**EVIDENCE FOR MAGMA OCEAN SOLIDIFICATION AT 4.36 Ga FROM $^{142}$Nd-$^{143}$Nd VARIATION IN MARE BASALTS.** A. M. Gaffney[1] and L. E. Borg[1], [1]Lawrence Livermore National Laboratory, Livermore, CA 94550; gaffney1@llnl.gov.

**Introduction:** The age of the Moon and the timing of lunar magma ocean solidification remain elusive, despite four decades of study. Ages determined for individual samples thought to be the oldest crustal rocks yield a wide range that is not entirely consistent with the magma ocean model of lunar differentiation. Specifically, ages of the ferroan anorthosites (FANs), argued to be primary crystallization products of the magma ocean, range from 4.29 to 4.53 Ga [e.g., 1, 2] and overlap ages of the Mg-suite samples. However, the Mg-suite is thought to represent the first pulse of magmatism *after* magma ocean solidification, and therefore should post-date FAN formation. These seemingly inconsistent ages may in part result from impact metamorphism, which can disturb the isotope systematics of individual rocks.

An alternative approach to determining the age of magma ocean solidification is to establish model ages for geochemical reservoirs that formed during magma ocean crystallization. One such reservoir comprises mafic cumulates that crystallized from the magma ocean and which, upon subsequent melting, generated the mare basalts. The combined $^{142}$Nd-$^{143}$Nd isotopic variation in mare basalts can be used to establish a model formation age of the mare basalt source. Several studies have taken this approach [3-6], but few analyses utilized the more accurate multi-dynamic mass spectrometry method. Additionally, corrections to $^{142}$Nd/$^{144}$Nd ratios due to neutron fluence effects are commonly larger than the analytical uncertainty. Here we present new $^{142}$Nd/$^{144}$Nd results for 16 mare basalts that show minimal neutron fluence effects and represent the compositional range of mare basalt sources.

**Methods:** We have completed $^{142}$Nd-$^{143}$Nd-$^{147}$Sm/$^{144}$Nd measurements on 16 mare basalts. These samples were analyzed previously for Hf and Sm isotopic compositions [7]. After complete digestion, sample solutions were split. One half was spiked with a mixed $^{149}$Sm-$^{150}$Nd tracer for Sm and Nd concentration analysis and Hf isotopic composition analysis. The other was spiked with a mixed $^{176}$Lu-$^{180}$Hf tracer for Lu and Hf concentration analysis and Sm and Nd isotopic composition analysis. Analytical procedures are described in [8, 9]. Neodymium isotopic compositions were measured on the ThermoElectron Triton TIMS at LLNL using a multi-dynamic analysis routine.

It has been recognized that neutron irradiation of the lunar surface modifies the isotopic composition of some elements (e.g., Sm, Gd, Nd, Hf) in some lunar samples. We previously developed a model that uses the measured stable Hf and Sm isotopic compositions to determine the thermal and epithermal neutron fluence that affected a particular sample [7]. These modeled fluences are then used to calculate a correction to the measured $^{142}$Nd/$^{144}$Nd and $^{143}$Nd/$^{144}$Nd values of the samples. The samples analyzed in this study were selected because, with a few exceptions, they were determined to have low neutron fluence histories based on previously measured $\varepsilon^{149}$Sm values [7]. Therefore, for most of the samples, the correction to $^{142}$Nd/$^{144}$Nd is less than 4 ppm. The Nd isotopic composition of four samples required substantial corrections. Nevertheless, the corrected data appear to be consistent with the uncorrected or minimally corrected Nd isotopic data (Fig. 1). The calculated corrections to $^{142}$Nd/$^{144}$Nd show a strong inverse correlation with measured $\varepsilon^{149}$Sm, and this correlation is used to apply a correction to measured $^{142}$Nd/$^{144}$Nd results published by other groups (Fig. 2).

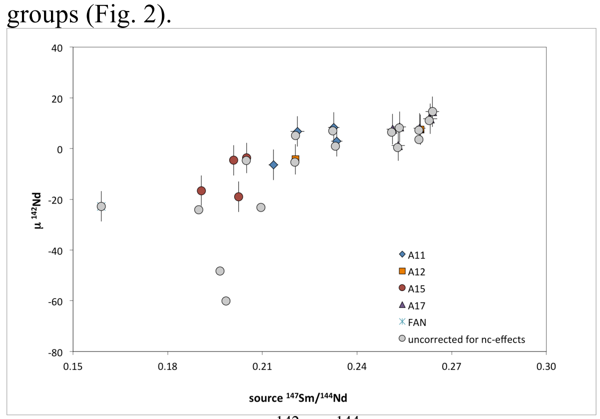


**Figure 1.** Comparison of $^{142}$Nd/$^{144}$Nd results as measured (gray symbols), to results corrected for the effects of neutron capture on $^{142}$Nd/$^{144}$Nd and $^{143}$Nd/$^{144}$Nd. $^{142}$Nd/$^{144}$Nd reported as ppm deviation from measured standard value of 1.141839. Source $^{147}$Sm/$^{144}$Nd calculation discussed in text.

**Results and Discussion:** The combined $^{142}$Nd-$^{143}$Nd systematics can be used to determine a model formation age for the mare basalt sources. From the initial $^{143}$Nd/$^{144}$Nd determined for each sample, the $^{147}$Sm/$^{144}$Nd of the source is calculated assuming a two-stage evolutionary history. This model assumes $^{142}$Nd and $^{143}$Nd ingrowth in a reservoir of chondritic composition, from the time of solar system formation until the time of lunar differentiation and formation of the mare basalt sources. The age of the source is calculated iteratively from the slope a linear regression of the data. In the final iteration, the age of source formation used to calculate the $^{147}$Sm/$^{144}$Nd of the source converges with the age determined from the slope of the isochron. Assuming a more complicated history prior to formation of the mare basalt source [e.g., 5], has little effect on the calculated source age, increasing it by less than 10 My. Because the age is calculated directly from the slope of a line regressed through the data, the $^{142}$Nd/$^{144}$Nd of the bulk Moon is not defined in the calculation. Instead, the age is based in the assumption that $^{142}$Nd and $^{143}$Nd reflect a common history prior to the formation of the basalt sources. From the combined $^{142}$Nd-$^{143}$Nd systematics of the mare basalts, we calculate a model age for formation of the mare basalt sources of 4355 +31/-39 Ma.

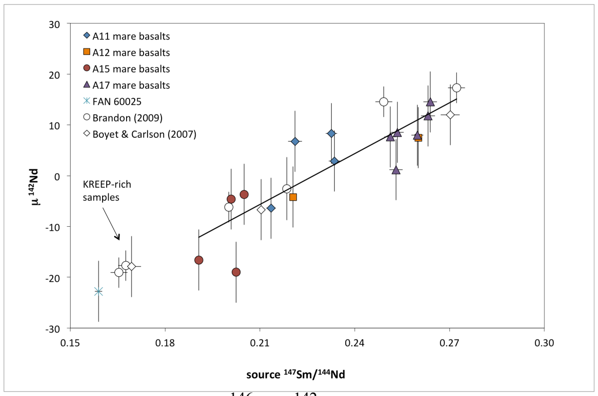


**Figure 2.** Whole rock $^{146}$Sm-$^{142}$Nd isochron of mare basalts (16 analyses from this study and 6 published multi-dynamic analyses [5, 6]) yield a model age for mare basalt source formation of 4355 +31/-39 Ma. Calculation uses $^{146}$Sm $t_{1/2}$ = 103 Ma and initial $^{146}$Sm/$^{144}$Nd of 0.00828 [16]. Using the parameters of [17] gives an age of 4414 +20/-26 Ma. One FAN [9] and 3 KREEP-rich samples [5, 6] are shown for reference, but are not included in the age calculation.

The co-linearity of KREEP-rich samples with mare basalts (Fig. 2) presents the possibility that $^{142}$Nd/$^{144}$Nd of the mare basalts may simply represent mixing of urKREEP with a common mare basalt source component. In this case, urKREEP would control the incompatible element isotopic characteristics of these samples and the age would not necessarily record lunar cumulate formation. However, the Hf isotopic data are not consistent with this interpretation. The $\varepsilon_{Hf}$ vs. $\varepsilon_{Nd\text{-}143}$ values of the mare basalts define two distinct trends, requiring incompatible trace element heterogeneity in the mare basalt sources that is preserved [8, 10]. Although some amount of mixing with urKREEP or another incompatible element enriched component is required [e.g., 11], these data clearly show that two distinct LREE-depleted sources are present. Although these sources are petrologically and geochemically distinct, the basalts derived from them define a common model formation age.

The age calculated here is in excellent agreement with $^{142}$Nd model ages determined in earlier studies [3-6]. The reproducibility of this age with different sets of samples and independent studies confirms that this is a reliable estimate of the formation age for mare basalt sources. Furthermore, this age is derived from samples from four Apollo landing sites and one meteorite launch site, and so dates an event with wide geographic representation. This age is concordant with urKREEP model ages determined using the Lu-Hf and $^{147}$Sm-$^{143}$Nd systems (4353 ± 37 and 4389 ± 45, respectively; Fig. 3) that are thought to represent the age of final magma ocean solidification. Some of the most precisely-dated FANs also have ages that are concordant with these model ages [9, 12]. Although a few lunar samples yield ages that are not consistent with a young age for magma ocean crystallization [13-15], the complementary geochemical characteristics of the mare basalt sources, urKREEP and the FANs, together with their concordant formation ages, strongly indicates that a widespread magmatic event occurred on the Moon at ca. 4.36 Ga, most plausibly attributed to solidification of a magma ocean.

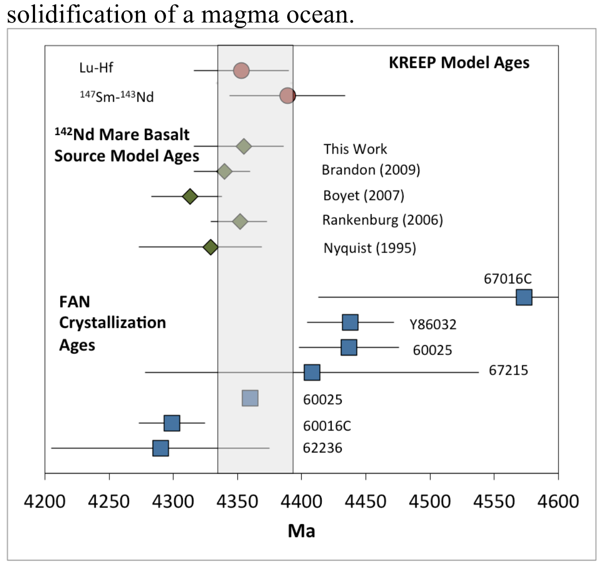


**Figure 3.** Summary of chronological constraints on the timing of magma ocean solidification. Vertical gray box is the average of Lu-Hf and $^{147}$Sm-$^{143}$Nd KREEP model ages [7] and the $^{142}$Nd mare basalt source model age determined here. FAN crystallization ages recalculated using Isoplot 4.15 from [1, 2, 12, 14, 18, 19].

**References:** [1] Alibert et al. (1994) *GCA* **58,** 2921; [2] Borg et al. (1999) *GCA* **63,** 2679; [3] Nyquist et al. (1995) *GCA* **59**, 2817; [4] Rankenburg et al. (2006) *Science* **312**, 1369; [5] Boyet & Carlson (2007) *EPSL* **262**, 505; [6] Brandon et al. (2009) *GCA* **73**, 6421; [7] Gaffney & Borg (2013) *LPSC* **XLIV***,* 1714; [8] Gaffney et al. (2011) *LPSC* **XLII**, 1337; [9] Borg et al. (2011) *Nature* **447,** 70; [10] Sprung et al. (2013) *EPSL* **380,** 77; [11] Snyder et al. (1992) *GCA* **56**, 3809; [12] Marks et al. (2014) this conference; [13] Shih C.-Y. et al. (1993) *GCA* **57**, 915-931; [14] Nyquist et al. (2006) *GCA* **70**, 5990; [15] Nemchin et al. (2009) *Nature Geo* DOI: 10.1038/ NGEO417; [16] Marks et al. (2013) *PNAS*, in review; [17] Kinoshita et al. (2012) *Science* **335**; [18] Carlson & Lugmair (1988) *EPSL* **90**, 119; [19] Norman et al. (2003) *MaPS* **38**, 645. This work performed under the auspices of the U.S. DOE by LLNL under contract DE-AC52-07NA27344.