ISOTOPIC CONSTRAINTS ON THE ORIGIN OF LUNAR FERROAN ANORTHOSITES

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Introduction: Ferroan anorthosites (FANs) are thought to be flotation cumulates formed by early crystallization of a lunar magma ocean. The lunar magma ocean model predicts that FANs will be the oldest lunar crustal rocks into which younger rocks, such as those of the Mg-suite, are intruded. The lunar magma ocean model also predicts that FANs will have isotopic systematics consistent with being derived from a nearly chondritic source. Testing these hypotheses has proved to be difficult because determining the ages and initial isotopic compositions of the FANs are hampered by the fact that FANs are nearly monomineralic, have low abundances of parent and daughter nuclides, and have been strongly shocked.

Despite these difficulties, several ferroan anorthosite suite rocks, characterized by high mafic mineral contents, have recently been dated using the Sm-Nd method. The results of these isotopic studies are not consistent with formation as flotation cumulates of a lunar magma ocean. From Figure 1 it is apparent that some Sm-Nd ages of the mafic FANs range from 4.29 to 4.56 Ga [1-4] and overlap the oldest Sm-Nd ages of Mg-suite rocks [5]. The fact that the four mafic FANs that have been dated have positive initial ε_{Nd}^{143} values of +1 to +3 [1-4] is also inconsistent with the magma ocean model. The possibility that the mafic FANs are derived from a LREE-depleted source has not received widespread acceptance, however. Instead, the internal Sm-Nd isochrons are assumed to be reset.

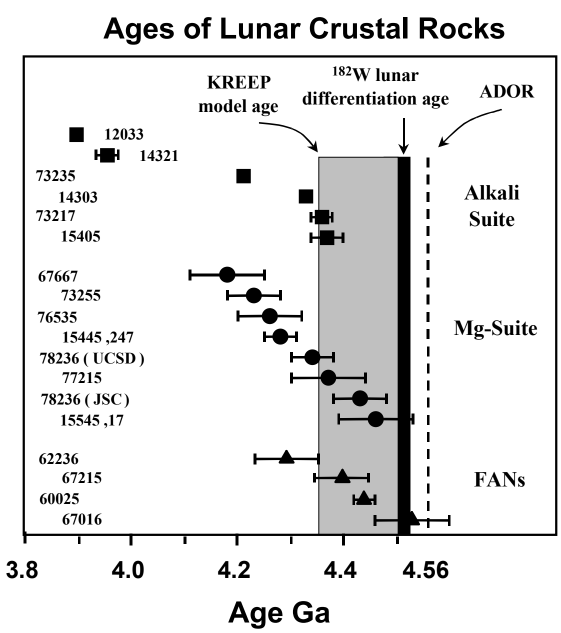

Figure 1. Sm-Nd ages of FANs and Mg-suite rocks and Pb-Pb ages of alkali suite rocks. Modified from [4].

In this abstract the whole rock Nd isotopic compositions of the mafic FANs are compared to the Nd isotopic compositions predicted for FANs crystallized from an initially chondritic magma ocean. This approach is not dependant on the assumption that the mineral phases that comprise the FANs are in equilibrium. Consequently this approach offers additional constraints on potential processes that could disturb the isotopic systematics of the mafic FANs.

Modeled Nd isotopic compositions of FANs: Snyder et al. [6] estimated the mineralogy and major and trace element compositions of the lunar magma ocean cumulates using a combination of phase equilibria and crystallization models. Using these models as a basis, the Nd isotopic systematics of the magma ocean cumulates are calculated. The calculated Nd isotopic compositions are then compared with the measured compositions of the mafic FANs.

Snyder et al. [6] calculated a fractionation sequence for the magma ocean using a lunar bulk composition of [7]. The sequence is as follows: (1) 0-40 Per Cent Solid (PCS) olivine; (2) 40-78 PCS orthopyroxene, (3) 78-86 PCS 53% plagioclase + 25% olivine + 22% pigeonite, (4) 86-95 PCS 38% clinopyroxene + 36% plagioclase + 26 % pigeonite, and (5) 95-99.5% PCS 34% pigeonite + 31% plagioclase + 24% clinopyroxene + 11% ilmenite. Snyder et al. [6] then calculated the REE abundances of the various cumulates assuming 4-5 x CI abundances of REE in the bulk moon. REE abundances were modeled in steps 1-2 assuming equilibrium fractional crystallization, whereas the later steps used fractional crystallization.

The Sm-Nd abundances of the anorthositic cumulates are calculated similarly, except that the modal mineralogy observed in the individual samples is used. This approach permits the modeled Nd isotopic compositions to be directly compared to the Nd isotopic compositions of the FANs. The FANs are assumed to have formed with their present mineral modes from the 78-86 PCS step [6]. The results of the model are not affected if the 86-95 PCS step is used instead. From the calculated $^{147}Sm/^{144}Nd$ ratios the present-day ε_{Nd}^{143} values of the anorthositic cumulates are determined.

The isotopic composition of the cumulates depend on when they formed. One estimate of the time of magma ocean crystallization comes from the 4.42 ± 0.07 Ga model age for KREEP [8]. This age is comparable, but slightly younger than the age estimated from the Hf-W isotopic system of 4.50-4.52 Ga [9-10]. For the models presented below, the lunar magma ocean is assumed to have crystallized at 4.50 Ga. Note, however, that the ε_{Nd}^{143} values of the anorthositic cumulates calculated by the model are not strongly dependent on this age because of the long half life of $^{147}Sm \rightarrow {}^{143}Nd$ chronometer ($t_{1/2}$ =106 Ga).

Modeled and whole rock ε_{Nd}^{143} values: Figure 2 is a plot of whole rock ε_{Nd}^{143} values of mafic FANs 60025, 62236, 67215c, and 67016c versus the ε_{Nd}^{143} value calculated for anorthositic cumulates with the modal mineralogy of these samples. It is apparent from this figure that the measured ε_{Nd}^{143} whole rock values are substantially higher than those predicted by the model.

This discrepancy could result from inadequacies of the model or disturbance of the Nd isotopic systematics of these FANs. The ε_{Nd}^{143} calculated for the anorthositic cumulates are dependent on the time of magma ocean crystallization, the $^{147}Sm/^{144}Nd$ ratio of the bulk Moon, and the Nd isotopic composition of the bulk Moon used in the models. However, to account for the differences between the modeled and measured ε_{Nd}^{143} whole rock values of FAN 60025, the model requires: (1) the crystallization of the magma ocean to have occurred at 3.85 Ga, (2) the bulk Moon to have $^{147}Sm/^{144}Nd$ ratio significantly higher than the chondritic value of 0.1967 (0.207) or, (3) the bulk Moon to have an initial ε_{Nd}^{143} value of +4.1. The situation is worse for samples that lie farther from the 1:1 line on Fig. 2. Another possibility is that the mafic FANs that have been dated contain a LREE-depleted component that was not considered in the models. Although this component must contain a large proportion of REEs, it has not been identified.

If the discrepancy between the modeled and measured ε_{Nd}^{143} values do not reflect inadequacies of the model, they could reflect disturbance of the Nd isotopic systematics of the mafic FANs. An open-system process is required to shift the Nd isotopic compositions of the mafic FANs to more radiogenic values. The addition of a component, characterized by a radiogenic Nd isotopic signature, to the FANs could account for their Sm-Nd isotopic systematics, but would require the FANs to be mixtures of rocks derived from very different sources. Alternatively, increasing the Sm/Nd ratio of the whole rock after crystallization will result in present-day ε_{Nd}^{143} values that are more radiogenic. However, significant amounts of Sm/Nd fractionation are required. To reproduce the whole rock ε_{Nd}^{143} value of 62236, ~10% of the Nd must be lost from the sample (assuming no Sm loss). Samples 67016c and 67215c require >20% loss of Nd. The large amount of Sm/Nd fractionation required by this explanation is difficult to reconcile with the geochemistry of the FANs, because it requires them to have highly shock-fractionated trace-element abundances. For example, if all REEs are fractionated linearly and according to mass, the REE patterns of the FANs must have been significantly more LREE-enriched than is observed today. It therefore seems unlikely that the elevated ε_{Nd}^{143} values of the mafic FANs reflect post crystallization fractionation of Sm from Nd.

There are at least two potential explanations for the Sm-Nd isotopic systematics of the FANs. First, the FANs could have crystallized from a strongly LREE-depleted magma ocean [12]. Whereas this could account for their elevated whole rock ε_{Nd}^{143} values it does not account for their elevated initial ε_{Nd}^{143} values or their apparent young ages. If this scenario is correct, the Sm-Nd isochrons of the FANs must be disturbed. Alternatively, the samples that have been analyzed could be derived by melting of mafic cumulates characterized by elevated $^{147}Sm/^{144}Nd$ ratios [4, 13]. If this scenario is correct, then the mafic FANs that have been dated may not be flotation cumulates of the magma ocean.

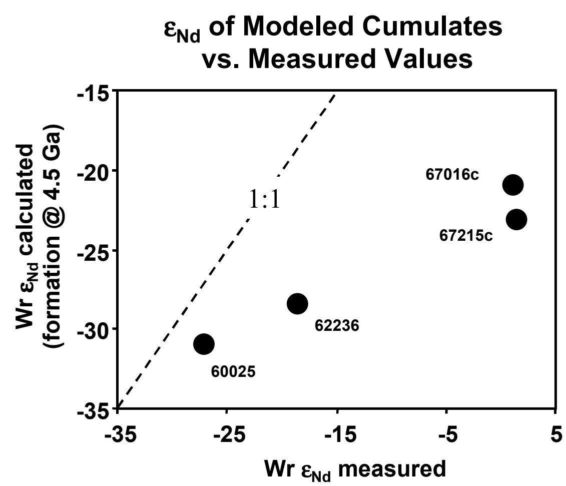

Figure 2. Present-day ε_{Nd}^{143} of modeled anorthositic cumulates vs. present-day whole rock values determined for FANs. Data from [1-4]. Whole rock value for 60025 calculated from mineral fractions assuming plag:ol:pig = 85:10:5. Note that the present-day ε_{Nd}^{143} of the FANs are more radiogenic than the calculated values.

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