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The Iron Isotopic Compositions of Basaltic Lunar Meteorites and Iron Isotopic Fractionation in the Lunar Magma Ocean

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Iron isotopes can provide a sensitive tracer of planetary-scale processes. However the δ^{57}Fe of the bulk silicate Moon (BSM) remains debated in part because a lack of lunar mantle samples and uncertainty in the degree to which silicate differentiation fractionates Fe isotopes in reducing systems. We present new high-precision δ^{57}Fe and whole rock geochemical data for a suite of basaltic lunar meteorites spanning a range of bulk compositions and eruption ages. We also reassess the δ^{57}Fe composition of the BSM, its relationship with lunar magma ocean (LMO) differentiation, as well as the wide range in δ^{57}Fe observed in the larger lunar basalt suite. All samples analyzed are isotopically heavier than chondrites with a δ^{57}Fe range of 0.078-0.220‰, similar to reported low-Ti basalts, and have rare earth element patterns indicating a wide range of geochemical enrichment (Fig. 1).

To investigate potential fractionation during silicate differentiation, we modeled δ^{57}Fe evolution during LMO crystallization (Fig. 2) using recent experimentally and theoretically determined mineral force constants for olivine, pyroxene, ilmenite, spinel, and basalt combined with cumulate modes, and calculated temperatures at stages of LMO crystallization from lunar petrologic models [1,2,3,4]. This model suggests that early high-temperature crystallization dominated by olivine induced minimal δ^{57}Fe fractionation. Isotopic fractionation remained minor through much of the moon's cooling history but became more pronounced as additional silicate phases began to crystallize and the assemblage evolved. In the final stages of LMO crystallization, the residual melt shifted toward slightly heavier δ^{57}Fe values. Future work will seek to produce a viable forward model of δ^{57}Fe fractionation in the LMO which accounts for the BSM δ^{57}Fe and can generate a range of basaltic compositions seen in nature.

[1] Cone et al. (2025). *Icarus*, *438*.
[2] Nie et al. (2021). *GCA*, *302*, 18–45.
[3] Nie, et al. (2025). *GCA*, *403*, 130–151.
[4] Prissel et al. (2024). *GCA*, *372*, 154–170.
[5] Ni et al. (2025). *LPSC*, Conference Abstract #2162.
[6] Weyer and Ionov (2007). *EPSL*, *259*(1-2), 119-133.

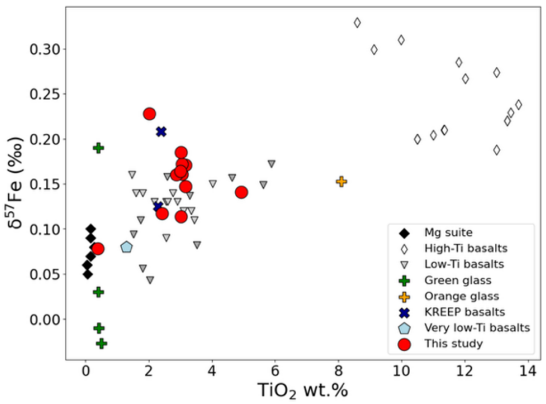

Figure 1: Lunar basalts analyzed in this study (red circles) plotted for δ^{57}Fe vs. TiO_2 accompanied by literature samples. The samples analyzed here are LAP 02205, LAP 02224, LAP 02226, LAP 02436, LAP 03632, LAP 04842, MIL 05035, NEA 039, NWA 032, NWA 6950, NWA 8632, and NWA 16286.

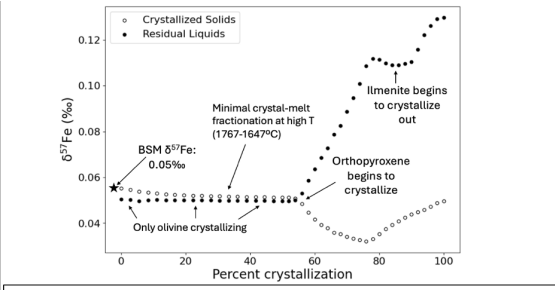

Figure 2: Liquid and cumulate crystallization trends of a putative Earth-like LMO isotopic composition of 0.05‰ based on lunar green glasses [5] following the methods of [6]. The black and white dots represent equilibrium-controlled isotopic compositions of the evolving liquids and cumulates. The trends have been plotted with variable fractionation factors calculated at different stages of magma ocean crystallization and accompanied cumulate mineralogy from the FRX50 model of [1]. The mineral force constants for olivine (175 N/m), clinopyroxene (205 N/m), orthopyroxene (219 N/m), ilmenite (156 N/m), spinel (167 N/m), and basalt (176 N/m) used to determine the equilibrium fractionation factors were reported in [2,3,4]. Iron isotopic fractionation follows a law of $1/T^2$, indicating Fe isotopic fractionation should be attenuated at higher temperatures.