

THORIUM AND SAMARIUM IN LUNAR PYROCLASTIC GLASSES: INSIGHTS INTO THE COMPOSITION OF THE LUNAR MANTLE AND BASALTIC MAGMATISM ON THE MOON. J. J. Hagerty¹, C. K. Shearer¹, and D. T. Vaniman². ¹University of New Mexico, Institute of Meteoritics, Dept. of Earth & Planetary Sciences, MSC03 2050, 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: Lunar pyroclastic glasses are thought to represent quenched products of near-primary melts from the deep lunar mantle [1], thus the composition of the glasses serves as a window into the lunar interior. High-pressure experiments on lunar pyroclastic glasses indicate that their temperature and pressure of multiple saturation is 1410-1500°C and 1.7-2.5 GPa [1]. If it is assumed that the points of multiple saturation represent the minimum depth of melting, then the basaltic magmas were generated at a depth of >400 km within the lunar mantle [1]. These high-pressure experiments in conjunction with trace element data have been interpreted as indicating that the basalts that the glasses represent were in equilibrium with olivine + orthopyroxene residua [2]. Such a mineral assemblage is incapable of fractionating Sm from Th during melting, which means that the Th/Sm of the glasses approximates the Th/Sm of the mantle sources for these magmas [2]. This abstract reports the Th and Sm concentrations of individual pyroclastic glasses from the Apollo 11, 12, 14, 15, and 17 landing sites and uses these data as a means to evaluate the distribution and abundances of Th and Sm in the lunar mantle.

Scientific Rationale and Analytical Approach: Th and Sm 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 SiO₂ content derived from microprobe analyses of individual glasses). Calibration curves were constructed using six basaltic glass standards that had Th and Sm concentrations that bracketed the range of expected concentrations in the unknowns. There was agreement between the ion probe results and bulk analyses of the A15 green and the A17 orange glasses. Major element analyses of these glasses have been well documented in previous studies [e.g. 1 and 3].

Fractional crystallization trajectories used in this study were determined by using the javaMELTS computational thermodynamics software [4, 5]. The

javaMELTS applet provides a way to calculate heterogeneous phase equilibria in magmatic systems as a function of bulk composition, temperature, and pressure. The liquidus option of the program was used to calculate the liquidus temperature for each starting composition at an *f*O₂ of IW and a pressure of 10 bars. The subsequent liquid compositions were monitored as the temperature was progressively stepped down to the solidus by ten-degree increments.

Data: In this study we analyzed Th and Sm in A11 orange glasses, A12 red glasses, A14 orange, red, black and yellow glasses, A15 green glasses (types A-E), A15 red and yellow glasses, and A17 orange glasses (see [3] for petrographic description). The lunar pyroclastic glasses show a wide range of Th and Sm concentrations and Th/Sm ratios (Fig. 1). The A14 glasses exhibit the largest range in compositions, with the A14 red and black glasses having the highest concentrations of Th and Sm. The A11 and A17 orange glass compositions cluster together, as do the A12 and A15 red glasses (Fig. 1). The Th/Sm ratios for the pyroclastic glasses range from 0.06 up to 0.27. The high-Ti glasses have the lowest Th/Sm ratio and the low-Ti glasses have the highest Th/Sm ratio, with the intermediate-Ti and the A14 glasses falling in between. The Th/Sm for urKREEP is 0.37 [6].

Assuming that the lunar pyroclastic glasses were derived from small to moderate degrees of partial melting (e.g., 5 - 20%) we used the SIMS data and the batch melting equation to calculate the composition of the source region for the glasses. Pertinent partition coefficients used in this study are shown in Table 1. Results of the source region compositional calculations are presented in Table 2. Clearly, glasses that had the highest Th and Sm values were derived from source regions that had the highest Th and Sm values. As expected, the averaged Th/Sm ratios for the source regions ranged from 0.06 to 0.27 (Table 2).

We also used ion microprobe data to estimate the potential range of Th and Sm in mare basalts that would be produced by the crystallization of near primary magmas. To accomplish this task, we used the javaMELTS program to trace the evolution of Th and Sm during the crystallization process (from 0 to 60% crystallization) and then produced a Th-Sm diagram that allowed us to compare the curves to previously measured mare basalt compositions (Fig. 2). Fig. 2 shows that Th and Sm behave similarly

during the process of fractional crystallization for the majority of the glass compositions, due to the incompatible nature of these elements. However, the A11 and A17 orange glasses have slightly higher Sm and slightly lower Th abundances than do the other glasses (Fig. 2). In total, all of the glass compositions measured in this study demonstrate fractional crystallization paths (at 60% crystallization) that span the entire range of mare basalt compositions.

Discussion and Conclusions: The variability of Th-Sm concentrations and Th/Sm ratios observed in these samples and their source regions indicates that there are distinct reservoirs with various Th-Sm concentrations and Th/Sm ratios. These data also indicate that Sm was fractionated from Th during the late stages of LMO crystallization. The data from the pyroclastic glasses indicate that there may be mixing between early cumulate sources and late cumulate sources (KREEP) within the lunar mantle. In particular, the A14 glasses seem to be a product of mixing with a KREEP component.

Since the pyroclastic glasses represent samples of melts derived from the lunar mantle, the data from this study can be combined with previous crustal measurements to provide a comprehensive view of the Th and Sm composition of the lunar mantle and the bulk Moon (assuming a very small, relatively homogenous lunar core). In an attempt to calculate the bulk Th and Sm content of the Moon, we have reviewed several models. One model assumes that the average Th and Sm values of the source regions for the A11 orange, A15 green, and A17 orange glasses represent the weighted average composition of the lunar mantle (Th = 0.101 ppm and Sm = 1.103 ppm). The TiO₂, Th, and Sm compositions of these calculated sources regions correspond to the 95 PCS values of LMO cumulates calculated by [7]. This information, in conjunction with the average crustal values of Th [8] and Sm [9] can be used to calculate the bulk Th and Sm composition of the Moon, assuming that the mantle represents 82.7% of the Moon and that the lunar crust represents 5.7% of the Moon. This calculation yields a bulk Th value of 0.092 ppm (92 ppb) and a bulk Sm value of 0.86 ppm (860 ppb) for the Moon.

References: [1] Papike et al. (1998) *RIMS*, 36, 5-1 to 5-234; [2] Shearer et al. (2002) *Proc 33rd LPSC*, CD-ROM #1621; [3] Delano (1986) *Proc 16th LPSC*, 275-300; [4] Ghiorso and Sack (1995) *Contrib. Mineral. Petrol.* 119, 197-212; [5] Asimow and Ghiorso (1998) *Am. Mineral.* 83, 1127-1132; [6] Warren and Wasson (1979) *Rev. Geophys. Space Phys.* 17, 73-88; [7] Snyder et al. (1992) *GCA*, 56, 3809-3823; [8] Taylor et al. (2002) *Proc. Moon Beyond 2002* abstract #3049; [9] Larimer (1986) *Origin of the Moon* pp. 145-171. [10] McKay (1986) *Geochim. Cosmochim. Acta*, 50, 69-79; [11] Weill and McKay (1975) *Proc. 6th LPSC*, 1143-1158; [12] Phinney and

Morrison (1990) *Geochim. Cosmochim. Acta*, 54, 1639-1654; [13] McKenzie and O’Nions (1991) *J. Petrol.*, 32, 1021-1091.

Table 1. Partition coefficients used

Mineral	Sm	Th	Reference
Olivine	0.0006	0.03	[10]
Orthopyroxene	0.022	0.13	[11]
Clinopyroxene	0.17	0.13	[10]
Plagioclase	0.017	0.0208	[12]
Spinel	0.01	0.01	[13]

Table 2. Avg. calc. source compositions (ppm) 5% melting.

Glass Type	Sm	Th	Th/Sm
Apollo 11 Orange Glass	0.50	0.03	0.06
Apollo 11 Green Glass	0.21	0.02	0.12
Apollo 12 Red Glass	0.69	0.06	0.09
Apollo 14 Green Glass	0.24	0.06	0.25
Apollo 14 Red-Black Glass	1.08	0.24	0.22
Apollo 15 Yellow Glass	0.58	0.13	0.22
Apollo 15 Red Glass	0.73	0.07	0.09
Apollo 15 Green Glass	0.07	0.02	0.26
Apollo 17 VLT Glass	0.45	0.03	0.07
Apollo 17 Orange Glass	0.11	0.03	0.27

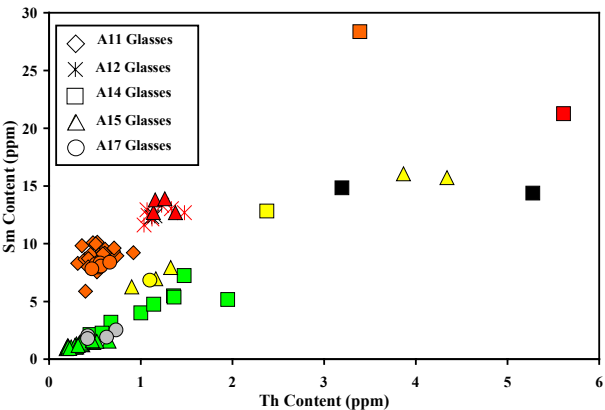


Figure 1. Plot of Th and Sm measured by SIMS. The colors of the symbols refer to the color of the glass that was measured.

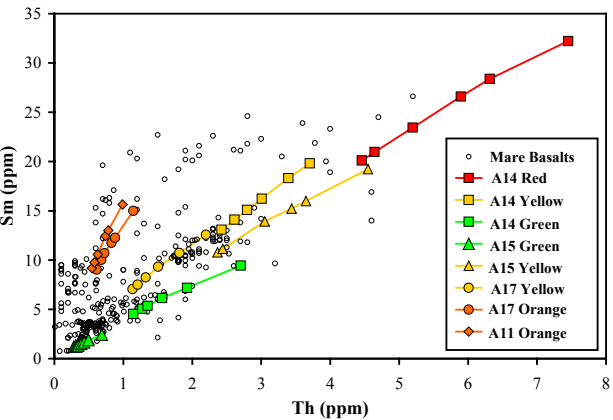


Figure 2. Plot of Th and Sm in mare basalts compared with frac. crystallization curves of source compositions calculated for the pyroclastic glasses. Each curve represents 0-60% frac. crystallization of olivine, pyx, plag, and spinel.