
ADDITIONAL EVIDENCE FOR YOUNG FERROAN ANORTHOSITIC MAGMATISM ON THE MOON FROM Sm-Nd ISOTOPIC MEASUREMENTS OF 60016 CLAST 3A

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Introduction: Lunar ferroan anorthosites (FANs) are thought to form as flotation cumulates of a global magma ocean and therefore represent the oldest crustal lithology. Although numerous studies to obtain ages on this suite of samples have been completed, the results are ambiguous and often contradict predictions based on petrogenetic models of magma ocean solidification. Specifically, ages for FANs and rocks from the Mg-suite overlap, suggesting that both types of magmatism were contemporaneous. Furthermore, the range of ages determined for FANs is 4.29 Ga to 4.5 Ga [1-2], significantly larger than predicted by thermal models suggesting the Moon solidified quickly [3]. In some cases, replicate analyses on the same samples have not yielded concordant ages, indicating that at least some age determinations are erroneous [4-5]. In order to better constrain the timing of FAN magmatism we have identified and analyzed FAN Clast 3A from lunar breccia 60016 using a combination of textural, microbeam, and isotopic techniques. Here we report the results of Sm-Nd isotope measurements.

Petrology and mineral chemistry: Figure 1 is a BSE image of the 3A clast from 60016. Last year we reported textural and mineral chemical data for this clast [6]. The clast is composed of 83% plagioclase (An~95), 15% pyroxene, and 2% olivine and is therefore classified as a noritic anorthosite. The calcic composition of the plagioclase (An95-96) and the low Mg# of the mafic minerals (Mg#65-67) cause the clast to plot within the FAN field on an Mg#-An digram. The sample is not highly cataclasized; coarse-grained fragments of plagioclase preserve the remnants of a plutonic texture. In this clast olivine is anhedral and partially to totally surrounded by anhedral pyroxene. Both orthopyroxene and clinopyroxene exhibit fine-scale exsolution lamellae. These textures are interpreted to indicate that this clast underwent partial recrystallization involving sub-solidus pyroxene growth and exsolution [6].

Rare earth element compositions were determined in situ on minerals by ion microprobe, as well as on mineral fractions and a whole rock prepared for Rb-Sr and Sm-Nd isotopic analyses. The clast has a slightly LREE-enriched REE pattern similar to other FAN samples [6]. Likewise, REE analyses of plagioclase and pyroxene by SIMS demonstrates compositional affinity between Clast 3A and FANs such as 60025.

Sm-Nd isotopic measurements: Mineral separates were obtained from a 2 gram fraction of Clast 3A. Individual samples were as large as possible in order to enable 142Nd/144Nd isotopic measurements to be completed. Fractions were digested and small (5%) aliquots were set aside for Rb-Sr measurements. The remaining 95% fraction were then spiked with a 99.988% 156Nd tracer that allowed isotopic composition and isotope dilution measurements to be made on the same fraction. During this procedure a hot plate malfunctioned and overheated, prohibiting accurate 147Sm/144Nd measurements to be made on the whole rock and plagioclase II fractions. Re-analysis of additional material is underway along with Rb-Sr and Ar-Ar measurements.

![Figure 1. Backscatter electron image of 60016 clast 3A.](image)

![Figure 2. 147Sm/144Nd plot of mineral fractions from Clast 3A.](image)

An age of 4300 ± 32 Ma is defined by the plagioclase I, pyroxene-olivine, and whole rock (fine) fractions (Fig. 2). The initial ε143Nd value derived from the regression is -0.22 ± 0.22 and is consistent with derivation from a source that had chondritic to slightly light REE-enriched REE pattern. This is consistent with the compositions predicted for FANs and KREEP-rich rocks[6].
An age of 4298 +57/-94 Ma was determined using the 146Sm-142Nd isotopic system (Fig. 3). This age is calculated using the initial 146Sm/142Sm ratio determined by Marks et al. [7] and the 103 Ma half-life. It is concordant and in good agreement with the 147Sm-143Nd age. An age of 4377 +38/-62 Ma is obtained if the half-life and initial 146Sm/142Sm of [8] are used. This regression defines an initial ε142Nd value of -0.63 ± 0.19 that is consistent with derivation from a source with an initial 142Nd/144Nd similar to that inferred for the Earth assuming a chondritic 147Sm/144Nd ratio of 0.1967.

The age of clast 3A is also calculated from the Nd-Nd isochron (Fig. 4). This age is defined by all five of the fractions because it is based solely on their measured Nd isotopic compositions. Thus, the spike-sample disequilibrium that affected the Sm-Nd chronometers will not affect the Nd-Nd chronometer. The Nd-Nd isochron yields an age of 4296 +58/-97 Ma and is concordant with the other Sm-Nd age determinations. There are relatively large uncertainties associated with ages derived from the 146Sm-142Nd decay system. This stems from the small variation of 142Nd/144Nd of only 22 ppm, indicating that 146Sm was nearly extinct at the time this sample formed. The small spread in 142Nd/144Nd indicates that the sample must be relatively young. The weighted average of all three ages is 4299 +24/-28 Ma and is the best representation of the Sm-Nd age of the sample.

Implications: Although ages ranging from 4.29 to 4.53 Ga have previously been reported for FANs, many of these ages demonstrate evidence for isotopic disturbance [2,9]. For example, the youngest FAN (62236) has a very high initial ε143Nd value, whereas the Sm-Nd data that define the age of the oldest FAN, (67016), demonstrate significant scatter [1-2]. In contrast, the age of FAN 60025 was determined using three isotopic systems and found to be 4360 ± 3 Ma. The age of Clast 3A is also defined by multiple concordant chronometers. The Sm-Nd isochrons for Clast 3A yield initial εNd values that are consistent with the petrogenesis of this rock suite. Thus, the 4299 +24/-28 Ma age likely records the crystallization age of the sample. This age conforms other young ages determined for FANs, such as 62236 and 60025, and indicates that FAN magmatism occurred fairly late in lunar history. Note that the age of Clast 3A overlaps ages reliably determined for some Mg-suite rocks, such as 76535, 78238, and 77215 [10-12], requiring both types of magmatism to be contemporaneous.

One explanation for the overlap of young FAN and Mg-suite ages is that these magma suites were produced by serial magmatism in which compositionally distinct portions of the lunar mantle underwent partial melting. This hypothesis does not provide an explanation for the widespread occurrence of FANs on the lunar surface, however. Alternatively, the young FANs may represent primordial cumulates of a late crystallizing magma ocean. If this scenario is correct, then the rapid cooling inferred for the magma ocean implies that FAN ages substantially older than 60025 are in error. In this scenario, the Mg-suite represents a secondary pulse of magmatism that apparently overlapped FAN magmatism as result of the limited resolution of current chronometry. The complex, and potentially extended, cooling histories inferred for FANs like Clast 3A and Mg-suite rocks like troctolite 76535 are consistent with this hypothesis.


Figure 3. 146Sm-142Nd plot of mineral fractions from Clast 3A. ε143Nd calculated using the average 142Nd/144Nd ratio of 1.141837 ± 7 (N = 45 measurements) for JNd.

Figure 4. 142Nd-144Nd isochron plot of 60016 clast 3A.

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