FINE-GRAINED CAIS AT THE NANOMETER SCALE: DISCOVERY OF A PRISTINE AGGREGATE OF SUB-µM CONDENSATES

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Introduction: Based on equilibrium thermodynamic calculations, the first solar system rocks are believed to have formed by gas-solid condensation from a gas of solar composition [1,2]. The refractory Ca-Al-rich inclusions (CAIs) from chondritic meteorites, the oldest rocks formed in the solar system, thus formed from high temperature condensate precursors having experienced a subsequent complex thermal history including multiple reheating events up to partial melting. In that respect, fine-grained CAIs with aggregate nodular textures, are widely believed to be preserved aggregates of early solar system condensates [3]. However, their fine grain size render them sensitive to secondary modifications by reheating or late fluid circulations on the parent-body. In order to better understand the nature of the first solar system condensates and to confront natural samples with the predictions of thermodynamics, we initiated a Transmission Electron Microscopy (TEM) study of several fine-grained CAIs from the barely metamorphosed reduced CV3 chondrite Efremovka. Here we report the discovery and the mineralogical characterization of an unusual fine-grained CAI E045-V.

Methods: High-resolution BSE images and X-ray maps of E045-V were obtained with field emission gun scanning electron microscopes (IMPMC Paris, ICMMO, Orsay). Several FIB sections (about 5 to 15 µm) were extracted from the CAI and thinned down to ~100 nm for TEM characterization using the 30 keV focused gallium ion beam at IEMN (Lille, France). Using a 200keV TEM (IMPMC, Paris), chemical analyses, X-ray mapping, Z-contrast imaging and conventional TEM imaging has been performed in order to characterize the CAI sections.

Results: E045-V is about 1.5 mm by 500 µm. It is composed of three different lithologies: (1) a compact extremely fine-grained core, (2) a mantle enriched in volatiles including Fe, Na and Si and (3) local inclusions of classical core-mantle spinel-melilite nodules. The compact fine-grained core is an extremely complex aggregate of 1 to 2 µm concentrically-zoned polymineralic nodules showing grains with sizes from 10 to 200 nm. Some crystals have perfectly euhedral shape while others have rounded shape. Triple junctions were sometimes observed. From core to rim the mineralogical sequence of individual nodules includes spinel, melilite, Ca-rich clinopyroxene and a Mg-Si-rich amorphous layer. The composition of pyroxene is extremely heterogeneous and varies from almost pure diopside to Ti-Al-rich fassaite at a sub-µm scale. Some nodules can be Ti-free while other could contain Al-Ti rich fassaite. Melilite contains up to 20 at% Mg. Fe content of the spinels can be up to 2 wt% independently of the spinels location. Fe-rich spinels and Fe-free spinels can be found at the center of nodules sometimes within a µm from each other. The nodules are cemented by interstitial anorthite. Euhedral crystals of zoned olivine with Fe-enriched rim are interspersed between the nodules. It is noticeable that some nodules contain multiple cores.

Discussion and conclusion: None of these observations have previously been reported in the literature. All crystals properties are very similar to those reported in experimental condensation [4], including crystal sizes, shapes and chemistry. This indicates that the E045-V CAI core is the most pristine condensate assemblage reported to date and can be used to shed light on the conditions of condensation. (1) The mineralogical sequence is close to that expected by equilibrium condensation with the exception of spinel, which appears to be the first phase to condense, most likely as a result of a kinetic control. (2) The amorphous rim observed around the nodules is an additional indication of incomplete equilibrium process. Its preservation testifies of a minimal secondary alteration of the nodules. (3) The presence of Fe-rich spinel inside unaltered nodules suggests either disequilibrium during condensation or more oxidizing conditions than expected in the inner disk [e.g. 1]. (4) Finally, the presence of multiple cores within single nodules indicates that coagulation of grains occurred as condensation proceeds. As a result, a thorough investigation of growth rates should give informations about the grain density in the inner protoplanetary disk.

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