A FIB/TEM STUDY OF THE MATRIX MINERALOGY OF CV3-REDUCED GROUP METEORITES. L. P. Keller[1] and J. Han[2], [1]ARES, Code XI3, NASA-JSC, 2101 NASA Parkway, Houston, TX 77058, USA (Lindsay.P.Keller@nasa.gov), [2]Department of Earth and Atmospheric Sciences, University of Houston, Houston TX, 77204, USA.

Introduction: The CV3 carbonaceous chondrites are subdivided into oxidized and reduced subgroups based on the chemistry and mineralogy of their opaque phases [1]. The reduced members have been minimally affected by thermal metamorphism and aqueous alteration and so appear to be mineralogically more primitive than the more altered oxidized subgroup, although several of the CV(red) group members are deformed with a fabric defined by flattened chondrules and inclusions. Despite the deformation, the mineralogy and petrography of the reduced group provides key data on nebular and parent body processes that were operating in the early solar system. Previous studies have investigated the matrix mineralogy of Leoville [2] and Vigarano [3,4]. Here we report results from a transmission electron microscope (TEM) study of the matrix mineralogy of two other members of the subgroup, Efremovka and Thiel Mountains (TIL) 07003.

Materials and Methods: We studied thin sections of the reduced CV3 chondrites Leoville, Efremovka, and TIL 07003 [5], and Vigarano. For Efremovka and TIL 07003 we extracted focused ion beam (FIB) electron transparent thin sections from matrix regions using a FEI Quanta 3D FIB instrument. For Leoville and Vigarano, we analyzed ion-milled sections. We used a JEOL 2500SE field-emission STEM to obtain images, electron diffraction data, and quantitative energy-dispersive X-ray (EDX) analyses and maps from the samples.

Results: The matrix of the CV3(red) samples is dominated by fine-grained (<1 μm), equant grains of ferroan olivine, with lesser coarser-grained Mg-rich low-Ca pyroxene, Ni-rich metal, and tiny hercynite-chromite-spinel grains. Typically, the olivine grains are deformed and show high dislocation and defect densities as noted by [4] in Vigarano. The matrix olivines exhibit a narrow compositional range between Fo40-Fo50 in Leoville, and TIL 07003, while those in Efremovka are more forsteritic and cluster around Fo55. The areas around and between larger μm-sized olivines are commonly filled by much finer (~0.1 μm) olivine grains (Fig. 1).

Enstatite occurs as rounded grains and plates that are typically 0.5-1 μm in size; electron diffraction and HRTEM data indicate a mixture of ortho- and clinopyroxene intergrown on a fine scale. The enstatite microstructures in Leoville matrix likely result from deformation effects as suggested by [6], although they may also represent the inversion of protoenstatite to mixtures of clino- and orthoenstatite on cooling from high temperatures. Fine-grained enstatite grains in TIL 07003 show higher Fe abundances (up to 3-4 at.% Fe) compared to the coarser-grained crystals (<0.5 at.% Fe).

Fe,Ni metal is the dominant opaque phase in CV3(red) matrix and shows varying grain sizes, while FeNi sulfides are uncommon. Most of the metal grains are submicrometer in size and consists of taenite (with 40-55 at.% Ni) and lesser kamacite (~5 at.% Ni). The matrix metal in these meteorites shows an unusual morphology occurring as highly anhedral grains with numerous embayments and reentrant features (Fig. 2). The larger metal grains are typically polycrystalline.

Tiny (~10-50 nm) spinel grains are common and widely distributed in CV3(red) matrix. The spinel compositions are solid solutions of hercynite-chromite-spinel, with Mg/Mg+Fe (at.) values clustering around 0.30. The Al/Al+Cr (at.) values are 0.9 in Efremovka, while those in TIL 07003 are more Cr-rich at 0.6. Many of the hercynites are too small to get accurate analyses without contributions from surrounding olivine in the FIB sections. The CV3(red) meteorites lack the feldspathoids (nepheline, sodalite) that are common in the oxidized subgroups, and also lack the Fe-rich and Ni-rich phases such as hedenbergite, fayalitic olivine (Fa>60), magnetite, pentlandite and high-Ni taenite (awaruite) that are common in the oxidized CV chondrites.

Both Vigarano and Efremovka contain minor fine-grained phyllosilicates in pore spaces between matrix olivine grains. The phyllosilicates show 1 nm basal spacings in high-resolution TEM images and are consistent with smectite group clays. The phyllosilicate abundance is much less than that observed in members of the Bali-like CV3 oxidized subgroup [7]. We have not observed evidence for aqueous alteration products in Leoville or TIL 07003.

Discussion: Matrix olivine compositions in the CV3(red) meteorites are fairly homogeneous and are consistent with thermal equilibration facilitated by their small grain sizes. The fine-grained hercynites are also homogeneous with respect to Mg#. The coarse-grained Mg-rich enstatites have not incorporated significant Fe consistent with the much slower diffusion rates for MgFe exchange in pyroxene compared to olivine [8]. The assemblage of ferroan olivine, enstatite and FeNi metal in CV3(red) matrix shows that it is mineralogically very primitive consistent with petrologic types <3.3. Abreu and Brearley [4] proposed that ferroan olivine in Vigarano matrix may have formed by thermal metamorphism of early formed amorphous silicates similar to those in the matrix of primitive CR chondrites. However, annealing of amorphous silicates typically results in polycrystalline grains showing equilibrium grains boundaries [e.g., 9, 10] that are not observed in the matrices of the meteorites in this study. We hypothesize that the the matrix mineralogy reflects formation and growth of these phases in the nebula, followed by limited parent body thermal effects that homogenized olivine compositions (although we recognize that the equilibrium condensation of ferroan olivine in the nebula is problematical e.g., [11]). The fine-grained olivine surrounding the coarser grains in matrix (Fig. 1) were likely formed in the same deformation event that flattened chondrules and inclusions by mechanical grinding between grains during the compression of matrix pore spaces.

The morphology of matrix metal grains (Fig. 2) is another unusual feature of this group of meteorites and either reflects the primary growth mode of the grains or represents an etching/erosional process by oxidizing parent body fluids. Support for the latter interpretation comes from the presence of curvilinear equilibrium grain boundaries internally compared to the irregular external boundaries. These features suggest annealing in the nebula or on the parent body, followed by dissolution from the exterior of the grains during aqueous alteration. The alteration of metal may have provided Fe to equilibrate olivines (and producing more Ni-rich metal in the process). We are exploring this hypothesis with more detailed analyses of the metal particle surfaces.

Minor amounts of phyllosilicates occur in Efremovka and Vigarano, but are lacking in the other analyzed members of the group. The lack of abundant aqueous alteration products in these meteorites implies a limited availability of fluids or that the low porosity in these matrices inhibited fluid access.

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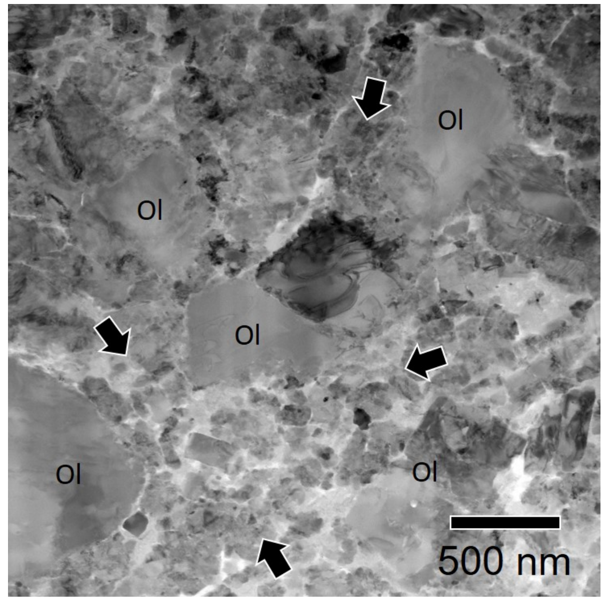

Figure 1. A brightfield STEM image from Efremovka matrix showing larger matrix olivine grains (“Ol”) surrounded by much finer grained olivines (arrows).

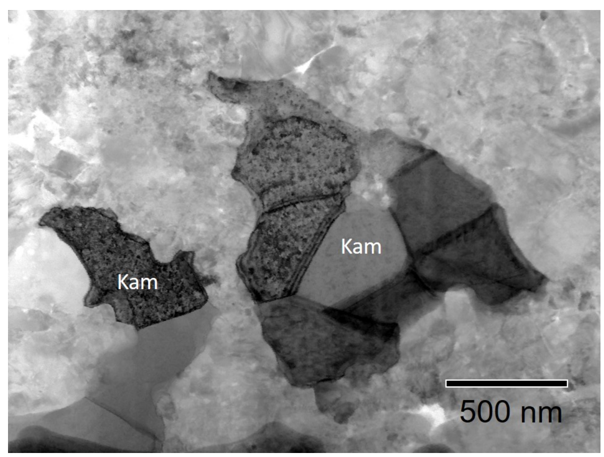

Figure 2. A brightfield STEM image of irregularly shaped kamacite grains (“Kam”) with reentrant and scalloped surfaces.