PEERING THROUGH A MARTIAN VEIL: ALHA84001 Sm-Nd AGE REVISITED. L. E. Nyquist[1] and C-Y. Shih[2], [1]KR/NASA Johnson Space Center, Houston, TX 77058 (E-mail: laurence.e.nyquist@nasa.gov), [2]Mail code: JE-23, ESCG/Jacobs Technology, P.O. Box 58477, Houston, TX 77258-8477 (chi-yu.shih-1@nasa.gov).

Introduction: The ancient Martian orthopyroxenite ALH 84001experienced 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 of feldspathic glass from igneous feldspars. In a later event, fractures in the granular bands became hosts to carbonate rosettes that often are 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 ^{147}Sm-^{143}Nd and ^{146}Sm-^{142}Nd 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 ^{146}Sm-^{142}Nd 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.

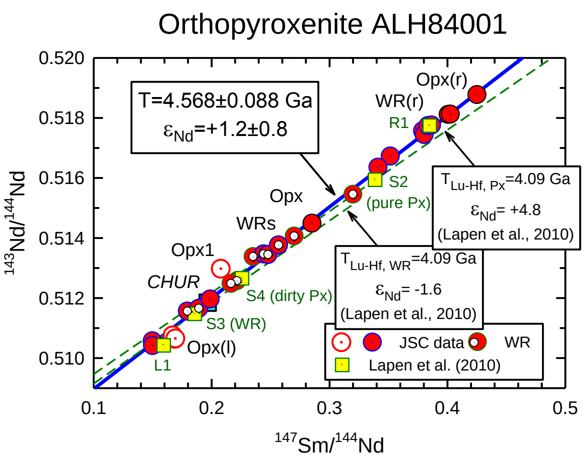

Figure 1. ^{147}Sm-^{143}Nd isochron plot for bulk samples and mineral separates of ALH84001. The isochron is fit to JSC data. Data from [5] adjusted for differing normalizations are shown for comparison.

^{147}Sm-^{143}Nd: Fig. 1 shows results for ^{147}Sm-^{143}Nd analyses at JSC of 22 bulk samples and mineral separates. An isochron fit (Isoplot model 1 [9]) gives an age of 4.568±0.088 Ga (2σ) and ε_{Nd} = +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 ^{147}Sm-^{143}Nd 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 ε_{Nd} ~+5 for orthopyroxene data from both labs implying a source of the ALH84001 parental magma depleted in LREE.

^{146}Sm-^{142}Nd: Fig. 2 shows Isoplot model 1 results for data for 16 samples yielding initial ^{146}Sm/^{144}Sm (I(Sm)) = 0.0031±0.0009 and ε^{142}Nd = -0.36±0.12 at CHUR ^{147}Sm/^{144}Nd = 0.1967 [10]. Elevated values of ε^{142}Nd >0 for the pyroxenes and ε^{142}Nd <0 for samples of low ^{147}Sm/^{144}Nd, 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 ^{147}Sm-^{143}Nd 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

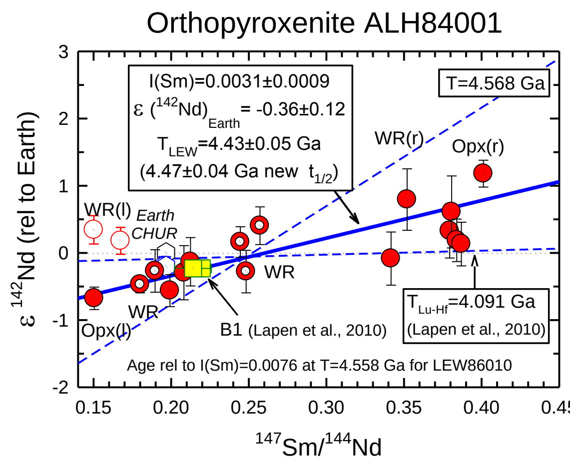

Figure 2. ^{146}Sm-^{142}Nd data for bulk samples and mineral separates of ALH84001.

= 4.568 Ga) is T=4.425 +0.039/-0.054 Ga. Alternatively, for the newly determined halflife 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 +0.035/-0.026 Ga. ε^{142}Nd = -0.23±0.05 reported by [5] for a large (~1 gm) bulk sample (B1) is consistent with this isochron if ^{147}Sm/^{144}Nd (not measured), is estimated from its measured ^{143}Nd/^{144}Nd ratio. ε^{142}Nd = +0.19±0.13 previously reported by [12] for a bulk sample is not plotted because ^{147}Sm/^{144}Nd was not measured. However, we do not consider this analysis to be inconsistent with the ^{146}Sm-^{142}Nd isochron because bulk ("WR") samples range up to ^{147}Sm/^{144}Nd ~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 AHL 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/^{144}Nd 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/^{144}Nd = 0.171 in NWA 7034 [16] equals that in the estimated Martian crust.

Nd isotopic evolution prior to the parent melt: Fig. 4 shows the ^{147}Sm-^{143}Nd (upper) and ^{146}Sm-^{142}Nd (lower) results (yellow parallelograms). Red and green (for [11]) curves show Nd isotopic evolution from an HED (Howardite-Eucrite-Diogenite) or Earth-like parent body at T = 4.568 Ga for ^{147}Sm/^{144}Nd = 0.17±0.01. Because the ^{147}Sm-^{143}Nd isochron was disturbed, the age it suggests may be biased to a value somewhat too old. The ^{146}Sm-^{142}Nd isochron probably represents a better estimate of a magmatic age of 4.4-4.5 Ga for ALH 84001. The modeled ^{142}Nd evolution is consistent with a LREE-enriched source as calculated for the parent magma from the REE abundances in pyroxene.

Conclusions: We tentatively identify disturbances evident in the Sm-Nd data with the early, strong deformation and thermal metamorphic event identified texturally [1]. This event likely reset the Lu-Hf age, and other ages for radiometric systems less robust than Sm-Nd. The Sm-Nd system is particularly robust as demonstrated most recently for chondrites [17] because both the isotopic parent and daughter are REE.

References: [1] Treiman A. H. (1998) *Meteoritics & Planet. Sci., 33*, 753–754. [2] Jagoutz E. et al. (1994) *Meteoritics 29,* 478-479. [3] Nyquist L. E. et al. (1995) *LPS XXVI*, 1065–1066. [4] Borg L. E. et al. (1999) *Science 286*, 90-94. [5] Lapen T. J. et al. (2010) *Science*, *328,* 347-351. [6] Barrat J.-A. and Bollinger C. D. (2010) *Meteoritics & Planet. Sci., 45,* 495–512. [7] Papike, J.J. et al. (1994) *LPSC XXV*, 1043-1044. [8] Wadhwa, M. and Crozaz, G. (1998) *Meteoritics & Planet. Sci., 33*, 685-692. [9] Lugwig K.R. (2008) Isoplot/Excel ver. 3.7. [10] Jacobsen S. B. and Wasserburg G. J. (1984) *EPSL 67*, 137-150. [11] Kinoshita N. et al. (2012) *Science 335*, 1614-1617. [12] Wadhwa, M. and Borg, L. (2006) *LPS XXXVII*, CD-ROM #2045. [13] Frei, D. et al. (2009) *Contrib. Mineral. Petrol.* 157, 473-490. [14] van Kan Parker, M. et al. (2010) *Contrib. Mineral. Petrol.* 159, 459-473. [15] Taylor S.R.and McLennan, S.M. (2009) *Planetary crusts: their composition, origin and evolution,* Cambridge Univ. Press. [16] Agee C. et al. (2013) *Science Express. Science* DOI: 10.1126. [17] Martin C. et al. (2012) *Ant. Met. 35*, 38.

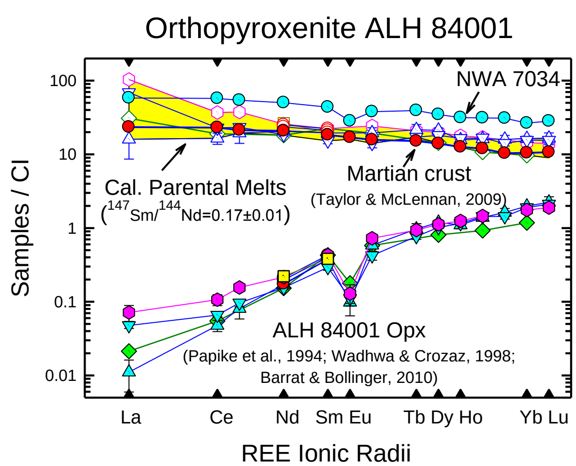

Figure 3. Modeled REE abundances in ALH84001 parent melt.

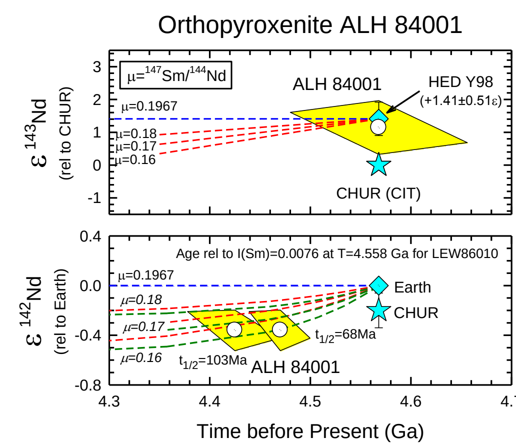

Figure 4. Modeled Nd-isotopic evolution between Mars' formation and crystallization of ALH84001.