Constraints on the formation age and evolution of the Moon from ^{142}Nd-^{143}Nd systematics of Apollo 12 basalts

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Introduction: The evolution of the Moon remains actively debated, despite over 40 years of continuous study of returned lunar samples. Early differentiation is generally accepted to have occurred through crystallization of a lunar magma ocean (LMO) as a result of the giant impact Moon-forming event during the first 30-100 Myr of solar system history (e.g. [1-4]).

As crystallization of the LMO progressed, plagioclase became a liquidus phase and buoyantly separated to form the primordial lunar crust as represented by the Ferroan Anorthosite Suite (FAN's). Until recently, reported FAN crystallization ages ranged from 4.54±0.12 Ga to 4.46±0.04 Ga ([5, 6]), consistent with an early Moon formation age [7]. Potentially more accurate FAN ages have been reported at 4.29±0.06 Ga (62236) and 4.36±0.03 Ga (60025) and may provide a clearer record of lunar crust formation (e.g. [8]). If these younger ages better define the timing of lunar crustal formation through rapid crystallization of the LMO, this would constrain the Moon formation age to as late as 150 to 200 Myr after the onset of solar system formation (OSSF, 4.569 Ga, [9]), compared to the currently favored time of 30 to 100 Myr.

Taking advantage of the short-lived radioactive decay of ^{146}Sm to ^{142}Nd (half-life of 103 My or 68 My, [10]), early lunar formation and differentiation can be assessed as fractionation of Sm/Nd in the first 300 to 500 Myr after the onset of solar system formation (OSSF) is recorded by variations in ^{142}Nd/^{144}Nd. High-precision Nd isotope data has previously ben reported for lunar mare basalts by [11-14]. These studies demonstrated ^{142}Nd/^{144}Nd variations and a strong correlation in ^{142}Nd-^{143}Nd isotope systematics. This relationship has been interpreted as an isochron an age of *c*. 215-255 Ma (i.e. 4.35 to 4.32 Ga) after OSSF. To further evaluate whether this coupled relationship records a late closure time for the Low-Ti, High-Ti and KREEP mantle source reservoirs, and potentially indicates a late Moon formation age, a lunar mantle closure ages by another process, or whether these previously reported data instead represents a mixing line with no age connotations, new Sm and Nd concentrations, high-precision Sm, and multistatic high-precision ^{142}Nd/^{144}Nd isotope data for Apollo 12 (9 samples) , 15 (2 samples) and 17 (3 samples) mare basalts are reported. This study focused on Apollo 12 samples as combined with selected Apollo 15 and 17 samples, the complete petrological range of the Apollo mare basalts is investigated and thus allows for a thorough evaluation of the issues discussed above. The new results are evaluated alongside, and reconciled with, LMO crystallization timescales, physical models of lunar formation and the lunar crustal rock record.

Results: The exposure of lunar samples to galactic cosmic rays promotes the production of neutrons which can result in a shift in the initial isotopic composition of samples ([11-15]). The isotope ^{149}Sm is used to monitor the neutron flux for Nd. From [16], the different Apollo landing sites experienced different doses of neutron fluence. Using the equations of [11] and exponential law fractionation corrections to correct Nd isotopes, the ε^{149}Sm of lunar basalts from this study range from -0.9±0.1 to 36.1±0.1 and plot as a line for ^{150}Sm/^{152}Sm versus ^{149}Sm/^{152}Sm. Neutron fluence corrected μ^{142}Nd data for samples repeated by this study are consistent with previously reported values. For the Apollo 12 suite, the ilmenite basalts exhibit higher μ^{142}Nd (+9.4±1.3 to +13.8±1.8) than the olivine and pigeonite basalts (-8.3±1.6 to +6.3±2.0). For corrected μ^{142}Nd, Apollo 2 samples of this study range from -8.3 to +13.8 (a 22.1 ppm range). Considering all high precision Nd isotope data to date, samples record a 38.4 ppm range [11, 12, 13, 15]. Three models were used to evaluate the new (neutron fluence corrected) μ^{142}Nd data. In model 1, bulk Moon formed with average chondritic values (^{147}Sm/^{144}Nd of 0.1964 and a present day μ^{142}Nd = -20). In model 2, the bulk Moon formed with average chondritic values for ^{147}Sm/^{144}Nd of 0.1964 but a present day μ^{142}Nd = -7.3 (following [16]). In model 3 (Fig. 1, t½ ^{146}Sm = 103 Myr), fractionation of Sm from Nd occurs at 4.538 Ga to produce a superchondritic reservoir with ^{147}Sm/^{144}Nd = 0.2136 and ^{146}Sm/^{144}Sm = 0.00649 [14]. This produces a present-day bulk Moon with ε^{143}Nd = +10.2 and μ^{142}Nd = 0.

In the chondritic model, because the High-Ti and KREEP sources formed at different times (4.45 Ga and 4.30 Ga respectively), the linear relationship would reflect reservoir mixing (e.g. [17]) and not a source closure age for the Sm-Nd isotopic system. This scenario is inconsistent with measured and calculated source Lu/Hf ratios (e.g. [14, 18]).

Despite the greater petrologic diversity exhibited by the Apollo 12 samples, and the distinct evolutionary history of the Low-Ti, High-Ti reservoirs and KREEP mantle source reservoirs, the new data presented here for μ^{142}Nd data of lunar mare basalts define a well-correlated ε^{143}Nd-μ^{142}Nd relationship and confirm this correlation found in earlier studies. This is best explained as an isochron and is interpreted as recording a lunar mantle closure age for the Sm-Nd system at *c*. 4.45 to 4.34 Ga, the absolute value of which depends on the μ^{142}Nd of the bulk Moon and which of the half-lives for ^{146}Sm is used (68 or 103 Myr).

Discussion: The coupled ^{143}Nd-^{142}Nd isochron age of *c*. 4.34 Ga, or 230 Ma after OSSF (when t½ ^{146}Sm = 103 Myr) defined by the Apollo 12, 15 and 17 mare basalts could represent the protracted cooling history of the LMO. This would support the presence of small volume melts within the lunar interior for hundreds of millions of years after the giant impact event and is consistent with the lunar crustal rock record, the lunar zircon record (4.42-3.90 Ga e.g. [19]), the KREEP source age, and a final lunar mantle closure time for Sm-Nd isotopes in the mare basalt sources. Alternatively, the Sm-Nd isotopic systematics of the Apollo mare basalts are not recording LMO processes. Instead, the Sm-Nd mantle closure age of *c*. 4.34 Ga may represent a post LMO solidification, late-stage, magmatic event during which isotopic re-equilibration of the mantle sources occurred. The idea of a late, widespread remelting event on the Moon during which isotopic systems closed/were reset, is also supported by multiple lunar samples [20, 21]: FAN 60025 (4.36 Ga), the oldest Mg-suite norite 77215 (4.33 Ga), the KREEP ^{147}Sm-^{143}Nd model age (4.36 Ga) and the Apollo 17 zircons (4.35-4.20 Ga, e.g. [19]). In this scenario, the LMO crystallized rapidly (e.g. *c*. 10 Ma, [22]) and the young FAN ages represent the products of re-melting of earlier formed lunar crust.

Many studies of the FAN suite have been predicated on the idea that samples represent direct crystallization products of a LMO, offer constraints on the composition of primordial LMO differentiates, and provide insights into ancient lunar crustal evolution. Future studies of the FAN suite, Apollo mare basalts and other lunar samples should therefore aim to evaluate geochemical, geochronological and geophysical data within the context of the potential scenarios discussed above.

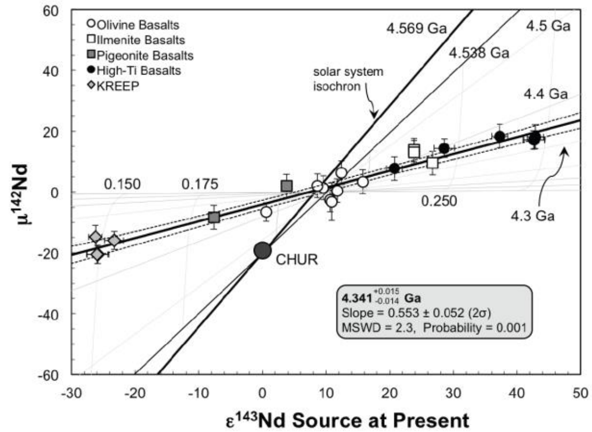

Fig. 1. Two-stage differentiation history for the Moon (after [14]) in which Sm and Nd are fractionated at 4.538 Ga (31 Ma OSSF). Differentiation as c. 4.34 Ga generates the Low-Ti, High-Ti and KREEP source reservoirs.

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