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The First Solar System Solids as Revealed Through Slice-and-View Imaging

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Introduction: Calcium-aluminum-rich inclusions (CAIs) are among the most significant materials within chondritic meteorites. In general, they are the largest physical objects in these primitive rocks, with some reaching centimeter sizes and being visible with the naked eye in hand specimens. They are composed of mineral phases that form at very high temperatures and which are predicted by thermodynamic models to be among the first solids to have condensed within a cooling gas of solar composition [e.g., 1]. Further, they have radiometric age dates that exceed those of all other solar materials [2]. CAIs therefore represent the first solids to have formed within our solar system, and analysis of them can provide a glimpse into the some of the earliest chemical and physical processes to have transpired during its formation [3-5].

The optical microscope and electron and ion microprobes have been used extensively to tease out information on the compositional properties of CAIs and have provided a wealth of information on them. Though steadily increasing, there are comparatively few studies that have investigated the microstructural aspects of refractory inclusions. With the advent of the focused-ion-beam scanning-electron-microscope (FIB-SEM) as a viable mineralogic tool [6] site-specific detailed analysis of CAI microstructure is possible. Here we apply FIB-SEM and slice-and-view imaging to reveal CAI microstructure in three dimensions.

Samples and Methods: We examined a fluffy type-A CAI previously identified in a petrographic thin section of the Allende CV3 chondrite. This sample was chosen in order to investigate the microstructure of an inclusion believed to have formed via condensation in the early solar nebula. We used the FEI Helios 660 FIB-SEM located at FEI headquarters to slice and image a local region of the CAI measuring 30 μm wide. Each slice measured approximately 10 nm thick and a total of 410 slices were made. The image resolution is 3072 × 2048 pixels with pixel dimensions of 10 nm × 13 nm × 10 nm for a total voxel size of 1300 nm^3. Backscattered electron (BSE) images were acquired using an acceleration voltage of 2 keV and probe current of 800 pA.

Results and Discussion: The local area that was measured is shown in Figure 1. This area is composed of the accretionary rim (AR) and the multi-layered shell around the CAI known as the Wark-Lovering Rim (WLR). The surface region of interest selected for slice-and-view measurements is composed of several mineral phases including pyroxene [$(Mg,Fe)SiO_3$], anorthite ($CaAl_2Si_2O_8$), melilite [$(Ca,Na)_2(MgAl)(Si,Al)_2O_7$], spinel ($MgAl_2O_4$), and hibonite ($CaAl_{12}O_{19}$). The pyroxene is the thickest surface layer (≈13 μm) in this area of the WLR sequence followed by anorthite (≈5 μm to 7 μm) and the spinel layer that is separated by smaller (<5 μm) subhedral melilite grains.

A series of BSE images acquired from the slice-and-view data set are shown in Figure 2. The surface of the thin section occurs in the bottom of the image and reveals an undulating topology. Pyroxene is the thickest layer (≈10 to 13 μm) in all slices of the data set, mirroring the trend observed at the surface and suggesting that its volume is relatively constant around the inclusion. Anorthite and melilite grains occur on the right-most edge of the pyroxene layer and vary in size, from several μm to not appearing, through the image stack. Small (≤ 2 μm) grains of melilite and anorthite also occur within the pyroxene layer throughout the image stack.

Several formation pathways have been proposed for the origins of WLRs around CAIs. These include condensation, metasomatic exchange, and flash heating, e.g., [3-5]. Pyroxene and melilite are considered primary phases formed via condensation in the early solar nebula, whereas some anorthite has been interpreted to form via secondary metosomatic alteration [3]. Previous analysis of this inclusion suggests that the pyroxene layer formed via condensation [7]. That we find anorthite and melilite inclusions within the pyroxene throughout the image stack points toward these phases having formed first, most likely via condensation, followed by nucleation of pyroxene around them. Examination of additional CAIs will reveal whether the observations made here are unique to this sample or are common to other type-A inclusions and thus indicative of broader scale processes within the solar nebula.

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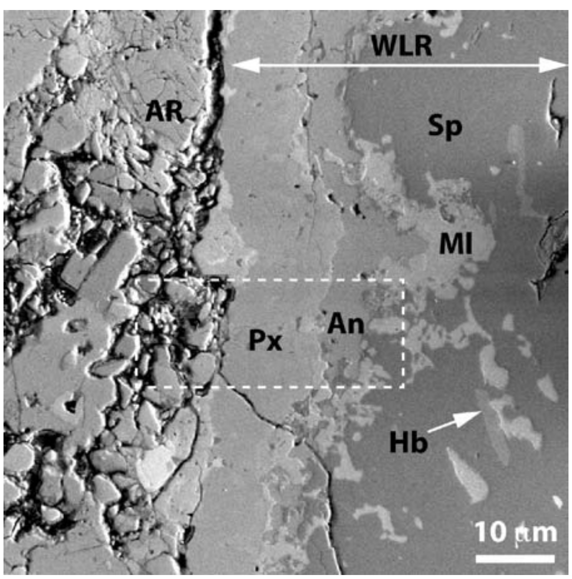

Figure 1. BSE image of the WLR and CAI as viewed from the surface. Area measured with slice-and-view imaging outlined by the white rectangle. Spinel (Sp), melilite (Ml), anorthite (An), pyroxene (Px), and hibonite (Hb) occur in the WLR adjacent to the accretionary rim (AR).

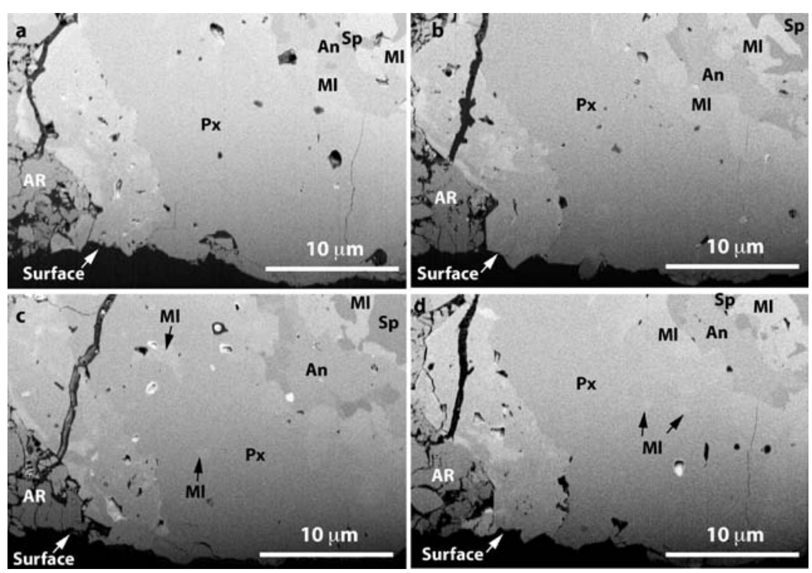

Figure 2. BSE images of several slices of the area shown in the white rectangle in Fig. 1.

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