ISOTOPIC SYSTEMATICS OF MAFIC AND FELSIC LUNAR CUMULATES. L.E. Borg[1], A.M. Gaffney[1], and J. B. Wimpenny[1], [1]Lawrence Livermore National Laboratory, Livermore, CA, USA.

Introduction: In 1995 Nyquist et al. [1] investigated the ^{146}Sm-^{142}Nd isotopic systematics of lunar basalts and began a cottage industry. They found that plotting ^{147}Sm/^{144}Nd of mare basalt source regions against ^{142}Nd/^{144}Nd measured in the whole rock yielded an age of ~4.35 Ga. They also discovered that the high neutron fluences encountered by many mare basalts required large corrections on both measured ^{142}Nd/^{144}Nd and calculated ^{147}Sm/^{144}Nd ratios. These measurements have been repeated many times [2-5, this study], and although the isotopic measurements have become more precise and neutron corrections have become more sophisticated, the ~4.35 Ga result has remained essentially constant.

The meaning of the ~4.35 Ga mare basalt whole rock isochron, however, is unclear. On one hand, it could represent the age of primordial solidification of the mare basalt source region during magma ocean solidification. This has generally not been a particularly popular view point because it requires some ancient ages determined for crustal samples, as well as some ion microprobe spots on lunar zircons, to be erroneous. The second interpretation of the ~4.35 Ga age is that it represents the time at which the mare basalt source regions last isotopically equilibrated at the time of mantle overturn following solidification of the magma ocean.

To evaluate these possibilities we have measured Sm-Nd and Lu-Hf, isotopic compositions of 30 mare basalts selected from Apollo 11, 12, 15, 17 and the lunar meteorite suite. The major and trace element compositions of these rocks have been determined so they could be selected to span the widest possible range of isotopic compositions. The first objective is to determine if there are systematic differences in ^{146}Sm-^{142}Nd isotopic compositions between basalts derived from lithologically distinct source regions or from different geographic locations on the Moon. Small differences might be expected if overturn did not result in complete re-equilibration of the mantle or was protracted over 20-30 Ma. The second objective is to compare the ^{146}Sm-^{142}Nd isotopic systematics of the basalts with those we have recently determined for anorthosite mineral fractions from samples 60025 and 60016 [6-7]. If the basalts and anorthosites are comagmatic cumulates of the magma ocean, then they are expected to share ^{146}Sm-^{142}Nd isotopic systematics. However, if the basalts are derived by overturn of the cumulate pile and the anorthosites derived by a different process, even if this process was contemporanouus with overturn, then the two rock suites are unlikely to have common isotopic systematics.

Methods: Samples were digested in Parr bombs using HF and HNO_3 acids. Aliquots were separated for elemental analysis and Rb-Sr, Sm-Nd, and Lu-Hf isotopic measurements. Chemical separation procedures are described in [8]. Nd, Sm, and Hf isotopic composition measurements were made on unspiked aliquots of the digested solutions, whereas isotope dilution measurement we made using ^{87}Rb-^{87}Sr, ^{149}Sm-^{150}Nd, and ^{176}Lu-^{179}Hf tracers. The isotopic composition of Nd was determined using a ThermoScientific Triton in dynamic mode. Samples were run at 4 to 7 volts of ^{144}Nd for 5 to 16 hours. Sm was run in static mode on the Triton, whereas Lu and Hf were run using a Nu-Plasma HR. Sm/Nd concentrations and Nd isotopic compositions were corrected for the effects of neutron capture following procedure described by [8] using Sm and Hf isotopic composition measurements.

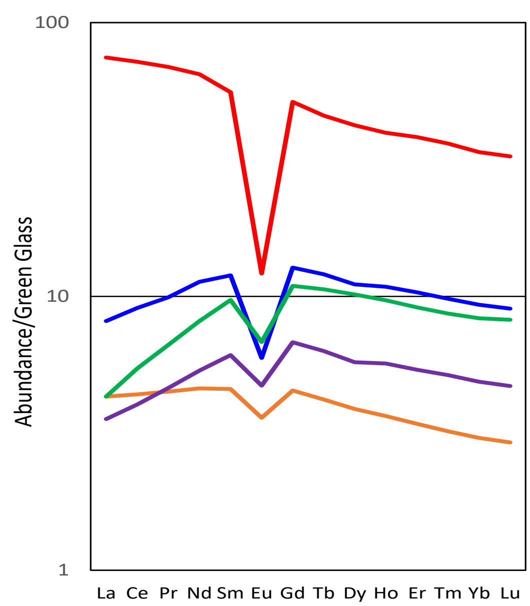

Figure 1. Representative patterns of basalts demonstrating petrogenetic diversity of samples analyzed in this study. Patterns defined by average of with similar REE abundances. Red = 15386; Orange = 12009, 12014, 12076, 15058, 15256, 15475, 15499, 15556, 15668, NWA 479, and NWA 4898; Blue = 10017, 10020, 10029, 10032, 10045, 12051, and 15388; Purple = 12045 and 12056; Green 10050, 70035, 70135, 70139, 71069, 71539, 74255, 74275, and NWA4734.

Samples: Sample were chosen for this investigation to span as wide a compositional and geographic range as possible [Figure 1]. In addition, all selected samples were chosen because they have plausible crystallization ages determined by previous investigations. From the Apollo 11 site both low K and high K high Ti basalts were selected. Olivine and ilmenite basalts were analyzed from Apollo 12. From Apollo 15 quartz normative, olivine normative, feldspathic, KREEP basalts, as well as hand-picked green glass beads from 15426 were analyzed. Ilmenite basalts were analyzed from Apollo 17, as well as three low Ti basalts from meteorites NWA479, NWA4734, and NWA4898. A complete list of samples analyzed in this investigation is presented in Figure 1 caption.

Results: The Sm-Nd isotopic data measured for the basalts is presented in Figure 2. These data are in good agreement with other investigations and yield a slope corresponding to an age of 4337 $^{+20}/_{-23}$ Ma. A 4.50 Ga reference line passing through Bulk Earth is plotted on Figure 2 to illustrate the near extinction of ^{146}Sm at the time of last equilibration of the lunar basalt source regions. All but two of the 30 basalts lie within uncertainty of the linear regression through the data. These deviations suggest a slight (~2 ppm) underestimation of the uncertainty on these measurements. The isochron yields an initial epsilon ^{142}Nd value of -0.16 ± 0.11. Note this value is calculated relative to growth in a terrestrial reservoir with present-day ^{147}Sm/^{144}Nd of 0.1967. The fact that this value is negative means that the lunar reservoir had a lower ^{142}Nd/^{144}Nd ratio at the time of its formation than the Bulk Earth. This is illustrated on Figure 2 by the position of the whole rock basalt isochron relative to the star symbol that represents the composition of Bulk Earth today.

Discussion: Figure 2 demonstrates that there is no measurable difference in the Sm-Nd isotopic systematics of the basalts derived from different locations on the Moon. Thus, the data suggest that lunar basalt source regions were in Sm-Nd isotopic equilibrium and formed at the same time, despite being separated by many hundreds of kilometers. Mineral fractions from ferroan anorthosite suite (FAS) samples 60016 [6] and 60025 [7] have also be plotted on Figure 2. The basalt and FAS data were obtained using the same mass spectrometry methods, the same family of Sm-Nd tracers, and were corrected for the effects of neutron capture in the same way. The fact that the Sm-Nd data from the two anorthosite samples overlap the basalt data implies that both anorthosites and basalts were derived from the same source around 4.34 Ga. This observation is difficult to reconcile with the hypothesis that the basalt isochron age records overturn of the lunar mantle, unless the anorthosites are also a byproduct of overturn. In other words, anorthosites 60016 and 60025 cannot be flotation cumulates of a magma ocean if the model age of the mare basalt source represents the time of overturn. This data is most consistent with mare basalt sources and FAS samples representing mafic and felsic cumulates derived by solidification of a magma ocean.

As noted previously [2-5] the basalt isochron does not intersect the bulk Earth Sm-Nd isotopic composition. Similar O, Ti, Cr, W, and Mo isotopic compositions of Moon and Earth suggest they are unlikely to have inherited different initial ^{142}Nd/^{144}Nd isotopic compositions from the solar nebula. Instead it seems likely that the Moon experienced a differentiation event prior to 4.34 Ga that fractionated Sm from Nd. This could reflect protracted solidification of the lunar mantle during primordial differentiation. Alternatively, it could reflect formation of the Moon from material enriched in primordial terrestrial crust and characterized by a low Sm/Nd ratio.

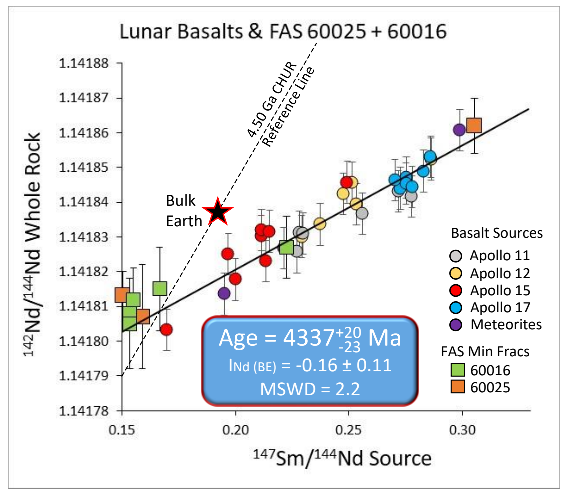

Figure 2. ^{147}Sm/^{144}Nd-^{142}Nd/^{144}Nd whole rock isochron of lunar basalts listed in Figure 1 caption. ^{147}Sm/^{144}Nd of the basalt source regions are calculated from measured ^{147}Sm/^{144}Nd and ^{143}Nd/^{144}Nd of the basalts using equation 1 of [9]. Slope of isochron calculated using all points from IsoPlot version 4.1. Mineral fractions from anorthosite samples 60016 [6] and 60025 [7] are plotted with basalt data and overlap.

References: [1] Nyquist et al. (1995) *GCA* **59,** 2817-37. [2] Rakenburg et al. (2006) *Sci.* **312,** 1369-72. [3] Boyet & Carlson (2007) *EPSL* **262,** 505-16. [4] Brandon et al. (2009) *GCA* **73,** 6421-45. [5] McLeod et al. (2012) *EPSL* **396,** 179-89. [6] Marks et al. (2014) LPSC 45 abst#1129. [7] Borg et al. (2011) *Nature* **477,** 20-72. [8] Gaffney & Borg (2014) *GCA* **140,** 227-40. [9] Borg et al. (2016) *GCA* **175,** 150-67.

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