

THE BEHAVIOR OF THORIUM IN LUNAR PICRITIC MAGMAS: IMPLICATIONS FOR THE BULK THORIUM CONTENT OF THE LUNAR MANTLE AND LUNAR HEAT FLOW. J. J. Hagerty¹, C. K. Shearer¹, and D. T. Vaniman². ¹University of New Mexico, Institute of Meteoritics, Dept. of Earth & Planetary Sciences, Albuquerque, NM 87131 U.S.A.; ²Los Alamos National Laboratory, Group EES-6, MS D462, Los Alamos, NM 87545 U.S.A. Email: jh2713@unm.edu

Introduction: Previous studies of heat flow from the lunar mantle have suggested that the amount of heat flow is strongly dependent on the abundance of radioactive isotopes in the mantle and is at least loosely correlated with Th content [1,2]. Measurements of heat flow from the Apollo missions had been used to imply that those measurements could be extended outside of KREEP terrains; however, the asymmetrical distribution of Th on the lunar surface and presumably in the deep lunar mantle challenges that notion. Fortunately, lunar pyroclastic glasses, which are thought to represent quenched products of near-primary melts from the deep lunar mantle [3], can provide information about the concentration of radiogenic elements in the lunar interior. High-pressure experiments on lunar picritic glasses indicate that the basalts they represent were in equilibrium with olivine + orthopyroxene residua [4]. Such a mineral assemblage is incapable of fractionating Sm from Th during melting, which means that the Sm/Th of the glass approximates the Sm/Th of the mantle sources for these magmas [4]. This abstract reports the Th and Sm results from in-situ analyses of pyroclastic glasses from the Apollo 11, 14, 15, and 17 landing sites as a means to evaluate Th and Sm systematics in the lunar mantle.

Scientific Rationale and Analytical Approach: Prior to trace element analysis, individual phases were imaged, mapped and analyzed for major elements using a JEOL 733 superprobe. Trace elements in the glasses were measured using the Cameca ims 4f operated on the University of New Mexico campus by the Institute of Meteoritics. Analyses were made using primary O⁻ ions accelerated through a nominal potential of 10 kV. A primary beam current of 15 nA was focused on the sample over a spot diameter of 10 to 15 μm. Sputtered secondary ions were energy filtered using a sample-offset voltage of 105 V and an energy window of ±25 V. Absolute concentrations of Th and Sm were calculated using empirical relationships of Trace Element/³⁰Si⁺ ratios (normalized to known SiO₂ content in each of the glasses). Calibration curves were constructed using six basaltic glass standards. Major element analyses of these glasses have been well documented in other studies [e.g. 3 and 5].

Data: In this study we analyzed Th and Sm in A11 orange glasses, A14 orange glasses, A15 green glasses (types A-E), A15 red glasses, A15 yellow glasses, and A17 orange glasses (figure 1) (see [5] for petrographic description). Glasses with similar major-element composition plot in unique groups in the Sm-Th plot. This diagram also shows that the A15 yellow glasses have the highest Th and Sm concentrations whereas the A15 green glasses have the lowest Th and Sm concentrations. The Sm/Th ratios for the A14 green, A15 green, and A15 yellow glasses are approximately 5. The Sm/Th for the A11 green, A15 red, and A17 orange glasses are 19, 11, and 15 respectively. Estimated values for KREEP are Th = 22 ppm, Sm = 48 ppm, and Sm/Th = 2.18 [6].

Because both Th and Sm behave as highly incompatible elements in basaltic systems, there should be a simple positive correlation between these two elements as observed in the planetary data set (i.e. lunar basalts) [4]. However, a compilation of lunar basalt data for Th and Sm [4] indicates that the relationship is much more complicated (Figure 2), thus suggesting that a better understanding of mare basalt source regions is needed. This point is further bolstered by comparing the Sm-Th values for KREEP and for the bulk silicate moon [7] (figure 2).

The equation for batch melting ($C_1/C_0 = 1/F$) was initially used to calculate the Th content in the source region of the picritic glasses based on the measured Th values (figure 3). Different values of F (e.g. 0.05, 0.1, 0.15, and 0.2) were used in order to approximate various degrees of partial melting. The calculated value of Th in the source region is largest for the A15 yellow glasses and lowest for the A15 green glasses (figure 3). The source for the A15 red glasses appears to have intermediate concentrations of Th (figure 3). Values for the uranium content in these sources can be approximated via the apparently constant lunar relationship Th/U = 3.7 [2]. A plot of U versus Th contents in the source region shows that the source for the A15 yellow glasses had the highest amount of U in the source (figure 4).

Discussion and Conclusions: High-pressure experiments indicate that the temperature and pressure of multiple saturation for the picritic glasses is located at 1410-1500°C and 1.7-2.5 GPa [3]. If it is assumed

that the point of multiple saturation represents the minimum depth of melting, then the picritic magmas were generated at >400 km within the lunar mantle [3]. This suggests that the pyroclastic glasses do indeed serve as ideal probes into the lunar mantle. The variability of Th concentrations and Sm/Th ratios observed in these samples indicates that there are distinct reservoirs with various enrichments and fractionations of both Th and Sm. The source regions for the A15 green glasses, representing early lunar magma ocean (LMO) cumulates, have calculated Th and U concentrations substantially lower than the bulk moon (figure 4). The data from the pyroclastic glasses also indicate that there may be mixing between early cumulate sources and late cumulate sources (KREEP) within the lunar mantle. The Apollo 14 green glasses seem to be a product of this mixing. Because of the asymmetrical distribution of KREEP, heat flow calculations for areas outside of the KREEP terrain should be based on substantially lower Th and U concentrations in the lunar mantle (i.e. $Th < 0.05$ ppm and $U < 0.025$ ppm). The asymmetrical distribution of these radiogenic elements must also have played an important role in the generation of mare basalts.

References: [1] Hsui (1979) *Proc 10th LPSC*, 2393-2402. [2] Warren and Rasmussen (1987) *JGR*, 92, 3453-3465; [3] Papike et al. (1998) *RIMS*, 36, 5-1 to 5-234; [4] Shearer et al. (2002) *Proc 33rd LPSC*, CD-ROM #1621; [5] Delano (1986) *Proc 16th LPSC*, 275-300; [6] Warren (1988) *Moon in Transition: Apollo 14, KREEP, and Evolved Lunar Rocks*, 106-110. [7] Newsom (1995) *Global Earth Physics: A Handbook of Physical Constants*, 159-189.

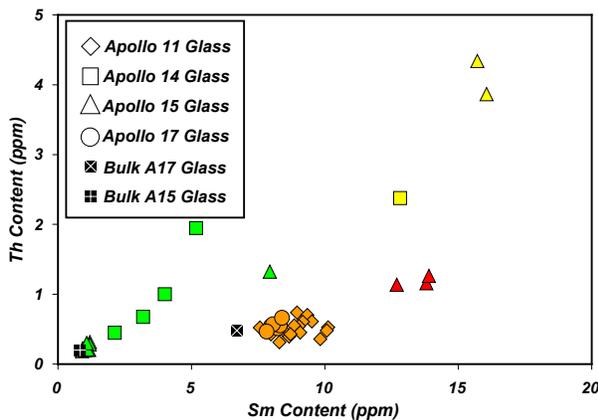


Figure 1. Plot of SIMS analyses of pyroclastic glasses. Each symbol represents a different landing site. The different colors represent different glass types from each of the landing sites (e.g. green symbols = green glasses).

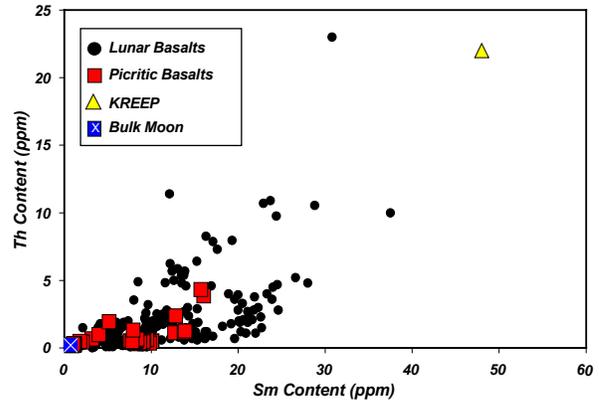


Figure 2. Plot of SIMS analyses of pyroclastic glasses from this study (red squares) compared to Th-Sm values for the bulk moon and for KREEP.

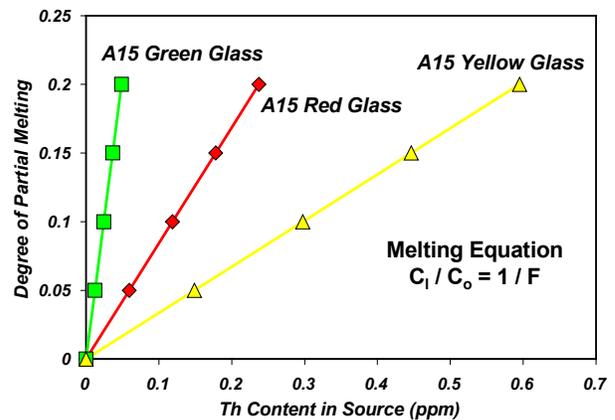


Figure 3. Plot of partial melting curves for the Apollo 15 pyroclastic glasses versus calculated Th content in the source region. C_1 = Concentration of Th in the melt. C_0 = concentration of Th in the solid, and F = fraction of melting.

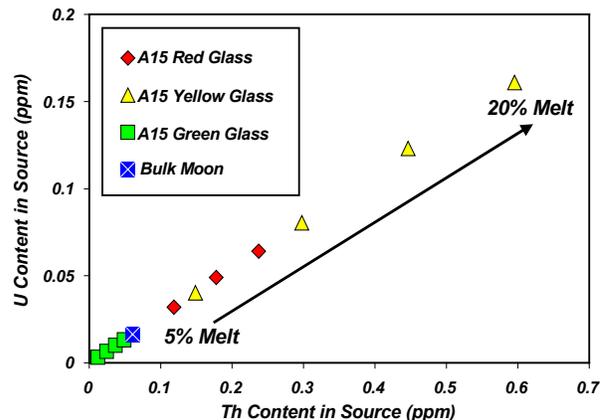


Figure 4. Plot of calculated U and Th contents in the source regions for the pyroclastic glasses. The arrow represents increasing degrees of partial melting for all of the A15 glasses shown.