NEW ^{142}Nd EVIDENCE FOR A NON-CHONDRITIC COMPOSITION OF THE MOON.

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Introduction: The coupled ^{147,146}Sm-^{143,142}Nd systematics of lunar samples has been extensively studied for estimating the timescale of lunar differentiation [1-3]. The published datasets yield consistent ages for Nd isotopic closure within the lunar mantle of ~200 Myr after CAI formation. Although this time constraint is consistent with estimates derived from Hf-W chronometry of the Moon (>60 Myr after CAI formation, [4]), there is debate as to whether this age has chronological significance. Furthermore, there are discrepancies regarding the Nd isotope composition of the bulk Moon. Rankenburg et al. [2] obtained a ε^{142}Nd vs. ^{147}Sm/^{144}Nd correlation for lunar samples passing though the chondritic reference value (^{147}Sm/^{144}Nd = 0.1967, ε^{142}Nd = -0.21 [5]), suggesting that the Moon has a chondritic bulk composition. In contrast, the other datasets [1,3] define a correlation line that passes ~10-20 ppm above, suggesting that the Moon has a superchondritic ^{147}Sm/^{144}Nd (~0.206, [6]), close to that of the early depleted Earth (EDM). We present new Sm-Nd data for a high-Ti mare basalt (70135), two low-Ti mare basalt (LAP 02205 and MIL 05035) and a KREEPy low-Ti mare basalt (NWA 2977). These data are used to evaluate the significance of the Sm-Nd systematics for constraining the timescale of lunar differentiation and the bulk Nd isotope composition of the Moon.

Methods: The ^{142}Nd measurements were performed in dynamic mode with amplifier rotation using the Thermo-Finnigan Triton TIMS at ETH Zurich. Each run was performed with a signal intensity of ~8 V for ^{142}Nd and at least 500 ratios were measured, resulting in within-run statistics of 2-5 ppm. Sm and Ce isobaric interferences were monitored but for all samples the interference corrections were insignificant. All isotope ratios were normalized to ^{146}Nd/^{144}Nd=0.7219 using the exponential law. Neodymium isotope compositions of the samples were determined relative to repeated measurements of the Nd standard JNdi-1 over one year that yield a ^{142}Nd/^{144}Nd of 1.141837 ± 0.000006 (n=50, 2σ SD) and a ^{143}Nd/^{144}Nd of 0.512035 ± 0.000012 (n=50, 2σ SD, static mode). The accuracy of our measurements was monitored by repeated measurements of two gravimetrically prepared spike-standard mixtures having ^{142}Nd anomalies of 23 and 84 ppm. Sm and Nd contents were measured by isotope dilution.

Results: Sm-Nd data obtained here are shown in Fig. 1a and 1b. For each sample, the ^{147}Sm/^{144}Nd source ratio is calculated using a three-stage model to reach its measured ^{143}Nd/^{144}Nd. The source first evolved with a chondritic ^{147}Sm/^{144}Nd ratio from 4.568 Ga ago until crystallization of the LMO at 218 Ma after CAI formation, then with the calculated ^{147}Sm/^{144}Nd ratio until the eruption age and finally with the measured ^{147}Sm/^{144}Nd ratio to its present-day value. The KREEPy meteorites have the lowest $(^{147}\text{Sm}/^{144}\text{Nd})_{\text{source}}$ (~0.16) and least radiogenic ε^{142}Nd (~-20 ppm). In contrast, the high-Ti mare basalt 70135 has the highest $(^{147}\text{Sm}/^{144}\text{Nd})_{\text{source}}$ (~0.29) and ε^{142}Nd (~+19 ppm). Low-Ti mare basalts have $(^{147}\text{Sm}/^{144}\text{Nd})_{\text{source}}$ and ε^{142}Nd intermediate between KREEP and high-Ti mare basalts.

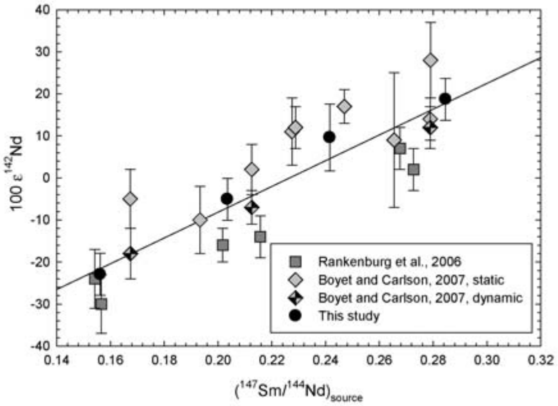

Figure 1a: ε^{142}Nd vs. ^{147}Sm/^{144}Nd source ratio for lunar samples. ε^{142}Nd are the deviation of the ^{142}Nd/^{144}Nd ratio of a sample relative to the terrestrial standard in part per 10,000.

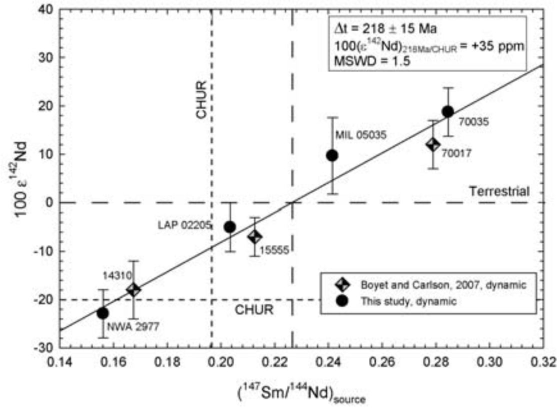

Figure 1b: ε^{142}Nd vs. ^{147}Sm/^{144}Nd source ratio for lunar samples measured in a dynamic mode. Note that the putative bulk Moon (present-day ε^{142}Nd=45 ppm, ^{147}Sm/^{144}Nd=0.221, Fig. 2) is not plotting on the lunar mantle correlation.

All samples plot along a well defined correlation line (MSWD = 1.5) that is, overall, in a reasonable agreement with earlier reported results [1-3]. The best agreement between our results and those reported previously is with dynamic measurements from Boyet and

Carlson [3]. Note that no dispersion is observed when static measurements are excluded (Fig. 1a, 1b).

Discussion: *Mantle isochron vs. mixing line.* Interpreted as an isochron, the slope of the ε^{142}Nd vs. ^{147}Sm/^{144}Nd correlation yields an age of 218 ± 15 Myr after CAI formation for lunar mantle differentiation and the y-intercept yields an initial ε^{142}Nd of +35 ppm relative to the CHUR value at 218 Myr. This initial ε^{142}Nd should correspond to the composition of KREEP and the mare basalt sources, and by inference of the bulk LMO at ~218 Myr. As illustrated in Fig. 2, this radiogenic ε^{142}Nd would require a bulk Moon with higher ^{147}Sm/^{144}Nd (~0.221) than the EDM. This estimate is obtained by assuming that the Moon formed at 4.568 Ga with an initial chondritic isotope composition. However, the Moon formed more than ~50 Myr after CAI formation, such that this estimate is a lower estimate. Thus, in this two-stage model, the lowest present-day ε^{142}Nd calculated for the bulk Moon would be ~45 ppm higher than the present-day ε^{142}Nd of chondrites, which is very unlikely. This lower estimate is similar to the ε^{142}Nd of the most radiogenic high Ti-mare basalts and therefore requires an unsampled lunar mantle reservoir with high ε^{142}Nd (>45 ppm relative to CHUR) to balance the low ε^{142}Nd (<45 ppm) for KREEP and the mare basalt sources. This is also apparent from the fact that the modeled bulk Moon plots well above the correlation line. The unrealistic high ^{147}Sm/^{144}Nd required to evolve to a radiogenic initial ε^{142}Nd combined with the need for a highly radiogenic and unsampled reservoir in the Moon suggest that the lunar mantle correlation is not an isochron. This is consistent with a model of Bourdon et al. [7] that shows that melting, radioactive decay and mixing can produce a linear array similar to the one observed. The slope of this correlation is then not only a function of lunar differentiation and the 200 Myr model age derived from the slope of the mantle correlation line does not date lunar differentiation. In fact, LMO crystallization at 50-100 Myr followed by later magma mixing, melting and cumulate overturn can produce the observed correlation line with an apparent age of ~200 Myr [7]. Consequently, the initial ε^{142}Nd and age obtained from the lunar mantle correlation line cannot be used to model the bulk composition of the Moon (Fig. 1, 2).

Non-chondritic Moon. Although the slope and the initial Nd isotope composition obtained from the lunar mantle correlation line have no chronological significance, the bulk composition of the LMO (and by inference of the bulk Moon) could still plot on this correlation line. In contrast to the results of Rankenburg et al. [3] but in good agreement with data obtained by Boyet and Carlson [2] and Nyquist [1], our dynamic data define a linear regression which at the chondritic ^{147}Sm/^{144}Nd has an ε^{142}Nd value that is ~10 ppm higher than chondrites. (Fig. 1). This clearly indicate that the bulk Moon cannot have a chondritic Sm/Nd ratio. Assuming a bulk Moon with a terrestrial ε^{142}Nd (=0), the mantle correlation gives a corresponding ^{147}Sm/^{144}Nd ratio of ~0.224 but the uncertainty on the slope of the correlation line permit a ^{147}Sm/^{144}Nd consistent with the composition of the Earth, Moon and Mars proposed by Caro et al. [8].

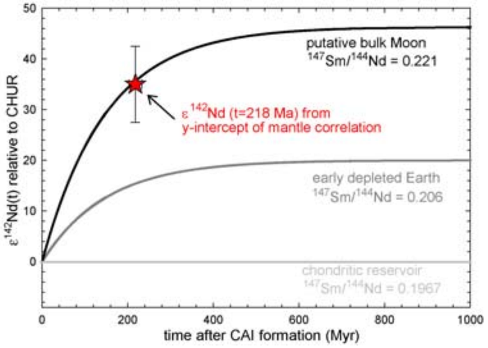

Figure 2: ε^{142}Nd relative to CHUR vs. time after CAI formation for the bulk Moon modeled using isochron parameters, the early depleted Earth [6] and the chondritic reservoir [5].

Conclusions: Our new Sm-Nd data for lunar rocks yield a linear regression in a plot of ε^{142}Nd vs. ^{147}Sm/^{144}Nd source ratio with a slope that is identical within error to those derived from earlier datasets, although an offset with Rankenburg et al. [3] is observed. This slope corresponds to an age of ~218 Myr after CAI formation, if the correlation is interpreted as an isochron. However, we show that the bulk composition of the Moon as calculated using a two-stage model and the initial ε^{142}Nd derived from the lunar mantle array plots far away from the lunar mantle array. This is highly unlikely and indicates that the observed correlation is chronologically meaningless. A model involving early lunar differentiation (50-100 Myr after CAI formation) combined with later melting, crystallization and mixing within the lunar mantle can reproduce the observed correlation. Consequenlty, the Sm-Nd systematics provide no tight constraints on the timescale of lunar differentiation. In contrast to an earlier study, the Sm-Nd systematics of lunar samples are inconsistent with a chondritic bulk composition of the Moon but rather indicate that the Moon has a superchondritic Sm/Nd ratio, consistent with the bulk composition of the Earth and Mars as proposed previously [8].

References: [1] Nyquist et al. (1995), *GCA 59*, 2817-2837. [2] Boyet et al. (2006), *EPSL 250*, 254-268. [3] Rankenburg et al. (2006), *Science 312*, 1369-1372. [4] Touboul et al., (2007) *Nature 450*, 1206-1209. [5] Jacobsen et al. (1984), *EPSL 67*, 137-150. [6] Caro et al. , *Nature 452*, 336-339. [7] Bourdon et al. (2008), *Phil. Trans. R. Soc. A 366*, 4105-4128. [8] Caro et al. (2008), *Nature 452*, 336-339