UNDERSTANDING THE EFFECTS OF ANTARCTIC WEATHERING ON THE PETROLOGIC AND SPECTRAL CHARACTERISTICS OF PRISTINE CR CARBONACEOUS CHONDRITES. N. M. Abreu[1], E. A. Cloutis[2], V. E. Hamilton[3] Earth Science, Penn State University – DuBois Campus, DuBois, PA, 15801, abreu@psu.edu, [2]Department of Geography, University of Winnipeg, 515 Portage Ave., Winnipeg, MB, Canada R3B 2E9, e.cloutis@uwinnipeg.ca, [3]Southwest Research Institute 1050 Walnut St. #300, Boulder, CO 80302 USA.

Introduction: Spectral matches between CRs and potential parent bodies are hindered by the effect of terrestrial weathering on the mineralogy of these meteorites [1]. We face multiple challenges to address this uncertainty. First, it is not clear what the characteristics of unweathered CRs are, because only Renazzo and anomalous Al Rais are observed falls. The fact that CR chondrites contain both large volumes of fine-grained metallic Fe and sub-micron amorphous silicates aggravates the effects of terrestrial weathering. Second, terrestrial alteration and asteroidal alteration products may resemble each other. Third, the effect of terrestrial weathering on amorphous Fe-Mg-rich silicates has not been studied. Fourth, because CR anhydrous silicates are generally Fe-poor, they have weak Fe-silicate-associated absorption bands, making them prone to overprinting by terrestrial weathering products. We are addressing these challenges by using SEM and TEM to study Elephant Moraine (EET) 92107 (C), EET 92161 (B/C), EET 92062 (Be), and EET 92105 (B), which belong to the same, pristine pairing group EET 92XXX, and span most of the range of Antarctic weathering in the CR suite. To indicate the degree to which Antarctic meteorites have been subjected to terrestrial weathering, curators use weathering grades A, B, C and e. Grades A-C denote increasing elemental mobilization and mineral replacement. Grade e is assigned to samples with evaporite deposits.

Methods: All the thin sections examined have at least some fusion crust, allowing examination of the effect of distance from the crust on terrestrial weathering. BSE/SEM full thin section mosaics and close-up images where obtained from all sections. Two FIB sections were prepared from each meteorite, using a Helios NanoLab 660. One FIB section was extracted from ~ 500 micron from the inner edge of the inner substrate region of the fusion crust, as described by [2], (termed “proximal”) and one from distance between 1-2mm of the inner substrate (termed “distal”). Each section was examined using a Talos F200X. 300-second, EDS X-ray elemental maps where collected for the full FIB sections and at higher magnifications for 5 selected regions for each FIB section. For each selected section, HAADF STEM, bright-field, and HRTEM images were collected.

Results: BSE images show that weathering of EET 92105 and EET 92062 is limited, consistent with their grade B. In both meteorites, exterior (>300 um) Fe-Ni nodules have discontinuous, <10 um rims containing Fe-oxyhydroxides. Smaller grains have continuous rims and sub-grain replacement. Fe-Ni in chondrule interiors shows minor replacement and discontinuous rims. Regions near weathered metal have high Fe and elongated, filamentous grains are present. Weathering features are more abundant, yet heterogeneously distributed in EET 92161 (B/C) and EET 92107 (C). In highly weathered regions, thick (>200 microns) cracks are fully occluded, Fe-Ni metal has been replaced, and adjacent matrix has high abundance of blocky, coarse (20-50 microns) opaques, and significantly higher Z-contrasts than regions near unoccluded cracks.

TEM observations show that all sections contain abundant carbonaceous materials. These materials are consistently amorphous and do not contain other elements (e.g., no O, N, Cl). All sections contain a few rounded, forsteritic olivine grains, with sharp boundaries between olivines and surrounding materials.

TEM Observations of Proximal $92XXX_p$ FIB sections. All proximal FIB sections contain mixtures of typical CR matrix with quenching textures, including the presence of elongated magnesioferrite spherules and presence of rounded, non-stoichiometric Fe-Mg silicate globules with short-range crystallographic order and sharp grain boundaries. The grain size of Fe-S phases is larger (generally > 50 nm across) than in typical CR matrix (5-50 nm – [3]). Fe-S grains are larger than those in typical EET 92XXX matrix. Ca is found in all proximal sections in one or more of the following occurrences: (1) blocky Ca-oxides, (2) Ca-carbonate-like grains, and (3) low-Ca pyroxenes. Thermal decomposition of Ca-carbonates may form Ca-oxides. Given the proximity to the fusion crust, this heating event probably occurred during ablation in the terrestrial atmosphere. The abundance of Ca-oxides in proximal sections is anticorrelated with Antarctic weathering grade, suggesting that in the more weathered samples (i.e., $EET107(C)_p$, $EET161(B/C)_p$), Ca-oxides dissolved in terrestrial water. Ca-oxides and water and known to produce a strong, exothermic reaction. Ca-carbonate-like grains are heterogeneously distributed throughout samples, well-facetted and hexagonal, and in some cases large (>1micron). Some of these grains show signs of plastic deformation and are decorated with magnesioferrite spherules, suggesting a pre-terrestrial origin. Ca-carbonate-like grains show C-deficiency compared to calcite, in particular on their outer edges. It is possible that these low-C compositions resulted from CO_2 losses during ablation, which would also be consistent with pre-terrestrial origin. Finally, low-Ca pyroxenes are scarce (<2-3 per section), range from 50-100 nm, and are associated with rounded, forsteritic olivine grains (100-1000 nm across). Opaque nanophases are ubiquitous in all proximal FIB sections, with Fe-S-bearing rounded grains being the most common. However, none of these grains have the foliated textures characteristic of tochilinite. The degree of oxidation of Fe-S phases increases with weathering grade. In extensively weathered EET107(C)$_p$, the only grains that show no O-signatures are those that have continuous carbonaceous shells. Fe-oxides are also common in all proximal sections. EET062(Be)$_p$ also contains large (~1micron), Fe-oxide-carbonaceous aggregates. Finally, carbonaceous matter generally occurs as nanoglobules in proximal FIB sections or as 10s of nm-thick shells around Fe(Ni)-sulfides. However, EET105(B)$_p$ has a large (>2microns), amorphous carbonaceous lath, intercepted by acicular Fe-oxides.

TEM Observations of Distal 92XXX$_d$ FIB sections. Matrix in all distal sections has the typical CR matrices texture, namely abundant, amorphous Fe-Mg silicates and Fe-Mg phyllosilicates both of which have variable Fe/Mg ratios, Fe-(Ni)-S bearing nanophases, and abundant carbonaceous materials: (1) as (100-500 nm) nanoglobules, (2) finely distributed (<20 nm) materials within Fe-Mg amorphous silicates, (3) 10s-nm shells around nanophase Fe(Ni)-sulfides. Calcium is not as abundant as in the proximal FIB sections, only occurring as well-facetted, large (2 microns) Ca-carbonate in association with Fe-sulfides in EET161(B/C)$_d$. There are no signs of C-deficiency or other compositional heterogeneities. Ca-oxides very scarce and only observed in EET107(C)$_d$ – this low abundance is consistent with formation by ablation processes that did not affect the meteorites' interiors. There are three S-occurrences, rounded, nanophase (<50 nm) Fe(Ni) grains in all distal sections, pure Fe-tochilinite in EET062(Be)$_d$, and an intergrowth of Fe-tochilinite with two silicate layers in EET107(C)$_d$. As in the proximal sections, the degree of oxidation of Fe-S phases increases with weathering grade – with EET107(C)$_d$ Fe-S nanophases showing the highest degrees of oxidation. Fe-tochilinite in EET062(Be)$_d$ is made up of complex, tightly packed chains of randomly oriented crystals and of fine-grained filaments distributed throughout the section. In one occurrence, fibrous tochilinite is intergrown with carbonaceous materials and located on the periphery of a 1-micron Fe-oxide grain.

Discussion: Given that Ca-bearing phases, tochilinite, and Fe-oxides are known to be scarce in weakly altered CR chondrites, to which the EET 92XXX pairing group belongs [3], it is not surprising that some section may contain these phases while others do not. However, it is noteworthy that Ca-oxides and nanophase Fe-oxides are only observed in proximal sections and that tochilinite is only observed in distal sections. Ablation probably resulted in loss of volatiles from Ca-carbonates and tochilinite, resulting in the formation of Ca-oxides and the breakdown of tochilinite. Although Fe-sulfides and oxides in proximal FIB sections came in contact with terrestrial water, there are no signs of tochilinite formation. This suggest that the Fe-oxyhydroxide nanolayers in EET062(Be)$_d$ and EET107(C)$_d$ Fe-tochilinites are preterrestrial, and did not form by Antarctic weathering that resulted in Fe-oxyhydroxides around Fe-Ni metal grains. Instead, terrestrial weathering seems to result in progressive replacement of nanophase Fe(Ni)-sulfides with rounded, nanophase Fe-oxides, which are more common both in the proximal FIB sections and in sections with higher weathering grades. Finally, the only effect that terrestrial weathering seems to have on Fe-Mg amorphous silicates is localized, heterogeneously distributed, Fe-enrichments near occluded fractures and Fe-Ni metal nodules. No increments in phyllosilicate abundances are observed. In addition, there is no evidence of replacement of the Fe-Mg silicate globules formed by ablation.

Conclusions: The effects of weathering on CR chondrites are very heterogeneous and generally limited to the oxidation of both Fe-Ni nodules and matrix Fe(Ni)-nanosulfides. However, this oxidation probably did not form tochilinite. Chondrule mesostasis and matrix adjacent to weathered Fe-Ni nodules record localized Fe-enrichments. Matrix silicates and carbonaceous matter are at most minimally affected by terrestrial weathering. Finally, matrix materials are ablation processes at larger distances from the fusion crust. Ca-oxides may have formed by thermal decomposition of Ca-carbonates. These Ca phases were likely to have been extremely reactive even under Antarctic conditions and rapidly removed from the meteorites.

The spectral reflectance properties of CR chondrites are consistent with this petrographic examination: Fe oxyhydroxides are spectrally dominant, overprinting any pre-existing Fe silicate absorption features.

References: [1] Cloutis et al. (2012) *Icarus, 217,* 389–407. [2] Genge M. J. and Grady M. M. (1999) *MAPS, 34,* 341-356. [3] Abreu N. M. (2016) *GCA, 194,* 91–122.