

IS ILMENITE ALWAYS THE DOMINANT CARRIER OF TITANIUM IN LUNAR MARE BASALTS?

M. A. Riner¹, M. S. Robinson¹, J. A. Tangeman² and R. C. Elphic³, ¹Department of Geological Sciences, Northwestern University, Center for Planetary Sciences, 1850 Campus Dr., Evanston, IL 60208, ²Containerless Research, Inc., Evanston, IL 60201, ³Los Alamos National Laboratory, Los Alamos, NM 87545.

Introduction: The dominant cause for lunar visible color differences is variations in the degree of soil maturity and the abundance of FeO and opaque minerals, such as ilmenite. The addition of opaque minerals to a lunar soil tends to decrease the overall reflectance and continuum slope (darkens and decreases “redness”). As a soil weathers its reflectance is also lowered but its slope increases (darkens and increases “redness”). By exploiting these color trends numerous studies have attempted to correlate the abundance of TiO₂ in the form of ilmenite to variations in blue to red ratios (i.e. 415 to 750 nm Clementine bandpasses) with varying degrees of success. Discrepancies between independent methods have been attributed to: unknown opaque phases in the lunar soil; overcorrection of thorium values in Lunar Prospector epithermal and thermal neutron data; mixing of highlands and mare basalt materials; and uncorrected scattered light effects. To investigate this problem we are examining the spectral differences between plausible lunar analog opaque mineral powders and their respective quenched glasses.

Background: Lunar ilmenite (FeTiO₃) is a potential ISRU source of oxygen and titanium metal. Additionally, ilmenite-rich soils preferentially retain solar wind volatiles H and He, that are also potential lunar resources. Understanding the distribution and abundance of ilmenite also serves to elucidate the Moon’s thermal history and formation of the crust. Additionally, titanium concentration is one of the most useful discriminators in classifying lunar mare basalts due to its substantial variation (<1 wt. % to > 14 wt. % TiO₂) [1]. The prevalence of titanium in mare basalts, relative to the terrestrial basalts, is curious and not yet satisfactorily explained.

The Hapke model [2] of lunar reflectance attributes the spectral properties of lunar soil to four components of the regolith: the ferrous iron (Fe²⁺) in silicate minerals and glasses; submicroscopic metallic iron (SMFe) grains produced in the maturation process; titanium in silicate minerals and glasses; and opaque phases (in the case of the Moon, often assumed to be mostly ilmenite). The presence of opaque phases causes an overall decrease in reflectance and spectral slope (less red, titanium rich basalts are sometimes referred to as “blue”). Increased maturation and added FeO cause a decrease in reflectance and an increase spectral slope (redder).

Lucey et al. [3] developed a method for estimating titanium abundance using the Clementine 415/750 nm ratio versus 750nm reflectance to define a Ti spectral parameter. Lucey notes that this method relies on the spectral properties of opaque minerals and the assumption that ilmenite is the dominant opaque mineral everywhere on the Moon.

The titanium abundances estimated by Lucey et al. are higher, by up to a factor of 2, than values from Lunar Prospector epithermal and thermal neutron data in some areas, as shown in Figure 1 [4]. Gillis et al. [5] modified the algorithm of Lucey et al. after observing spectral similarities of landing sites corresponding to outliers on the plot of Ti spectral parameter versus measured TiO₂ content of returned samples. By separating the two trends and applying independent fits to the data they found TiO₂ abundances more consistent with Lunar Prospector epithermal and thermal neutron values.

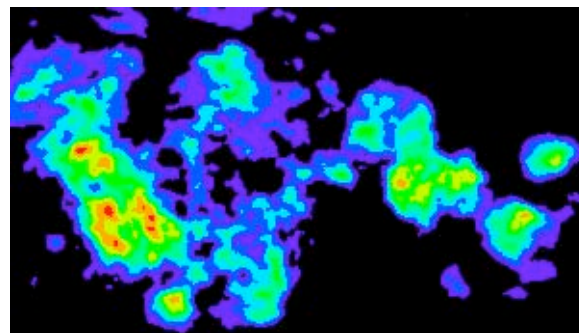


Figure 1 – Clementine derived TiO₂ minus Lunar Prospector TiO₂ abundance estimate difference map. Values range from zero (black) to eight (red) wt. %. Area shown includes all major nearside mare deposits: latitude range 55°N to 30°S, longitude range 80°W to 70°E.

As mentioned above the discrepancy between titanium abundance estimates from different measurement techniques may be the result of unknown opaque phases in the lunar soil. The majority of observed mare basalts are not represented by returned samples [6] and the high titanium basalts returned from Apollos 11 and 17 are ilmenite-rich. It is possible that other opaque phases are significant in unsampled mare basalt soils. Most lunar spinels sampled from Apollo and Luna landing sites have

compositions that fall between chromite (FeCr_2O_4) and ulvöspinel (Fe_2TiO_4), and spinels make up as much as 10% of the volume of some basalt samples from the Apollo 12 and 15 landing sites [1]. We propose that ulvöspinel may be the dominant opaque in some areas of the Moon and its reflectance is different enough from ilmenite to impact the Lucey method to an appreciable degree. To investigate this hypothesis we measured the reflectance of ilmenite and ulvöspinel powders processed in the same fashion. Additionally, we are producing quenched glasses of the powders to partially simulate space weathering effects.

Methods: Three samples, basalt, ulvöspinel, and ilmenite were separately pulverized in a tungsten carbide canister and sieved to particle sizes less than 90 microns. An ulvöspinel-rich basalt was synthesized by mixing 15 wt % ulvöspinel powder and 85 wt.% basalt powder.

The ulvöspinel-rich basalt powder was vitrified using containerless processing methods, specifically, aerodynamic levitation, coupled with continuous wave CO_2 laser heating. Approximately two grams of powder were prepared for levitation by laser melting small portions of the powder into ~1.5 mm diameter spheroids. Each spheroid was then levitated in argon gas in a conical nozzle levitator and melted with the CO_2 laser. Argon was used to simulate the inert conditions that occur on the Moon. Each molten levitating droplet was held isothermally in the argon gas jet for ~30 seconds, and then cooled by blocking the laser. Under these containerless conditions, glass formed easily from the titanium-rich basalt spheroids. Next the sample was pulverized in a tungsten carbide canister and sieved to particle sizes less than 90 microns to match the mineral powders.

Five samples: basalt, ulvöspinel, ulvöspinel-rich basalt, vitrified ulvöspinel-rich basalt, and ilmenite, were measured at room temperature with a high-resolution fiber optic spectrometer (Ocean Optics HR2000CG-UV-NI) that is sensitive over the range 200-1100 nm. The samples were illuminated with a DH-2000-s light source equipped with both a deuterium (210-400nm) bulb and halogen (360-1500nm) bulb. The source and reflected light share the same fiber optic probe, resulting in a near zero degree phase angle. The sample spectra are corrected using a spectralon reference and dark measurements. The precision on the measurements is about 2% within a given session and from day-to-day. The accuracy of the measurements has not yet been checked with another instrument, but we hope to have such measurements in the near future.

Discussion: Ulvöspinel and ilmenite are spectrally similar above 700 nm, but differ significantly in the visible, with the maximum separation at about 500 nm, shown in Figure 2. If ulvöspinel does occur as a major carrier of titanium in some mare basalts, the spectral difference could explain some of the discrepancy between the Clementine and Lunar Prospector results. The vitrification procedure is a promising method of partially simulating the effects of space weathering (agglutinate production) which tends to reduce spectral contrast. Continued measurement of the spectral reflectance of analog opaque minerals and their glass equivalents is necessary to further investigate the differences between titanium abundance estimates of the lunar surface. Different methods of titanium abundance estimation reflect differing assumptions regarding the mineralogy and chemistry of the lunar surface, requiring the use of a variety of investigation techniques.

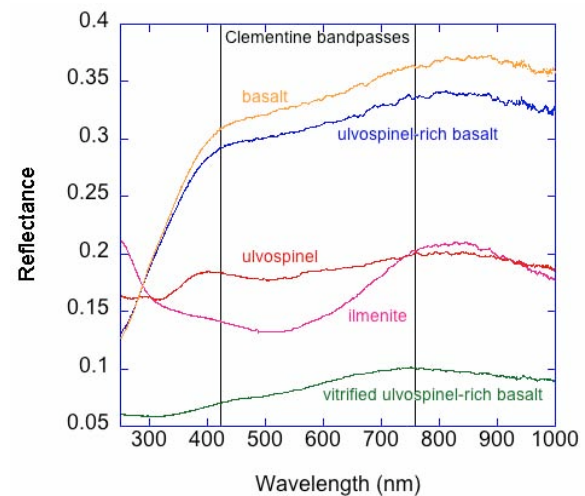


Figure 2 – Laboratory reflectance spectra (relative to spectralon) for basalt, ulvöspinel, ulvöspinel-rich basalt, vitrified ulvöspinel-rich basalt and ilmenite. Ulvöspinel-rich basalt is a mixture of 15 wt. % ulvöspinel and 85 wt. % basalt. All samples are < 90-micron particle size. Vertical lines indicate Clementine bandpasses at 415 and 750nm.

References: [1] Papike, J. et al. (1991) in *Lunar Sourcebook*, 137-175. [2] Hapke B. et al. (1975) *JGR* 80, 2431-2443.; Rava B. and Hapke B. (1987) *Icarus*, 71, 397-429. [3] Lucey P. G. et al. (1996) *LPS XXVII*, Abstract, 781-782; Blewett D. T. et al. (1997) *JGR* 102, 16319-16325. [4] Elphic R. C. et al. (2002) *JGR* 107, 5024. [5] Gillis J. J. et al. (2003) *JGR* 108, 5009. [6] Pieters C. M. (1978) *LPS IX*, 2825-2849.