# TEXTURAL AND COMPOSITIONAL CONSIDERATIONS FOR MAPPING ILMENITE ON THE LUNAR SURFACE USING VIS-NIR REFLECTANCE SPECTROSCOPY.

K.M. Robertson[1], S. Li[2]., R.E. Milliken[1], C.M. Pieters[1] and P. Isaacson[1] Dept. of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI, 02912, [2]Hawaii Institute of Geophysics and Planetology, University of Hawaii, Honolulu, HI.

Introduction: The characterization of returned lunar samples from the Apollo and Luna missions has revealed that many mare basalts exhibit elevated TiO_2 abundance relative to terrestrial mid-ocean ridge basalts and basalts from other planetary bodies. The specific Ti-oxide present in a given basalt records information about the fO_2 at the time of crystallization [1,2], and thus knowledge of specific Ti-oxide mineralogy can be used to constrain the magmatic evolution of the moon.

To date, returned lunar basalt samples represent a very limited sampling of the lunar maria, therefore, global assessments of their mineralogy and chemistry must rely on remotely-sensed data. Hapke's radiative transfer model (RTM) provides a robust method for quantitative un-mixing of visible-near infrared (VIS-NIR) spectra acquired for airless bodies [3,4] and could be a viable method for mapping the distribution of Ti-bearing mineralogy. The unique nature of these opaque Fe-Ti oxide phases however, creates complex spectral reflectance properties [5,6] that can be difficult to characterize using existing models. Ilmenite in particular exhibits variable opacity as a function of wavelength and particle size, resulting in highly non-linear spectral reflectance properties [6,7]. Diagnostic spectral features of ilmenite include an increase in reflectance near 1 μm and a sharp upturn in reflectance in the NIR (>1.7 μm). These characteristics have an effect on spectra of bulk Ti-rich basalts that is disproportionate to ilmenite content and that varies with ilmenite texture (Fig. 1) and composition (Fig. 2).

Understanding the physical and chemical properties that affect the spectral properties of Fe-Ti oxides in lunar basalts and regolith is critical in order to accurately map Fe-Ti oxide abundance from remotely sensed data. Here we demonstrate how ilmenite textural and composition affect the spectral properties of high-Ti lunar basalts at VIS-NIR wavelengths and discuss the implications for ilmenite mapping of the Moon using Hapke modeling.

Methods: A suite of seven Apollo 17 high-Ti lunar basalts (70017, 70035, 70215, 74275, 71055, 75075, 78598) were selected based on their high ilmenite content over a wide range of textures, ranging from very fine-grained aphanites to coarse grained basalts. Elemental maps were derived from thin sections on an electron microprobe for modal mineralogy and textural analyses. Corresponding slabs were ground and sieved to large (>125 μm) and then small (<45 μm) size fractions for analysis on the bi-directional (BDR) spectrometer at the NASA RELAB facility at Brown Uni-
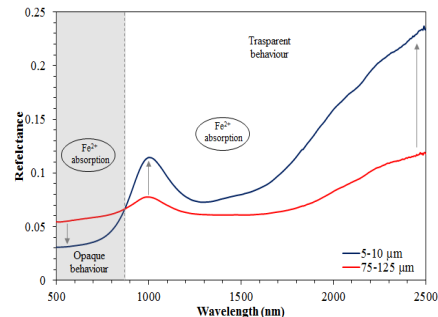

Fig. 1. Spectra of synthetic ilmenite for coarse and fine particle sizes. Shaded region highlights the spectral region where ilmenite displays high opacity. Grey arrows specify the diagnostic spectral features that are strongly influenced by ilmenite texture (crystal/particle size).

versity. Spectral parameters were calculated from the reflectance data and correlated to texture and composition.

Reflectance data were also used to test spectral un-mixing using a modified Hapke RTM [8]. Model inputs were the measured reflectance data, viewing geometry (*i, e, g*), mineral densities, and endmember single scattering albedo (derived from the Hapke model). Single scattering albedo of mineral endmembers were used to avoid errors due to large uncertainties in the optical constants of ilmenite. Multiple spectral endmembers for each phase were used in the model to better represent the variable bulk compositions of the entire sample suite. Endmembers included lunar mineral separates (ilmenite/plag/augite/pigeonite) from the Lunar Rock and Mineral Characterization Consortium [6], 13 additional pyroxenes (synthetic and from meteorites), and
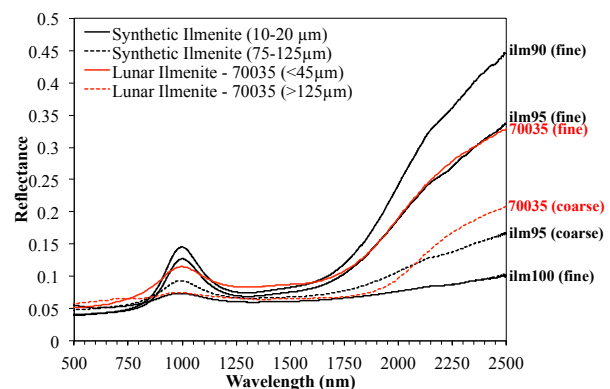
Fig. 2. Spectra of synthetic ilmenite-geikelite solid solution where Mg substitutes for Fe [9] illustrates how increasing Mg content results in similar spectral effects as decreasing particle size (increased spectral slope at longer wavelength, increased reflectance peak at 1000 nm).
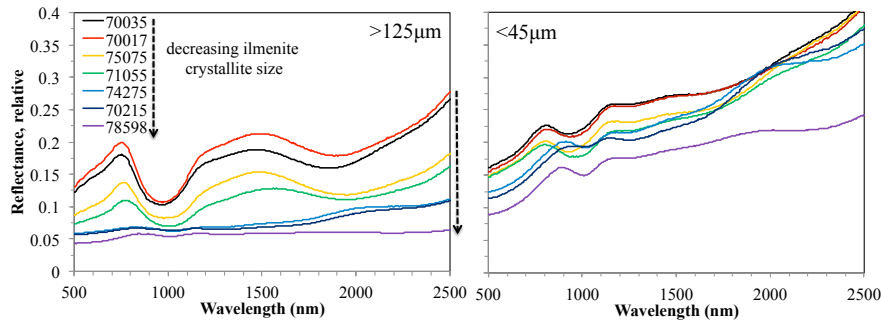
Fig. 3. BDR measurements of the high-Ti lunar basalt samples arranged from coarsest to finest ilmenite crystallite size (as shown by stippled arrow). For the >125 μm powders spectra of the course ilmenite samples are dominated by pyroxene while spectra for the fine ilmenite samples are more dominated by ilmenite. For the finer <45 μm powders, spectra of all samples are strongly affected by ilmenite.

spectra of a suite of synthetic ilmenite with variable Fe-Mg composition [9].

Results: Reflectance spectra for the suite of lunar basalts are shown in Fig. 3. Spectra for the larger size fractions (>125 μm) of the coarse-grained basalt samples are broadly similar to spectra of pure pyroxene, indicating that the spectrally dominant phase in these samples is pyroxene despite the presence of >10% absorbing coarse grained ilmenite. This suggests that most of the photons exiting these powders have experienced volume scattering with pyroxene and that the likelihood of a photon surviving interaction with ilmenite is low at all wavelengths. The spectral dominance of pyroxene is likely related to ilmenite being less volumetrically abundant in the sample, but it will also be related to how the ilmenite is *distributed* within the material. This is supported by examining the spectra of the <45 μm size fraction for the same samples. In those spectra (Fig. 3b) ilmenite is the spectrally dominant phase, even though the ilmenite abundance is the same as in the larger size fraction. Spectra for the smaller (<45 μm) size fractions display more consistent shapes between samples and all appear to be 'ilmenite-like'.

Relatively minor variations in the Mg^{2+} content of ilmenite can also have significant control over reflectance values near 1 μm and at wavelengths >1.8 μm (Fig. 2). Increasing the Mg^{2+} content in the ilmenite structure results in stronger spectral contrast at VIS-NIR wavelengths that are similar to the observed textural effects. As an example, the ilmenite mineral separates for sample 70035 are consistent with a 95% iron-Mg content (Fe#) for both small and large sieve size ranges. This observed compositional effect on spectral shape of ilmenite highlights the importance of choosing spectral

endmembers that are chemically representative of the lunar surface, especially considering that the Fe# of ilmenite in this suite of lunar samples varies from 85-98% Fe.
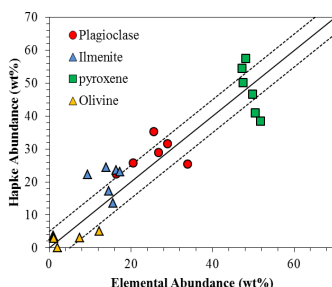
Modal abundance values for the <45 μm lunar basalt powders were estimated using the modified Hapke un-mixing model (Fig. 4). Spectral modeling of High-Ti lunar basalts improves dramatically when additional endmembers (OPX, CPX, and Ilm90-Ilm100) are included to account for compositional variations. Modal abundances for ilmenite are similar to measured microprobe values and show an improvement when compared to previous modeling attempts which systematically overestimated ilmenite abundance [7, 10]

Conclusion: It is shown that the presence of small amounts of ilmenite in lunar basalts causes suppression of pyroxene, olivine, and plagioclase absorption features, lowers reflectance values, and induces a stronger 'red' spectral slope at wavelengths >1.8 μm. These effects are significantly stronger for samples with fine-grained ilmenite crystals compared with coarse-grained samples that have similar ilmenite abundance. It is the ilmenite particle size and shape, not necessarily the abundance that dominates the spectral properties of high-Ti lunar basalts.

The Fe-Mg content of ilmenite is also important in controlling VIS-NIR spectral properties. It is expected that spectral mixing models that rely on a Mg-free pure ilmenite endmember (Fe#=100) will yield less accurate results, perhaps significantly so, compared with using a lunar-like ilmenite of Fe#=85-95. These results indicate that a lunar basalt sample with a lower abundance of fine-grained ilmenite with slightly higher Mg content could exhibit a spectrum with an apparently stronger ilmenite signature when compared with the spectrum of a basalt with more abundant, coarser ilmenite.

Fig. 4. Hapke modeling results are shown here for small (<45μm) lunar basalt size fractions. Modeled abundances include lunar sample endmembers supplemented with additional pyx and ilm endmembers to account for compositional variability.

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