Rb-Sr AND Sm-Nd ISOTOPIC STUDIES OF ANTARCTIC NAKHLITE MIL 03346. C.-Y. Shih[1], L. E. Nyquist[2], and Y. Reese[3], [1]Mail Code JE-23, ESCG/Jacobs Sverdrup, P.O. Box 58477, Houston, TX 77258-8477, chi-yu.shih1@jsc.nasa.gov; [2]Mail Code KR, NASA Johnson Space Center, 2101 NASA Parkway, Houston, TX 77058, l.nyquist@jsc.nasa.gov; [3]Mail Code JE-23, ESCG/Muniz Engineering, Houston, TX 77058, young.reese1@jsc.nasa.gov.

Introduction: Nakhlites are olivine-bearing clinopyroxenites with cumulate textures, and probably came from Mars [*e.g.*, 1]. A total of seven nakhlites have been identified so far. Unlike other martian meteorites (*e.g.*, shergottites), nakhlites have been only moderately shocked and their original igneous textures are still well-preserved. Also, these meteorites have similarly older crystallization ages of ~1.3 Ga compared to shergottites with ages of ~0.18-0.57 Ga [*e.g.*, 2]. MIL 03346 is characterized by abundant (~20 vol %) glassy mesostasis, indicating that it cooled rapidly and probably formed near the top [3] or at the bottom [4] of the chilled margin of a thick intrusive body. The mesostasis quenched from the trapped intercumulus liquid may provide information on the parent magma compositions of the nakhlites. In this report, we present Rb-Sr and Sm-Nd isotopic data for MIL 03346, discuss correlation of its age with those of other nakhlites and the nature of their source regions in the Martian mantle.

Samples and Analytical Procedures: An interior piece of MIL 03346,56, was broken up, one medium fragment plus fines weighing ~0.9 g was picked out for this study. The sample was further crushed gently to pass a nylon sieve of opening size <149 µm. About 0.2 g was taken as the bulk rock sample (WR). The rest of the sample was sieved into 149-74 µm and <74 µm size fractions. Mineral separations were made by density separations using heavy liquids. At density fraction 3.32-3.45 g/cm^3, we obtained a light green clinopyroxene "core" sample (Cpx1, 2) of >95% purity. In the slightly higher density fraction (3.45-3.7 g/cm^3), a dark green sample of clinopyroxene "rim" (Cpx3) was obtained. A small amount of olivine sample (Ol and Ol2) was separated with a heavy liquid of density >3.7 g/cm^3. The black glassy mesotasis sample (Gl) was mainly concentrated in the density fraction <3.32 g/cm^3. In addition, a bulk rock and a clinopyroxene "core" sample were washed with 2N HCl in an ultrasonic bath for 10 minutes to eliminate possible post-crystallization, pre- or terrestrial, contamination. Both the residues (r) and leaches (l) of these samples were also analyzed.

Rb-Sr isotopic results: The ^{87}Rb/^{86}Sr and ^{87}Sr/^{86}Sr data for ten MIL 03346 samples are shown in Fig 1. Eight unwashed and wash residue samples (solid circles) form a linear array corresponding to an age T=1.29±0.12 Ga for $\lambda(^{87}\text{Rb})$ =0.01402 Ga^{-1} and I(Sr)=0.70267±0.00016 (solid line) using the Williamson regression program [5]. The errors for age reduce slightly to ±0.11 Ga while those for I(Sr) remain unchanged when the York [6] or the Isoplot program is used. However, one small olivine (Ol) sample separated from the fine size fraction is off the isochron and may contain significant amounts of martian aqueous alteration clay minerals [4, 7]. Also, the two acid-washed leachates (open circles) plot completely off the isochron indicative of post-crystallization alterations. The Rb-Sr age and I(Sr) for MIL 03346 is similar to those of four other dated nakhlites. A two-stage model calculation indicates that the ^{87}Rb/^{86}Sr for its source region is ~0.078.

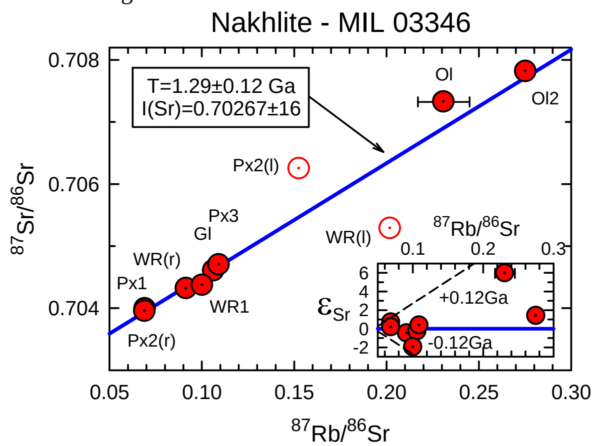

Figure 1. Rb-Sr data of MIL 03346.

The mesostasis sample has the highest Rb (15.4 ppm) and Sr (418 ppm) among the mineral separates, consistent with being a intercumulus trapped melt containing albitic feldspar glass components [8]. The high Sr content in MIL 03346 compared to other nakhlites is probably associated with its high mesostasis content.

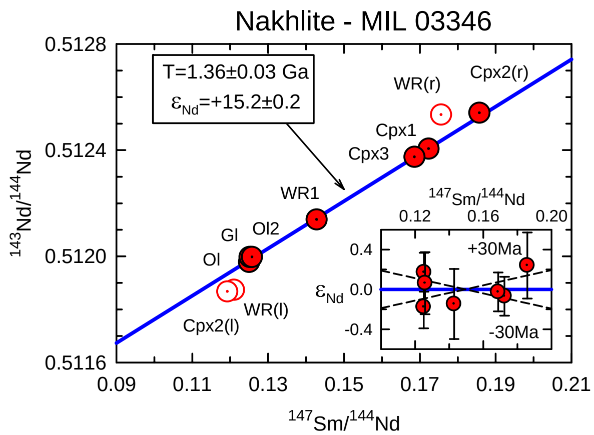

Figure 2. Sm-Nd data of MIL 03346.

Sm-Nd isotopic results: Fig. 2 shows ^{147}Sm/^{144}Nd and ^{143}Nd/^{144}Nd data of the same ten samples as in Fig. 1. Seven samples (solid circles) including one acid-washed clinopyroxene core sample form a linear array corresponding to an age of 1.36±0.03 Ga for $\lambda(^{147}\text{Sm})$=0.00654 Ga^{-1} and initial ε_{Nd}=+15.2±0.2 using the Williamson regression program [5]. If the York [6] or Isoplot program is used, the error limits for age are increased slightly to ±37 Ma while those for initial ε_{Nd} value remain unchanged. As in the Rb-Sr isotopic system, two leachate samples (open circles) lie off the isochron, probably containing secondary alteration products. However, the acid washed bulk sample datum also plots off the isochron. The reason is unclear. This Sm-Nd age is in good agreement with the 1.37 Ga Ar-Ar age averaged over all extractions of a whole rock MIL 03346 sample [9] as well as other nakhlite ages determined by various radiometric dating techniques [*e.g.* 9-14].

The Sm isotopic composition of a bulk rock sample does not show any isotopic anomalies relative to the Ames Sm standard. Failure to detect either an ^{149}Sm deficit (ε^{149}Sm =-0.01±0.22) or an ^{150}Sm enrichment (ε^{150}Sm = -0.02±0.37) is consistent with a short exposure age for MIL 03346. Noble gases and nuclear track data give a young exposure age of 9.5±1 Ma for the meteorite [15].

The mesostasis sample has the highest Sm (26xCI) and Nd (41xCI) abundances and is the most LREE-enriched of the separated components of MIL 03346. Comparing to other nakhlites, the high REE contents of MIL 03346 (Sm~10xCI and Nd~14xCI) seem to be related to its high mesotasis amounts, suggesting a close resemblance to NWA 819 [16].

Petrogenetic implications: The ε_{Nd}-values and ages of five nakhlites are summarized in Fig. 3. The parallelograms defined by the estimated uncertainties for each nakhlite do not overlap significantly, showing that nakhlite parent magmas came from different flows. Also, they could have come from multiple isotopically distinct sources at different times. Based on two-stage model calculations, the nakhlite source ^{147}Sm/^{144}Nd ratios could have varied from ~0.231 to ~0.237. Nakhlite volcanisms probably lasted at least 20 Ma. From the cooling rates of the nakhlites, it has been suggested that they all could have been derived from a single cumulate pile [3]. We consider this to be unlikely, as it would require unacceptable large expansions of the error limits on the isotopic data (Fig. 3). A recent study of olivine textures and abundances in nakhlites [17] also suggested a complex history of multiple lava flows in the region of the nakhlite source crater (Syrtis Major [18] ?).

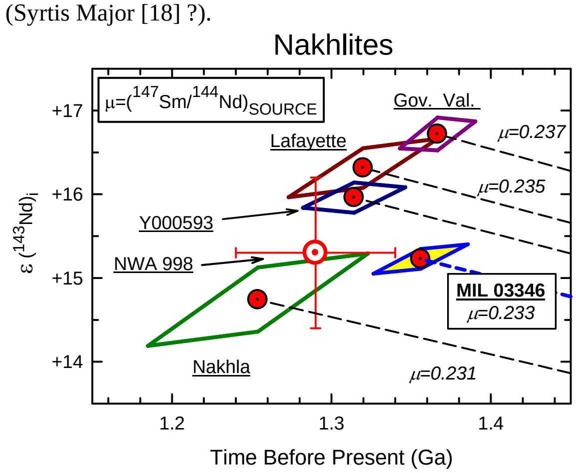

Figure 3. ε_{Nd} vs. T(age) of nakhlites.

Fig. 4 shows the ε_{Nd}-value and age of MIL 03346 with evolution paths (broken lines) calculated for a two-stage model. The calculated source ^{147}Sm/^{144}Nd ratio for MIL 03346 is ~0.233, or ~18% depleted in LREE relative to an assumed undifferentiated primitive martian mantle similar to chondrites (CHUR). As discussed in [19], we assume this depleted MIL source is a garnet-bearing peridotitic cumulate having Nd=1xCI, Sm=1.2xCI, and ^{147}Sm/^{144}Nd=0.233 at 1.36 Ga ago. We suggest such a depleted source was an early cumulate from a thick magma ocean established very early, probably soon after martian core formation, and while ^{182}Hf still was alive [20, 21]. The MIL source evolved until 1.36 Ga ago, when a partial melting event occurred, forming MIL parental magma similar in composition to the glassy mesostasis found in MIL 03346. We suggest this magma was intruded upward to the martian subsurface. As it cooled down, crystals of clinopyroxene and olivine settled, trapping a small portion of the parent magma to form MIL 03346. The 1% melt required in this model for the MIL-forming event at 1.36 Ga has 26xCI Sm and 41xCI Nd, matching the MIL mesostasis composition very well. Other alternatives are also permissible for slightly different source mineralogy, chemical composition, and degrees of melting. Both the two-stage model described above or the three-stage model described in [12] can explain the small positive ^{142}Nd anomalies (~+0.6 ε) [21, 22] of nakhlites.

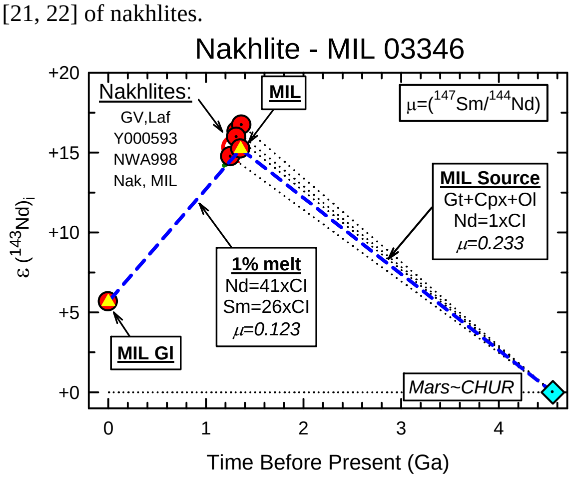

Figure 4. ε_{Nd} vs. T(age) of MIL 03446.

References: [1] Treiman A.H. (2005) *Chemie der Erde* **65**, 203-270. [2] Nyquist L.E. *et al.* (2001) *Chronology and Evolution of Mars*, , R. Kallenbach, J. Geiss, W.K. Hartmann, Eds. 96, 105-164. Kluwer Academic Publ. Dordrecht/ Boston/London. [3] Mikouchi T. *et al.* (2005) *Lunar Planet. Sci.* **XXXVI**, CD-ROM #1944. [4] Grady M.M. *et al.* (2005) *Meteoritics Planet. Sci.* **40**, A59. [5] Williamson J.H. (1968) *Canadian J. Phys.* **46**, 1845-1847. [6] York D. (1966) *Can. J. Phys.* **44**, 1079-1086. [7] Stopar J.D. *et al.* (2005) *Lunar Planet. Sci.* **XXXVI**, CD-ROM #1547. [8] Anand M. *et al.* (2005) *Lunar Planet. Sci.* **XXXVI**, CD-ROM #1639. [9] Bogard D.D. and Garrison D.H. (2006) this vol. [10] Nakamura N. *et al.* (1982) *Geochim. Cosmochim. Acta* **46**, 1555-1573. [11] Shih C.-Y. *et al.* (1998) *Lunar Planet. Sci.* **XXIX**, CD-ROM #1145. [12] Shih C.-Y. *et al.* (1999) *Meteoritics Planet. Sci.* **34**, 647-655. [13] Misawa K. *et al.* (2005) *Ant. Met. Res.* **18**, 133-151. [14] Carlson R.W. and Irving A.J. (2004) *Lunar Planet. Sci.* **XXXV**, CD-ROM #1442. [15] Murty S.V.S. *et al.* (2005) *Lunar Planet. Sci.* **XXXVI**, CD-ROM #1280. [16] Sautter V. *et al.* (2002) *Earth Planet. Sci. Lett.*. **195**, 223-238. [17] Lentz R.C.F. *et al.* (2005) *Meteoritics Planet. Sci.* **40**, A91. [18] Harvey R.P. and Hamilton V.E. (2005) *Lunar Planet. Sci.* **XXXVI**, CD-ROM #1019. [19] Shih C.-Y. *et al.* (2005) *Ant. Met. Res.* **18**, 46-65. [20] Lee D.C and Halliday A.N. (1997) *Nature* **388**, 854-857. [21] Foley C.N. *et al* (2005) *Geochim. Cosmochim. Acta* **69**, 4557-4571. [22] Harper C.L. Jr. *et al.* (1995) *Science* **267**, 213-217.