

OXYGEN ISOTOPE VARIATION IN THE MOON AND IMPLICATIONS FOR THE GIANT IMPACT.

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Introduction: One of the most important revelations from the lunar samples returned by the Apollo missions was that the oxygen isotope composition of the Earth and the Moon were indistinguishable from one another. The Giant Impact Hypothesis has long been held as the favored explanation for the Moon's origin. However, the classic style models for the Giant Impact predicted that the Moon would have accreted from approximately 70-90% of the proto-lunar impactor Theia [1], which has proven to be a major issue for the Giant Impact Hypothesis since their oxygen isotope ratios have been found to be nearly identical [2,3,4]. This compositional conundrum has placed major limitations on modeling the impact and has led to many models and hypotheses that sought to explain these similarities through massive homogenization of the two bodies immediately following the collision.

In this work we show that the Earth and Moon are, in fact, different with respect to their oxygen isotope compositions. The oxygen isotope variation found in lunar samples has a strong correlation with lithology and can be explained through the mixing of a contaminating light vapor phase, generated through mass independent fractionation during the Giant Impact, and material from the impactor 'Theia'.

$\Delta^{17}\text{O}$ Analyses: A number of recent high-precision oxygen isotope studies have shown a disagreement when it comes to the similarity of $\Delta^{17}\text{O}$ values for the Earth and Moon. Herwartz *et al.* [2] suggested a 12 ± 3 ppm (0.012‰) difference while Young *et al.* [3] and Greenwood *et al.* [4] demonstrate that there is practically no identifiable $\Delta^{17}\text{O}$ difference, with the Earth and Moon being separated by -1 ± 5 ppm (-0.001‰) and 4 ± 3 ppm (0.004‰) respectively.

We expand on previous work by performing high-precision triple oxygen isotope analyses on whole-rock, volcanic glasses, and mineral separates from a wide variety of lunar lithologies using laser fluorination. Our analytical precision was based on the repeated analysis of a San Carlos olivine internal standard and is $\pm 0.138\text{‰}$ for $\delta^{18}\text{O}$ and $\pm 0.004\text{‰}$ for $\Delta^{17}\text{O}$ ($n = 44$, 1σ SD).

Results: If the $\Delta^{17}\text{O}$ values obtained from our measurements of bulk lunar samples are averaged to determine the value for the bulk silicate Moon, as was done in previous studies, a value of $-0.049 \pm 0.007\text{‰}$ (1σ SD, $n = 23$) (Fig. 1) is obtained. Likewise, averaging our measurements of the terrestrial suite of samples, to obtain a bulk silicate Earth value, produces a

$\Delta^{17}\text{O}$ value of $-0.052 \pm 0.004\text{‰}$ (1σ SD, $n = 22$) (Fig.1). Based on these data alone, the averages would indicate that the Earth and Moon appear indistinguishable, which would be consistent with the findings of most previous studies. However, it is noteworthy that the lunar samples have nearly double the $\Delta^{17}\text{O}$ variability compared to Earth.

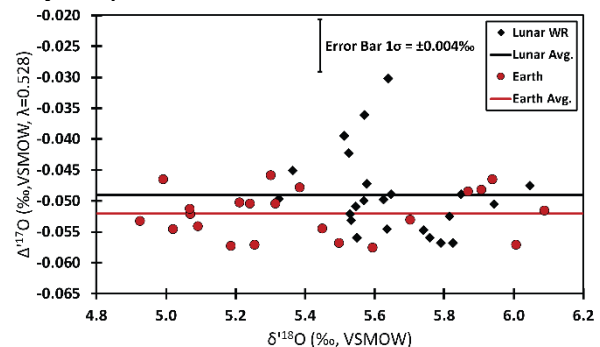


Figure 1: $\Delta^{17}\text{O}$ vs. $\delta^{18}\text{O}$ for lunar and terrestrial samples

Given our precision for these $\Delta^{17}\text{O}$ measurements, this variation cannot be simply explained away as noise or error within the measurements. This becomes more apparent when the $\Delta^{17}\text{O}$ values are compared to lithological type (Fig. 2) and distinct differences can be seen between different lunar rock types. Therefore, simply averaging all the lunar lithologies together does not provide an accurate estimation of the lunar mantle.

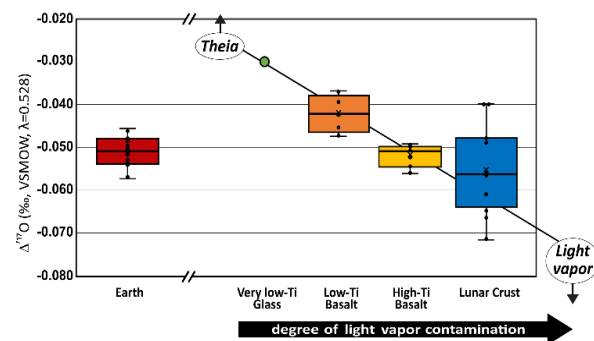


Figure 2: $\Delta^{17}\text{O}$ values for different lunar lithologies and Earth

High- and Low-Ti Basalt Variation: The mare basalts and volcanic glasses show a trend of decreasing $\Delta^{17}\text{O}$ values with increasing TiO_2 content (Fig. 3). The low-Ti basalts have a $\Delta^{17}\text{O}$ range between -0.037 and -0.047‰ with an average value of -0.042‰. The high-Ti basalts range from -0.046 to -0.056‰ and have an

average of -0.052% . This difference between samples with high- and low-Ti contents becomes even more apparent when comparing the lunar volcanic glasses, which represent examples of near primary magmas [5]. The Apollo 15 very low-Ti green glass and Apollo 17 high-Ti orange glass have $\Delta^{17}\text{O}$ values of -0.030% and -0.049% respectively (Fig. 3).

We propose that this variation seen in lunar $\Delta^{17}\text{O}$ is the product of two component mixing between distinct isotopic reservoirs. The first reservoir consists of the deep lunar mantle material, which retains the original $\Delta^{17}\text{O}$ value of the proto-lunar impactor, and the second is a low $\Delta^{17}\text{O}$ component that is formed from the incorporation of a condensed silicate vapor atmosphere that formed during the Giant Impact.

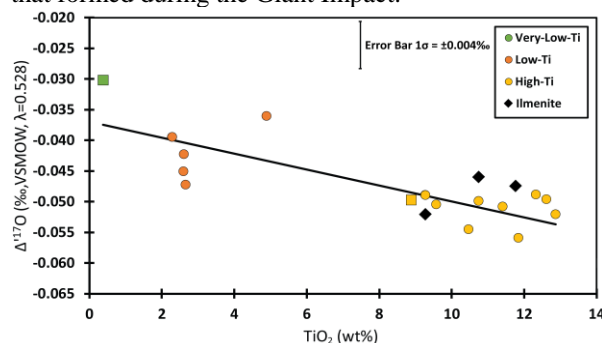


Figure 3: $\Delta^{17}\text{O}$ vs. TiO_2 content for high- and low-Ti lunar mare basalts (circles) and volcanic glasses (squares).

Light Silicate Vapor Contamination: As suggested by previous work [6,7], a silicate vapor envelope forms around the molten Moon immediately following the Giant Impact. Experimental evidence from Chakraborty *et al.* [8] indicates that when condensing SiO_2 from heated SiO gas in the presence of hydrogen, the $\Delta^{17}\text{O}$ value of the residual gas becomes lighter through a mass independent fractionation process. This would produce a residual vapor that becomes isotopically lighter as the Moon condensed. The early-formed condensate, with high $\Delta^{17}\text{O}$ values, would be well-mixed back into the lunar magma ocean (LMO) quickly following the Giant Impact. The low $\Delta^{17}\text{O}$ material, delivered later, could remain sequestered in the viscous surface layer of an early stratified magma ocean [9], preventing mixing of this component into the LMO.

Light Signature Incorporation: Any samples that may have assimilated or mixed with this surface layer contamination would have their $\Delta^{17}\text{O}$ value lowered to some degree by this interaction. How this light signature is then incorporated into different lunar lithologies can be explained through their petrogenesis. Early-formed crustal samples, including the anorthosites and Mg-suite rocks generally have the lowest $\Delta^{17}\text{O}$ values we measured, implying the largest degree of light va-

por incorporation. This is consistent with their respective formation processes. On the other end of the spectrum, the deeply sourced very low-Ti green glass presumably has the lowest amount of light vapor contamination and the highest $\Delta^{17}\text{O}$ value (-0.030%).

The high- and low-Ti mare basalts are thought to have been produced from hybridized magmas that formed when mantle overturn brought dense ilmenite cumulates into contact with deep olivine and pyroxene cumulates [10]. Since these ilmenite cumulates formed during the final stages of LMO crystallization near the top of the LMO cumulate pile, they incorporated the light vapor contamination. Therefore, hybridized magmas that had a larger ilmenite cumulate contribution produced high-Ti basalts with lighter $\Delta^{17}\text{O}$ values. Conversely, hybridized magmas that had a lower ilmenite cumulate contribution produced low-Ti basalts with heavier $\Delta^{17}\text{O}$ values, consistent with the trend seen between TiO_2 and $\Delta^{17}\text{O}$.

Implications: The variation seen in lunar $\Delta^{17}\text{O}$ values can be explained by the mixing of a proto-lunar Theia component, preserved in the lunar interior, and a light vapor contaminated component from near the surface of the LMO. Preservation of this variation supports a heterogeneous LMO, and therefore, simple averaging of lunar basalts provides a poor estimation of the lunar mantle $\Delta^{17}\text{O}$ value. Disagreement between previous studies may, in part, be the result of the lithology of the samples selected.

We have identified a relatively uncontaminated representation of the lunar mantle in the form of the very low-Ti green glass, thereby allowing us to determine a possible minimum $\Delta^{17}\text{O}$ value for Theia (-0.030%). This Theia value is clearly different from the value we measured for the Earth's bulk silicate mantle (-0.052%), implying a difference of 0.022% and that the impactor's distinct oxygen isotope composition was not completely lost through homogenization during the Giant Impact. This realization of a difference in $\Delta^{17}\text{O}$ values between the Earth and Moon removes the constraint that Giant Impact models must include a mechanism for homogenizing the oxygen isotopes between the two bodies.

References: [1] Canup R. M. and Asphaug E. D. (2001) *Nat.*, 412, 708–712. [2] Herwartz D. et al. (2014) *Sci.*, 344, 1146–1150. [3] Young E. D. et al. (2016) *Sci.*, 351, 493–496. [4] Greenwood R. C. et al. (2018) *Sci. Adv.*, 4, eaao5928. [5] Shearer C. K. et al. (1996) *GCA*, 60, 509–528 [6] Canup R. M. (2004) *An. Rev.*, 42, 441–475 [7] Pahlevan K. and Stevenson D. J. (2007) *EPSL*, 262, 438–449. [8] Chakraborty S. et al. (2013) *Sci.*, 342, 463–466. [9] Spera F. J. (1992) *GCA*, 56, 2253–2265. [10] Kesson S. E. and Ringwood A. E. (1976) *EPSL*, 30, 155–163.