MIL 07687 – AN INTRIGUING, VERY LOW PETROLOGIC TYPE 3 CARBONACEOUS CHONDRITE WITH A UNIQUE STYLE OF AQUEOUS ALTERATION Adrian J. Brearley, Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM87131, USA. e-mail: brearley@unm.edu

Introduction: Carbonaceous chondrites are among the most chemically pristine planetary materials available for study. They provide invaluable insights into the earliest history of our solar system, as well as geologic processes on small asteroidal parent bodies. One of the remarkable aspects of research on carbonaceous chondrites is the continued discovery of unique types of chondrites, particularly in samples collected in Antarctica. These meteorites add important, new constraints on the diversity of processes that contributed to the formation of these enigmatic meteorites. Here we report the mineralogical characteristics of a unique unequilibrated carbonaceous chondrite, MIL 07687, which was originally classified as a CO3 chondrite [1].

Methods: One polished thin section of MIL 07687 was studied by BSE imaging using a FEI Quanta 3D DualBeam® FEGSEM/FIB. Full spectral X-ray maps of the entire thin section were obtained using an EDAX Apollo 40 Silicon Drift Detector (SDD) EDS detector. Additional X-ray maps of individual chondrules and regions of matrix were also obtained. FIB sections for TEM analysis were prepared from selected regions of matrix using the FEI Quanta 3D. FIB samples were removed from the thin section using the in situ lift out technique with an Omniprobe 200 micromanipulator

Results: MIL 07687 has the typical textural characteristics of a low petrologic type carbonaceous chondrite. It consists of fine-grained matrix in which coarser-grained components such as chondrules, refractory inclusions and mineral fragments are embedded. Based on modal analysis of combined X-ray maps using Adobe Photoshop® CS4, MIL 07687 has the surprisingly high abundance of matrix of 68±3vol%, measured on an approximately 9.5 x 6.5 mm thin section. Coarser-grained olivine and pyroxene in chondrules and mineral fragments constitute ~23 vol% of the meteorite. The chondrule population is dominated by Mg-rich type IA and IAB chondrules; type IIAs are in relatively low abundance. Most chondrules are irregular to subrounded in shape and chondrule fragments are common. Chondrule sizes are variable; most chondrules are <500 µm in size, ranging down to <100 µm, however, rare, larger chondrules up to a millimeter in size are present in the thin section. Chondrule glass is present in many chondrules, but shows evidence of minor dissolution and replacement where glass is in direct contact with matrix. Unlike CO3 chondrites, fine-grained rims around chondrules etc., are extremely rare and, if present, are poorly defined.

Refractory inclusions are rare in MIL 07687. Three small, (200-300 µm) melilite-rich, spinel-bearing inclusions were found in the thin section, one of these being enclosed within an AOA. In addition, 22 very small CAIs (<70 µm) in size, dominantly melilite-rich, were also identified by X-ray mapping. In addition, ~50 ameboid olivine aggregates, ranging in size from <100 µm up to a maximum of ~600 µm in size were also identified. Most AOAs lie in the range 200-350 µm.

Matrix: Matrix is texturally and mineralogically complex in MIL 07687. BSE imaging shows that matrix consists of highly irregular-shaped regions, a few hundred microns to a millimeter in size with distinct contrast in BSE images (Fig. 1). These variations are primarily due to variations in Fe content. The relationships between these different regions of matrix are complex. Typically, the more Fe-rich regions embay and finger into the Fe-poor matrix regions and the boundary between the two regions is frequently defined by a distinct Fe-enriched zone ~30-50µm in width.

SEM imaging of the two distinct regions of the matrix show that they have textural characteristics which are unusual for a CO3 chondrite. Most regions of matrix are characterized by a high abundance of a fibrous phase which occurs as randomly oriented crystallites or radiating sets of fibers, that are up to 5 µm in the length

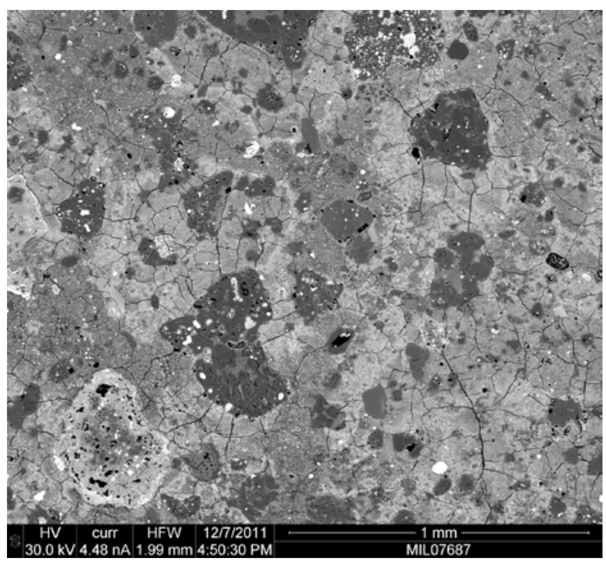

Figure 1. BSE image of characteristic region of MIL 07687 showing the relationship between distinct regions of matrix, Fe-rich and Fe-poor. The Fe-rich matrix regions are dominated by fibrous Fe oxyhydro-oxides, whereas the darker gray, comparatively Fe-poor regions of matrix appear to be unaltered and have more pristine textural characteristics.

and typically <0.5 µm in thickness. Other finer grained phases occur interstitially to the fibrous phase, but are too fine-grained to resolve by SEM.

TEM samples of regions of matrix containing the fibrous phase were prepared using FIB techniques. TEM studies show that the fibrous phase occurs as elongate grains, up to 2.5 µm long, but <0.2 µm in width, which appear to have overgrown irregularly-shaped, lower Z-regions that vary in size from 0.1 to 1.4 µm in their largest dimension. EDS analysis shows that the fibrous phase is very FeO-rich and is compositionally variable with a range as follows: FeO=74-92 wt%, SiO_2 =1-11 wt%, MgO = 0.2-10 wt%, S=0.5-5 wt%, Al_2O_3 = 0.1-3.2 wt% and NiO = 0.8-6 wt%. High resolution TEM shows that the fibers are not well-formed single crystals, but consist of slightly misoriented, nanoscale domains or nanocrystallites. In some grains, the domains are parallel to subparallel and diffract relatively coherently to provide a diffuse single crystal diffraction pattern. However, other grains consist of randomly-oriented nanocrystallites that give ring electron diffraction patterns. Analysis of the diffraction data for the FeO-rich phase has not yet provided a definitive identification. However, the data are most consistent with either ferrihydrite or akaganéite. Surprisingly, no phyllosilicate phases occur in the matrix.

Ca-sulfate grains up to 60 µm in size occur distributed randomly through the matrix at an abundance of ~1 vol%. FEGSEM imaging shows that many of the Ca-sulfate grains have partially replaced Ca-carbonate grains to different degrees. Ca-sulfate also occurs as very thin veins (<3 µm in width) at the interface between some chondrules and the surrounding matrix. These veins are discontinuous, but can extend for up to 200 µm. These veins may be due to terrestrial weathering, however, there is no evidence that the veins are more abundant close to the fusion crust that is present on one edge of the thin section.

Discussion: MIL 07687 exhibits several unusual characteristics which indicate that it is not a CO3 chondrite. First, MIL 07687 has an unusually high abundance of matrix which lies outside the normal range for CO chondrites. Average CO3 chondrite abundance is 34 vol% [2], c.f. ~68% for MIL 07687. Second, fine-grained rims that are abundant in CO3 chondrites [3] are essentially absent in MIL 07687. Third, the abundance of refractory inclusions, particularly AOAs, is much lower in MIL 07687 than in CO chondrites.

MIL 07687 shows no detectable evidence of thermal metamorphism and is certainly a type 3.0 chondrite. There is no evidence of metamorphic zoning in olivines, mesostasis is glassy in all chondrules studied and ferroan olivines show no evidence of exsolution of fine-scale chromite, when imaged by FEGSEM. The Cr_2O_3 content of ferroan olivines remains to be determined by EPMA to confirm the exact classification, but all indications are that a very low petrologic type classification is likely, certainly <3.05 [4].

MIL 07687 provides a unique view of aqueous alteration in carbonaceous chondrites and appears to represent a very rare example of a chondrite that records a state of partial alteration of fine-grained matrix. Based on textural and mineralogical characteristics, the Fe-rich matrix appears to represent aqueously-altered material, whereas the Fe-poorer material is the relatively unaltered protolith. This interpretation is consistent with the fact that the Fe-rich regions of the matrix consist largely of the fibrous Fe-oxyhydro-oxide phase, whereas the less Fe-rich matrix has a much finer-grained, heterogeneous texture, that more closely resembles matrix in unaltered pristine chondrites such as ALHA 77307 [3]. TEM studies of these regions of matrix are in progress to determine if this interpretation is correct. It is unusual that such heterogeneous degrees of alteration are present locally within the same meteorite, but implies that the availability of water was highly localized, rather than being pervasively distributed throughout porosity. The Fe-rich boundary zones between altered and unaltered matrix may represent reaction fronts similar to those surrounding altered metal grains in CM2 chondrites [5].

Conclusions: MIL 07687 is a unique type 3.0 chondrite that has experienced a highly unusual alteration history. The matrix has only been partially altered and boundaries between altered and unaltered matrix are readily observable. The meteorite therefore preserves a record of the aqueous alteration process while it was in progress. The widespread presence of fibrous Fe-oxyhydro-oxides in the matrix indicates that alteration occurred under highly oxidizing conditions. Oxidizing conditions are also indicated by replacement of Ca-carbonate by Ca-sulfate, i.e. that sulfate was a common ion in the altering solutions. Even though alteration of matrix was extensive in many regions, chondrule glass shows minimal evidence of alteration. This observation indicates that chondrule glasses only begin to show significant evidence of alteration after advanced hydration of the adjacent matrix.

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