MAJOR AND TRACE ELEMENTS IN NAKHLITE MIL 03346 WITH A FOCUS ON AQUEOUS ALTERATION PRODUCTS. J. D. Stopar[1], G. J. Taylor[1], and M. D. Norman[2], [1]SOEST/HIGP, University of Hawaii at Manoa, 1680 East-West Rd., Honolulu, HI, 96822 (jstopar@higp.hawaii.edu), [2]Research School of Earth Sciences, Australian National University, Canberra ACT 0200, Australia.

Introduction: The nakhlites are important pieces of Mars because they contain the products of martian aqueous alteration processes [1]. MIL 03346 is a recent Antarctic find and is currently a subject of intense study because it contains alteration products similar to those identified as "martian" in other nakhlites, including iddingsite and anhydrite. Characterization of the secondary products in MIL 03346 is important in order to understand how this meteorite relates to other nakhlites, and MIL 03346 may hold important clues about aqueous processes on Mars. We present major and trace element chemistry mineral phases in MIL 03346 with a focus on secondary aqueous alteration products.

Methods: Major elements were determined for a number of mineral phases in MIL 03346 using the Cameca SX50 electron microprobe at the University of Hawaii (see [2]). Trace element abundances were determined using a 193 nm excimer laser ablation (LA) ICPMS at the Australian National University. A laser spot diameter of 70 µm and repetition rates of 4Hz for spot analyses or 10 Hz for traverses across larger areas were used for analyses of olivine, augite, and mesostasis. For smaller phases, particularly alteration products, a spot diameter of 19 µm and 3 Hz repetition rate was used. Instrument sensitivity was calibrated using the NIST 612 glass. Each analysis was normalized to either CaO or SiO_2 to compensate for variations in ablation efficiency of different materials based on EMPA analysis of the same phase.

LA-ICPMS as a tool to study aqueous alteration products. While providing a large amount of trace element data (38 elements), the instrumental configuration used for this study was not able to determine several elements that are potentially important tracers of chemical weathering and aqueous activity such as K (due to interference with Ar gas), many light elements such as H and S (due to high background), and negative ions such as Cl^-. Additionally, Th and U, two other elements thought to reflect martian weathering processes [e.g., 3-4], were typically below detection limits. This technique is, however, sensitive to LREE enrichments and Ce anomalies, which commonly result from terrestrial aqueous alteration.

Samples: Electron microprobe compositional data were collected from MIL 03346 thin section ,94 (previously described by [2]). The modal abundances of phases in this section were determined from electron microprobe X-ray elemental maps: 80.6 vol% clinopyroxene, 2.7% olivine phenocryst, 16.0% mesostasis (0.8% silica and 1.4% FeTi oxides), 0.07% Ca-sulfates, and 0.63% other alteration (including olivine veins[1] and mesostasis alteration, which [5] determined to be altered pyrrhotite). These modal abundances (updated from [2]) are consistent with the nakhlite modal abundances complied in [5].

LA-ICPMS was conducted on two thick sections (,173 and ,174) of MIL 03346. These thick sections have similar petrology to thin section MIL 03346,94 except that olivine phenocrysts are less abundant. There is only one small cross-section of an olivine phenocryst available in each of these sections (and being adjacent sections they may be two different cross-sections of the same phenocryst). Thus, the availability of olivine alteration products analyzed by LA-ICPMS was limited.

Results: Despite the difficulties associated with analyzing small alteration products, major and trace element abundances were successfully collected from a number of primary and secondary phases in MIL 03346.

Major Elements. The average composition of the clinopyroxene is $En_{37}Fs_{23}Wo_{40}$ (augite core) with a Fe-rich rim ($En_{13.4}Fs_{46.1}Wo_{40.4}$). Olivine phenocrysts are ~Fo_{43} with rims that range from Fo_{33} to Fo_{10}. Interstitial Fe-rich olivine is ~Fo_6. The average composition of "weathered" or altered olivine is 6.4% MgO, 42.4% FeO, 37.7% SiO_2, representing an increase in SiO_2 and a decrease in MgO and FeO compared to the olivine cores. The olivine veins have an average composition of 3.1% MgO, 37.8% FeO, and 42.4% SiO_2, which represents a further decrease in MgO and FeO and an additional increase in SiO_2. Both altered olivine and the olivine veins have low EMPA totals that may represent hydration. S is elevated in both the weathered olivine and the olivine veins.

Trace Elements. REE patterns for a number of MIL 03346 mineral phases are shown in Figs. 1-3. Abundances are normalized to mean CI abundances from Beer and Palme (1993, updated) in [6]. In general, our trace element patterns are consistent with those from other nakhlites and with previous results from MIL 03346 [5, 7]. In our analyses, REE abundances in olivine cores and rims are often below detection limits.

Discussion: Mesostasis in MIL 03346 is enriched in LREEs like in other nakhlites (Fig. 1). Olivine melt inclusions 1.1 and 1.3 have REE patterns similar to the whole rock, consistent with crystallization of the rock as a closed system. Inclusion 1.2 is more enriched in LREEs than other melt inclusions in nakhlites. The similar LREE-enrichment seen in the analysis of a mesostasis alteration vein suggests that the LREE-enrichment in Inclusion 1.2 is related to alteration. A positive Eu anomaly in the analysis of fine-grained mesostasis not seen in bulk mesostasis implies that feldspar represents a significant portion of that analysis.

Alteration veins within clinopyroxene are enriched in LREEs compared to both augite cores and clinopyroxene Fe-rich rims (Fig. 2). The veins and altered clinopyroxenes, like the Fe-rich rims, have larger negative Eu anomalies than the augite

[1] In this abstract "vein" refers to aqueous alteration unless otherwise noted.

cores. The REE patterns of altered clinopyroxenes and veins in clinopyroxenes are similar to gypsum in Gov. Valadares, except that LREEs are less enriched (esp., La) compared to gypsum. The mesostasis alteration vein is also similar to the Gov. Valadares gypsum, except REE abundances are higher and La is more enriched (Figs. 1-2) compared to gypsum.

Altered olivine and the olivine veins analyzed here have MgO, FeO, and SiO_2 similar to analyses of iddingsite in other nakhlites [5, 8]. The more dramatic change in MgO and SiO_2 relative to FeO from olivine interiors to areas of incipient olivine alteration and veins suggests that dissolved FeO is less mobile, and may reflect rapid oxidation of Fe^{2+} to Fe^{3+} [9].

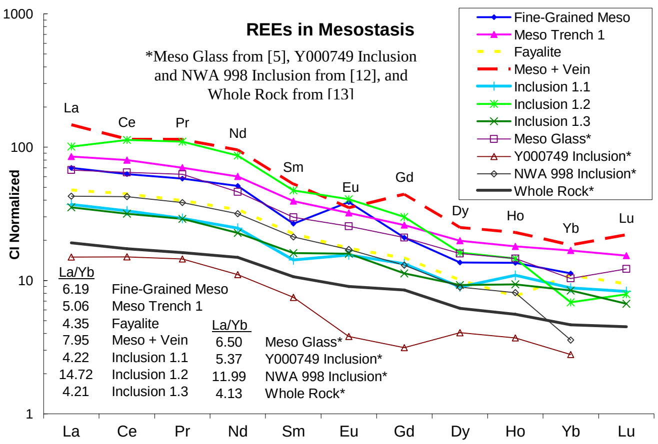

Figure 1: LREE-enriched mesostasis and related phases. La/Yb ratios given are similar to published REE values. Inclusions 1.1, 1.2, and 1.3 are different analyses on the same olivine melt inclusion.

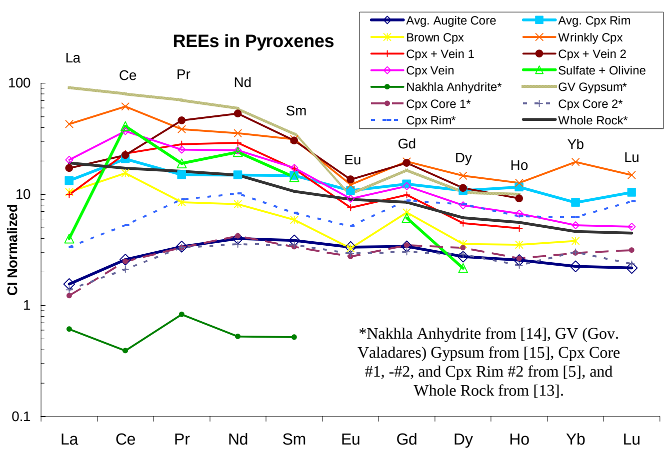

Figure 2: REEs in pyroxenes. Augite pattern and abundance is consistent with [5]. Clinopyroxene rims have a higher abundance of REEs than [5]. Ce anomalies may be the product of terrestrial alteration. The phase labeled "Sulfate + Olivine" is an anhydrite-bearing vein in olivine and has a similar REE pattern, except for depletion in La, to clinopyroxene alteration veins, altered clinopyroxene, and the mesostasis alteration vein in Fig. 1.

Olivine veins show REE enrichments compared to olivine cores, rims, and areas of incipient olivine alteration. The enrichment of REEs in veins compared to cores suggests the emplacement of REEs from the fluid phase during aqueous processes. However, we must consider the possibility that at least some of the LREE enrichment in the olivine veins is terrestrial.

Terrestrial alteration. Two lines of evidence often cited as tracers for terrestrial contamination are positive and/or negative Ce anomalies in olivine and pyroxene and an LREE enrichment in olivine [e.g., 10]. Ce anomalies can be created if Ce^{3+} is oxidized to Ce^{4+}, as has been suggested for both hot and cold deserts [11]. A number of our analyses on a variety of different phases show a Ce anomaly. However, no terrestrial LREE enrichment or Ce anomaly was observed in bulk mesostasis, olivine melt inclusions, and the interstitial Fe-rich olivine. Some clinopyroxene cores and rims were also free of Ce anomalies.

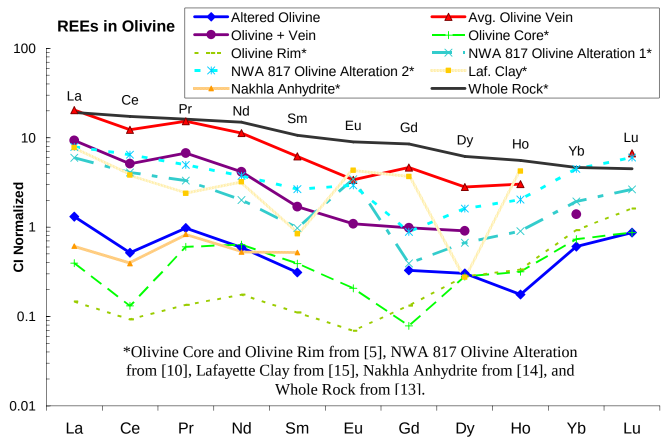

Figure 3: REEs in olivine and its alteration products compared to selected alteration products in other nakhlites. None of the REE patterns are similar to Lafayette clay. Olivine alteration and veins lack the positive Eu anomaly observed in NWA 817 [11]. Ce anomalies may be products of terrestrial alteration.

References: [1] Wentworth, S. J. et al. (2005) *Icarus, 174*, 383-395. [2] Stopar, J. D. et al. (2005) *LPSC XXXVI* #1547. [3] Stopar, J. D. et al. (2004) *LPSC XXXV*, #1429. [4] Taylor, G. J. et al. (2007) *JGR*, doi:10.1029/ 2006JE002676. [5] Day, J. M. D. et al. (2006) *MAPS., 41(4)*, 581-606. [6] Palme, H. and Jones, A. (2003) *Treatise on Geochemistry*, *1*, 41-61. [7] Wadhwa, M. and Borg, L. E. (2006) *LPSC XXXVII*, #2045. [8] Treiman, A. H. and Lindstrom, D. J. (1997) *JGR*, *102*, 9153-9163. [9] Tosca, N. J. et al. (2003) *Sixth Mars*, #3178. [10] Gillet, P. et al. (2002) *EPSL*, *203*, 431-444. [11] Crozaz, G. et al. (2003) *GCA*, *67*, 4727-4741. [12] Wadhwa, M. et al. (2004) *Antarct. Met. Res.*, *17*, 97-116. [13] Barrat, J. A. et al. (2006) *LPSC XXXVII*, #1569. [14] Bridges, J. C. and Grady, M. M. (1999) *MAPS.*, *34*, 407-415. [15] Bridges, J. C. and Grady, M. M. (2000) *EPSL*, *176*, 267-279.