EVIDENCE THAT UVVIS RATIO IS NOT A SIMPLE LINEAR FUNCTION OF TiO_2 CONTENT FOR LUNAR MARE BASALTS.

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Introduction: Lunar basalts exhibit obvious variations in ultraviolet-visible (UVVIS) color and these variations have been attributed to Ti content [1], the major compositional variable in mare basalts. Charette [2] first showed that Ti content in lunar samples is correlated with telescopic measurements of UVVIS ratio in mature (agglutinate rich) basaltic regolith, whereby samples with high TiO_2 concentrations exhibit relatively flatter and "bluer" UVVIS slopes (e.g., Mare Tranquillitatis) than basalts with lower concentrations in TiO_2, which are considered to be redder (e.g., central Mare Serenitatis). The optical properties of spectrally neutral opaques are suggested to influence the relationship between UVVIS spectral slope and Ti [3, 4]. Ilmenite, the major carrier of Ti and the principal oxide phase in lunar soils, is dark and spectrally neutral relative to the spectrally red mature lunar mare soils. Consequently, the UVVIS color ratio has been one of the most widely used spectral parameters in lunar science to estimate the TiO_2 composition of mature mare basalts. The extent to which color variations are dependent upon TiO_2 or other compositional parameters, however, is not well established. For example, uncertainties in the Charette relation were revealed with failure to accurately predict the low-Ti contents of the Luna 24 basalts. Consequently we examine the correlation between UVVIS color and TiO_2 content by integrating Clementine Spectral Reflectance (CSR) and Lunar Prospector neutron spectrometer (LPNS) data.

Data: Clementine collected 11-band multispectral data (415, 750, 900, 950, 1000, 1100, 1250, 1500, 2000, 2620, and 2792 nm) at 100-200 meter per pixel spatial resolution for most of the lunar surface [5]. We used CSR images processed by the USGS with calibrations of [6-8]. From these data color ratio maps are made using the 415 and 750 nm images. ISIS (Integrate Software for Imagers and Spectrometers) was used to reproject the full-resolution CSR data to match the resolution of the LPNS using bilinear interpolation.

The data reduction method of [9, 10] is used to map the distribution of TiO_2 in the lunar soil using Lunar Prospector data. The LPNS data provide independent measurements of titanium at half-degree resolution (~15 km/pixel), which we use to test the correlation between TiO_2 content and CSR data. Although LPNS data cover broad areas, they provide direct, global measurements of TiO_2 that serve as ground-truth to the CSR data. So where as before there were only 6 ground-truth points in the Charette relation, there are now over a thousand data points with which to rigorously test the correlation between UVVIS and TiO_2.
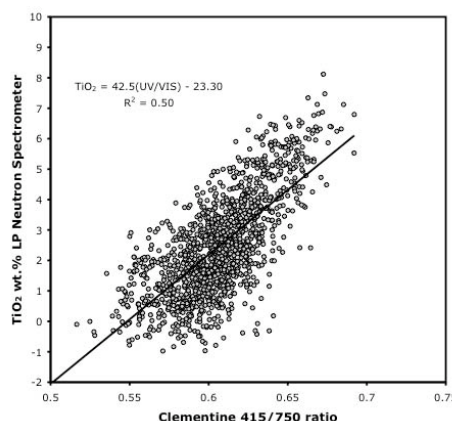

Fig. 1. LPNS data for TiO_2 versus CSR UVVIS ratio for all mare areas >15 wt% FeO. The black line represents the linear regression to all the data.

$TiO_2 = 42.5(UV/VIS) - 23.30$
$R^2 = 0.50$

Observations: A comparison between LPNS TiO_2 and Clementine UVVIS data (Fig. 1) for all mare areas with greater than 15 wt% FeO, shows that while a positive correlation exists between the two data sets, the ability to accurately predict TiO_2 concentration from a UV/VIS value, that is the 415/750 ratio, is rather poor. For example, the current accuracy of the ability of the UVVIS color ratio to predict TiO_2 composition, a UV/VIS value of 0.6 could represent TiO_2 values in the range of 0 to 4 wt% TiO_2 (equivalent to 2±2wt% or 100% relative error). Clearly a better technique for predicting TiO_2 from remotely sensed data is needed.

The data in Fig. 2, however, represent eighteen individual regions of interest that were selected on the basis of uniform UVVIS color. By selecting mare regions with uniform color, we are able collect data for major, yet discrete areas, and avoid compositional boundary regions. This approach allows the minimization of compositional and spectral mixing effects as well as scattered light effects observed in Fig. 1. These regions of interest include all major near side maria, some multiple times due to their vastness (e.g. Imbrium and Procellarum), and range in size from 8,000 km^2 to 36,000 km^2, with the average ~20,000 km^2. Both the compositional and spectral information were extracted from the respective 2×2 degree data sets. For comparison, Clementine UVVIS data and sample TiO_2 data for the Apollo and Luna landing sites are plotted in Fig. 2. These ground-truth data also lie within the two separate trends defined by the remotely sensed data.

With these carefully selected data, the UVVIS-TiO_2 trend is not linear as presumed by previous studies. Figure 2 reveals that basalts with about 2 wt% TiO_2 or less exhibit a lower UVVIS slope than basalts with >2 wt%

TiO_2. These two slopes are illustrated in the Fig. 2 inset. The two trends intersect at 0.5 TiO_2 wt% and 0.55 UV-VIS ratio and show evidence of an apparent transition from the shallow slope to the steeper slope that occurs at 2 wt% TiO_2 and 0.62 UVVIS (This inflection is coincident with the UV/VIS one of the cutoff criteria developed by [11] for determining which of two empirical equations would be used to calculate TiO_2 composition from CSR data). Because the UVVIS-TiO_2 data are traditionally fit with a single trend, a possible outcome of the presence of two trends is that TiO_2 distribution may be bimodal as the sample data suggest and not an artifact of sampling.
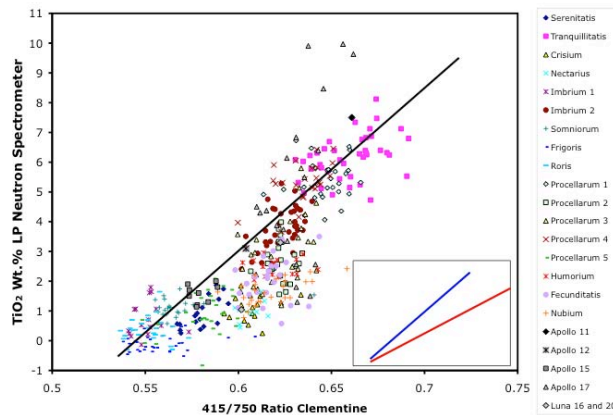

Fig 2. LPNS TiO_2 data compared with CSR UVVIS ratio for selected regions of interest. Black line represents regression line of Fig. 1. Inset red and blue lines represent upper and lower regressions to the two data trends.

We suggest that the data distribution in Fig 1 is partially an artifact of mixing between geologic materials that comprise these two spectral trends. Data collected from contiguous areas along the boundary between high-Ti and high-FeO and low-Ti maria in the Imbrium-Procellarum region, and the border of Mare Serenitatis fill in the data gaps of Fig. 2 yielding the data distribution in Fig. 1. Without the mixing zone basalts, the relation appears to be better characterized by two trends possibly with a common origin but with different slopes. The two groups are divided on the basis of UV-VIS slope, and the sum of FeO+TiO_2 (Fig. 2). Mare areas with a sum of 21 or greater for these two elements lie along the upper slope. Assessing both FeO and TiO_2 discriminates between mare basalts with relatively high (>6.5 wt% TiO_2) and low TiO_2 contents (<2.5 wt%), and average FeO contents (~17.5 wt%). Comparing the two trends at face value suggest that the basalts with >21 FeO-TiO_2 appear spectrally redder, i.e., lie to the left of the red trend line, than the <21 FeO+TiO_2 basalts.

There are at least 2 possible explanations for the dual trend. The first possibility is sensitivity to ilmenite grain size. The effectiveness of ilmenite as an absorber is a strong function of its grain size. If there are system-atic differences in ilmenite grain size among mare units, the influence of ilmenite on color relative to its abundance will not be consistent. Also the larger grain ilmenite would exhibit bluer spectra the smaller grain size. Thus, it may be possible to explain the dual trend in Fig 2 as the result of low-Ti basalts that are coarser grained than the higher Ti-basalts. This grain size effect also agrees with overall reflectance values, whereby the low-Ti larger grain basalts appear brighter in the UV-VIS than the high-Ti finer grain basalts.

A second possibility is that UVVIS continuum of the <21 FeO+TiO_2 basalts is affected by bulk iron content. A comparison between UVVIS ratio and FeO content, which are subdivided by TiO_2 content, reveals that basalts with >20 wt% FeO appear bluer than basalts with similar TiO_2 contents but <20 wt% FeO. This effect, however, is only observed for basalts with <4 wt% TiO_2. With TiO_2 content >4 wt% ilmenite may dominant the UV/VIS ratio lessening the affect FeO has on the spectra of the silicate portion. On this basis, basalts with high FeO contents would appear bluer than basalts with similar TiO_2 compositions but lower FeO contents. Thus, the flatter UVVIS-TiO_2 trend of low-Ti trend in Fig. 2 is likely the result of increasing iron content of the silicate portion of the basalts. As the iron content of olivine and pyroxene phases increases they become darker and more opaque; thus, causing the overall spectrum to become more like ilmenite. Within the high-Ti basalts the mafic silicates are relatively depleted in FeO content because the iron has gone into ilmenite phase.

Conclusions: Comparison of the UVVIS data with LPNS TiO_2 data suggests that the UVVIS data does not yield accurate estimates of TiO_2. A single correlation trend between TiO_2 and UV/VIS ratio presupposes that a single process or component imparts color to lunar soils as a function of Ti content. Our results suggest that other effects, such as ilmenite grain size or FeO content, may contribute to UVVIS color so that estimates of TiO_2 from spectral properties will require supporting information (e.g., Clementine 2.7 μm data and 70-cm radar data [12, 13]) beyond UVVIS ratios.

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