

THE ISOTOPIC COMPOSITION OF MAGNESIUM IN BULK LUNAR SOILS. R. Chakrabarti¹ and S. B. Jacobsen², ^{1,2}Department of Earth and Planetary Sciences and Origins of Life Initiative, Harvard University, 20 Oxford Street, Cambridge, MA 02138 (¹rama@eps.harvard.edu and ²jacobsen@neodymium.harvard.edu)

Introduction: Lunar soils provide important clues about the composition of the lunar crust and evidence for the dynamic processes in the inner Solar System. Lunar soils preserve a complex history of billions of years of impacts and mixing, although meteoritic components contribute less than 2% to the soil composition. Surface layers of lunar soils can also be altered by irradiation of solar wind energetic particles which have energies of 1 keV per nucleon [1]. This leads to erosion by sputtering, implantation, as well as recoil implantation [2]. The energy distribution of sputtered atoms match the escape velocity of atoms from the lunar surface, particularly for elements with masses between 16 and 40 [1] and this could potentially lead to fractionation of isotopes of these light elements. Additionally, the surface of the Moon has been constantly bombarded by cosmic rays because there is no magnetic field to deflect the rays or an atmosphere to absorb them. The cosmic ray bombardment on the lunar surface produces secondary neutrons that are then thermalized by the lunar soil and interact with elements having high neutron capture cross sections. Effects of neutron capture on lunar soils have been well documented for elements with large neutron capture cross sections. For example, changes in ¹⁵⁸Gd/¹⁵⁷Gd of 0.8% and ¹⁵⁰Sm/¹⁴⁹Sm of 0.06% have been observed [3].

Mass dependent fractionation has been observed for O, Si, S and K isotopes, with lunar soils being preferentially enriched in the heavier isotopes [e.g. 4,5]. Similar effects have been observed for Ca isotopes although the effects are smaller [6]. Enrichments of the heavier Si and O isotopes in lunar soils have been explained by thermal volatilization following meteorite impact, gravitational mass selection and re-deposition [4]. Other proposed mechanisms to explain stable isotope fractionation in lunar soils include formation of volatile compounds in a chemical reaction following solar wind hydrogen [7].

Mg has three isotopes (masses 24, 25 and 26) with a 4-8% mass difference between the isotopes. Large fractionation of Mg isotopes has been documented in Ca-Al-rich inclusions [8] and laboratory experiments have demonstrated selective enrichment of heavier isotopes of Mg (as well as Ca, Si) in evaporation residues [9]. However, no significant stable isotope fractionation of Mg has been observed in lunar soils [1]. Barring one sample which shows a 0.9-1.7‰ per amu effect, most variations reported are within the analytical uncertainties ($\pm 0.5\%$) of the TIMS measurements [1]. With improvements in Multi-Collector Inductively

Coupled Plasma Mass Spectrometry (MC-ICPMS), Mg isotope ratios can now be measured with analytical uncertainties an order of magnitude better than the early TIMS measurements [e.g. 10]. We report Mg isotope measurements in 14 lunar soil samples from the Apollo 14 and 16 missions.

Analytical Methods: Approximately 100 mg of each soil sample was dissolved in HF-HNO₃ acid mixtures in a Teflon “bomb” heated to 130°C for one week. Upon complete dissolution, a 1% aliquot of the solution was taken for trace element [11] and Mg isotopic measurements. Separation and purification of Mg was performed using Biorad 50W-X12 (200-400 mesh) cation exchange resin following our laboratory protocol [12]. Mg isotope ratios were measured using a GVI Isoprobe-P MC-ICPMS at Harvard University in the static mode by standard-sample bracketing to correct for instrumental mass bias. Purified Mg solutions were introduced using an APEX-Q spray chamber fitted with an additional desolvator (ACM from ESI) and a PFA nebulizer with an uptake rate of 100 μ l/min. We used a combination of He and H₂ in the collision cell, a unique feature of the Isoprobe-P, to eliminate isobaric molecular interferences (e.g. C₂⁺, CN⁺) on all isotopes of Mg. All our measurements were performed with a resolving power (R_{power} , 5%, 95%) of ~ 1100 . In a given analytical session, a particular sample or standard was measured 3-4 times w.r.t. 4-5 measurements of DSM3 standard [13]. All standards and samples were measured at least in 2 different sessions during the course of this study and we report the averages of all these measurements.

Results and Discussion: During the course of this study, we have measured four pure Mg standards including Cambridge1 [13], Harvard AA, Harvard-SPEX and Harvard-JM [12] along with chemically processed seawater samples and our results are consistent with previously published values of these standards. $\delta^{26}\text{Mg}$ of the San Carlos olivine and Peace River ordinary chondrite analyzed during the course of this study are -0.50 ± 0.08 (2SE) and -0.45 ± 0.09 (2SE), respectively, which are consistent with our previous measurements of these samples [12].

$\delta^{26}\text{Mg}$ of the Apollo 14 soils analyzed in this study range from -0.47 to -0.31 with an average $\delta^{26}\text{Mg} = -0.40 \pm 0.07$ (2SE). $\delta^{26}\text{Mg}$ of the Apollo 16 soils mostly cluster from -0.53 to -0.19 except for one sample (60010, 4810) with $\delta^{26}\text{Mg} = -1.18$. This measurement was verified by multiple procedural repeats. The average $\delta^{26}\text{Mg}$ of the Apollo 16 soils (-0.46 ± 0.16 , 2SE) is

similar to that of the Apollo 14 soils (Fig. 1). All samples analyzed in this study show mass dependent Mg isotopic fractionation. $\delta^{26}\text{Mg}$ of lunar soils analyzed in this study are similar to our analysis of a lunar basalt (this study) as well as those of whole-rock ilmenite and olivine-rich lunar basalts and crystalline breccia from an earlier study by us [12] and are also indistinguishable from our previous estimates of the $\delta^{26}\text{Mg}$ of the bulk silicate Earth, which is chondritic in Mg isotopes ($\delta^{26}\text{Mg} = -0.52 \pm 0.04$) [12]. In contrast, Wiechert and Halliday [14] reported much heavier $\delta^{26}\text{Mg}$ for lunar basalts with low-Ti basalts showing heavier $\delta^{26}\text{Mg}$ compared to high-Ti basalts.

Trace element concentrations [11, 15] indicate that the Apollo 14 soil samples of this study have a high KREEP component showing very high REE concentrations and large negative Eu anomaly whereas, most Apollo 16 soils of this study, while having an order of magnitude lower REE concentration, still have a KREEP component giving rise to a negative Eu anomaly, consistent with the study of [16]. Only one soil sample of this study (60009, 2074) has the characteristic positive Eu anomaly and a low Nd concentration that defines the lunar highlands and is a true signature of the plagioclase flotation crust [11]. Mg isotopic composition of these lunar soils, although derived from different lunar crustal components, are broadly indistinguishable from one another and similar to our previous estimate of the Mg isotopic composition of the Moon [12] as well as that of a lunar basalt (15386,3800) analyzed in this study (Fig 1). This observation is consistent with expected lack of stable isotopic fractionation during high-T mantle processes.

Three Apollo 16 soils and one Apollo 14 soil analyzed in this study show slightly heavier $\delta^{26}\text{Mg}$ whereas another Apollo 16 soil sample shows distinctly lighter $\delta^{26}\text{Mg}$. High temperature volatilization could explain the slightly heavy $\delta^{26}\text{Mg}$ in some lunar soils (heavy residues). However, given that Mg and Si have similar volatilities, the much larger Si isotopic fractionation in lunar soils [4,5] requires an additional mechanism. Alternatively, irradiation by solar wind particles could result in heavier Mg isotopic compositions in lunar soils, although such an effect is expected only in the top 100s of angstroms of the exposed surface. The sample 60010, 4810 which shows the lightest $\delta^{26}\text{Mg}$ shows the largest neutron capture effects in Sm isotopes, compared to all other samples of this study [11]. Neutron capture cross section of Mg is small (approximately 63 milli-barns) and a factor of 10^6 smaller than that of Sm [17]. Hence, it is unlikely that neutron capture reactions would effect the Mg isotopic compositions of these soils. Alternatively, the

light $\delta^{26}\text{Mg}$ in this sample could be explained by evaporation-condensation reactions.

Overall, our data indicate that the Mg isotopic composition of lunar soils are broadly similar to that of the bulk Moon, Earth and chondrites and suggests that Mg isotopes remain relatively undisturbed during various types of space irradiation processes and primarily reflect the parent body composition (barring mineral effects). At the current level of analytical precision, Mg isotopes are broadly homogeneous in the inner Solar System and are not the ideal proxy for studying planetary processes.

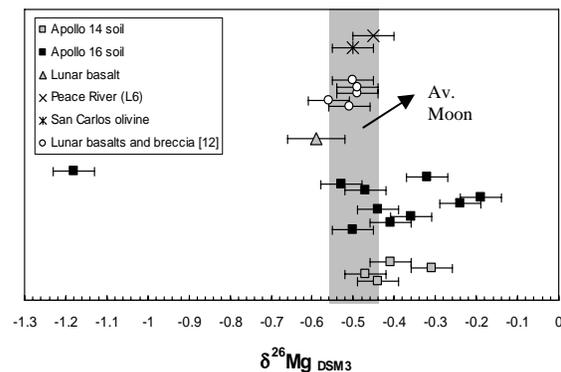


Figure 1. Stable Mg isotopic composition of lunar soils compared with one lunar basalt, one ordinary chondrite, olivines from the San Carlos peridotite (this study), as well as other lunar basalts and crystalline breccia from [12].

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