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Magnesium isotopic composition of the Moon

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Abstract

The Mg isotopic compositions of 47 well-characterized lunar samples, including mare basalts, highland rocks, regolith breccias, and mare and highland soils were measured to address the behavior of Mg isotopes during lunar magmatic differentiation, constrain the Mg isotopic composition of the Moon, and evaluate the degree of Mg isotopic fractionation between planetary bodies. The $\delta^{26}Mg$ values range from -0.61 ± 0.03‰ to 0.02 ± 0.06‰ in 22 mare basalts, from -0.34 ± 0.04‰ to -0.18 ± 0.06‰ in 3 highland rocks, from -0.33 ± 0.05‰ to -0.14 ± 0.08‰ in 7 regolith breccias, from -0.23 ± 0.05‰ to -0.14 ± 0.07‰ in 6 highland soils, and from -0.41 ± 0.05‰ to -0.20 ± 0.09‰ in 9 mare soils. The limited Mg isotopic variation among bulk mare and highland soils and regolith breccias indicates negligible Mg isotope fractionation by lunar surface processes. By contrast, the large Mg isotopic fractionation between low-Ti and high-Ti basalts suggests the source heterogeneity produced during fractional crystallization of the lunar magma ocean, with ilmenite having lighter Mg isotopic compositions than olivine and pyroxene. Overall, the Moon has a weighted average Mg isotopic composition ($\delta^{26}Mg = -0.26 \pm 0.16$‰) indistinguishable from the Earth ($\delta^{26}Mg = -0.25 \pm 0.07$‰) and chondrites ($\delta^{26}Mg = -0.28 \pm 0.06$‰), suggesting homogeneous Mg isotopic distribution in the solar system and the lack of Mg isotope fractionation during the Moon-forming giant impact.

1. INTRODUCTION

Isotopic studies of terrestrial and lunar samples can provide insight into the complex processes that govern planetary accretion and differentiation. For instance, despite the large variation of oxygen isotopes in the solar system, the Earth and the Moon have identical O isotopic compositions (Clayton et al., 1973; Wiechert et al., 2001; Spicuzza et al., 2007; Hallis et al., 2010; Liu et al., 2010a), suggesting that materials in the proto-Moon and proto-Earth were from the same sources or well-mixed during the giant impact (Wiechert et al., 2001; Pahlevan and Stevenson, 2007).

Magnesium is a moderately refractory element in the solar system, with a condensation temperature of ~1400 K (Lodders, 2003). In addition to the non-mass-dependent isotope anomalies produced by the decay of short-lived ^{26}Al to ^{26}Mg (Lee et al., 1977), Mg isotopes can also fractionate mass dependently at high temperatures during condensation and evaporation processes, as observed from calcium–aluminum-rich inclusions (CAIs) (e.g., Clayton

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and Mayeda, 1977; Wasserburg et al., 1977; Lee et al., 1979; Niederer and Papanastassiou, 1984; Niederer et al., 1985; Clayton et al., 1988) and chondrules (Galy et al., 2000; Young et al., 2002), and as shown by experimental and theoretical studies (Davis et al., 1990; Richter et al., 2002, 2007). Knowledge of Mg isotopic compositions of terrestrial and extraterrestrial materials, therefore, can potentially be used to study the origin, formation, and differentiation of planetary objects (Richter et al., 2002; Young et al., 2002; Norman et al., 2006; Teng et al., 2007, 2010; Wiechert and Halliday, 2007). For example, Wiechert and Halliday (2007) found the Earth has heavy Mg isotopic compositions relative to chondrites. They interpreted the Mg isotope heterogeneity in the solar system as reflecting the physical separation and sorting of the chondrules and CAIs in the proto-planetary disk. However, more recent comprehensive studies on terrestrial basalts, komatiites and peridotites indicate that the Earth has a Mg isotopic composition indistinguishable from chondrites within uncertainties (Teng et al., 2007, 2010; Handler et al., 2009; Yang et al., 2009; Bourdon et al., 2010; Chakrabarti and Jacobsen, 2010; Dauphas et al., 2010; Schiller et al., 2010; Huang et al., 2011; Liu et al., 2011; Pogge von Strandmann et al., 2011; Xiao et al., 2013).

Studies of the Mg isotopic composition of the Moon can shed light on Mg isotopic distribution in the solar system. Compared to the Earth and chondrites, our understanding of the Mg isotopic composition of the Moon is still a subject of controversy. *In-situ* analyses reveal homogeneous Mg isotopic compositions in lunar mare basalts, glasses and impact melts, similar to the Earth and chondrites at $\sim\pm 0.2‰\ amu^{-1}$ (2SD) (Warren et al., 2005; Norman et al., 2006). By contrast, Wiechert and Halliday (2007), by using solution method MC-ICPMS with a higher precision ($\sim\pm 0.05‰\ amu^{-1}$, 2SD), found that Mg isotopic composition of the Moon is $\sim$0.09‰ amu^{-1} heavier than that of the Earth, and both the Earth and Moon are heavier than chondrites. With similar precision, Chakrabarti and Jacobsen (2010) reported that the Moon has an identical Mg isotopic composition to chondrites. Nonetheless, the values for most terrestrial and chondrite samples reported by Chakrabarti and Jacobsen (2010) and Wiechert and Halliday (2007) are different from those reported by other groups (Teng et al., 2007, 2010; Handler et al., 2009; Yang et al., 2009; Bourdon et al., 2010; Dauphas et al., 2010; Schiller et al., 2010; Huang et al., 2011; Liu et al., 2011; Pogge von Strandmann et al., 2011; Xiao et al., 2013).

To better constrain the Mg isotopic composition of the Moon, understand behaviors of Mg isotopes during the lunar-forming giant impact and lunar magmatism, and evaluate the extent of Mg isotopic heterogeneity in the solar system, we have studied 47 well-characterized samples from all major types of lunar rocks returned by the Apollo 11, 12, 14, 15, 16 and 17 missions. Our results show limited Mg isotopic variation in lunar highland rocks, breccias, soil samples and low-Ti basalts, which are similar to terrestrial basalts and chondrites. By contrast, high-Ti basalts tend to have light Mg isotopic compositions, which may reflect the source heterogeneity produced during differentiation of the lunar magma ocean (LMO).

2. SAMPLES

The samples investigated in this study are from the same collection as those studied by Batchelor et al. (1997) and some of those studied for oxygen and iron isotopes by Spicuzza et al. (2007) and Liu et al. (2010a). They represent a diverse spectrum of sample types including highland rocks, mare volcanic rocks, regolith breccias, and mare and highland lunar soils, with a broad range of lunar geological settings and geochemical properties (Fig. 1 and Table 1). Petrography, mineralogy, and major- and trace-element compositions of these samples are available in the lunar sample compendium (Meyer, 2004–2011).

2.1. Highland rocks

Highland rocks are classified into four major groups: ferroan-anorthosites, Mg-rich suite rocks, gabbros/norites, and alkali-suite rocks (e.g., Lucey et al., 2006). The lunar highlands, decidedly older than the maria, were subjected to heavy bombardment, and primary igneous rocks were broken, mixed, and melted into various types of breccias. Three highland rocks from Apollo 14 and 16 were analyzed for Mg isotopes in this study (Table 1).

2.2. Mare volcanic rocks

Mare volcanic rocks include various types of basalts that were derived from partial melting of cumulates originally formed by the LMO crystallization. On the basis of the bulk-rock TiO_2 content, mare basalts are classified into high-Ti basalts (HT) (>6 wt.% TiO_2), low-Ti (LT) basalts (1.5–6 wt.% TiO_2), and very low-Ti (VLT) basalts (<1.5 wt.% TiO_2) (Neal and Taylor, 1992). The basalt samples from the Apollo 12 and 15 missions are mostly low-Ti basalts, whereas those from the Apollo 11 and 17 missions consist mainly of high-Ti basalts. Based on mineralogy, and major- and trace-element compositions, Apollo 12 basalts

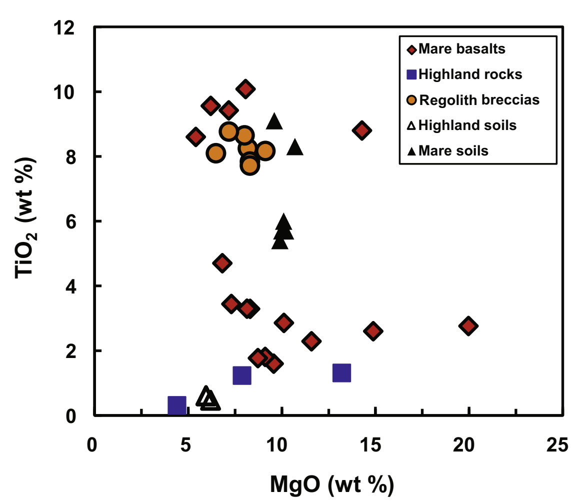

Fig. 1. Variation of TiO_2 versus MgO contents for lunar samples studied here. Data are reported in Table 1.