_s/\text{FeO}$  indicates that 1) mature highland soils can be distinguished from non-mature highland soils using remote optical methods (such as 0.76 $\mu$ m/0.99 $\mu$ m), even with data of limited spectral range 2) the relative concentration of Fe-bearing minerals can be estimated remotely for mature highland soils using either the band depth or the visible albedo, and 3) the degree of immaturity of highland soils may be estimated remotely by methods such as 0.76 $\mu$ m/0.99 $\mu$ m. It is important to note, however, that although limited spectral data such as the SSI data provide extremely valuable information, the accuracy of the compositional and maturity interpretations from this type of data are limited to general properties. A larger spectral range (into the near-infrared) is necessary in order to fully analyze the lunar continuum and the character of the superimposed diagnostic absorption bands.

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**References:** 1) Morris R.V. (1978) *Proc. LPSC IX*, 2287; 2) Charette M.P. et al. (1976) *Proc. LSC VII*, 2579; 3) McEwen et al. (1993) These volumes.

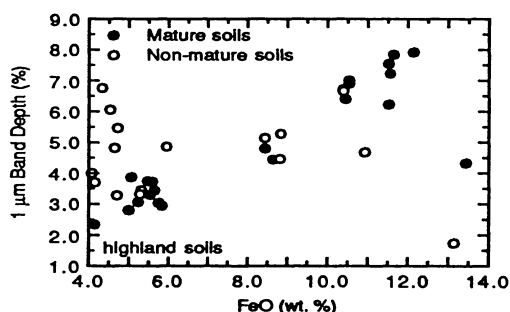


Figure 1: Iron concentration (wt.% FeO) for lunar highland soils versus band depth measured after continuum removal. Note the correlation for the mature soils (defined as soils with  $I_s/\text{FeO} \geq 60$ ; see 1).

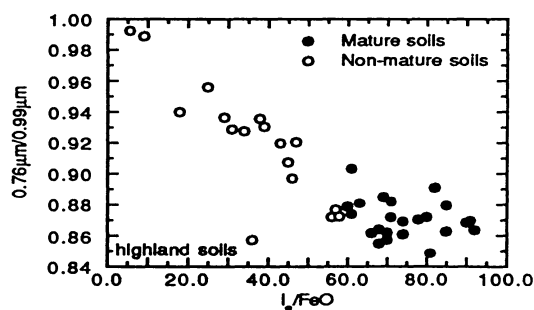


Figure 2: Maturity as measured by  $I_s/\text{FeO}$  versus 0.76 $\mu$ m/0.99 $\mu$ m for lunar highland soils. Mature soils are characterized by 0.76 $\mu$ m/0.99 $\mu$ m less than approximately 0.90. Note the linear trend for non-mature soils.

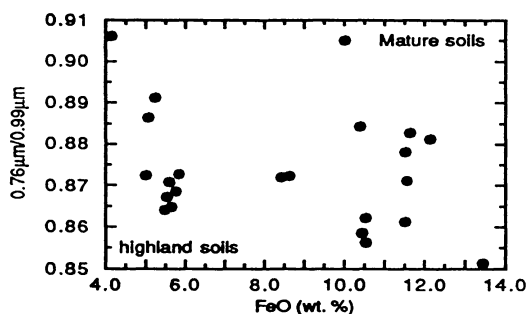


Figure 3: Iron concentration (wt.% FeO) versus 0.76 $\mu$ m/0.99 $\mu$ m for mature highland soils. Note the lack of correlation.

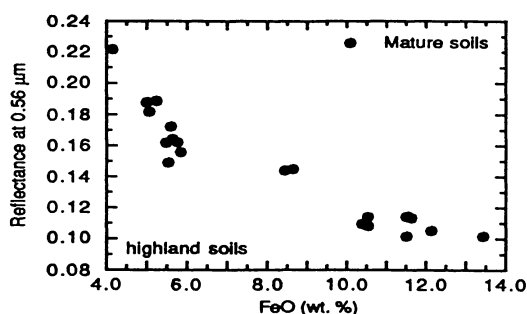


Figure 4: Iron concentration (wt.% FeO) versus reflectance at 0.56 $\mu$ m for mature highland soils.