NEGATIVE ε_{Nd} IN ANORTHOSITIC CLASTS IN YAMATO 86032 AND MAC88105: EVIDENCE FOR THE LMO?

L. E. Nyquist[1], D. D. Bogard[1], C. Y. Shih[2], H. Wiesmann[2], [1]Mail Code SR, NASA Johnson Space Center, Houston, TX 77058, l.nyquist@jsc.nasa.gov, [2]Mail Code C23, Lockheed-Martin Space Mission Systems and Service Co., 2400 NASA Road 1, Houston, TX 77058.

Introduction: Positive ε_{Nd} values for several lunar ferroan anorthosites (FANs) present a conundrum for the lunar magma ocean (LMO) model [1]. In the simplest version of the LMO model, a magma ocean with initially chondritic relative abundances of the REE evolves such that the magma residuum becomes progressively enriched in LREE, until the point of plagioclase crystallization. At that juncture, the lunar crust begins to form by flotation of plagioclase above a magma of greater density. A quantitative model for evolution of ε_{Nd} to negative values during this process is presented by [2]. A more complex scenario also has been advanced as a possible explanation of positive ε_{Nd} for FANs [3]. We present chronologic and isotopic data for anorthositic clasts from two lunar meteorites derivative from the lunar crust, possibly the farside crust. Exactly how these clasts fit into the known spectrum of FAN and Mg-suite rocks is somewhat unclear, and a topic of ongoing study [4]. Nevertheless, data for them show that positive ε_{Nd} was not a universal feature of the early lunar crust, and that complex models yielding positive ε_{Nd} in the late-stage magma ocean probably are unneccessary.

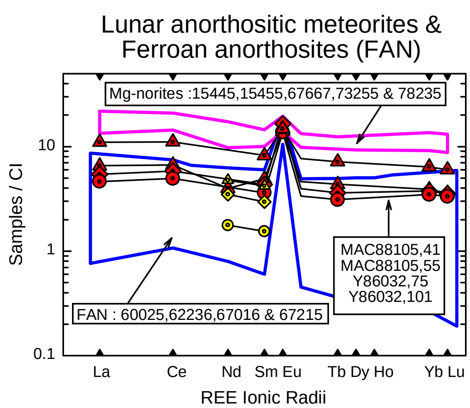

Figure 1. Chondrite-normalized REE abundances of lunar meteorite anorthositic clasts compared to those of FAN and Mg-suite rocks. Data for MAC88105 and Y86032 from [8,9]. Sm and Nd data are also shown for the clasts analysed in this investigation (yellow).

Meteorite clasts: The clasts considered here are W1 from MAC88105, and a "gray clast" (GC) from Yamato 86032. The latter was extracted from our allocation Y86032,116. Polished thin section PTS 83-1 from an area adjacent to our sample shows a finely brecciated anorthositic clast similar to the BB clast of Y-82192 [5,6]. Lithic clasts in Y86032 generally have An~96.5, En~70-80, but individual pyroxene fragments in the matrix are more ferroan [6]. Compositions of coexisting plagioclase, olivine, and low-Ca pyroxene in lithic clasts in the paired sample Y-82193 bridge the "gap" between ferroan anorthosites and Mg-suite rocks [7]. Published REE abundances of the large white clast [8] fall within the FAN field (Figure 1). The Sm and Nd abundances of clast GC are ~2-3X higher than for FANs 60025 and 62236, the lowest values for FANs, but are ~1.5-4X lower than those in FANs 67215 and 67016.

MAC88105W1 was described as a highland feldspathic breccia by [9], and as a relatively coarse-grained, highly anorthositic impact-melt breccia by [10]. Roughly half the clast consists of plagioclase mineral fragments which probably never melted [10]. Mineral compositions in W1 are An ~97.3, En ~60,

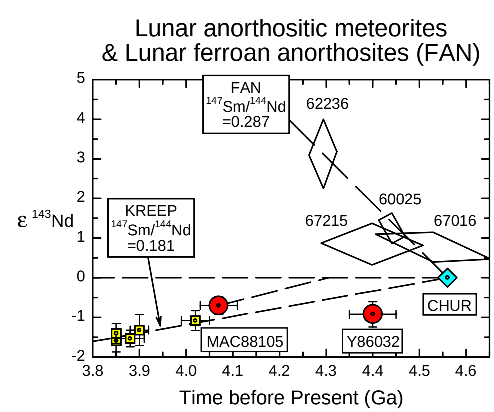

Figure 2. (T, ε_{Nd}) diagram for FANs and anorthositic lunar meteorite clasts.

[10] placing this clast in the FAN group. Thus, although both clasts are breccias, they are FAN breccias.

Ar-Ar ages: Ar-Ar ages for both clasts were reported by [11], and have been combined with Sm-Nd data [12] for bulk samples for a (T,ε_{Nd}) plot (Figure 2). In contrast to ε_{Nd} values determined from Sm-Nd mineral isochrons, $\varepsilon_{Nd} < 0$ for these FAN breccia clasts, and plot in the vicinity of the evolution line between the CHUR (Chondritic Uniform Reservoir) datum at 4.56 Ga ago, and lunar KREEP at ~3.85-3.90 Ga ago.

The isotopic characteristics of KREEP are widely accepted as determined by the presence of an urKREEP residuum from magma ocean crystallization in the source region of the KREEP basalts. Thus, the negative ε_{Nd} values of these FAN breccias also are implied to be traceable to magma ocean evolution.

The Ar-Ar ages of the clasts are only lower limits to the actual crystallization ages of the protolith, however, and one must consider the implication of possible older ages on the isotopic systematics. For MAC88105W1, ε_{Nd} would be negative for ages younger than the CHUR model age of ~4.3 Ga, becoming positive and of the order of values for 67215, 67016, and 60025 for ages ~4.4-4.5 Ga. However, this is not the case for the Y86032 clast for which ε_{Nd} is <0 for all ages younger than ~4.56 Ga.

Discussion: The MAC88105W1 data do not provide conclusive evidence for negative ε_{Nd} for FANs. Although its composition is generally consistent with that of FANs, this impact melt breccia could be a mixed lithology containing contributions from Mg-suite rocks. The W1 clast is surrounded by matrix of considerably higher REE abundances approaching those of Mg-suite rocks (MAC88105,41 in Figure 1). Also, it has a relatively evolved initial $^{87}Sr/^{86}Sr$ ratio, similar to those of Mg-suite rocks One could hypothesize a protolith of mixed Mg-suite and FAN lithology of average age ~4.3-4.4 Ga and zero-to- slightly positive ε_{Nd}. The Ar-Ar age of such a mixed lithology could have been reset to ~4.1 Ga during brecciation. This scenario seems not only possible, but likely.

The same considerations do not hold for the Y86032GC clast, however. There is no indication in either the REE or isotopic data that this breccia contains anything but FAN lithologies. The initial $^{87}Sr/^{86}Sr$ data are completely consistent with those of other FANs. Most importantly, its Ar-Ar age of ~4.4 Ga shows that major Ar degassing was coincident with, or only slightly later than, crystallization of the FAN protolith. Thus, this clast has been shielded against major thermal events affecting the megaregolith since that time. Additonally, Y86032 has a comparatively young cosmic ray exposure age of ~11 Ma [13], and no evidence of secondary neutron capture by Sm. Whether or not this clast is pristine in regard to contamination by meteoritic siderophile elements, it appears to be pristine in regard to processes that could potentially disturb its isotopic systematics. Thus, the ε_{Nd} value derived for it appears to be robust.

Having even one FAN with negative ε_{Nd} removes the neccessity of assuming that the magma ocean had evolved to positive ε_{Nd} values, but does not explain positive ε_{Nd} for the majority of FANs. Those data suggest FAN petrogenesis was a localized phenomenon, possibly in addition to being related to magma ocean crystallization. The alternative appears to be an appeal to open-system processes occurring in the megaregolith that may have affected the Nd isotopic composition and/or Sm/Nd ratios of the FANs. Comparing the data for the Y86032M matrix sample to that for Y86032GC supports this idea (Figure 3). An isochron for FAN pyroxenes and Y86032GC yields an apparent age of 4.49±0.09 Ga and ε_{Nd} = 0.0±0.8 for the FANs (Figure 3), consistent with derivation from a chondritic magma ocean. Open-system processes may have affected FAN plagioclase more severely than FAN pyroxene, consistent with generally higher REE diffusion rates in plagioclase than pyroxene. The ~10X higher REE abundances in Mg-suite rocks than in FANs suggests that the major reservoir of radiogenic Nd in crustal areas lacking KREEP may be Mg-suite pyroxenes. How such Nd could have entered FAN plagioclase during major thermal events such as basin formation near 3.9 Ga, for example, is unclear.

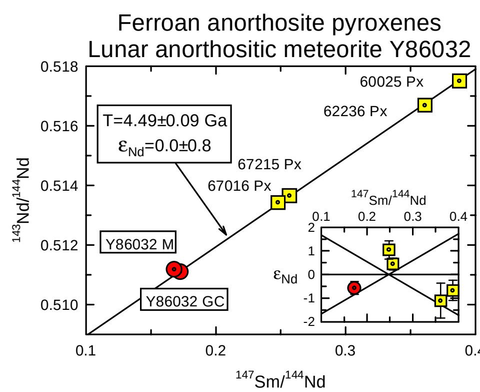

Figure 3. Sm-Nd ischron for Y86032GC and pyroxene mineral separates from other FANs.

References: [1] Borg L. et al. (1999) *GCA, 63*, 2679-2691. [2] Borg L. et al. (2002), this meeting. [3] Warren P. H. (2001) *Meteoritics & Planet. Sci., 36,9,* A219-A220. [4] Takeda H. et al. (2002), this meeting. [5] Takeda H. et al. (1989) *Proc. NIPR Symp. Antarct. Met., 2,* 3-14. [6] Takeda et al. (1987) *Mem. NIPR*, *46,* 43-55. [7] Takeda et al. (1990) *Proc. 20th Lun. Plan. Sci. Conf.*, 91-100. [8] Lindstrom M. M. et al. (1991) *Proc. NIPR Symp. Antarct. Met., 4,* 12-32. [9] Lindstrom M. M. et al. (1991) *GCA, 55,* 3089-3103. [10] Warren P. H. and Kallenmeyn G. W. (1991) *GCA, 55,* 3123-3138. [11] Bogard D. D. et al. (2000) *LPS XXXI,* abs. #1138. [12] Nyquist L. E. et al. (1996) *LPS XXVII,* 971-972. [13] Eugster O. et al. (1991*) GCA*, *55,* 3139-3148.