REMOTE DETERMINATION OF LUNAR SOIL MATURITY

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Space weathering processes on the Moon (such as micrometeorite bombardment and solar-wind ion bombardment) affect the optical properties of an exposed lunar soil. The main spectral/optical effects of space weathering are a reduction of reflectance, attenuation of the 1-μm ferrous absorption band, and a red-sloped continuum creation (Fisher and Pieters, 1994). Fisher and Pieters (1994, 1996) developed one approach to determine the maturity of lunar soil from Clementine spectral data. This method is based on a relationship between the values of 750nm/950nm of reflectance of lunar soils and their measured I_s/FeO values.

Lucey et al. (1995, 1998a, 1998b) proposed to estimate the maturity of lunar soils from Clementine UVVIS data using a method which decorrelates the effects of variations in Fe^{2+} concentration from the effects of soil maturity. The method calculates the Euclidean distance from 750nm reflectance and values of 950nm/750nm ratio to the hypothetical "hypermature very dark and very red endmember", ("optimized origin") and takes this value as an estimate of optical maturity defined as parameter ρ (high values correspond to immature materials, low values correspond to mature materials) (Jolliff, 1999).

The amount of fused glassy particles and others agglutinates in the lunar upper layer is the direct index of the soil reworking caused be the micrometeorite bombardment. Besides, this micrometeorite bombardment is also responsible for the mechanical process through which the large particles are broken down into smaller ones. McKay et al. (1991) showed that increasingly mature soils become progressively finer-grained, better-sorted, and composed of a greater proportion of agglutinates.

Altogether, the increasing rate of the fused glassy fragments, of agglutinates, and of fine size fraction in the regolith affects the polarization of the light reflected by an exposed lunar soil. Therefore, polarimetric properties of the lunar regolith may be modified by the soil reworking process in the course of time. In 1966 Dollfus already showed that the maximum of polarization for powders, laboratory taken as lunar soil analogs irradiated by protons flux (simulation of the solar wind radiation on the Moon), is reduced in the red part of the spectrum. So, the determination of the maturity level of a lunar soil could be based on the spectropolarimetric properties of the regolith upper layer.

Shevchenko et al. (1993), Shevchenko (1994), and Pinet et al. (1997) developed the method to determine the maturity of lunar soil by using spectropolarimetric ratio $P_{max}(B)/P_{max}(R)$ for blue (B) and red (R) spectral regions. On the basis of known laboratory results and telescopic data, it was found that spectropolarization ratio Pmax(419nm)/Pmax(641nm) could be used as a remote sensing parameter of lunar soil maturity. This parameter does not correlate with the soil chemical composition (for example, with FeO content) but a good anticorrelation (r = -0.951) was found with I_s/FeO values for Apollo and Luna landing sites (Shevchenko, 1994; Shevchenko et al., 1999). The data show a strong dependence between this parameter and the exposure age of the lunar surface layer. So, it is possible to consider spectropolarization ratio Pmax(419nm)/Pmax(641nm) as an independent remote sensing index of the lunar soil maturity level.

A detailed remote sensing survey of ten lunar regions of mare and highland types has been carried out by means of Clementine spectro-imaging data with the purpose of establishing the regional distribution of the maturity state and weight percent of iron content in the lunar soils. The spectral dataset has been instrumentally calibrated and a radiometric calibration using previous telescopic spectra has been made, resulting in the production of absolute reflectance spectra organized in regional image cubes (Pinet et al., 1993; Pinet et al., 1995; Pinet et al., 1996; Pinet et al., 1997).

The data are used to obtain a scale of conformity between spectral index of maturity ρ and spectropolarization index established by Shevchenko et al. (1999). A special optimization technique has been developed on the basin of maximal likelihood, to locate very precisely the spectropolarimetric telescopic observations available (Kvaratskhelia, 1988) in the Clementine regional mosaics. In Fig. 1a, is shown the Clementine image of crater Proclus which is a very young lunar crater, with an extensive ray system. The boxes inside the crater exhibit for the process for the search of the real site position operates from the reference catalog (Shevchenko et al.,1999). Size of the each box is 5.6x5.6 km that is resolution of the telescopic observations for these sites. In Fig 1b, is shown another regional example related to the Reiner-γ formation – crater Reiner region. The box sizes are the same. The red boxes indi

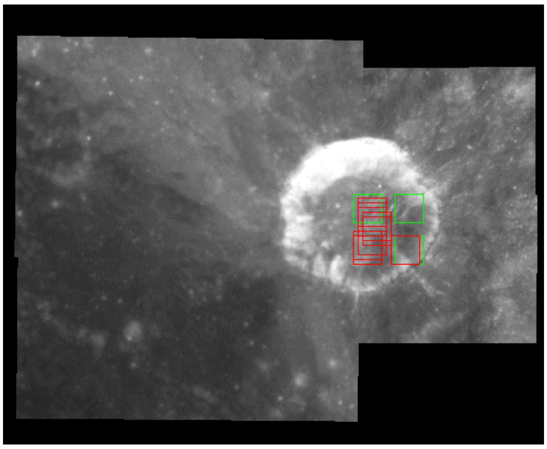

Fig. 1a

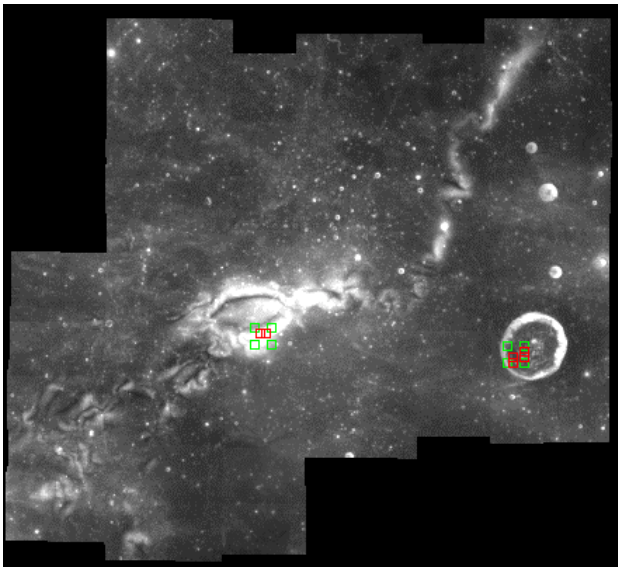

Fig. 1b

display the most probable positions of the sites.

The Reiner-γ formation (swirl) is one of the most young feature on the lunar surface. Center of bright rays system – crater Proclus is probably very young lunar object too. Given the likely recent origin of these features, one may consider the age of their formation as nearly equal as to the exposure age of their soils.

On the other hand, soils of old formations such as highland craters have been exposed for an extended period of time. It means that most of the petrographic and chemical parameters of maturity should have reached steady-state values with exposure time. In that case, any local variation seen in the soil maturity should be explained as the result of space weathering process. Examples of such lunar regions are given for highland craters Alphonsus and Gassendi examined here. Relative mature soil can be found in these formations.

As mentioned above, ten lunar surface zones are chosen for the purpose of this study. The list includes the highland crater Alpetragius, mare units in Mare Humorum and in Oceanus Procellarum near by Aristarchus, post-mare craters Aristarchus, Herodotus, and Reiner, which have different ages of emplacement.

On the bases of these data, a scale of conformity between the two types of maturity index is obtained. The diagram, depicted in Fig. 2, plots the spectropolarization index P_{max}(419nm)/P_{max}(641nm) versus the spectral index of maturity ρ (Lucey's parameter). The

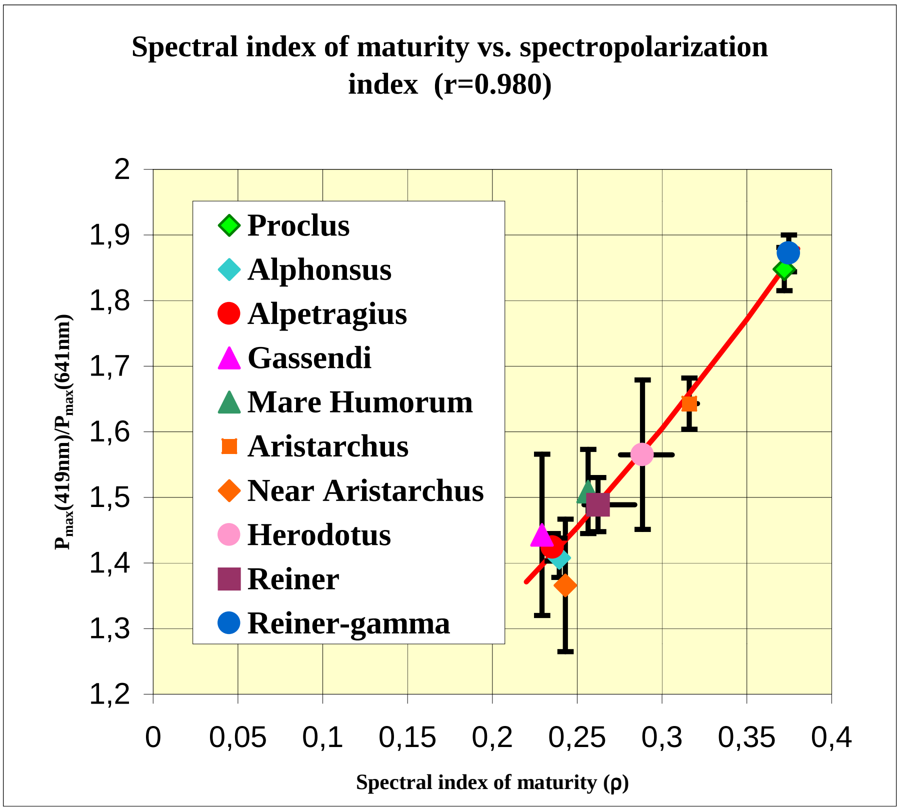

Fig. 2

interval of maturity index covers the geological formation time span from recent impact to old highland craters.

These quantities display a good correlation (exponential regression) with a correlation coefficient *r* = 0.980 for the interval of spectral index of maturity, ranging from ρ = 0.22 to 0.38. Shevchenko et al. (1999) shows that the spectropolarization index represented, as ratio P_{max}(419nm)/P_{max}(641nm), correlates directly with maturity index I_s/FeO established by Morris (1978). The correlation coefficient between the average values of Morris' parameter for Apollo and Luna landing sites and the P_{max}(419nm)/P_{max}(641nm) values for the same places derived from telescopic observations is *r* = –0.951. Making use of the dependence mentioned above it is then possible to build a graph of maturity index I_s/FeO versus the spectral index of maturity ρ.

Fig. 3 shows the type of relationship between I_s/FeO and ρ. The Apollo and Luna landing sites data, combined with the ten selected lunar features data, are used to establish the graph in the interval of ρ from about 0.23 to 0.38. The data concerning the most mature surface soils arise from the individual sample stations at the Apollo-17 landing site and are used to establish the graph in the range ρ = 0.12 to 0.23. The estimates of parameter ρ are derived from Clementine UV-VIS reflectance values for Apollo 17 landing-site sample stations published recently by Jolliff (1999, Tab. 2). Average values of I_s/FeO for the sample stations are compiled by Jolliff (1999) from Morris' data (1978). Part of the plot from ρ = 0 to

0.12 is extrapolated from the linear trend observed data of Apollo 17 stations. It is needed to point out that value ρ = 0 (Lucey's "optimized origin") asymptotic behavior only.

As a matter of fact, a few lunar fine fraction samples (soils with grain size < 250 μm) from Apollo-15, Apollo-16, and Apollo-17 set of lunar soils display a maturity corresponding to the measured values of I_s/FeO ~ 100; for other samples, values of I_s/FeO decrease to a few units (Morris, 1978).

So, the modelled relationship between I_s/FeO and ρ proposed for remote sensing data in Fig. 3 relies on laboratory estimates produced for I_s/FeO.

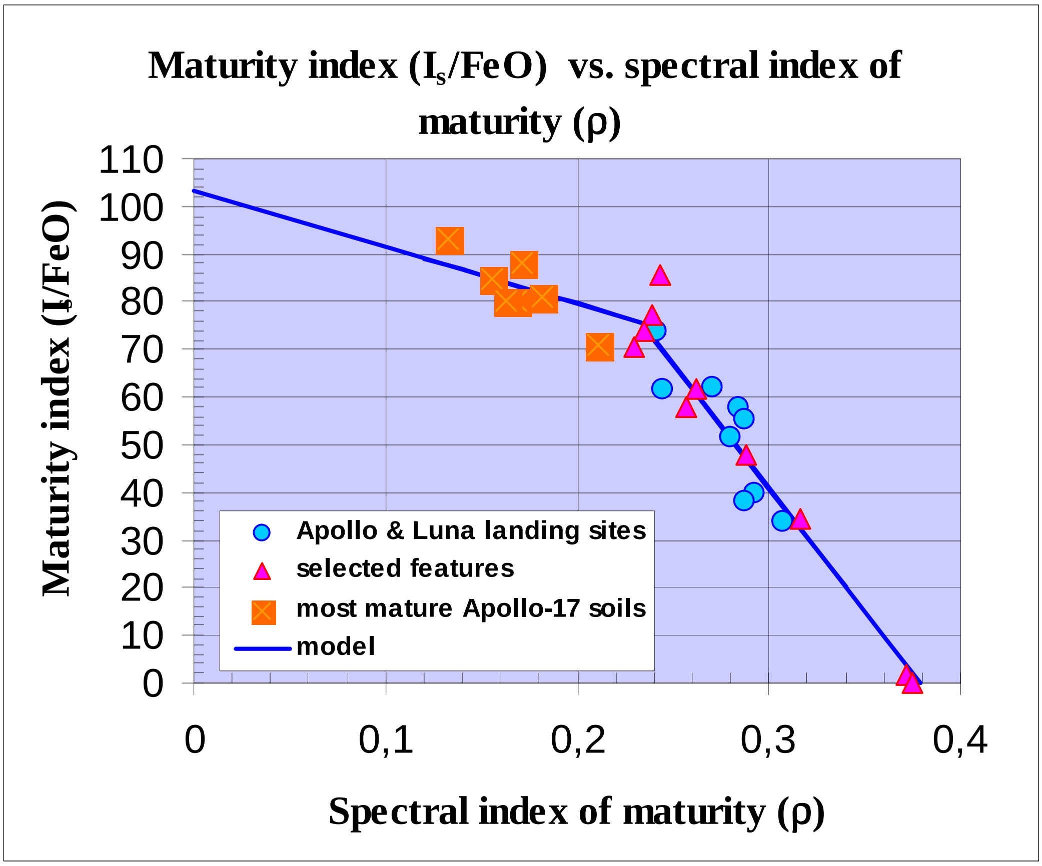

Fig. 3

According to Morris's classification (Morris, 1976), mature soils are defined as soils described by I_s/FeO > 60, but immature soils are characterized by I_s/FeO < 30. Submature soils are those with intermediate values.

As it follows from the plot in Fig. 3, a significant inflection of the curve is seen for values of I_s/FeO ~ 70 – 75. As revealed by Fisher and Pieters (1994), when a soil reaches maturity, optical properties no longer change with further exposure. The trend shown in Fig. 3, is consistent with this effect which is accounted here by the curve flattening of the spectral index of maturity values at I_s/FeO > 70 – 75.

Indeed, the coefficient of correlation between the maturity index and the spectral index of maturity for groups of the Apollo and Luna landing sites data and of the selected features data is r = -0.963, but for the group of the most mature Apollo-17 soils data the coefficient of correlation is only r = -0.668.

The time scale required for a soil to reach maturity (and an optical steady-state) is probably from one hundred to several hundred million years for fresh material that has not been previously exposed (Fisher and Pieters, 1994).

Based on the calculation of the submicroscopic iron production rate, Morris (1977) obtained a value of exposure age equal to about 100 Myr for cumulative exposure time required to reach the level of maturity characterized by value of I_s/FeO = 50.

Shevchenko (1994) and Pinet et al. (1997) from correlation between maturity index and exposure age of a collection of lunar samples found that exposure age of 100 Myr corresponds to maturity index value of I_s/FeO ~ 75. It is nearly average maturity of the Apollo-11 landing site and the maturity level of samples 10010 – 10011, the exposure age of which is about 100 Myr (Poupeau et al., 1980).

The present results suggest, that the slope in flexion detected for I_s/FeO values around 75 is indicative of the beginning of the asymptotic behavior expected for a lunar regolithic soil when it reaches maturity steady-state. The implication is that one should be careful when interpreting ρ relative estimates less than 0.22 +/-0.02 in terms of local variations of maturity in the lunar regolith, at the 100 – 200 m resolution available with Clementine.

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