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Magnesium isotopic composition of olivine from the Earth, Mars, Moon, and pallasite parent body

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[1] To investigate the nebular history of material contributing to the terrestrial planets, and search for evidence of a high-temperature origin of the Moon, we measured Mg isotopic compositions of primitive olivines from the Earth, Moon, Mars, and pallasite parent body using laser-ablation multi-collector ICPMS. No temporal variation in the Earth's mantle since at least 3.8 Ga, and only limited variations in the compositions of mantle sources from diverse tectonic settings were found. Earth, Moon, Mars, and differentiated asteroids appear to have formed from a nebular reservoir that was homogeneous with respect to Mg isotopes. This implies either a minor role for evaporation-condensation in the inner solar system, or a limited variation in the proportion of refractory CAI-like material contributing to the terrestrial planets. The Mg isotopic composition of the Moon is identical to the Earth's mantle, placing strong constraints on any volatility-related fractionation that occurred during formation of the Moon.

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1. Introduction

[2] Refractory inclusions in chondritic meteorites have Mg and Si isotopic compositions consistent with mass fractionation during evaporation at very high temperatures ($\geq$1400°C) in the solar nebula [*Richter et al.*, 2000]. The astrophysical setting in which this thermal processing occurred is not well understood, but it may be due to exposure to intense radiation from the early Sun and transport of refractory residues outward to perhaps several AU [*Shu et al.*, 2001]. Magnesium isotopic compositions therefore might provide one way to track the relative contributions of refractory material to the terrestrial planets and asteroids. In addition, recent reports suggest that Mg isotopic compositions of mantle olivine may record melting and fluid migration within the Earth's mantle [*Pearson et al.*, 2006].

[3] Here we present a reconnaissance study of Mg isotopic compositions in olivine from (1) peridotite mantle xenoliths with a range of depletion ages and melting/metasomatic histories, (2) primitive ocean island and island arc picrites, (3) the Chassigny martian meteorite, (4) the Brenham pallasite meteorite, and (5) Apollo 12 lunar mare basalts. These data allow us to search for evidence of temperature-dependent isotopic fractionation during formation of the terrestrial planets and investigate possible source effects in the terrestrial mantle.

2. Methods

[4] Analytical methods are described in detail by *Norman et al.* [2006]. Briefly, separated olivine crystals were mounted in epoxy and polished to expose grain interiors. Magnesium isotopic compositions of individual grains were measured using a Neptune multi-collector ICPMS and an excimer laser. Ablation was conducted under a helium atmosphere in a custom-built, small volume sample cell similar to that described by *Eggins et al.* [1998] using a Compex UV pulsed ArF excimer laser (193 nm). The laser was operated at 80 mJ/pulse, a repetition rate of 5 Hz and either 47 μm or 62 μm spot diameters. The sample gas flow was mixed with Ar downstream of the ablation chamber and passed through a mixing cell prior to introduction into the ICP. Corrections for a composition-dependent matrix effect were applied to the Chassigny and lunar samples using synthetic olivines analyzed with the unknowns [*Norman et al.*, 2006].

[5] Data are reported as epsilon unit (parts in 10^4) deviations per amu relative to a crystal of San Carlos olivine using the standard-unknown bracketing method (hereafter denoted ε_{sc}) to correct for instrument drift and provide a direct comparison with the terrestrial mantle. Typically 3 sample analyses were bracketed by two analyses of the San Carlos olivine, with the ε_{sc} values of the samples calculated relative to the average composition of the two bracketing SC analyses. San Carlos olivine is a reasonable approximation of average terrestrial mantle. *Pearson et al.* [2006] show that the Mg isotopic composition of San Carlos olivine is $\sim$2 ε-units/amu heavier than the DSM-3 solution standard, which approximates the chondritic Mg isotopic composition [*Galy et al.*, 2000]. This is within our analytical precision of ± 2 ε_{sc} (2SD) established by replicate analyses of mantle olivines [*Norman et al.*, 2006].

3. Results

3.1. Mantle Peridotites

[6] Olivines from two suites of well-characterized mantle peridotites were analyzed. One suite comprises modally metasomatised peridotite from southeastern Australia [*Yaxley et al.*, 1991, 1997, 1998; *Yaxley and Kamenetsky*, 1999]. The other suite represents Early Archean peridotite enclaves from Southwest Greenland [*Friend et al.*, 2002; *Bennett et al.*, 2002].

[7] Peridotite xenoliths from southeastern Australia were recovered from Tertiary to Recent alkali basalts at Mt.

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Table 1. Mg Isotopic Compositions of Olivine

Sample	Fo	ε^{25Mg}_{SC}	ε^{26Mg}_{SC}	n
		Southeast Australia		
76994	89.4	0.5	0.2	3
71000	89.4	−2.3	−3.0	3
71006	87.5	−0.9	−0.9	3
76997	91.2	−1.6	−2.1	3
SH-35	91.2	−1.8	−2.3	3
71001	88.5	−1.3	−1.5	3
70972	91.0	−1.6	−2.1	3
71004	93.8	−1.1	−1.4	3
76993	90.7	−1.3	−1.4	3
Average		−1.2	−1.6	27
2SD		1.5	1.8	
		SW Greenland		
G01/03	90.3	−2.4	−2.4	3
G01/55	86.9	−1.3	−1.3	3
G97/15	88.5	−2.2	−1.9	3
G97/13	86.4	−1.7	−1.5	3
G97/05	89.6	−0.7	−0.4	3
G01/56	86.5	−2.1	−1.7	3
G01/84	83.8	−2.9	−2.6	3
G93/48	90.3	−1.5	−1.7	6
Average		−1.9	−1.7	27
2SD		1.4	1.4	
		Mauna Loa		
Average	88.8	0.3	0.7	12
2SD		2.8	2.8	
		Kilauea		
Average	87.2	−1.09	−1.75	5
2SD		1.66	2.30	
		Ko'olau		
Average	88.0	−1.07	−0.48	6
2SD		1.62	2.41	
		Vanuatu		
Average	93	−0.95	−0.65	5
2SD		3.16	3.43	
		Chassigny		
Average	70	0.69	1.65	7
2SD		0.80	0.86	
		Brenham		
Average	88	−0.08	0.07	6
2SD		1.54	1.47	
		Apollo 12 Mare Basalts		
Average	48–75	−0.4	0.2	22
2SD		3.8	4.2	

Shadwell and Mt. Leura of the Newer Volcanic Province, Victoria. They are apatite-bearing spinel harzburgites, lherzolites and wehrlites with porphyoclastic textures and petrographic and mineral chemical evidence of interactions between harzburgitic mantle and sodic dolomitic carbonatite melt. Accessory metasomatic phases include apatite, amphibole and rarely phlogopite. All samples contain irregularly shaped patches and veins of siliceous, aluminous glass often crowded with microphenocrysts of secondary clinopyroxene, olivine and Cr-spinel. These glassy patches were interpreted as decompression melting products of clinopyroxene, hydrous phases (amphibole and phlogopite) and apatite, formed during transport of the xenoliths from mantle lithosphere to surface by their host magma [*Yaxley and Kamenetsky*, 1999; *Yaxley et al.*, 1997]. Forsterite contents of primary olivine range from 87.5 to 93.8 (Table 1). Re-Os melt depletion ages of the Mt. Shadwell and Mt. Leura peridotites range from 863 Ma to 1924 Ma [*Handler et al.*, 1997].

[8] The oldest terrestrial olivines are from 9 Early Archean spinel peridotites from southern West Greenland. Four samples (G97-15, G97-13, G97-05 and G93-48) are dunites and hartzburgites from large (>100 m^2) ultramafic enclaves hosted by early Archean tonalites that occur approximately 20 km to the south of the Isua supracrustal belt. Field relationships, chemistry and geochronology of these units are described by *Friend et al.* [2002]. These peridotites have LREE-depleted to slightly enriched patterns and have not been modally metasomatised. Their mineralogy more closely resembles olivine-rich normal oceanic mantle rather than orthopyroxene-rich cratonic mantle lithosphere. U-Pb zircon ages from cross-cutting orthogneisses indicate minimum ages of 3810 Ma for the ultramafic enclaves. Os isotopic studies of these peridotites yielded the most primitive terrestrial compositions yet measured [*Bennett et al.*, 2002] providing additional confirmation of their ca. 3800 Ma ages. The other 5 samples are from ultramafic bodies that are part of the Akilia association found on the islands south of Ameralik fjord, near Nuuk, West Greenland [*Nutman et al.*, 1996]. On the basis of zircon U-Pb ages of associated gneisses, these ultramafic units is considered to be >3850 Ma [*Nutman et al.*, 2002]. A minimum age of 3650 Ma is provided by the SHRIMP U-Pb ages of rare metamorphic zircons found within the peridotites (A. P. Nutman and C. R. L. Friend, unpublished data, 2004). Representative compositions of the olivines are given in Table 1.

[9] The Proterozoic mantle peridotites from southeastern Australia and the Early Archean peridotites from southern West Greenland provide information about the Mg isotopic evolution of the mantle through time, in widely different locations, and compositional variations related to modal metasomatism of the lithospheric mantle. The SW Greenland peridotites have Mg isotopic compositions ranging from $\varepsilon_{sc} = -1$ to -3 (Figure 1 and Table 1). The Mt. Shadwell peridotites extend to somewhat lighter values of -2.5 to $+0.5$ ε_{sc} (Figure 1 and Table 1).

3.2. Hawaiian Picrites

[10] Picritic lavas from Mauna Loa (sample M6-13), Kilauea (sample KIL-1-10), and Ko'olau (sample KOO-17a) volcanoes were selected to represent geochemical diversity in the Hawaiian plume [*Norman and Garcia*, 1999]. Olivine phenocrysts with primitive major element compositions (Fo$_{88-91}$ [*Davis et al.*, 2003; *Norman and Garcia*, 1999]) were measured for this study. Mg isotopic compositions of these phenocrysts range from $\varepsilon_{sc} = -2.5$ to $+2.5$ (Figure 1 and Table 1). Mauna Loa olivines extend to somewhat heavier Mg isotopic compositions than those from Kilauea and Ko'olau (Figure 1). The mean Mg isotopic compositions of olivine from all three volcanoes are within analytical uncertainty of the San Carlos reference olivine (Table 1).

3.3. Arc Picrite

[11] Olivines phenocrysts in picritic lava 68622 from Ambae volcano, Vanuatu volcanic arc [*Eggins*, 1993] have unusually magnesian compositions (up to Fo$_{93}$). Mg isoto-

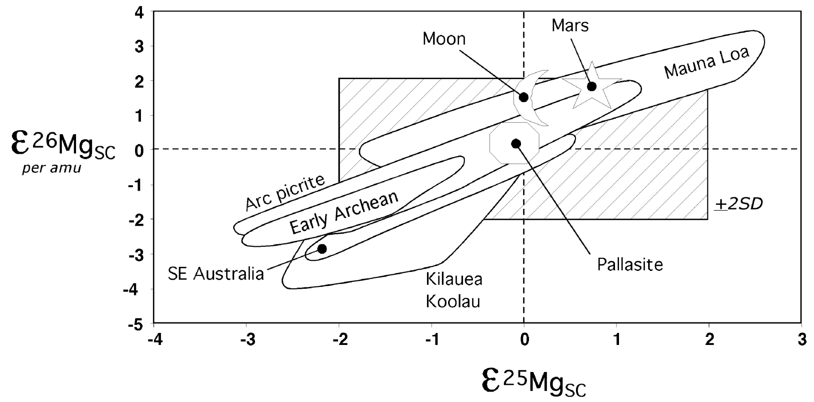

Figure 1. ^{25}Mg/^{24}Mg and ^{26}Mg/^{24}Mg isotopic compositions measured in olivine from the terrestrial mantle, primitive ocean island and arc basalts, the Chassigny martian meteorite, Apollo 12 lunar mare basalts, and the Brenham pallasite meteorite relative to the San Carlos reference olivine (ε_{SC}). Analytical uncertainty (2SD) estimated from replicate analysis of terrestrial mantle olivine is indicated by the hatched box.

pic compositions of these phenocrysts range from $\varepsilon_{sc} = -3$ to +1 (Figure 1 and Table 1). The mean Mg isotopic composition of these arc picrite olivines is within the 2SD analytical uncertainty of the San Carlos reference olivine.

3.4. Chassigny Martian Meteorite

[12] The Chassigny meteorite is a dunite composed of ~90% olivine (Fo$_{68\text{-}70}$ [*McSween and Treiman*, 1998]). The petrology and geochemistry of Chassigny shows that it formed as an igneous cumulate, whereas its young crystallization age (1.3 Ga), oxidized mineralogy, carbonate and sulfate alteration, and oxygen isotopic composition are consistent with an origin on Mars. The Fo-corrected Mg isotopic composition of olivine from Chassigny ranges from ε_{SC} = +0.1 to ±1.3 (Figure 1), with an average composition of $\varepsilon_{SC} = +0.7 \pm 0.8$ (Table 1).

3.5. Pallasite Parent Body

[13] The Brenham meteorite is a main group pallasite with Fo$_{88}$ olivines [*Mittlefehldt et al.*, 1998]. Pallasites represent olivine+metal cumulates from one or more differentiated asteroids, and so provide a comparison of Mg isotopic compositions in primitive igneous meteorites with the Earth, Moon, and Mars. The Mg isotopic composition of olivine from Brenham ranges from $\varepsilon_{SC} = -1.2$ to +1.2 (Figure 1) with an average composition identical to the San Carlos reference olivine (Table 1).

3.6. Lunar Mare Basalts

[14] Olivines from four Apollo 12 lunar mare basalts (12009, 12035, 12040, 12075) were analyzed for their Mg isotopic composition in order to compare the composition of the Earth and Moon and test for possible high-T signatures of a Moon-forming giant impact. Olivines from the Apollo 12 basalts are Fo$_{48\text{-}75}$ [*Bombardieri et al.*, 2005]. The mean Fo-corrected Mg isotopic composition of olivine from the four Apollo 12 mare basalts is indistinguishable from the San Carlos reference olivine (Table 1) [*Norman et al.*, 2006]. The standard deviation (2SD) of the 22 analyses of lunar olivines is about twice that of the analytical uncertainty established by replicate analyses of terrestrial mantle olivine (~±4 ε-units; Table 1), likely reflecting the combined effects of decreased measurement precision from the smaller Mg signal obtained on these Fe-rich lunar olivines and propagation of uncertainties in the Fo-correction procedure rather than real isotopic variability in these lavas. There are no resolvable differences in mean Mg isotopic composition among the mare basalts analyzed for this study.

4. Discussion

[15] We have measured the Mg isotopic composition of olivine with a range of origins, tectonic settings, source compositions, and planetary bodies. Despite this diversity, only an extremely small variation in Mg isotopic composition has been detected that is barely outside of our analytical uncertainty. There appears to be no temporal evolution in the Mg isotopic composition of the Earth's mantle since at least 3.8 Ga, and limited variations related to processes occurring in the mantle. Modal metasomatic enrichment evident in the Victorian xenoliths did not have a strong effect on Mg-isotopic composition of olivine, and there is no evidence for a systematic offset in the compositions of magmatic phenocrysts relative to the mantle. Similarly, subduction and formation of mantle plume source regions did not modify the Mg isotopic composition of the mantle to any great extent. Our data imply a much more restricted range of Mg isotopic compositions in the terrestrial mantle than reported by *Pearson et al.* [2006]. The total range for all of the samples reported here is ~5–6 ε-units (0.5–0.6 per mil/amu) relative to the San Carlos reference olivine (Figure 1). This is about 5x less variation than that reported for peridotite xenoliths from the lithospheric mantle by *Pearson et al.* [2006]. Additional work is needed to resolve this difference.

[16] The Earth, Moon, Mars, and differentiated asteroids share a common Mg isotopic composition, within our analytical uncertainty. The terrestrial planets appear to have formed from a nebular reservoir that was homogeneous with respect to Mg isotopes. This places strong constraints on any high-temperature volatility-related fractionation of Mg that could have occurred during formation of the terrestrial planets, including a Moon-forming giant impact event. Either a minor role for evaporation-condensation in the inner solar system prior to accretion or a limited variation

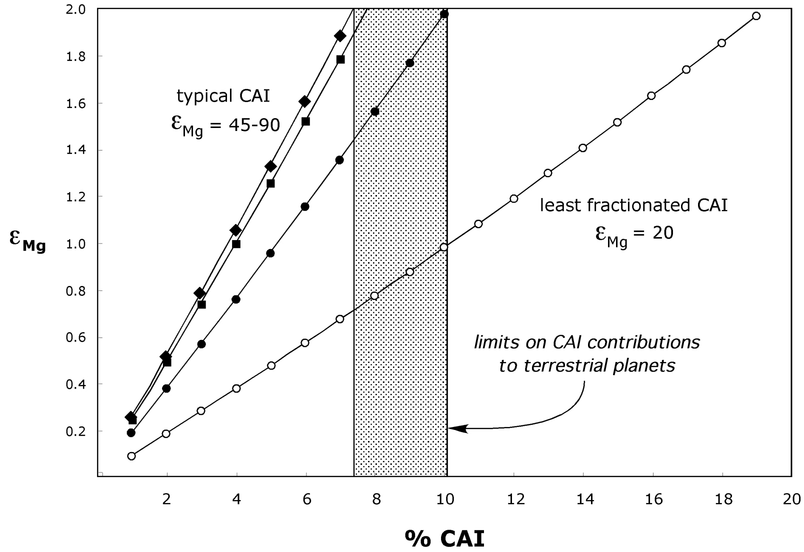

Figure 2. Mg isotopic compositions place limits on the proportion of refractory, CAI-like material that was incorporated into Mars, the Moon, and the pallasite parent body relative to Earth. Addition of up to ~7–10% of material with typical CAI compositions (ε_{SC} = +45–90; hatched box), or up to ~18–20% of less refractory material similar to the least fractionated CAIs is allowed by our analytical uncertainty. The terrestrial mantle is assumed to have 38.6% MgO and ε_{SC} = 0. CAI compositions are from the experiments of *Richter et al.* [2000].

in the proportion of fractionated, refractory material contributing to the terrestrial planets is implied. The limited range of Mg isotopes mirrors the constancy of potassium isotopes within the inner Solar System [*Humayun and Clayton*, 1995], despite the first-order control that volatility apparently exerted on the distribution of element abundances in the terrestrial planets [*McDonough*, 2003].

[17] We can place limits on the relative proportions of refractory residues contributing to the terrestrial planets and differentiated asteroids by comparing the measured Mg isotopic compositions with those predicted for mixtures of terrestrial mantle and refractory components similar to calcium-aluminum rich inclusions (CAIs) found in chondritic meteorites. Figure 2 shows curves generated by mixing of the terrestrial mantle with components having fractionated Mg isotopic compositions generated by evaporation experiments on bulk compositions similar to CAIs at nebular conditions [*Richter et al.*, 2000]. For compositions typical of CAI's (ε_{Mg} = 50–100 [*Clayton et al.*, 1988]) the limits imposed by our analytical precision of ±2 ε-units (0.2 per mil) allows addition of up to 7–10% refractory material in the Moon, Mars, and differentiated asteroids relative to Earth (Figure 2). Less refractory material can contribute larger fractions, e.g., up to about 20% for minimally fractionated CAI composition with $\varepsilon_{Mg} = 20$ (Figure 2).

[18] Yet to be determined is how the measured Mg isotopic compositions of the terrestrial planets compare to predictions of the X-wind astrophysical model for the early Solar System in which mixing of material with diverse thermal histories can occur at planetary distances in the solar nebula [*Shu et al.*, 2001]. Variations of a few percent in the relative contributions of refractory material to the terrestrial planets and asteroids may be allowed by the X-wind model (F. Shu, personal communication, 2004), although existing astrophysical theory and observations apparently do not provide hard constraints. Improved analytical precision would place further limits on the range of Mg isotopic compositions in the inner Solar System and accretion of the terrestrial planets.

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