

MAGNITUDE OF STABLE ISOTOPE FRACTIONATION IN LUNAR BASALTS.

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Introduction: Numerous investigations of traditional and nontraditional stable isotopes in lunar basalts have been carried out. The first-order observation is the remarkable overall similarity of the stable isotope composition of the elements between lunar and terrestrial samples. Nonetheless, at least two differences have been discovered in isotopes of volatile elements when lunar basalts are compared with terrestrial basalts. One is that the average stable isotope ratio in lunar basalts for a given volatile element may be slightly offset with heavy isotope enrichment. For example, lunar mare basalts have a mean $\delta^{66}\text{Zn}/^{64}\text{Zn}$ value of $1.4 \pm 0.5\%$ [1], higher than terrestrial basalts by 1.1‰. For $^{41}\text{K}/^{39}\text{K}$, lunar basalts are about 0.4‰ more enriched than terrestrial basalts [2]. For $^{87}\text{Rb}/^{85}\text{Rb}$, lunar basalts appear to be 0.17‰ more enriched than terrestrial basalts [3]. The overall slight enrichment of heavy isotopes in the Moon relative to the Earth is often attributed to the global depletion of volatiles in the Moon relative to the Earth [1-3].

The focus of this work is on another difference: stable isotope ratios of some volatile elements often show much larger fractionation (variability) in lunar basalts than terrestrial basalts [4-8]. One key question is: what controls the difference in the magnitude of stable isotope fractionation in lunar basalts compared to terrestrial basalts?

In this work, I examine the magnitude of isotope fractionation in lunar basalts for volatile elements and how it is related to condensation temperature or volcanic degassing. The relation is used to discuss the mechanism for such isotope fractionation.

Magnitude of Stable Isotope Fractionation: To quantify the magnitude of stable isotope fractionation for different elements and different isotopes, a parameter Z (referred to as the normalized magnitude of isotope fractionation) is defined as the relative isotope fractionation ($\ln(R_{\max}/R_{\min})$, where R_{\max} and R_{\min} are the measured maximum and minimum isotope ratios in lunar basalts) divided by the relative mass difference ($\ln(m_{\text{heavy}}/m_{\text{light}})$ where m_{heavy} and m_{light} are the masses of the heavy and light isotopes in the isotope ratio):

$$Z = \frac{\ln(R_{\max}/R_{\min})}{\ln(m_{\text{heavy}}/m_{\text{light}})}.$$

The values of R_{\max} and R_{\min} are only for basalt samples, including microbeam analyses of melt

inclusions glass beads, and apatite in basalts, but excluding lunar impact melts, rusty rock, lunar soil samples, and analyses of whole glass beads which may include condensates, because the purpose is to examine the effect of volcanic processes. With the above definition, the parameter Z is independent of the isotope ratio used for the same element (such as $^{68}\text{Zn}/^{64}\text{Zn}$ versus $^{67}\text{Zn}/^{64}\text{Zn}$ versus $^{66}\text{Zn}/^{64}\text{Zn}$) for mass-dependent fractionations and it also accounts for the fact that the isotope ratio of a lighter element can be fractionated more than that of a heavier element. Available data [4-10] show that the normalized magnitude of isotope fractionation in lunar basalts is largest for H ($Z \approx 4$), followed by Cl ($Z \approx 0.8$), Zn ($Z \approx 0.2$), Cu ($Z \approx 0.07$), and S ($Z \approx 0.004$ using more recent high-precision data [9], or 0.05 using [10]).

Possible Control of the Magnitude of Isotope Fractionation in Lunar Basalts:

The first possible control is the condensation temperature T_c [11,12]. There are two different sets of condensation temperatures: One set by Lodders [17], with T_c for the interested elements from low to high being: H ($T_c = 182$ K), S (664 K), Zn (724 K), Cl (948 K), and Cu (1037 K). The other more recent set is by Wood et al. [12], with T_c being: S (672 K), Zn (704 K), Cl (472 K), and Cu (1034 K) [12].

The normalized magnitude of stable isotope fractionation Z is plotted against the two sets of T_c in Figure 1. It can be seen that Z is not related to T_c of [11], but is well related to T_c of [12] except for S. That S isotope spread in lunar basalts is smaller than expected from T_c values might be related to the small number of basalt samples measured.

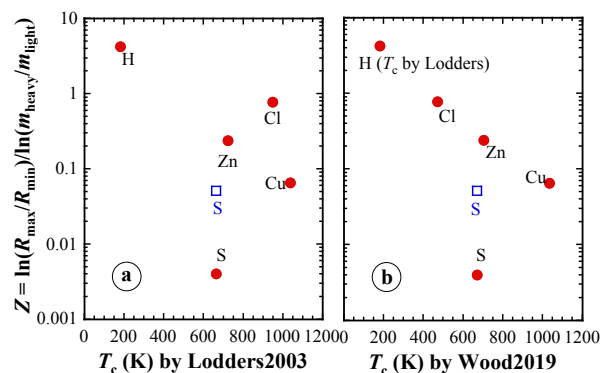


Fig. 1. Normalized magnitude of stable isotope fractionation (Z) versus two sets of condensation temperature T_c .

An alternative is that the magnitude of stable isotope fractionation in lunar basalts is due to post-eruptive volcanic degassing, and hence may be related to the degree of loss of volatiles by post-eruptive degassing. This loss has been quantified by [13,14] using the ratio $C_{\text{OHMI}}/C_{\text{GB}}$, where C_{OHMI} is the concentration of a volatile element in olivine-hosted melt inclusions (representing pre-eruptive volatiles) and C_{GB} is that in glass beads (representing post-eruptive volatiles) in Apollo sample 74220. A larger $C_{\text{OHMI}}/C_{\text{GB}}$ ratio means greater extent of post-eruptive loss of the element. Use only the data for elements with $C_{\text{OHMI}}/C_{\text{GB}} > 2$ (which are more reliably determined). The relation between Z and $C_{\text{OHMI}}/C_{\text{GB}}$ is shown in Fig. 2: There exists a good positive correlation (almost linear in log-log plot) between the normalized magnitude of isotope fractionation (Z) and the post-eruptive depletion factor of the volatile element ($C_{\text{OHMI}}/C_{\text{GB}}$). The relation means that the degree of isotope fractionation increases with increasing degree of degassing, which is expected. Hence, it seems that the larger variation in stable isotope ratios in lunar basalts compared with terrestrial basalts is mainly due to more extensive degree of post-eruptive degassing of the volatile elements in near-vacuum lunar settings than terrestrial settings. Much of the isotope ratio variation might be due to diffusive fractionation (rather than equilibrium degassing), which is able to generate large isotope fractionations [15]. Jiang et al. [16] showed that $\delta^{68}\text{Zn}/^{64}\text{Zn}$ in tektites also exhibits large variability (-0.79‰ to 4.16‰), indicating that high-temperature degassing of Zn from a melt, similar to lunar volcanic degassing, can indeed fractionate Zn isotopes significantly.

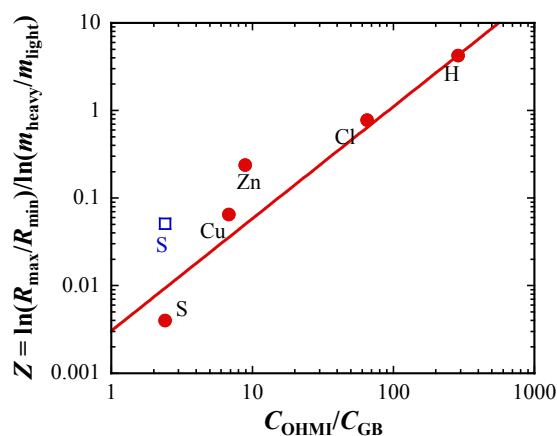


Fig. 2. Normalized magnitude of stable isotope fractionation (Z) versus depletion factor $C_{\text{OHMI}}/C_{\text{GB}}$.

Discussion: The magnitude of isotope fractionation in lunar basalts seems to be roughly

correlated with either the condensation temperature of [12], or slightly better relation to the degree of post-eruptive volatile loss. The former relation is consistent with isotope fractionation during global volatile depletion (especially if more S isotope data in the future show that S isotope ratio variability is larger than shown here so that Z for S isotopes lies in the trend in Fig. 1b), and the latter is consistent with isotope fractionation during local volcanic degassing. Overall, local volcanic degassing seems to be a better explanation for the large isotope ratio variability in lunar basalts. Local isotope fractionation may also arise from condensation of volatiles onto glass beads as well as during impact, which are not included in the discussion here.

The data in Figs. 1 and 2 are based on limited data. More data are needed to confirm and quantify the relation between the magnitude of isotope fractionation and other parameters. A systematic examination of degassing loss of all volatiles would provide key information in future assessment of loss of volatiles by volcanic degassing, as well as stable isotope ratio variability in lunar basalts if the element has two or more stable isotopes. Assessing degassing loss of volatiles is essential not only for understanding stable isotope ratio variations, but more importantly for accurate determination of the abundances of volatile elements in the Moon. Such determination is critical for understanding the origin of the Moon.

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