LOW AND HIGH TEMPERATURE AQUEOUS ALTERATION OF THE MATRICES OF CR CHONDRITES: NANO-SEM, EPMA, AND TEM STUDY. N. M. Abreu. Earth Science, Pennsylvania State University - DuBois. E-mail: abreu@psu.edu.

Introduction: CR chondrites are primitive meteorites that show a broad range of aqueous alteration features from nearly pristine [1] to fully altered [2]. However, as more CR chondrites have become available for study, a complex alteration record is beginning to emerge [3-6]. Here, I present observations of Antarctic four unpaired CR chondrites, MIL 07513, MIL 07525, LAP 04516, and GRO 03116, whose matrices have not been previously studied. In addition, observations of matrix and opaques in CR chondrites GRO 95577 and GRA 06100 were also conducted.

Methods: An ESEM FEI Quanta 200 and a Nova NanoSEM 630 were used to characterize petrographic thin sections all meteorites. Multiple regions of matrix in MIL 07513, LAP 04516, and GRO 03116 were analyzed by EPMA for 13 elements (Na, Mg, Al, Si, P, S, K, Ca, Fe, and Ni) using a 10 µm-beam at a Cameca sx-100 and at a JEOL 8900. Finally, regions of typical matrix were sectioned using a FIB for study using a JEOL 2010F STEM.

Results: MIL 07513, MIL 07525, LAP 04516 sections show only limited signs of terrestrial alteration, such as rust staining or networks of ferryhydrite veins. This is consistent with their classification as weathering type B. GRO 03116, on the other hand, has been extensively weathered. Consequently, most opaque materials in GRO 03116 consist of foliated masses of Fe-oxides, with relict kamacite and taenite in their interiors. Opaque nodules in the other chondrites appear to be intact. Opaques in MIL 07513 are complex interlocking assemblages similar to those in GRA 06100.

While MIL 07513, MIL 07525, and GRO 03116 have very fine-grained matrices, LAP 04516 has a very heterogeneous texture, containing abundant clasts and mineral fragments (Fig. 1). MIL 07513, LAP 04516, and GRO 03116 are characterized by widespread presence of secondary phases such as phyllosilicates and fine-grained magnetite throughout all regions studied. GRO 03116 is particularly rich in wispy magnetite and Fe-sulfide grains (Fig. 1). MIL 07525 has the lowest abundance of secondary phases, followed by MIL 07513 which is nearly devoid of Fe-sulfides.

In MIL 07513, LAP 04516, and GRO 03116 matrices, abundance patterns are nearly flat and close to CI chondrite abundance for the refractory and moderately refractory lithophile elements. These meteorites are very enriched in Fe and strongly depleted in S. MIL 07513 is depleted in S by nearly two order of magnitude with respect to CI chondrites. In these three chondrites, Fe is inversely correlated with both S and Si, suggesting that the main host phases of matrix Fe are neither sulfides not silicates. This compositional feature is consistent with TEM observations, which show that although Fe-sulfides, Fe-bearing phyllosilicates and amorphous silicates are present, these meteorites also contain Fe-Ni-Cr oxides and magnetite.

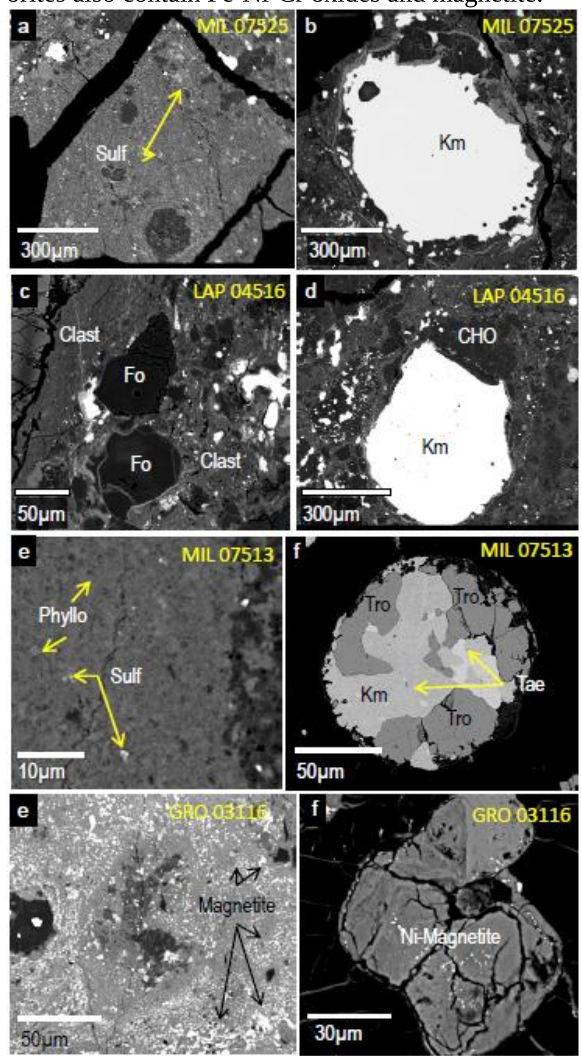

Figure 1: BSE images of typical matrix and opaques in MIL 07525, LAP 04516, MIL 07513, and GRO 03116.

Discussion: As shown in Figs. 1 and 2, the alteration history of CR chondrites is largely determined by the redistribution of Fe and the formation/loss of its host phases. [1] argued that the most pristine CR chondrites have very Fe-rich matrices, dominated by Fe-rich amorphous silicates and Fe-sulfides. In contrast, altered matrices CR2 chondrites are rich in magnetite, which is thought to have formed from progressive removal of Fe in matrices. However, in some altered CRs (e.g., GRO 95577 [2], GRO 03116 [4], GRA 06100 [3], and MIL 04513), large, and abundant metal grains appear to have been extensively altered.

In addition to containing abundant altered metal, GRO 03116, GRA 06100, and MIL 04513 appear to have a different aqueous alteration history from other CR chondrites. Compared with other altered CR chondrites, chondrules in GRO 03116, GRA 06100, and MIL 04513 are not as rich in phyllosilicates, which is also reflected in very high elemental totals (~99-100 wt.%). Furthermore, the matrices of these three meteorites have the highest Fe concentrations observed in the CR group (Fig. 2) and rare calcite.

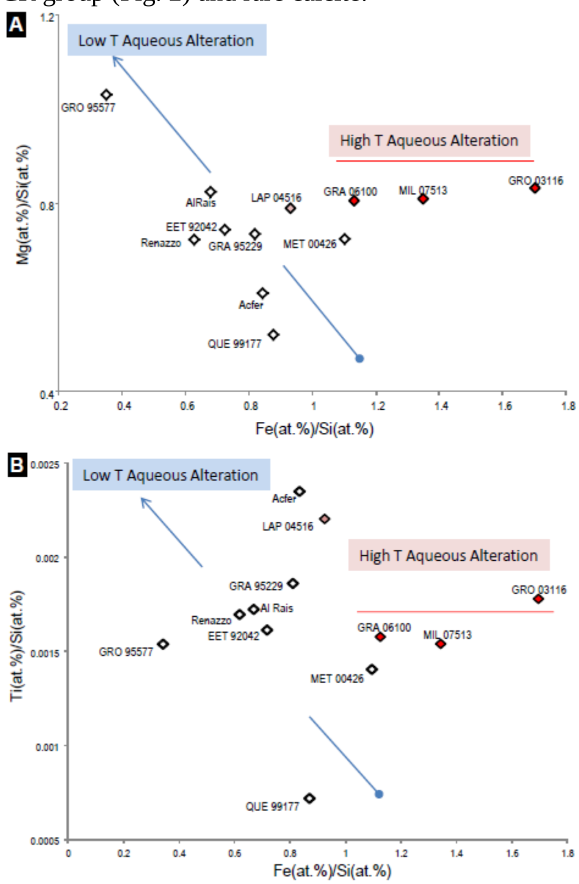

Figure 2: Element/silicon ratios for CR chondrite matrices normalized to CI chondrites. Two evolutionary tracks, a low temperature aqueous alteration and a high temperature aqueous alteration, can be distinguished on the basis of preferential mobilization of Fe with respect to Mg and Ti (a similar pattern is observed for Al). Filled diamonds correspond to analytical data from this study. Analytical data for other meteorites obtained from: [1,2,7]. Modified from [8].

Based on these differences, two evolutionary tracks of aqueous alteration in the CR parent body are proposed. The first track follows the trajectory outlined by [9], in which alteration results in removal of Fe from the fine-grained silicate-rich materials and precipitations of magnetite. As magnetite forms, Mg and Ti remain in the silicate phases. Thus, these elements are effectively enriched in the fine-grained portion of extensively altered CR chondrites in Track 1.

In Track 2, the matrix could continue to become more Fe-rich despite magnetite formation, since the main source of Fe would be pre-existing large metal nodules. Under such conditions, the concentration of Ti and Mg in matrix would remain constant, as observed in Track 2. It is possible that matrices of chondrites in Track 2 evolved in a different manner because alteration occurred at a higher temperature than alteration in Track 1. Unlike most CR chondrites GRO 03116 and GRA 06100 have been recognized to have undergone mild to moderate metamorphism [4].

However, Fe enrichment observed in GRO 03116 matrix could be partly attributed to terrestrial weathering, since its mineralogy suggest that this meteorite has undergone limited asteroidal aqueous alteration at low temperature than GRA 06100 [3]. Terrestrial weathering produce a wide array of “metallic” (Fe-Ni-S) and “sialic” (Fe-Si-Al) rust and Fe-rich oxi-hydroxides [10]. These features are often differentiated from asteroidal aqueous alteration on the basis of their distinct chemical composition (e.g., oxidation state, mineral assemblages). However, how amorphous silicates, such as the ones common in many CR chondrites [e.g., 1] behave during terrestrial weathering is a largely unexplored question.

Conclusions: Composition of CR chondrite matrices are proposed to evolved along two different tracks as a consequence of aqueous alteration. In Track 1, the Fe/Si ratio is inversely correlated with the Mg/Si, Ti/Si, and Al/Si ratios, via progressive formation of magnetite. In Track 2, Mg/Si, Ti/Si, and Al/Si remain flat as Fe is removed from altering Fe-Ni metal nodules.

References: [1] Abreu N. M. and Brearley A. J. 2010. *GCA*, *74*, 1146-1171. [2] Weisberg M. K. and Huber H. 2001. *MAPS*, *42*, 1495-1503 [3] Abreu N. M. 2011. *MAPS*, *46*, A5211. [4] Abreu N. M. and Stanek G. L. 2009. *LPS XL*, Abstract #2393. [5] Briani et al. 2010. *MAPS*, *45*, 5234. [6] Schrader D. L. et al. 2011. *GCA*, *75*, 308-325. [7] Weisberg M. K. et al. 1993. *GCA*, *57*, 1567-1586. [8] Abreu N. M. and Brearley A. J. 2008. *LPS XXXIX*, Abstract #2013. [9] Kallemeyn et al. (1994) *GCA*, *58*, 2873-2888. [10] Zolensky M. E. and Gooding J. L. 1986.

Acknowledgements: Funded by NNX11AH10G grant to NMA and conducted at the MRI– Penn State, Smithsonian Institution and ARES-JSC. Antarctic meteorite specimens kindly provided by MWG.