Microscale distribution and behavior of Th, REE, and K during regolith formation processes on the Moon: Implications for remote sensing of the surfaces of airless planetary bodies.

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Introduction: Remotely sensed geochemical data provide extremely valuable information concerning the global distribution of elements on a planetary surface, and are valuable in the identification of major crustal terranes. Planetary geochemical maps of the Moon and Mars for several elements such as Th, rare earth elements (REE), K, and Fe have been or are currently being prepared and have yielded significant insights into large-scale planetary processes [e.g., 1,2,3,4]. With respect to the lunar surface, the most precise chemical information obtained by remote sensing thus far has been collected by the Lunar Prospector and Clementine missions, which characterized the Fe, Th and REE concentrations of the lunar regolith across the entire surface of the planet. These measurements represent compositional variation in planetary regolith that reflect bedrock geology/geochemistry to varying degrees. It is important to understand how regolith processes affect the behavior of Th, REE, and K when interpreting these data. For example, Th, REE and often K, are enriched in finer fractions of the lunar regolith [5,6]. Enrichments may represent higher KREEP or exotic component(s) in the finer fraction, or simple comminution of friable mesostasis and feldspar into the finest soil fraction. For example, Papike et al. [7] observed that impact-induced volatilization will fractionate K from the REE.

Delano [8] and Vaniman [9] demonstrated that glasses in lunar regoliths and regolith breccias can provide abundant information about impact melting and the igneous lithologies from which glasses are derived. In order to achieve this goal, the affects of impact melting on primary crustal chemical signatures were examined in regolith glasses. In this study, we combine electron and ion microprobe techniques in the analysis of Sm, Th, K, and major elements. In doing so, we demonstrate the effect of impact volatilization on K/(Sm,Th) ratios in regolith glasses and examine concentrations of these constituents in potential lunar crustal lithologies. These data sets will contribute to a more accurate interpretation of planetary information obtained through remote sensing.

Analytical Methods: The samples analyzed in this study (14004-78, 14004-79, 14004-81, 14004-82, 14160-144, 14160-148, 14263-26, 14316-16) are thin sections of lunar regolith containing both impact and volcanic glasses. The glasses were first identified by plane light microscopy and backscattered imaging using UNM's JEOL JXA 8200 electron microprobe (EMP) facilities. Potential analysis points were chosen and categorized based on glass color and size; previous surveys of this data set by Vaniman [9] were based on color, morphology and size. Major element chemistry was determined by energy dispersive spectrometry, at an accelerating voltage of 15 kV, a beam current of 20 nA, using a spot size of 10 µm. Trace elements (Sm, Th) in the glasses were measured using the Cameca ims 4f ion microprobe in the Institute of Meteoritics at the University of New Mexico. An O^- primary beam was used, operating at 12.5 kV. A primary beam current of 15 nA resulted in a spot size of ~15-20 µm. Isobaric interferences were minimized by energy filtering the secondary beam using a voltage offset of 75 V, and an energy window of ± 25 V. Intensities of ^{147}Sm and ^{232}Th were normalized to known SiO_2 concentration, previously analyzed using electron microprobe. Intensities were normalized to absolute concentrations using a set of six glasses of varying composition, both synthetic and natural. The calibration curves for Th had correlation coefficients of 0.993-0.999, while those for Sm had values of 0.999. Concentrations of Th to 0.05 ppm are significant.

Results: Analyses from this study are compared to those defined by Vaniman [9] for a larger Apollo 14 glass population in a plot of Al_2O_3 vs. SiO_2 (Fig. 1). This diagram differentiates mare volcanic glasses that are generally lower in Al_2O_3 from impact glasses. Many of the impact glasses cluster around the average Apollo 14 soil composition, while other glasses exhibit compositional trajectories that enrich Al_2O_3 at near constant SiO_2, enrich Al_2O_3 at the expense of SiO_2 (HASP glass population), or enrich SiO_2 at near constant Al_2O_3. Thorium and Sm in the glasses exhibit a wide compositional range (<1-50 ppm and <1-125 ppm, respectively), are highly correlated, and plot along a line that includes KREEP (Fig. 2). The glasses that cluster around the average Apollo 14 soil composition in Figure 1 also have Th and Sm similar to the average Apollo 14 soil concentrations (Th=15.1 ppm, Sm=28.7 ppm). Thorium is also highly correlated with Ba except in the high-Si glasses. Unlike the high-Si lithologies from other sites, these glasses have relatively low Th. Some of the higher Th values tend to be associated with volcanic glass compositions. Relative to major elements, Th is lower in the high-Al, low-Fe glasses (Fig. 3) and is generally correlated to K. K/Th

and K/Sm show the greatest correlation in glasses with compositions similar to Apollo 14 soil. Calculated Th values based on the major element relationship to K (Th (ppm) = (K_2O (wt.%) * 24.3) – 0.82) is generally within 30% of measured Th values. It is less rigorous for granite and high-Al compositions where the correlation between K and Th is weak.

Discussion: This pilot study of Th in impact glasses from the Apollo 14 site illustrates several important points. First, Th abundances in the glasses exhibit a wide range in composition with the largest range and highest values generally associated with basaltic glass compositions with a high KREEP component. Lower Th values tend to be associated with glasses with a FAN composition. The absolute abundances of Th should be affected by impact processes, because volatilization of Si and other major elements will cause Th abundance to increase. Th/Sm, Ca/Ti, Ti/Al are unaffected by even the most severe impact-volatilization processes. Therefore, the Th/Sm will reflect target composition. For example, many of the glasses that have major element compositions similar to average soil have a unique Th/Sm ratio, in comparison to granite and high-Al compositions. Distinct Th/Ti and Th/FeO (Fig. 3) ratios can be used to identify FAN, basalt, and "granite" precursor compositions. Unlike Th/Ti, K/Th and K/Sm will be severely affected by volatilization. These preliminary results suggest that glasses in the regolith may be an important tool for exploring Th and Th/Sm in regolith and igneous lithologies and evaluating the role of impact-volatilization in fractionating volatile from non-volatile elements.

References: [1] Gillis et al. (2004) GCA 68, 3791-3805. [2] Lawrence et al. (2000) *J. Geophys. Res.,*105, 20307-20331. [3] Taylor et al. (2003) 6th Inter. Conf. Mars. Abstract3207. [4] Taylor et al. (2004) LPS XXXV, abstract1808. [5] Papike et al. (1982) Rev. Geophys. Space Phys. 20, 761-826. [6] Haskin and Korotev (1977) GCA 41, 921-939. [7] Papike et al. (1997) Amer. Mineral. 82,630-634. [8] Delano (1988) Proc. 18th LPSC, 59-65. [9] Vaniman (1990) Proc. 20th LPSC, 209-217.

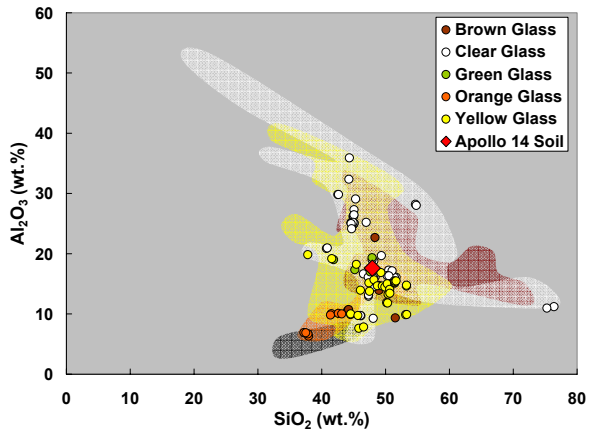

Figure 1. Plot of Al_2O_3 vs. SiO_2 based on electron microprobe analyses. Shaded regions represent those fields defined by Vaniman [9].

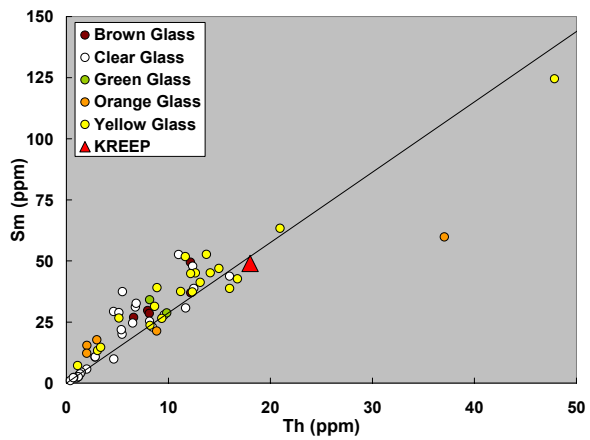

Figure 2. Plot of Sm vs. Th based on ion microprobe analyses.

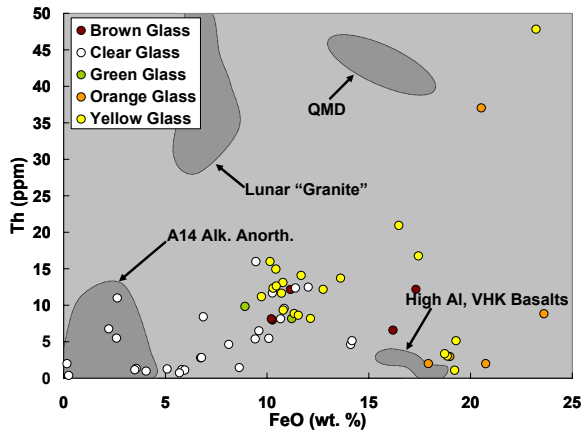

Figure 3. Plot of Th vs. FeO based on electron microprobe and ion microprobe analyses. QMD = Quartz Monzodiorite.