OXYGEN ISOTOPES OF LUNAR ROCKS: DIFFERENT SOURCES FOR DIFFERENT HI-Ti BASALTS?

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Introduction: Oxygen isotopes of planetary materials provide important constraints on the genesis and evolution of their parent planetary bodies. The general consensus about the formation of Earth-Moon system is that a Mars-sized planetary body impacted a proto-Earth off center and contributed 70%-90% of its material to the Moon [1,2]. The impactor (Thea) is not expected to have the identical oxygen isotope signature of the proto-Earth, yet all three-oxygen isotopes studies of lunar rocks fail to identify any deviation from terrestrial fractionation line [e.g. 3-6] and thus put severe constrains on the giant impact model for the origin of the Earth-Moon system. Exchange between proto-Earth and Thea is suggested to achieve the oxygen isotope equilibrium [7]. A recent model on the dynamics of the turbulent mixing between the terrestrial magma ocean and proto-lunar magma disk suggests that the equilibration can be achieved within 100-250 years [8].

Oxygen isotopes of lunar mare basalts can also provide information about the lunar mantle [5, 6]. High-Ti basalts have been determined to have lower $\delta^{18}O$ (0.20-0.25 ‰) than low-Ti basalts [5, 6, 9], suggesting possible different sources for these basalt types. In addition the difference in $\delta^{18}O$ values (0.18 ‰) between lunar low-Ti basalt and MORB may reflect different oxygen isotopes in proto-Earth and the Thea impactor [9]. Here, we present $\delta^{18}O$ analyses of 17 lunar mare basalts using the air-lock laser-fluorination technique of Spicuzza et al. [10]. A group of high-Ti basalts (**HTB**) with ~ 9 wt% TiO_2 was determined to have $\delta^{18}O$ values higher than HTB values from basalts with 13 wt% TiO_2, indicating either fractionation effects or different source regions for high-Ti basalts.

Methods: Lunar mare basalts studied include Apollo 12 and 15 low-Ti basalts (**LTB**) and Apollo 11 and 17 high-Ti basalts with 8.6-13.4 wt% TiO_2. All samples studied are low-K (<0.2 wt%) and low-Al (≤11.0 wt%) varieties [11]. Powders were ground from small splits of samples allotted to minimize mode effects; especially since the mode-effect was clearly demonstrated for the coarse-grained basalt 15555 [6].

Oxygen isotope analyses were performed at the University of Wisconsin. Rock powders (2-3 mg) were reacted using a 30W CO_2 laser, with BrF_5 as the fluorinating agent . Oxygen purification was achieved utilizing an in-line Hg-diffusion pump (to remove any F_2) and standard cryogenic methods. In this proce-
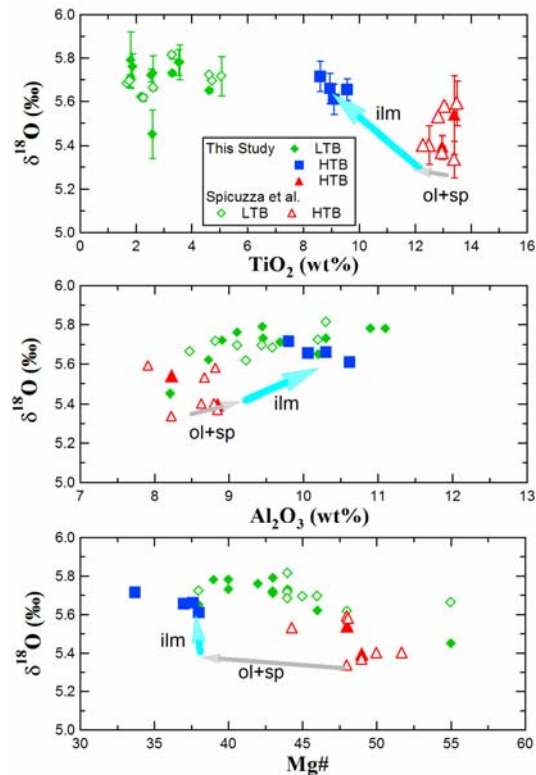

Figure 1. Oxygen isotopes of mare basalts vs. their bulk compositions. Arrows show, schematically, the crystal fractionation effects on liquid compositions.

dure, the oxygen was converted to CO_2 and is different from [6] where O_2 gas was frozen on to a mole sieve. Analyses were performed on three separate days over a two month period. Two to three aliquots of each sample were analyzed. Seven to ten aliquots of garnet standard (UWG-2, recommended $\delta^{18}O$ = 5.80‰) were analyzed on the same day to check the precision and accuracy of the analyses. $\delta^{18}O$ values of lunar basalts were then corrected for the day-to-day variation (≤0.05‰ for $\delta^{18}O$).

Results: Oxygen isotope values and bulk-rock compositions of the samples are reported in Table 1 and plotted with data from [6] in Figure 1. These new results are remarkably consistent with those in Spicuzza et al. [6], despite the use of different analytical procedures. Average $\delta^{18}O$ values for Apollo 12 and 15 LTBs (5.67 ±0.14 ‰ and 5.72 ±0.06 ‰) are in excellent agreement with those in [6] (5.73 ±0.06 ‰ and 5.65 ±0.11 ‰). The average value of two HTBs with 13 wt% TiO_2 (5.47 ±0.11 ‰) is also consistent with that in [6] (5.46 ±0.11 ‰). Different sub-samples

of three mare basalts studied in [6] (Table 1) also compare very well. Combining our new results with Spicuzza et al. [6], the average $\delta^{18}O$ values are **5.70 ±0.08 ‰** for LTBs (ignoring the problematic 15555 sample) and **5.44 ±0.09 ‰** for HTBs with 13wt% TiO_2.

An interesting feature of our results is that HTBs with ~9 wt% TiO_2 have higher $\delta^{18}O$ values (average 5.66 ±0.06 ‰) than HTBs with ~13 wt% TiO_2 with no overlap in the data. Instead, the 9 wt% HTB's fall in the lower half of the range defined by LTBs (5.70 ±0.08 ‰). The $\delta^{18}O$ values of all HTBs show negative correlations with bulk-rock Mg# and TiO_2, but positive correlations with Al_2O_3 (Fig. 1).

Discussion: Oxygen isotopes of mare basalts are consistent with our previous findings in [6] in that mantle sources of all mare basalts seem be in oxygen isotope equilibrium. LTBs show statistically significant difference from MORB, may imply a possible difference in $\delta^{18}O$ between Earth's mantle and lunar mantle.

For HTBs, the systematic variation of $\delta^{18}O$ with bulk-rock chemistry can be explained by different mantle sources or fractional crystallization. Different mantle sources, representing different cumulate piles crystallized from the lunar magma ocean, were proposed to explain the diverse types of mare basalts (see [12] for an excellent review). Different mantle sources of mare basalts are also consistent with Li-Hf-Sr-Nd data (e.g., [13]) and can explain different $\delta^{18}O$ values between HTBs with ~9 wt% TiO_2 and those with 13 wt% TiO_2. This would put an additional constraint on the reconstruction the bulk composition of the Moon.

Correlations of $\delta^{18}O$ with bulk-rock chemistry for HTBs are generally consistent with fractional crystallization. This possibility can be tested with a simple mass-balance calculation using $\delta^{18}O$ values for HTB minerals (olivine, 5.1‰; ilmenite, 4‰; [14]). Experimental petrology on similar HTBs suggests that olivine and Fe-Ti-Cr spinels (± high-Ca px ± armalcolite) are the early liquidus phases, followed by ilmenite. Fractionation factor between terrestrial Fe-Ti-Cr spinel and olivine at 1200°C is ~0.998 [15]. Depending on the proportion and the composition of mineral phase, fractionating these phase can drive liquid Mg# down without too much changes in TiO_2 and $\delta^{18}O$ (gray arrow in Fig.1). Subsequent removal of ilmenite can decrease liquid TiO_2 greatly with larger increase in $\delta^{18}O$ (turquoise arrow in Fig. 1). This is generally consistent with changes in mineral modes: 9 wt% TiO_2 HTBs lack those few percentages of olivine seen in the 13 wt% TiO_2 HTBs, and contain lower contents of opaque minerals. For the observed change in TiO_2 (~4 wt%)of HTBs, <9 wt% of ilmenite would need to be removed, which will increase $\delta^{18}O$ by ~0.2‰ and Al_2O_3 by 2 wt%, consistent with the observation. However, a more-sophisticated model is needed to address this effect.

Summary: New oxygen isotope data of mare basalts, supported by previous results, show diversity in low K HTBs, which could reflect heterogeneous source within this group or the effects of fractional crystallization. If these basalts come from different sources, it would demand more sophisticated models for reconstructing the bulk composition of the Moon.

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Table 1. Oxygen isotopes of lunar mare basalts.

Sample No.	Rock Type	n	$\delta^{18}O$	1σ	$\delta^{18}O$ S07
low Ti basalt					
12002,188	Olivine basalt	2	5.45	0.11	
12021,286	Pigeonite basalt	2	5.78	0.06	
12051,37	Pigeonite basalt	2	5.65	0.01	5.72
					5.81
12052,153	Olivine basalt	2	5.73	0.01	±0.02
12064,87	Ilmenite basalt	2	5.78	0.08	
	Average		5.67	0.14	
15476,7	Pigeonite basalt	2	5.71	0.01	
15495,129	Pigeonite basalt	2	5.76	0.06	
15075,52	Q-norm basalt	2	5.79	0.13	
					5.61
15555,87	O-norm basalt	2	5.62	0	±0.20
15556,194	O-norm basalt	2	5.73	0.08	
15557,26	O-norm basalt	2	5.72	0.03	
	Average		5.72	0.06	
high Ti basalt					
10044,116	B1-type basalt	2	5.61	0.04	
71539,17	A-type basalt	2	5.72	0.04	
75015,1	unknown	2	5.66	0.11	
75035,149	A-type basalt	2	5.66	0.06	
	Average		5.66	0.06	
70035,9	B2-type basalt	2	5.40	0.05	
75075, 158	B1-type basalt	3	5.54	0.18	
	Average		5.47	0.10	

Italic numbers are samples with possible mode effects. N: number of replicates. 1σ: 1 standard deviation of replicate analyses. S07: data from Spicuzza et al. [6].