Introduction: The ancient Martian orthopyroxenite ALH 84001 experienced a complex history of impact and aqueous alteration events. Treiman [1] identified petrographic evidence for its involvement in four or five crater-forming impacts following its initial crystallization “in a body of magma somewhere beneath Mars’ surface”. Adopting his relative chronology of events, fractured, granular bands present in ALH84001 were formed in an early (first?) impact event. The accompanying thermal metamorphism homogenized mineral compositions and probably was accompanied by production offeldspathic glass from igneous feldspars. In a later event, fractures in the granular bands became hosts to carbonate rosettes that are often found in association with the feldspathic glass. Sm-Nd studies [2,3] yielded ages of ~4.5 Ga, and carbonate formation was dated at 3.90±0.04 Ga by the Rb-Sr method and 4.04±0.10 Ga by the U-Th-Pb method [4]. The Sm-Nd ages have been cited as giving the time of igneous crystallization of ALH84001, an interpretation challenged by [5] on the basis of an ~4.1 Ga Lu-Hf age.

Here we summarize 147Sm/144Nd and 146Sm/142Nd analyses performed at JSC. Further, using REE data [6-8], we model the REE abundance pattern of the basaltic magma parental to ALH84001 cumulus orthopyroxene. We find the 146Sm/142Nd isotopic data to be consistent with isotopic evolution in material having the modeled Sm/Nd ratio from a time very close to the planet’s formation to igneous crystallization of ALH84001 as inferred from the Sm-Nd studies.

147Sm-143Nd: Fig. 1 shows results for 147Sm/144Nd analyses at JSC of 22 bulk samples and mineral separates. An isochron fit (Isosplot model 1 [9]) gives an age of 4.568±0.088 Ga (2σ) and εNd = +1.2±0.8 relative to a Chondritic Uniform Reservoir (CHUR, [10]). These values are within uncertainty of those originally reported for five bulk samples and a pyroxene separate [3]. We attribute an apparently irreducible scatter in the 147Sm-143Nd data (MSWD ~ 100) to post-magmatic disturbance of the Sm-Nd system.

A more restricted set of Sm-Nd data from [5] is in good agreement with our own. An isochron fit to four data presented by [5] (S2-S3-S4-R1) gives an age of ~4.63 Ga. (Their bulk rock leachate datum (L1) is omitted from the regression). Tentatively adopting the ~4.09 Ga Lu-Hf age as the crystallization age and orthopyroxene as an end-member component on a hypothetical mixing line results in a calculated εNd ~+5 for orthopyroxene data from both labs implying a source of the ALH84001 parental magma depleted in LREE.

146Sm-142Nd: Fig. 2 shows Isosplot model 1 results for data for 16 samples yielding initial 146Sm/144Sm ([I(Sm)] = 0.0031±0.0009 and ε142Nd = -0.36±0.12 at CHUR. 147Sm/144Nd = 0.1967 [10]. Elevated values of ε142Nd >0 for the pyroxenes and ε142Nd <0 for samples of low 147Sm/144Nd, particularly for leachate Opx(L) (~phosphates) and bulk rock samples, are inconsistent with the ~4.09 Ga Lu-Hf age. MSWD = 5.1 shows these data to be much less disturbed by post-magmatic reheating than the 147Sm-143Nd data, probably because events later than ~4.1 Ga are not registered. The age calculated relative I(Sm)=0.0076 and T=4.558 Ga for angrite LEW 86010 (equivalent to I(Sm)=0.0081 at T

Figure 1. 147Sm-143Nd isochron plot for bulk samples and mineral separates of ALH84001. The isochron is fit to JSC data. Data from [5] adjusted for differing normalizations are shown for comparison.

Figure 2. 146Sm-142Nd data for bulk samples and mineral separates of ALH84001.
= 4.568 Ga) is $T=4.425 \pm 0.039/-0.054$ Ga. Alternatively, for the newly determined half-life of $^{146}$Sm ($t_{1/2} = 68$ Ma [11]) and I(Sm)=0.0084 at 4.568 Ga, the calculated relative age of ALH 84001 is $4.470 \pm 0.035/-0.026$ Ga. $^\varepsilon_{142}$Nd $= -0.23^{\pm .05}$ reported by [5] for a large (~1 gm) bulk sample (B1) is consistent with this isochron if $^{147}$Sm/144Nd (not measured), is estimated from its measured $^{144}$Nd/144Sm ratio. $^\varepsilon_{142}$Nd $= +0.19^{\pm .13}$ previously reported by [12] for a bulk sample is not plotted because $^{147}$Sm/144Nd was not measured. However, we do not consider this analysis to be inconsistent with the $^{144}$Sm-$^{142}$Nd isochron because bulk (“WR”) samples range up to $^{147}$Sm/144Nd ~0.3 as required by this analysis (Fig. 1). Taken together, the $^{142}$Nd analyses of [5] and [12] are inconsistent with a nearly flat isochron as required by an age of ~4.1 Ga.

Modeled REE abundances in parent melt: In Fig. 3, solid symbols represent REE patterns for orthopyroxene samples from ALH 84001, taken from ion microprobe analyses of mineral grains [7, 8] and ICP-MS analyses of orthopyroxene separates [6]. Open symbols represent REE patterns for melts parental to the orthopyroxene as calculated using the average of seven sets of REE distribution coefficients in Opx [6, 13, 14]. The calculated parental melts are high in REE abundances, are LREE-enriched, and have an average $^{147}$Sm/144Nd of 0.17±0.01. The REE pattern of Martian crust [15] and NWA 7034 [16] are also plotted for comparison. The calculated REE abundances in the parental melts match those estimated for the Martian crust very well. Similarly high REE abundances occur in NWA 7034 [16], but differ by being slightly higher in overall REE abundances and having a negative Eu anomaly. Interestingly, $^{147}$Sm/144Nd = 0.171 in NWA 7034 [16] equals that in the estimated Martian crust.

Nd isotopic evolution prior to the parent melt:

$$\mu_{147}^\text{Sm}/\text{Nd}$$

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**Figure 3.** Modeled REE abundances in ALH84001 parent melt.

**Figure 4.** Modeled Nd-isotopic evolution between Mars' formation and crystallization of ALH84001.