MICROSTRUCTURAL RECORD OF EVOLVING CONDENSATION PROCESSES IN FINE-GRAINED Ca-Al-RICH INCLUSIONS FROM THE REDUCED CV3 CHONDRITES.

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Introduction: Fine-grained, spinel-rich Ca-Al-rich inclusions (FGIs) in carbonaceous chondrites consist of numerous layered nodules having cores of spinel, hibonite, and/or perovskite surrounded by multiple thin layers of melilite, anorthite, diopside, and/or olivine [e.g., 1,2]. They are interpreted as aggregates of direct high-temperature condensates from an ^{16}O-rich nebular gas that escaped significant melting [e.g., 3,4]. However, FGIs are very complex objects composed of intimate intergrowths of fine-grained refractory phases and show extremely large variations in mineralogy, modal abundance, and textures. Thus, detailed FIB/TEM analyses of FGIs are required to fully characterize their micro-to-nanometer scale textures, mineralogy, and chemical compositions and hence elucidate their formation processes and conditions in the early solar nebula. Here, we present our on-going study of pristine FGIs from the reduced CV3 chondrites Efremovka and Thiel Mountains (TIL) 07003 and 07007 that have minimal evidence for secondary parent body alteration [5].

Methods: We identified six FGIs from Efremovka using a JEOL 7600F SEM at NASA JSC [6]. We used a FEI Quanta 3D SEM/FIB in order to document the detailed petrologic and mineralogical characteristics of FGIs from Efremovka and to prepare TEM sections from them. The sections were examined in detail using a JEOL 2500SE field emission scanning TEM equipped with a Thermo-Noran thin window energy dispersive X-ray spectrometer. In addition, eleven FGIs from TIL 07003 and twelve FGIs from TIL 07007 were identified and studied their petrology and mineralogy using a JEOL JXA-8530F EPMA at KOPRI.

Results & Discussion: The FGIs from Efremovka and TIL 07003 and 07007 are irregularly-shaped, often elongated inclusions (up to ~4 mm in size) that share the basic internal structure consisting of numerous nodules of a core of spinel ± hibonite ± perovskite, each nodule is surrounded by thin sequential layers of ±melilite, ±anorthite, and pyroxene. None of the FGIs are porous. Significant variations in mineralogy, modal abundance, and nodule size and shape among the inclusions are observed. Five inclusions from TIL 07003 and six inclusions from TIL 07007 show a mineral zoning with a distinct core-mantle structure. Only seven inclusions (one from TIL 07003 and six from TIL 07007) are surrounded by an olivine-rich accretionary rim.

Our preliminary SEM and TEM analyses of FGIs from Efremovka and TIL 07003 and 07007 are consistent with their condensation origin. We infer the evolving sequence of high-temperature condensation and gas-solid reactions that grew single grains into layered nodules: perovskite condensation > hibonite condensation > spinel formation by reaction of hibonite + $Mg_{(g)}$ > Al,Ti-pyroxene formation by reaction of spinel + perovskite + $Si_{(g)}$ > zoned melilite formation by reaction of spinel + $Si_{(g)}$ + $Ca_{(g)}$ > zoned pyroxene formation by reaction of melilite + spinel + $Si_{(g)}$ + $Mg_{(g)}$ ± $Ti_{(g)}$ ± perovskite > forsteritic olivine condensation > anorthite replacing melilite + Al-diopside. All the reactions did not go to completion, protecting underlying grains from further back reactions [7]. This inferred mineral formation sequence differs from that predicted by thermodynamic calculations, suggestive of disequilibrium conditions during CAI formation. The first inconsistency between the observed vs. predicted mineral condensation sequence is the complete absence of corundum as the first phase to form in FGIs, suggesting that minor corundum condensed first and reacted completely with $Ca_{(g)}$ to form hibonite [8]. However, corundum as the first condensate must form by homogenous nucleation, which requires a nebular gas at temperatures higher than hibonite condensation for a long time [9]. Thus, rapid cooling of a nebular gas may have suppressed homogenous nucleation of corundum, instead allowed the gas to cool into the temperature ranges of perovskite and hibonite condensation [10]. The second inconsistency addresses a long-standing question regarding spinel formation before melilite. The presence of stacking defects in hibonite and its crystallographic orientation relationships with adjacent spinel suggest that spinel formation after hibonite and before melilite was kinetically controlled process due to their structural similarity [10].

Detailed FIB/TEM analyses, as well as coordinated O and Mg isotopic study using SIMS and NanoSIMS, of FGIs in Efremovka and TIL 07003 and 07007 are under way, in particular to better understand the origin and nature of the observed mineral zoning in some FGIs.

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