

TRACKING LUNAR MAGMATIC DIFFERENTIATION USING MAGNESIUM ISOTOPES. F. Sedaghatpour¹ and S. B. Jacobsen¹, ¹Department of Earth and Planetary Sciences, Harvard University, 20 Oxford street, Cambridge MA 02138, USA (fsedaghatpour@fas.harvard.edu, Jacobsen@neodymium.harvard.edu)

Introduction: Magnesium with large relative mass differences (~8%) between its three stable isotopes and being a major element in terrestrial planetary objects has been used as a geochemical tracer for low-temperature [1, 2] and high-temperature processes [3, 4]. Since Mg is a lithophile element, and its isotopic fractionation is only influenced by mineral crystallization and not affected by the core formation process, it could be a unique tool to study planetary magmatic differentiation. Previous studies of terrestrial samples have shown limited Mg isotope fractionations in igneous rocks from Earth [5, 6]. However, Mg isotopes in parent bodies that have gone through different magmatic processes with different conditions of heat sources, pressure, time scales, etc. could behave differently [7, 8]. In order to have a better understanding of Mg isotope behavior during the lunar magmatic differentiation, we studied a well-represented set of lunar samples including pristine anorthositic rocks, basalts, breccias, lunar meteorites, and lunar mineral separates for the first time to the best of our knowledge.

Analytical method: Approximately 10-100 mg (whole rocks) and 2-10 mg (mineral separates) of well-mixed powdered samples were dissolved in a mixture of HF-HCl-HNO₃ using a CEM MARS 6 microwave digestion system through a three-step procedure. Upon complete dissolution, Mg separation was performed by ion-exchange chromatography using cation exchange Bio-Rad AG50W-X12 (200-400 mesh) resin in 1 N HNO₃ media following previously established procedures [6]. Each sample was processed through the column chemistry 2-3 times to ensure a complete separation of Mg. Magnesium isotope ratios were measured with our new Nu Plasma II MC-ICPMS in a low-resolution mode, wet plasma and the standard-sample bracketing method. We report the measurement averages based on at least two different session analyses for all standards and samples.

Result and Discussion: During the course of this study and setting up the new Nu Plasma II MC-ICPMS in our laboratory for Mg isotopic measurement, we have analyzed several pure Mg standard solutions, several standard rocks, and silicate samples over 10 months. Our long-term reproducibility is $\pm 0.07\%$ (2SD) which results in uncertainty ($2\sigma_{\text{mean}}$, 2SE) of $\pm 0.01\%$. Magnesium isotopic compositions of three pure standards as well as seawater agree with those of reported by [6] (Fig.1). Mg isotopic compositions of the pure Standard-Spex, standard rocks, and San Carlos olivine are heavier (~0.3‰) and in agreement with those reported by other groups [9 and references in].

To avoid any discrepancy, we performed the same dissolution and column chemistry processes previously used in our laboratory [6], and considered all parameters that could cause any interlaboratory mass bias [6, 9]. However, Mg isotope ratios in this study are measured by a Nu Plasma II MC-ICPMS under wet plasma condition whereas a GV Isoprobe-P MC-ICPMS in the static mode was used to measure the Mg isotope ratios by [6] (Fig.1). Although there is some discrepancy with previous work, all the data presented here are self-consistent with respect to the DSM3 standard.

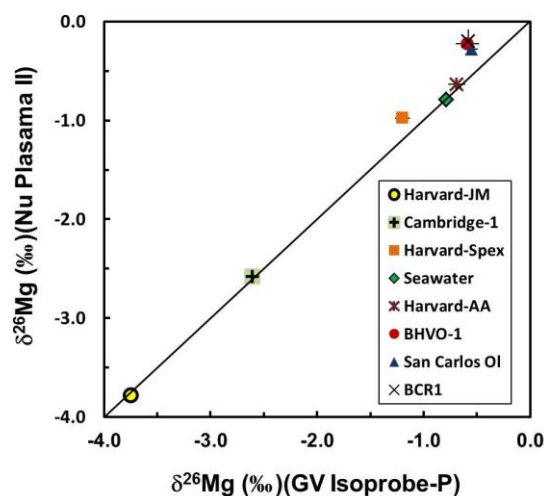


Fig.1 Stable Mg isotope data for pure standards, seawater, and terrestrial standards measured at Harvard University by GV Isoprobe-P MC-ICPMS [6] and new Nu Plasma II MC-ICPMS (present study). ($\delta^{26}\text{Mg} = [(^{26}\text{Mg}/^{24}\text{Mg})_{\text{sample}} / (^{26}\text{Mg}/^{24}\text{Mg})_{\text{DSM3}} - 1] \times 1000$).

Magnesium isotopic compositions of all pure standards, terrestrial silicate rocks, seawater, and lunar samples measured in this study lie on a single mass-dependent fractionation line with a best-fit slope of 0.519, which is in agreement with previous studies [5-10]. $\delta^{26}\text{Mg}$ values range from -1.08‰ to 0.08‰ in all lunar samples and from -0.59‰ to 0.48‰ in lunar minerals (Fig.2 and 3). Ilmenites from a low-Ti basalt (12021), and a high-Ti sample (10061) with different levels of purities are measured, and their $\delta^{26}\text{Mg}$ values range from -0.58 ‰ to -0.13 ‰ (Fig.2). All lunar meteorites, lunar breccias and impact melts (except 14321, 1803), a cataclastic dunite (72415, 89), a troctolite (76535, 171), two anorthosites, and some lunar basalts are overlapped with the Mg isotopic composition of the Moon ($\delta^{26}\text{Mg} = -0.26 \pm 0.16 \%$) reported

by [7] which is similar to that of the Earth ($\delta^{26}\text{Mg} = -0.25 \pm 0.06 \text{‰}$, [5]). Similar Mg isotopic composition of two oldest pristine lunar rocks, 72415 (dunite) and 76535 (troctolite), as well as lunar meteorites which are random samplings of both near- and far-side of the Moon to those of the Earth and chondrites agree with Mg isotope homogeneity in the inner solar system suggested by others [6, 8] (Fig.2). Lunar breccia 14321, 1803 which was collected from near the edge of Cone Crater has the lightest isotopic composition among all samples measured in this study. The light Mg isotopic composition of this breccia could be related to the evaporation-condensation process during the impact events.

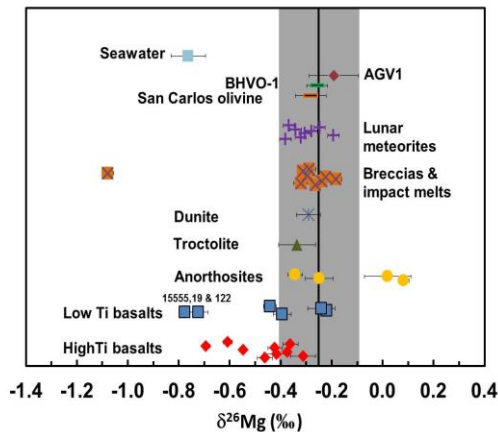


Fig.2 Stable Mg isotope data for seawater, terrestrial standards, lunar meteorites, and lunar samples from Apollo Missions. The solid line and grey bar represent the average $\delta^{26}\text{Mg}$ of -0.26 and two standard deviation of ± 0.16 for the Moon reported by [7].

Two slabs of low-Ti basalt 15555, 19 and 122, are significantly lighter than other low-Ti basalts. This anomaly is consistent with different $\delta^{18}\text{O}$ values for different aliquots of this sample [11] and its heavier Mg isotopic anomaly reported for another slab by [7]. All these data reflect the heterogeneity of sample 15555 and could be explained by the Fe-Mg exchange during diffusion [12]. High-Ti lunar samples indicate a wide range of $\delta^{26}\text{Mg}$ values and in agreement with previous studies [7, 13]. Also [7] suggested heterogeneous cumulate sources, produced during lunar magmatic differentiation (LMD) with high-Ti basalt cumulate with high abundance of isotopically light ilmenite, as a possible source of this anomaly. On the other hand, two pristine highland rocks (60015 & 60025), which originated from lunar crust formed by plagioclase flotation from the lunar magma ocean (LMO), are enriched in heavy Mg isotopes. These isotopic variations could be a record of Mg isotopic fractionation during the magmatic differentiation in LMO in contrast to the limited

Mg isotopic fractionation in terrestrial igneous rocks. This hypothesis could be further confirmed by isotopic measurements of mineral separates and whole rocks.

Fig.3 shows that plagioclase separated from 76535 is heavier than the whole rock ($\sim 0.8 \text{‰}$). In addition, $\delta^{26}\text{Mg}$ values of olivines, pyroxene and ilmenites with different purities suggest that isotopically light pyroxene produced by LMD could be the source of light Ti-basalts rather than ilmenite (Fig.3). Overall this study indicates Mg isotopes as a valuable tracer for magmatic differentiation of the Moon and other planetary objects that have gone through higher degrees of partial melting as compared to the Earth.

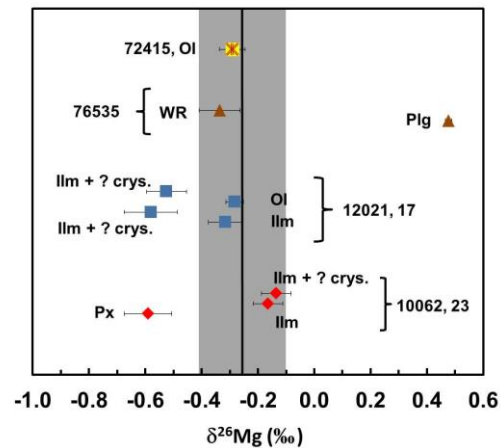


Fig.3 Stable Mg isotope data for a lunar troctolite (76535) and its plagioclase (Plg) separate, and olivine (Ol), pyroxene (Px), and ilmenite (Ilm) separates from lunar samples 10062, 12021, and 72415. Crys. are the crystalline impurities with ilmenite separates that were hard to separate. The solid line and grey bar represent the average $\delta^{26}\text{Mg}$ of -0.26 and two standard deviation of ± 0.16 for the Moon reported by [7].

References: [1] Blättler C. L. et al. (2015) *EPSL*, 419, 32-42. [2] Tipper et al. (2012) *EPSL*, 333-334, 35-45. [3] Ke S. et al. (2016) *Chem. Geol.*, 437, 109-119. [4] Richter F. M. et al. (2007) *GCA*, 71, 5544-5546. [5] Teng F.-Z. et al. (2010) *GCA*, 74, 4150-4166. [6] Chakrabarti R. and Jacobsen S. B. [7] Sedaghatpour F. et al. (2013) *GCA*, 120, 1-16. [8] Schiller M. et al. (2017), *Geochem. PL*, 3, 22-31 (2010) *EPSL*, 293, 349-358. [9] Teng F.-Z. et al. (2015), *G-Cubed*, 16, 3197-3209. [10] Young E. D. and Galy A. (2004) *Rev. Mineral. Geochem.* 55, 197-230. [11] Spicuzza M. J. et al. (2007) *EPSL*, 253, 254-265. [12] Richter F. M. *LPS XLVII*, Abstract #1146. [13] Weichert U. and Halliday A.N. (2007) *EPSL*, 256, 360-371.