

LITHIUM ISOTOPE CONSTRAINTS ON MAGMA OCEAN DIFFERENTIATION AND THE COMPOSITION OF THE TERRESTRIAL PLANETS. J.M.D. Day¹, R.L. Rudnick¹, W.F. McDonough¹, R.J. Walker¹ and L.A. Taylor², ¹Dept. Geology, Univ. Maryland, College Park, MD 20740 (jamesday@geol.umd.edu), ²Dept. Earth Planet. Sci., Univ. Tennessee, Knoxville, TN, 37996.

Introduction: The magma ocean differentiation model provides a cogent explanation for much of the lithological, geochemical and isotopic variation seen in lunar rocks (e.g., [1, 2]). Further to understanding planetary evolution it is important to elucidate the nature of lunar differentiation, especially how it fractionated elemental and isotopic compositions. In this regard lithium, the lightest of the metals, is of particular interest, since its isotopic abundances in lunar rocks may reflect accretion [3] and differentiation processes [4]. Furthermore, the anhydrous nature of the Moon allows direct study of isotopic fractionation during igneous differentiation, avoiding the secondary effects of weathering. Here, we analyze the Li isotopic compositions of well-studied mare basalts [2, 5] in order to investigate Li isotopic fractionation during igneous differentiation. Secondly, considering the O-isotopic compositional link between the Earth and Moon [2, 6], it may also be possible to infer the Li isotopic composition of the bulk-silicate Earth (BSE) based on the composition of lunar mantle-derived melts.

Methods: The analyses were performed at the University of Maryland, where Li was purified using digestion and column separation techniques outlined in [7]. Li isotopic and elemental compositions were measured using a Nu-Plasma MC-ICP-MS via the method of [8] with a precision of better than $\pm 1\%$ on $\delta^7\text{Li}$ and $\pm 10\%$ on Li concentration (2σ for both). Blank contributions consistently represented $<0.6\%$ of the total measured lithium. A terrestrial standard was measured with lunar samples, BHVO-2: $\delta^7\text{Li}$ 4.8 \pm 0.5‰, Li = 4.5 \pm 0.3 ppm (2σ ; $n = 7$).

Results: Results for 4 low-Ti Apollo 15 and 3 high-Ti Apollo 17 mare basalts reveal that the high-Ti mare basalts have generally higher Li concentrations than low-Ti basalts (Fig. 1). Previous studies [3, 4], also note somewhat elevated $\delta^7\text{Li}$ -values for high-Ti mare basalts relative to low-Ti variants, although our data are systematically lower than those reported previously. To test for inter-laboratory bias we are currently analyzing a suite of samples also analysed by [3] and [4]. Isotopic effects from cosmogenic exposure are negligible in the context of interpreting lunar mare basalt Li isotope data ($<0.1\%$; [3, 4]). Although $\delta^7\text{Li}$ for low- and high-Ti mare basalt groups overlap within error, combined averages from this study, and others [3, 4], indicate heavier $\delta^7\text{Li}$ in high-Ti basalts and $\delta^7\text{Li}$ close to that estimated for bulk silicate Earth for low-

Ti mare basalts (Fig. 1). The average Li isotope composition of lunar glasses falls within the low- and high-Ti mare basalt groups at $4.6 \pm 1.0\%$.

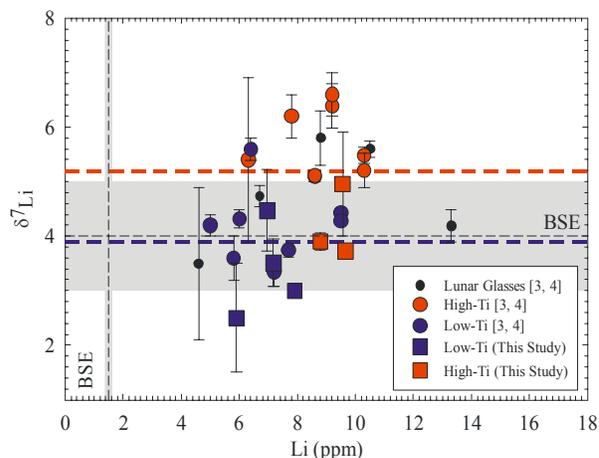


Figure 1: Li concentration versus $\delta^7\text{Li}$ (‰) for low- and high-Ti mare basalts and lunar pyroclastic glasses. Dashed red line represents high-Ti average, dashed blue line, low-Ti average. Data for estimated bulk silicate Earth (BSE: black dashed line, with grey fields denoting error) from [9] and lunar data from this study, [3] and [4].

Discussion: Previous studies have suggested O [2, 10] and Mg [11] isotopic differences between low- and high-Ti basalts. These differences have been interpreted as indicating mineralogically diverse mantle sources for mare basalts. The predicted consequence of magma ocean differentiation [12], includes a thick feldspathic crust overlaying a heterogeneous lunar mantle of olivine-pyroxene, with late-stage ilmenite-rich materials that convectively mixed with deeper portions of the mantle. In the near-total absence of water on the Moon, any Li isotopic variations between low- and high-Ti mare basalts would point to a mineralogical control in their mantle source regions. Based on the relationship between O and Li (Fig. 2), the late-stage ilmenite-rich materials that likely contribute to high-Ti mare basalt magmatism may be distinguished by isotopically heavy Li and light O via isotopic fractionation during magmatic differentiation. Simple Rayleigh-type fractionation at even moderate crystal/melt fractionation ($\alpha = \sim 0.999$) would result in greater Li concentrations and higher $\delta^7\text{Li}$ values in late-crystallizing materials after $\sim 75\%$ crystallization during magma ocean differentiation. For example,

ilmenite-rich cumulates, thought to form at ~95% magma ocean solidification [12], would have $\delta^7\text{Li} > 6\%$ assuming an initial silicate Moon composition close to chondritic [9, 13]. Any resolveable differences in Li isotope compositions between high- and low-Ti basalt would constrain the amount of re-mixing of Ti-rich materials into the lunar mantle, as required from phase equilibria of low- and high-Ti basalts (e.g., [14]). Using the currently available Li data (Fig. 1), we can restrict this to, at most, <20% of high-Ti mare basalt reservoirs. The notion of Li isotope variations as a consequence of magma ocean differentiation is consistent with the arguments of [4], and along with previous observations (outlined in [15]), point to a strongly differentiated Moon. Considering the lack of obvious isotopic fractionation at low degrees of partial melting (e.g., [16]), further work on Li isotopes in lunar basalts will place constraints on Li isotope fractionation as a plausible process during large-scale magma ocean igneous differentiation.

A second consideration is the Li isotopic composition of the Earth-Moon system. O-isotope studies have shown that the Moon and Earth have indistinguishable $\Delta^{17}\text{O}$ and therefore are likely formed from the same raw material [2, 10]. Considering the absence of hydrospheric processing and corresponding anticipated lack of large non-magmatic isotopic fractionations for Li, lunar basalts might offer important insights into the Li isotope compositions of the inner planets.

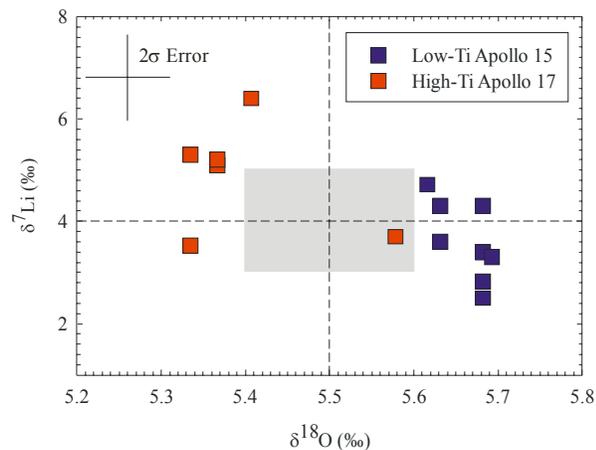


Figure 2: $\delta^{18}\text{O}$ versus $\delta^7\text{Li}$ for low-Ti Apollo 15 and high-Ti Apollo 17 mare basalts. Dashed line and grey box indicates the estimated compositional averages and field of terrestrial mantle volcanic products derived from the Earth's depleted upper mantle (i.e., MORB). Although there is overlap at the 2σ level of analytical error, there are notable differences in stable isotope compositions for lunar basalts. Data from this study, [2], [3] and [4].

Since no *bonafide* lunar mantle rocks have ever been collected, the best proxies for the lunar mantle $\delta^7\text{Li}$ composition are low-Ti lavas derived from early-formed lunar magma ocean cumulates which have suffered minimal isotopic fractionation of Li. We base this assumption partly on O-isotopes, where calculated differences in $\delta^{18}\text{O}$ of olivine between low-Ti mare basalts and MORB (the most voluminous volcanic product from Earth's mantle) are identical [2]. It is therefore notable that $\delta^7\text{Li}$ compositions of low-Ti mare basalts overlap the estimated mantle composition of the Earth at ~+4‰ (Fig. 2). These observations are consistent with previous studies [3, 4] that have shown similar $\delta^7\text{Li}$ compositions for the SNC (Mars) and HED (Vesta) groups of meteorites.

The Li isotope compositions of chondritic meteorites are similar to bulk estimates for the terrestrial planets [9, 13]. Furthermore, there are Li isotopic differences between carbonaceous, ordinary and enstatite chondrites, with CV3 and CO3 chondrites being some of the most isotopically heavy of all the chondrite groups [9, 13]. As a result, Seitz *et al.* [9] have suggested that the building-blocks of the inner solar system planets were similar to carbonaceous chondrite-type materials in terms of Li. This hypothesis appears inconsistent with oxygen isotope data that suggests a closer link for Earth with enstatite chondrite-type materials and a shift in $\Delta^{18}\text{O}$ between terrestrial and lunar materials, SNC meteorites and HED meteorite groups. Alternatives include the possibility that hierarchical planetary embryo formation [17] acted to fractionate stable isotopes from their originally 'chondritic' compositions, or that the building-blocks of the terrestrial planets differed from the modern day flux of chondritic meteorites.

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