

MIXING OF SURFACE MATERIALS INVESTIGATED BY SPECTRAL MIXTURE ANALYSIS WITH THE MOON MINERALOGY MAPPER. J.-Ph. Combe¹, T. B. McCord¹, G. Y. Kramer¹, C. M. Pieters², L. A. Taylor³, N. E. Petro⁴, J. W. Boardman⁵, J. F. Mustard², J. M. Sunshine⁶, S. Tompkins⁷, R.O. Green⁸ and the M³ Team.

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Introduction: Mixing of surface materials observed by remote sensing is of key importance for the mapping of surface units, as well as the identification and quantification of surface components, which is the main task of the imaging spectrometer Moon Mineralogy Mapper (M³) [1] onboard Chandrayaan-1. Specifically, the knowledge of the origin location of surface materials is decisive for deriving information about the bulk structure and composition of both the crust and the mantle. Mixtures that can be detected in reflectance spectra in the visible and near-infrared are the result of 1) materials that are natively mixed, like the minerals in a rock [2,3], or subsequent coating involved in surface maturity processes [e.g. 4,6], 2) mixing processes that mostly involve contamination by remote components [e.g. 7,8], 3) juxtaposed materials or shadows that are observed within the same field of view [9], or 4) materials that cause adjacency effects in the signal [10], such as scattered light at scales larger than a pixel size. Thus, mixtures may have implications for the interpretation of the lithology, which is the basis for understanding the geology at all scales, and modeling the evolution of the Moon. When performing spectral analysis it is crucial to investigate mixing processes both in the signal and at the surface. Various mixing approaches exist in spectral analysis. Radiative transfer models [2,3,11] account for intimate mixtures due to scattering at the grain interfaces. Linear unmixing relies on mathematical inversion by mean square minimization that has the properties of describing areal mixtures of surface materials by linear combinations of spectral components (endmembers). In the present study, we perform linear Spectral Mixture Analysis (SMA) [12] both for spectral endmembers selection and to produce corresponding image fractions. This method is convenient for an initial assessment of large data sets [13] prior to using more sophisticated methods for compositional analysis [14-15]. This approach is not designed to model all of the mixing processes aforementioned, since [16] have evaluated errors of ~20% on absolute quantifications. Our intent is to calculate maps of relative variations in order to provide a first order contextual characterization of the

surface compositional units. This step is a start toward more quantitative results through adaptation of the model. We also present validation tests of repeatability using various observations of the same area acquired with various geometries of illumination.

M³ reflectance hyperspectral data: We have used a mosaic of all M³ images that cover ~95% of the surface and 10-20 nm spectral sampling. In order to avoid the effects of thermal emission, the analysis is performed in the range 0.4-2.18 μm (65 channels). A sphere-based Lommel-Seeliger photometric correction has been performed to standardize the effects of the geometry of illumination at large scales (this leaves all the effects of the topography in the data) [17]. We have also benefited from the repeated observations (morning and afternoon) of smaller areas to perform some validation tests.

Method: We perform the SMA using the Multiple-Endmember Linear Spectral-Unmixing Model (MELSUM, [13,18]) that allows limiting the number of components used in a model and guarantees positive mixing coefficients. A spectrum of shade is collected from the average of several pixels in projected shadow from inside an old crater, of which the surface appears of homogenous composition. The sum of the mixing coefficients is constrained to one.

In the present study, the spectral endmembers are collected from the image that will be unmixed (Fig. 1). Using our own iterative approach, we start with the two most-representative spectra of mature highlands and mature mare soils as input for MELSUM. Then, we analyze the residuals from MELSUM to define more endmembers.

Results: From a global scale, spectral endmembers that represent the greatest amount of the data are interpreted in terms of the presence of minerals in the soils (Fig. 1). They describe what are known to be the most abundant components at the surface of the Moon: anorthosite, high-calcium pyroxene (HCP), low calcium pyroxene (LCP), olivine and three types of mature soils (High-Ti and low-Ti mare, and highlands). Additional spectral endmembers exist but are not shown here; although meaningful, they define units of more limited areas. Thus, the analysis of the

residuals appears effective to identify any type of spectral endmember confined in small areas, such as spectra of fresh materials exposed by recent impacts. Detailed analysis at full resolution is beyond the scope of this abstract. Concerning the method, similar processing performed at regional scale under different illuminations as validation (not shown here) provide similar endmembers and image fractions. The largest part of the illumination effects is present in the shadow endmember and in the residuals.

The principal image fractions show details in the compositional and spatial structure (Fig. 2). They mostly illustrate identification and mapping of mare basalt soils with variations of titanium in mare basalt (Fig. 2b) calcium and iron in pyroxenes, highlands, and impact-ejecta contamination. Plagioclase-rich soils (anorthosite) are detected in the highlands, especially in the south hemisphere, with few spots in fresh impact craters (e.g. Copernicus). Distribution of mafic minerals is highly correlated with the mare basalts. However, spots are found also in fresh impact craters where materials from the mantle have been excavated through the crust (e.g. Aristillus for HCP, Tycho, for LCP, Aristarchus for olivine). Olivine fraction (not shown here) is weak but it describes a homogenous unit in Oceanus Procellarum and Mare Imbrium, around Aristarchus. The map of mature soils is a good indicator of the location of fresh impact craters (low fraction). These results show very similar spatial distributions to the mineralogical maps obtained by

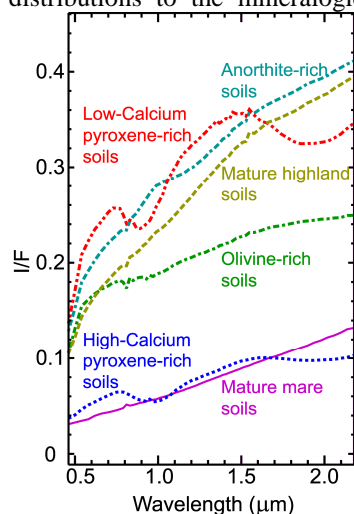


Fig. 1: Reflectance spectral endmembers of lunar soils selected from an M^3 image mosaic of the nearside of the Moon. Presence of minerals is the interpretation of spectral shapes.

[11] using a radiative transfer model on Clementine data, although image fractions are simply indicators of relative detections of minerals presents in the soils.

Conclusions and perspectives: The spectral endmember selection and image fractions presented here offer an alternative approach that may complement traditional methods, and thus it may reinforce the interpretations. Further development will be focused on more detailed descriptions of the lithology, mixing processes, and quantitative estimate of the surface maturity of the various lunar soils. In theory, image fractions are representative of areal mixtures of materials. A step forward will be the use of a radiative transfer model to calculate more accurate abundances of minerals from the spectral endmembers, and then to derive mineral maps from the image fractions.

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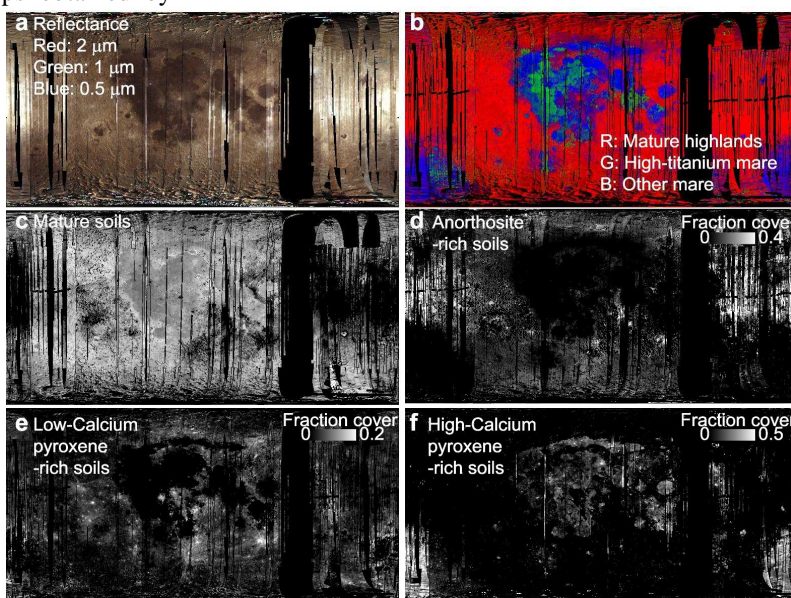


Fig. 2: Moon nearside hemispheric mosaic of M^3 images. a – Reflectance color composite with Lommel-Seeliger photometric correction applied. b – f: Image fractions of spectral endmembers of soils from spectral mixture analysis, where: b – General lithologies. c – Mature soils (mare and highlands). d – Anorthosite-rich. d – Mature mare. e – Low-calcium pyroxene-rich. f – High-calcium pyroxene-rich.