

A DEEP LUNAR MAGMA OCEAN BASED ON NEODYMIUM, STRONTIUM AND HAFNIUM ISOTOPE MASS BALANCE. M. C. Ranen¹ and S. B. Jacobsen¹, ¹Department of Earth and Planetary Sciences, Harvard University, 20 Oxford Street, Cambridge, MA 02138, USA. (ranen@fas.harvard.edu).

Introduction: The size of the lunar magma ocean has major implications for the method and duration of lunar formation as well as for the thermal history and evolution of the lunar interior. However, the depth of the initial Lunar magma ocean has remained controversial. Estimates based on Al mass balance range from 250-500 km [1]. A seismic discontinuity at ~ 500 km has been inferred to separate the upper and lower lunar mantles [2]. Here we estimate the size of the magma ocean by using an improved mass balance based on the long-lived chronometers (Sm-Nd, Rb-Sr, Lu-Hf). Our results have significant implications for the interpretation of extinct nuclide data (¹⁸²Hf-¹⁸²W and ¹⁴⁶Sm-¹⁴²Nd) and therefore for the age of the Moon as well as the duration of magma ocean crystallization.

Model: Isotopic mass balance has been previously used to estimate the size of the depleted terrestrial mantle [3]. Here we carry out a similar model for the Moon. The Moon can be roughly divided into three reservoirs: (1) a bulk Moon as well as any undifferentiated mantle, (2) a depleted mantle, and (3) an enriched crust. For a given isotopic system with a parent/daughter fractionation factor of f_i , an isotopic composition ε_i , and a daughter concentration of C_i , the mass fraction of enriched crust is

$$\frac{M_3}{M_2 + M_3} = \frac{\varepsilon_2 C_1}{(\varepsilon_2 - \varepsilon_3) C_3} = \frac{f_2 C_1}{(f_2 - f_3) C_3}$$

ε_{Nd} and ε_{Hf} are defined as the deviation in parts per 10,000 from a chondritic source. ε_{Sr} is the deviation in parts per 10,000 from a bulk silicate Moon now having a ⁸⁷Rb/⁸⁶Sr = 0.042 and ⁸⁷Sr/⁸⁶Sr = 0.7017. Rb/Sr parameters were derived from mass balance considerations. Table 1 lists isotopic values as well as current estimates for the composition of the bulk silicate Moon (BSM). BSM concentrations were estimated to be 2.7 times the C1 values except for Rb (derived from Rb-Sr systematics) and W (derived from La/W ratios).

The average composition of the crust: Crustal parameters are based on the three terrane crust of Jolliff et al. [4]. A mass balance relationship for Th was scaled to provide a 40 km average crust depth [5]. Concentrations of other elements were scaled to Th by their relative enrichment factors. Isotopic compositions of the crust are an average of literature data such as those summarized by [6].

The average composition of the depleted mantle: The depleted lunar mantle is a combination of low-Ti basalt sources with a smaller amount of late crystalliz-

ing high-Ti cumulates. Present day ε values for the crust and depleted mantle sources for each isotopic system were derived by extrapolating initial ε values from 4.537 Ga to the present time. Figure 1 shows relevant data for the Sm/Nd and Rb/Sr systems. Concentrations of elements in the mantle were calculated by mass balance using our estimates for the bulk silicate Moon. Figure 2 gives elemental patterns for the crust and depleted mantle normalized to the bulk silicate Moon.

Table 1. Mass balance for lunar crust and mantle

	Bulk Silicate Moon ¹	Crust ¹	Depleted Mantle ¹
Th	0.0794	1.05 ± 0.15	0.0152 ± 0.0051
Rb	0.304	3.5 ± 0.5	0.093 ± 0.031
W	0.01389	0.139 ± 0.019	0.0056 ± 0.0020
La	0.6337	5.78 ± 0.80	0.294 ± 0.098
Nd	1.22	9.55 ± 1.34	0.669 ± 0.224
Hf	0.2808	1.99 ± 0.28	0.168 ± 0.056
Sr	21.0	150 ± 20	12.5 ± 4.2
Sm	0.3972	2.69 ± 0.30	0.246 ± 0.082
Lu	0.0656	0.299 ± 0.042	0.0501 ± 0.0167
$f^{Sm/Nd}$	= 0	-0.135 ± 0.020	0.120 ± 0.044
$\varepsilon_{Nd}(0)$	= 0	-15 ± 5	13.5 ± 5.0
$f^{Lu/Hf}$	= 0	-0.40 ± 0.20	0.69 ± 0.30
$\varepsilon_{Hf}(0)$	= 0	-45 ± 20	70 ± 30
⁸⁷ Rb/ ⁸⁶ Sr	0.042	0.063 ± 0.020	0.0297 ± 0.0059
⁸⁷ Sr/ ⁸⁶ Sr	0.7017	0.7033 ± 0.0004	0.70089 ± 0.00040
$f^{Rb/Sr}$	= 0	0.50 ± 0.18	-0.30 ± 0.14
$\varepsilon_{Sr}(0)$	= 0	14 ± 5	-11.5 ± 5.0
$f^{Hf/W}$	17	11.7 ± 1.6	25.7 ± 3.6
$\varepsilon_w(0)$	1.5	0.5 ± 0.5	1.5 ± 0.5
$\varepsilon_{142Nd}(0)$	0	-0.2 ± 0.1	0.2 ± 0.1

¹ All element concentrations in ppm

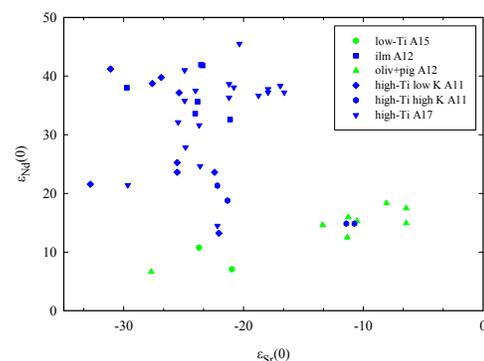


Figure 1. $\varepsilon_{Nd}(0)$ versus $\varepsilon_{Sr}(0)$ values for the depleted mantle.

Mass balance for the silicate Moon: The mass balance equation was solved for each of the three long lived chronometers. The mass fraction of the depleted mantle to the whole Moon was calculated and con-

verted to a depth using a mean silicate density of 3.4 g/cm^3 (figure 3).

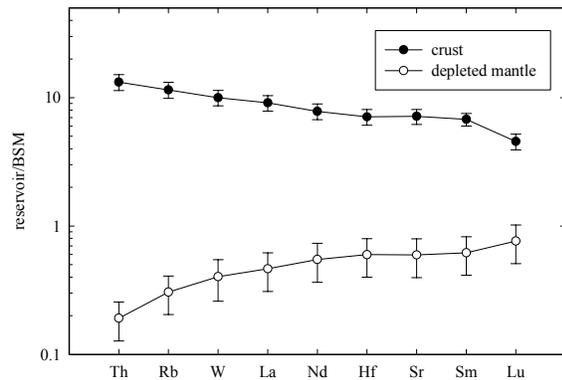


Figure 2. Elemental patterns for the average lunar depleted mantle and the average lunar crust.

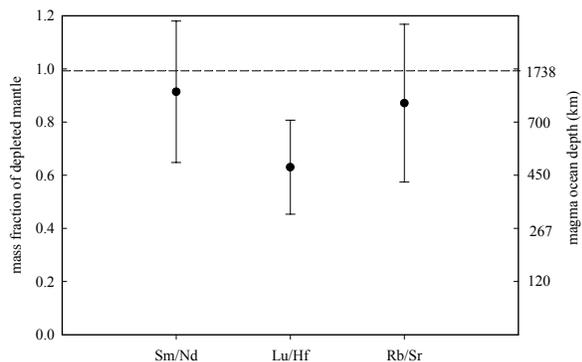


Figure 3. Mass balance results for three long-lived chronometers.

Discussion: The depleted mantle is a reservoir complementary to an enriched crust. With the current estimates for isotopic fractionation factors, a 70 km crust is so enriched that there is not enough mantle material to give a bulk fractionation factor of 0. A crustal depth of 40 km, consistent with a reinterpretation of seismic data, gives a more reasonable estimate for the size of the depleted mantle. This depleted mantle makes up over 85% of the total mass of the Moon according to the Sm/Nd and Rb/Sr systems (fig 3). The Lu-Hf system gives a smaller depleted mantle but there is little data to constrain the fractionation factor of the enriched crust.

A crystallization history of the lunar magma ocean predicts that early olivine-rich cumulates such as those sampled by the Apollo 15 green glasses were only slightly depleted in Nd isotopes [7]. Further Crystallization of the magma ocean produced later cumulates such as the high-Ti source region that were increasingly depleted while flotation of the lunar crust created

the enriched source. Hence, a large depleted lunar mantle should also be thought of as evidence for a greater than 1000 km deep magma ocean. A deep magma ocean is consistent with recent modeling results of the energy of the giant impact on Earth that led to the formation of the Moon [8].

The isotopic composition of the Feldspathic Highland Terrane is not well constrained. There are only Sm-Nd data for three Ferroan Anorthites, thought to represent the pristine highland crust. Lu-Hf data exists for a very small number of samples, only three of these representing an enriched source. We have obtained soil samples from Apollo 16 drill cores that sample the highland crust as well as KREEP rich soils from Apollo 14. While all lunar soils represent billions of years of mixing, the highland end members and average crustal components should be able to be extrapolated from the data. Research is underway to determine trace element as well as Sm-Nd, Rb-Sr, Lu-Hf, and Hf-W isotopic compositions of these soils. The soil results will allow for a more reliable estimate of the parameters for the lunar Highlands crust.

Extinct nuclides: ^{182}Hf - ^{182}W systematics [9] together with $f^{\text{Hf/W}}$ ratios of the lunar crust and mantle and recent re-evaluation of lunar W isotopic data [10] suggest that it took >10 Ma for the main phase of magma ocean crystallization. ^{146}Sm - ^{142}Nd systematics of KREEP [11,12] and low-Ti basalts [12] suggests that this was at $\sim 70 \pm 60$ Ma after the formation of the Moon while the high Ti basalts source [12] may have formed ~ 200 Ma later.

Conclusions: The current isotopic evidence supports a large depleted lunar mantle to complement a significantly enriched lunar crust. With a limited amount of lunar volcanism and partial melting subsequent to formation, the easiest way for such a sizeable portion of the lunar mantle to become depleted is through crystallization of a deep magma ocean.

References: [1] Mueller S. et al. (1988) *JGR* 93, 6338-6352. [2] Hood L.L. and Jones J.H. (1987) *PLPSC 17*, E396-E410. [3] Jacobsen S.B. and Wasserburg G.J. (1979) *JGR* 84, 7411-7427. [4] Jolliff B.L. et al. (2000) *JGR* 105, 4197-4216. [5] Lognonne P. et al. (2003) *EPSL* 211, 27-44. [6] Snyder G.A. et al. (2000) in *Origin of the Earth and Moon* 361-395. [7] Shih C.-Y. et al. (2001) *LPS XXXII* abs. #1401. [8] Cameron A.G.W. (2000) in *Origin of the Earth and Moon* 133-145. [9] Harper C.L. and Jacobsen S.B. (1996) *GCA* 60, 1131-1153. [10] Lee D.C. et al. (2002) *EPSL* 198, 267-274. [11] Jacobsen S.B. and Harper C.L. (1996) *AGU Monograph* 95, 47-74. [12] Nyquist L.E. et al. (1995) *GCA* 59, 2817-2837.