# MAPPING TECHNOLOGICALLY AND ECONOMICALLY IMPORTANT MATERIALS AT LUNAR AND TERRESTRIAL SITES USING MOON MINERALOGY MAPPER ($M^3$) AND ADVANCED SPACEBORNE THERMAL EMISSION AND REFLECTION RADIOMETER (ASTER) DATA

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## Dedication

For my mother.

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## ABSTRACT

This dissertation comprises three distinct research projects, all of which employ the use of remote sensing and digital image processing methods for the discovery and characterization of mineral resources. Two of the research projects focus on the use of hyperspectral data to identify water and ilmenite on the lunar surface. The third research project involves the use of multispectral data to map alunite in copper porphyry and epithermal silver-gold deposits. Our approach to these problems result in innovative algorithms and geological interpretations that are of use to both planetary science and exploration and the terrestrial mineral industry.

**Project I:** Towards the late stages of differentiation of the early lunar magma ocean, the remaining material would have been enriched with thorium, water, hydroxyl, and other incompatible species. Using results from the Lunar Prospector Gamma Ray Spectrometer (LP-GRS), we selected thorium (Th) anomalies on the Moon in an effort to detect material rich in KREEP (potassium, rare earth elements, phosphorus) using hyperspectral imagery. Four sites were chosen: Lassell Crater, Hansteen Alpha, Gruithuisen Domes, and Compton-Belkovich Thorium Anomaly (CBTA). Three of these sites are non-mare volcanic features within the Procellarum KREEP Terrane (PKT), while Compton-Belkovich is located on the lunar farside. The Moon Mineralogy Mapper ($M^3$) hyperspectral imager was used to analyze the composition of these locations. The spectra gathered from all four study sites all show pronounced absorptions at ~2.8 μm, indicating hydroxyl or water. This is significant for three reasons: (1) the strong absorption of hydroxyl/water shown at each of these volcanic sites supports the hypothesis that the lunar mantle is more hydrous than previously thought; (2) it suggests that KREEP may lie, possibly as uncoupled pods, beneath the anorthositic highlands near Compton-

Belkovich as well as underlying other areas outside the previously defined PKT; and (3) it suggests that non-mare silicic volcanic features would have erupted prior to mare basalts due to their increased abundance of magmatic water, consistent with basaltic underplating.

**Project II:** KREEP material on the Moon is shown to be relatively rich in ilmenite ($FeTiO_3$). By targeting areas with anomalously high Th signatures, as seen by LP-ThGRS, we attempt to determine if Th hotspots are associated with ilmenite-rich basalts. To map ilmenite, we employ a band depth technique that takes advantage of the fact that the visible-infrared reflectance spectrum of ilmenite exhibits low reflectance and a flat continuum slope. As a result, the spectra of ilmenite-bearing mare basalts will have a reduced 1-μm absorption. We demonstrate this effect by plotting ilmenite concentrations from Apollo basalt samples against the $M^3$-derived, 1-μm absorption depths associated with the locations from which the samples were collected. A least-squares regression to the ilmenite vs. 1-μm absorption data is then used to predict ilmenite concentrations of mare basalts from $M^3$ spectra. Using this methodology, we built ilmenite maps for the following nearside mare: western Mare Imbrium; southern Oceanus Procellarum; eastern Mare Nubium; Mare Serenitatis; and Tranquillitatis. Based on the concentrations of Th and ilmenite associated with the eruptions, we determined that at least three eruption episodes of mare basalts occurred, each with different geochemical signatures. In addition we identified late stage (<3.1 Gya) ilmenite- and Th-rich basalts within the PKT, which we suggest were supplied by the arrival of a KREEP-, and ilmenite-rich plume that formed at the core-mantle boundary after ilmenite-rich and KREEP-rich melts sank into the mantle. However, areas outside of PKT, such as Tranquillitatis and Serenatatis, do not exhibit both high KREEP and high ilmenite concentrations. Instead, early stage basaltic eruptions – consisting of low-Th, ilmenite-rich basalts are present at Mare Tranquillitatis and Th- and ilmenite-poor basalts are

present at Serenitatis. We propose two possible scenarios to explain this. In the first, the Ti-rich but Th-poor mare basalts would have erupted after (or during) a degree-1 downwelling that affected the nearby PKT early in lunar history. The KREEP may have never existed at these locations, or it was removed by the degree-1 downwelling, which redistributed that material and concentrated it in the PKT. In the second scenario, the Ti-rich but Th-poor mare basalts would have erupted prior to the degree-1 downwelling. In this case, the ilmenite-rich cumulates may have existed at the time of melt generation. However, the lack of Th would imply that KREEP did not exist at all at these locations.

**Project III:** Alunite ($KAl_3(SO_4)_2(OH)_6$) is a sulfate mineral that is commonly found in argillic alteration zones of porphyry and epithermal systems, and in other supergene enriched mineral deposits. Using ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) data, we target spectral features associated with hydroxyl ($OH^-$) and sulfate ($SO_4^{2-}$). Previous studies have used OH- absorptions near 2.2 µm to target alunite, but their methods can confuse alunite with carbonates, detrital clays, iron oxides, and jarosite. We use a logical operator approach to increase our confidence in targeting alunite and delineate it from carbonates, detrital clays, iron oxides, and jarosite. The first logical operator targets a doublet absorption near 2.2 µm associated with $OH^-$ in alunite, detrital clays, and carbonates. It also targets the negative spectral slope between 0.8 and 1.65 µm, in order to delineate alunite from iron oxide and jarosite. We also develop a second logical operator that targets the 9-µm absorption associated with $SO_4^{2-}$ in alunite, jarosite, and quartz. To test the effectiveness of our logical operator methodology in places where carbonates, detrital clays, limonite, and vegetation not related to porphyry and epithermal systems are present, we conduct a ground truth investigation at Cuprite Hills, Nevada. We show that the alunite identified by our alunite map is

spatially correlative to the regions indicated by AVIRIS mineral maps to contain alunite. Our improved methodology for locating alunite with ASTER data is an inexpensive, easy, and reliable method for discovering new porphyry and epithermal mineral deposits that can be applied to a variety of exploration problems.

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# CHAPTER 1: INTRODUCTION

This dissertation comprises three research projects presented in the form of manuscripts for submission to professional journals. The author of this dissertation (Douglas Laurance Standart) is the lead author and analyst of each chapter. All three manuscripts employ the use of remote sensing and digital image processing methods for the discovery and characterization of mineral resources. Chapter 2 focuses on the use of hyperspectral data to identify water at the locations of silicic volcanic features on the Moon. Chapter 3 focuses on the use of hyperspectral data to target and estimate the concentration of ilmenite in mare basalts on the nearside of the Moon. Chapter 4 focuses on the use of multispectral data to map the mineral alunite as a proxy for locating copper porphyry and epithermal silver-gold deposits. The approach to these problems has resulted in innovative algorithms and geological interpretations that are of great potential use to planetary science and exploration and also to the terrestrial mineral industry.



## 1. Lunar Water and Ilmenite (Chapters 2 and 3)

### 1.1 Motivation for Study

The lunar surface hosts a variety of potentially exploitable resources, and *in-situ* resource utilization (ISRU) of those resources will be a key technology in sustained human exploration of the solar system. ISRU involves using native materials to sustain prolonged activity at a remote site, such as at a lunar outpost (Duke et al., 2006). The discovery and characterization of exploitable water, in the form of molecular water ($H_2O$) or hydroxyl (OH), and of high concentrations of extractable ilmenite ($FeTiO_3$), an ore of titanium, is important for the exploration of the lunar surface. A lunar outpost will require water for multiple reasons. The most obvious reason is for drinking, but water can also be broken down to create rocket engine

propellant in the form of oxygen and hydrogen (Duke et al., 2006). The oxygen can also be used for life support, and the hydrogen can be used as consumable in fuel cells and other catalytic reactions (Duke et al., 2006). Due to the high tensile strength, fatigue resistance, and crack resistance of titanium (Duke et al., 2006), it can be used in metal alloys to make spare spaceship parts, spare robot parts, or building materials for the lunar outpost (Duke et al., 2006).

In parallel with the planetary exploration significance of this work, this research also has important scientific implications. Our understanding of lunar water – including its origin, distribution, and abundance – in the form of both OH and $H_2O$, is also poorly understood. Until recently, the Moon has been thought of as being fairly anhydrous relative to Earth (Klima et al., 2013). However, lunar samples and various remotely-sensed datasets have suggested that the Moon is not as dry as previously thought (Pieters et al., 2009; McCubbin et al., 2010; McCubbin et al., 2011; Klima et al., 2013). Most of this water is attributed to non-magmatic sources, such as solar wind implantation or comet/meteor bombardment (Hodges, 2002). Magmatic water, on the other hand, is water that is intrinsic to the Moon. The presence of magmatic water on the Moon could have major implications for the formation of the lunar crust. Since water lowers the melting point of rocks, water would allow the generation of magmas at lower temperatures than anhydrous material. Because the lunar KREEP (potassium, rare earth elements, phosphorus) is thought to contain water (Elkins-Tanton and Grove, 2011), water may also be a useful indicator of KREEP-enriched lithologies, which can aid in the remote detection of KREEP, and potentially indicate that KREEP is not limited to the Procellarum KREEP terrane (PKT).

In searching for water and titanium, I investigate a fundamental geologic and geochemical asymmetry of the lunar crust. The distribution of basaltic, basin-filling maria (dominantly on the lunar near side) is part of a distinction often referred to as the mare-highland

dichotomy (Zhong et al., 1999; Zhong et al., 2000; Parmentier et al., 2002; Shearer et al., 2006). The abundance of KREEP on the nearside of the Moon could explain the origin of the mare basalts, particularly the large amounts of Th-rich mare basalts within the PKT (Wieczorek and Phillips, 2000). This is because large amounts of radiogenic heat-producing elements may be present in KREEP, and those heat-producing elements would have promoted heating and melting of the mantle, allowing a prolonged volcanic history (Wieczorek and Phillips, 2000).

It is not known whether the KREEP is continuous or discontinuous in the lunar subsurface, since it is not seen at the surface on the farside. A better understanding of the distribution of KREEP will help explain the lunar dichotomy. For example, if KREEP is a continuous layer throughout the lunar subsurface, or if it distributed in places other than the nearside of the Moon, it is possible that it was not the main reason for prolonged volcanism on the nearside. Instead, it is possible that another mechanism was responsible for the prolonged volcanism on the Moon, such as a nearside plume like the one proposed by Andrews-Hanna et al. (2014). Such a plume would drive melting of the lower crust for a prolonged period of time. Those KREEP and Ti- rich melts would then erupt to the surface above the plume. On the other hand, if KREEP were continuous then why don't we see prolonged volcanism elsewhere on the Moon, since radiogenic heat producing elements would encourage melt generation?

The research presented in Chapters 2 and 3 provides evidence for KREEP-enriched lithologies on the lunar farside, challenging the previously accepted extent of KREEP-enriched mare basalts. My results suggest a mechanism for both ilmenite- and KREEP-rich basalt emplacement on the lunar nearside that involves a Ti- and KREEP-rich plume that was created after a dense layer sank to the core-mantle boundary early in lunar history, dragging Ti- and KREEP-rich material with it. Over time, the Ti- and KREEP-rich materials would have mixed

and become thermally buoyant and would have risen back to the base of the crust in the form of a plume (Zhong et al., 2000, Parmentier et al., 2002).

## 1.2 Goals and Objectives

Chapters 2 and 3 aim to answer the following research questions:

(1) Why does Th appear to be restricted to the Procellarum KREEP terrane, and does it occur with high concentrions of ilmenite?

(2) Do useful materials, such as $OH^-$, $H_2O$, REEs and ilmenite, appear in high abundances at Th hotspots? If so, why?

(3) What constraints can we place on the evolution of the lunar crust using Moon Mineralogy Mapper ($M^3$) data?

The specific objectives that allow these questions to be answered are:

- Implement a methodology for remotely detecting and estimating the abundance of water using hyperspectral data of the lunar surface.
- Produce water abundance maps for areas of suspected high-silica volcanic rocks on the nearside and farside of the Moon.
- Develop a methodology for remotely detecting ilmenite using hyperspectral data of the lunar surface.
- Calibrate the ilmenite-mapping algorithm in order to allow reliable determination of ilmenite concentrations.
- Produce ilmenite abundance maps for a suite of mare on the lunar nearside.

## 1.3 Research Products and Their Significance

In the process of investigating the asymmetry of the lunar crust using hyperspectral data, I develop ilmenite maps for several maria on the nearside of the Moon and maps showing the possible locations of magmatic water for several non-mare silicic features distributed throughout the Moon.

Chapter 2, "Detecting Magmatic $OH^-/H_2O$ at Sites of Non-mare Silicic Volcanism on the Moon Using the Moon Mineralogy Mapper ($M^3$)", is co-authored with Dr. Jose M. Hurtado, Jr. and is in the form of a manuscript to be submitted for peer review to the *Journal of Geophysical Research: Planets*. Chapter 2 focuses on a set of nearside silicic volcanic features – e.g., Lassell Massif, Gruithuisen Domes, Hansteen Alpha (Figure 1) – in an effort to understand the distribution of KREEP and to determine if magmatic water is present in multiple locations on the Moon. I compare the silicic volcanic features to a set of thorium anomalies, including the Compton Belkovich Thorium Anomaly (CBTA), and to mare-type basalts on the lunar farside. In these comparisons I have sought to find compositional relationships between nearside and farside non-mare silicic lithologies, such as the presence of KREEP-related incompatible elements (e.g., Th, $OH^-$, $H_2O$), that can both illuminate the chemical geodynamics of the Moon and aid the discovery of potential resources. For example, I map the spatial relationships of silicic volcanic features with respect to the current boundaries of the PKT (Figure 1) and their water concentrations. This provides insight into the extent of KREEP and, therefore, an idea of how the stages of lunar differentiation may have occurred. I show the first evidence for hydrous KREEP-related incompatible elements at CBTA that indicate a KREEP presence outside the PKT, indicating that KREEP is not only on the nearside, and is possibly a continuous layer or in the form of pods, sills, or dikes on the farside (Figure 2). In addition, the presence of water at the non-mare silicic features has implications for the generation of lunar partial melts, such as

whether basaltic underplating (Hagerty et al., 2006) or silicic liquid immiscibility (Hagerty et al., 2006) is the primary mechanism for generating silicic melts on the Moon.

Chapter 3, "Targeting Ilmenite in Mare Basalts Using the Moon Mineralogy Mapper", is co-authored with Dr. Jose M. Hurtado, Jr. and is in the form of a manuscript to be submitted for peer review to the journal *Icarus*. KREEP material on the Moon has been shown to contain ilmenite (Shearer et al., 2006), and I target areas with anomalously high Th signatures, and therefore KREEP, (Figure 3) as a proxy for ilmenite-rich basalts. In doing, I map the highest concentrations of ilmenite-rich material on the nearside of the Moon. Geophysical models (Zhong et al., 1999; Parmentier et al., 2002; Shearer et al., 2006) have shown that KREEP- and Ti-rich melts could have mixed during a downwelling early in lunar geologic history and that they may have subsequently reaccumulated at the base of the crust. I do not show any indication of a correlation between Th and ilmenite concentrations in mare basalts in chapter 3. I suggest that an additional factor, such as age, should be considered. In Chapter 3, I show that three stages of eruptions occurred within the PKT, each with a different geochemical signature. Outside of the PKT, the eruption model that I propose is not applicable, possibly because the plume that fed eruptions in the PKT did not affect areas outside of the PKT.



**2. Terrestrial Mineral Exploration (Chapter 4)**

**2.1 Motivation for Study**

Regional mineral exploration is a critical first step for junior and major mining companies. The ability to cheaply and quickly find mineral deposits, such as porphyry copper and epithermal silver-gold, would not only help mineral exploration companies find additional deposits, but it would also spark an explosion in regional explorations efforts. For example,

Anglo-American reported that the average cost per kimberlite discovery used to be ~$1 million, but with multispectral and hyperspectral mapping the cost per kimberlite discovery has been reduced to ~$300,000 (Toovey, 2011).

Alunite is a hydrothermal clay that is associated with porphyry copper deposits (PCD) and epithermal silver-gold deposits (ESGD) (Guilbert and Park, 2007). Alunite contains several spectral features (i.e. 2.17-2.2 µm $OH^-$ absorption, 9 µm $SO_4^{2-}$ absorption, negative slope between 0.8 and 1.65 µm; Figure 4) that make it a good remote sensing proxy for PCDs and ESGDs (Mars and Rowan, 2006). However, previous attempts to use remote sensing to map alunite, such as the argillic logical operator developed by Mars and Rowan (2006) ,cannot distinguish alunite from carbonates, detrital clays, jarosite, and iron oxides. In addition to improving existing methods, there is also a need for a methodology that can map alunite using cheap and easy to use multispectral data and that can yield results with similar accuracy to what is possible with hyperspectral data. Such a methodology would allow mining companies to expand their exploration programs without spending large amounts of their exploration budget on hyperspectral imagery, data which may not be possible to acquire in the first place.



**2.2 Goals and Objectives**

Chapters 4 aims to answer the following research questions:

(1) How much can we improve on previous methods of targeting alunite with ASTER data by focusing on spectral features uniquely associated with alunite, such as the 2.17-2.2-µm $OH^-$ absorption, the 9-µm $SO_4^{2-}$ absorption, and the negative spectral slope between 0.8 and 1.65 µm?

(2) How much more or less effective is ASTER data when used to target alunite? How does the accuracy of ASTER compare to higher spectral and spatial resolution platforms?

The specific objectives that allow these questions to be answered are:

- Implement a methodology that uses ASTER data to remotely detect alunite while also reducing the commission errors associated with carbonates, detrital clays, jarosite and iron oxides.
- Produce alunite maps for areas of suspected hydrothermal alteration at Cuprite Hills, NV.
- Compare the resulting alunite map with mineral maps generated by the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) hyperspectral instrument, argillic alteration maps created by Ashley and Abrams (1980), and the argillic logical operator map of Mars and Rowan (2006).
- Acquire samples from Cuprite Hills and measure their reflectance spectra to act as ground truth for my logical operator maps.

## 2.3 Research Products and Their Significance

Chapter 4, “Targeting Alunite in Epithermal and Copper Porphyry Deposits Using ASTER VNIR, SWIR, and TIR Imagery”, is co-authored with Dr. Jose M. Hurtado, Jr. and Dr. Philip C. Goodell and is in the form of a manuscript to be submitted for peer review to the journal *Economic Geology*. The research uses Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) multispectral data to accurately map alunite. The $OH^-$ and $SO_4^{2-}$ logical operators that I describe in Chapter 4 have proven to be effective at detecting alunite. By using samples from Cuprite Hills as ground truth, and alunite maps from previous studies (Ashley and Abrams, 1980; Swayze et al., 2014), I was able to show that the alunite map