MAGNESIUM ISOTOPES IN LUNAR ROCKS AND GLASSES AND IMPLICATIONS FOR ORIGIN OF THE MOON

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Volatile depletion was a ubiquitous concomitant of planet formation, especially in the inner solar system. Isotopic variations of Mg, a major element with three stable isotopes, can potentially provide insight into this important aspect of planetary origin [1-4]. Refractory components within chondrites have δ^{25}Mg up to +10 ‰ [4]. Relatively large variations (up to 3 ‰) have even been reported for terrestrial mantle samples [5]. Lunar samples are of interest because the "bone dry" Moon is often envisaged as a product of some extraordinary process(es) that gave it a refractory-element enriched bulk composition; and because various types of spherules dispersed in the lunar regolith formed by ballistic transport of molten droplets.

For this study, we employed a UV laser-ablation MC-ICPMS system to measure Mg isotope ratios in mafic components of highland impact melt breccia 65785 and Apollo 12 mare basalts 12006, 12009, 12012 and 12016; mare volcanic spheroids from Apollo 15 (15427 green glasses) and Apollo 17 (74002 black spheroids); and spheroids, presumably almost all of impact melt origin, from highland soils 61241 and 65700. We used a standard-sample comparison method to correct for mass fractionation in the MC-ICPMS instrument. The laser was a 213 nm system operated at a sample fluence of ~ J/cm². Spot diameters were 50-75 μm for crystalline samples, 40 μm for mare volcanic spheroids, and as narrow as 25 μm for highland impact spheroids; with pit depths of order 20 μm. Our δ^{25}Mg precision, inferred from analyses of olivine from the terrestrial San Carlos (USNM#136718) peridotite, is ±0.2‰. We have also obtained similar (but still preliminary) results by applying a 193 nm excimer laser to fused glasses of several lunar meteorites.

Previously, Esat and Taylor [2] (data mostly originally published by [6]) reported 13 lunar δ^{25}Mg analyses, 4 for breccia 67016 and 9 for mare volcanic glasses. They found no fractionation vs. terrestrial Mg, but their data were imprecise, with an "analytical reproducibility" of 1.5 ‰. Norman et al. [3] showed far more precise LA-MCICP-MS data for Apollo 12 olivines, but they found it necessary to correct for a strong matrix effect. In their initial data, the most FeO-rich olivines (Fo~50) appeared ~1.4 ‰ heavier than the San Carlos (SC) reference terrestrial olivine. After correction for FeO, the data of [3] indicate close similarity between lunar basalts and various Earth mafic rocks. Our measurements showed no such FeO-linked matrix effect. We did

notice a similar effect when we tested an instrumental configuration with a 193-nm laser combined with a small sample cell that we normally used only in conjunction with a 213-nm laser. But with the two configurations normally employed, we observed no correlation between *mg* (over the range 29-80 mol%) and δ^{25}Mg.
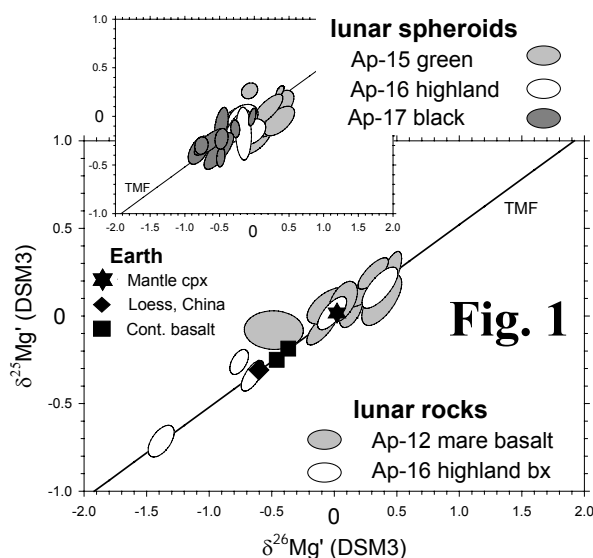
Fig. 1

Our results (Fig. 1; error ellipses are 1-σ) indicate little systematic fractionation vs. Earth's mantle for any of the five types of analyzed lunar material. Only a single 65785 spot (dominantly pyroxene) yielded a result several sigma from 0. Note that the regolith spheroid analyses show greater scatter, as a result of the lesser spot diameters (and lower signal) required for these tiny samples. Even so, it appears that the Apollo 15 green VLT-mare glasses are significantly heavier than their Apollo 17 high-Ti counterparts.

By far the most abundant refractory elements are Al and Ca. By some estimates [e.g., 7-9] these elements are not significantly enriched in the bulk Moon. However, Fig. 2 compares the estimated bulk-Moon Al/Mg ratio according to Taylor [10; cf. 2] with a variety of chondrites analyzed by Jarosewich [11], the solar photosphere [12], and estimated bulk compositions for Earth, Mars and the HED asteroid (literature estimates, averaged; from review by [7]). Compared to the bulk solar system, to Earth, or to chondrites of similar FeO/MnO, Taylor's [10] estimated Moon is enriched in Al by a factor of ~1.75.

Fig. 2
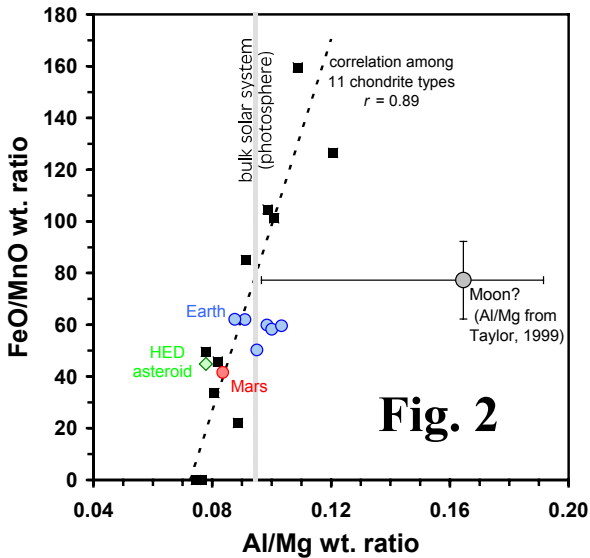
The issues of volatile depletion and refractory enrichment are not necessarily related. For 10 of the 11 basic types of chondrites [11], total depletion of every constituent with volatility (i.e., solar nebula condensation temperature: [13]) between that of Si and the most volatile of all (H_2O) would increase the concentrations of all elements more refractory than Si by a factor of 1.02-1.09 (average 1.05), an "enrichment" that, in a bulk planet, must be hard to detect. The refractory enrichments could conceivably arise by preferential accretion of some minor, almost pure-refractory component. However, the only realistic candidates for such a role among chondritic materials, the CAIs, have highly distinctive O-isotopic compositions [14]. If the refractory-enriched bulk Moon hypothesis is correct, the enrichments are more plausibly the result of loss of less refractory major oxides during high-temperature processing. Ignoring potential fractionation among FeO + MgO + SiO_2 (FeO is more volatile than MgO [15], yet the Moon is widely [e.g., 8-10] claimed to be not depleted but enriched in FeO/MgO in comparison to Earth), a 1.75-fold enrichment in refractory elements would require that 43% of a former complement of Mg was lost.

The Moon is generally believed to have formed as a result of a giant impact between Earth and a roughly Mars-sized intruder. According to Canup [16], 28% of the post-impact orbiting matter in a nominal giant impact model is heated to >5000°C, and only 24% is at <2000°C. The ultimate formation of the Moon from such an orbiting silicate cloud remains a major extrapolation, but it is not unreasonable to suppose that the major oxides might have recondensed less efficiently than Al, Ca and other refractories. The hypothesis of refractory-enrichment by differential recondensation goes back to one of the very earliest formulations of the giant

impact hypothesis [17].

For the purpose of testing such hypotheses, an advantage of Mg is that it is a major element. Humayun and Clayton [18] observed no K isotopic effects in lunar samples, and Poitrasson et al. [19] observed only very small effects in Fe. As a minor element much more volatile than bulk lunar-terrestrial matter, K was conceivably accreted preponderantly in a minor volatile-rich component whose provenance and/or physical evolution were atypical of the bulk Moon and Earth. No such exceptionality can be invoked for Mg (or Fe).

The precise Mg-isotopic match between the Moon and other primitive materials, including Earth's mantle, implies that Rayleigh distillation can be eliminated as a potential mechanism for achieving the putative extraordinary enrichments in refractory lithophile elements. However, ideal Rayleigh distillation requires that heating and vaporization (or cooling and condensation) occur on a time scale commensurate with the time scale for mixing within the condensed material [1]. It is still possible, in principle, that the giant impact origin of the Moon led to a major volatility-depletion of Mg. But credibility is further strained by the popular notion [e.g, 2, 8-10] of a large enrichment in the comparatively volatile FeO vs. the Earth. Systematically subchondritic Nb/Ta ratios among lunar rocks [20] (cf. the precise Moon-Earth matches in O [14] and Cr [21] isotopes) suggest at least 35% of the Moon was derived from the Earth.

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