MICRO-MINERALOGY OF CALCIUM-ALUMINUM-RICH INCLUSIONS FROM ALLENDE.

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High resolution scanning electron microscope (SEM) observations of separated phases from Ca-Al-rich coarse-grained inclusions from Allende have revealed a fascinating wealth of micron-size mineral inclusions whose structures are not only eye-catching but uniquely informative as well. Such varied mineralogies as 0.4 μm perovskite hexagons on spinel or 1 μm spinel pyramids on hibonite as well as 0.1 μm Fe grains inside vesicles in melilite and Ni-Fe particles in spinel raise questions concerning the formation of coarse-grained inclusions which existing models cannot answer. The texture of micron-size crystals and their grain-to-grain contacts generally argue for condensation, while the mineralogy of neighboring phases is often more consistent with liquid crystallization.

We have examined five coarse-grained Allende inclusions, using crystals hand-picked from the same mineral separates used in oxygen isotope (1) and trace element (2) studies. Minerals were identified with a solid state x-ray analyzer.

The most striking feature we have observed is the ubiquitous presence of small perovskite crystals ranging in size from < 0.1 μm to 10 μm, epitaxially grown on the exterior surfaces of euhedral spinel grains. Perovskite is most abundant in Al 1-16, a Type A inclusion (3) in which spinel is originally poikilitically enclosed by melilite. Numerous spinels survive the mineral separation with their original surfaces intact and it is these pristine external surfaces which are invariably covered by epitaxial perovskite crystals. The spinel grains themselves are sharply euhedral, showing no evidence of rounded edges due to reaction with enclosing melilite. The variety of perovskite morphologies (ranging from hexagons to pyramids to laths) and the distribution of numerous, independently nucleated perovskite crystals across spinel surfaces strongly suggest growth by condensation. The substantial gaps at phase boundaries, particularly between perovskite and overlying second generation spinel, also would not be expected with crystallization from a liquid. As convincingly as these textural arguments in favor of condensation may be, we are faced with the problem that the observed sequence of mineral formation, spinel-perovskite-spinel-melilite, does not agree with the equilibrium condensation model (4). The mineralogy appears to favor liquid crystallization (5).

Although SEM observations show that perovskite occupies up to ~10% by volume of spinel, perovskite was not detected on x-ray powder spectra of the spinel separate (1, 2). Trace element abundances reported for "pure" spinel phases may well be affected by perovskite contamination.

Perovskite grown epitaxially on spinel is also found in NNNH 3666, a Type B inclusion (3). Spinel is included within Ti-bearing pyroxene and separated crystals have a rounded-euhedral appearance with facets not nearly so sharp as on Al 1-16 spinel. Perovskite appears as hexagonal platelets.
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(£ 0.4 μm in size) and as hemispherical mounds with no clear crystalline structure. The rounded spinel edges and distorted perovskite morphology may indicate reaction with encompassing spinel. In both Al 1-16 and NMNH 3666 perovskite is observed only on original, external spinel faces. Spinel and perovskite cannot have co-crystallized and the texture fixes the mineral formation sequence: spinel-perovskite-pyroxene. The observed sequence again fails to agree with the predictions of equilibrium condensation (4).

Except for the distinctly sharp-cornered spinels in Al 1-16 spinels from all inclusions, enclosed in either pyroxene or melilite, have nearly identical appearances, rounded-euhedral. Spinels from the remaining three inclusions do not, however, show any evidence of perovskite on their external surfaces. This absence of previously ubiquitous perovskite is not understood. Perhaps perovskite originally condensed on these spinels but has subsequently reacted.

A limited sequence of formation is also indicated by the mineralogy of Al-NO-1 and Al-NO-2. These are unusual inclusions because both contain significant amounts of hibonite. Most of the hibonite is intergrown with spinel, perovskite, and anorthite with grain sizes < 10 μm, but we have observed a few euhedral single crystals of hibonite up to 50 μm in size. On the external surfaces of these crystals we find epitaxial growths of small spinel crystals. In contrast to previous studies (5) the order of mineral formation is clear-hibonite followed by spinel- and actually agrees with the predictions of condensation theory (4). No evidence of pure Al₂O₃ was found in either inclusion, suggesting that hibonite instead may have been the initial condensate. Large single crystals of hibonite from these two inclusions would be good candidates for Mg isotope measurements.

The final inclusion studied—Al384, a large Type B inclusion—contains several features which are difficult to fit into any theory of formation but are indicative of the complexity of coarse-grained inclusions if one looks sufficiently hard. Melilite crystals (> 100 μm in size) from the rim of Al384 contain numerous spherical vesicles ranging up to 50 μm in diameter. The vesicles themselves contain either triangular arrays of triangular Fe grains < 0.1 μm in size or a large variety of unidentified Mg, Fe-rich crystals. The vesicles may be a remnant of post-formation metamorphism which redistributed trace elements in this inclusion (2). The interior crystals may have grown from a vapor or by exsolution.

The microscopic Fe grains lining some vesicles are nearly pure Fe (< 2% Ni). In contrast a metal particle ~10 μm in size protruding out of the side of a euhedral spinel crystal in Al384 is 60 to 70% Ni. No refractory siderophile elements were detected with a solid state analyzer. Although the Ni-Fe particle has not reacted with the spinel and we observe a gap at the Ni-Fe spinel interface, it is extremely difficult to form this Ni-Fe particle by condensation. Such Ni-rich metal should not condense from a gas of solar composition. This particle has nearly the same composition as metal grains in the matrix, identified as Ni₃Fe (6); a similarity unlikely to be simply fortuitous.
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These SEM observations illustrate the variety and complexity of Ca-Al-rich coarse-grained Allende inclusions on a micron-scale. The numerous small-scale features revealed by the SEM cannot be produced in a single formation event but are the signature of subsequent metamorphic alteration. The identity of the $^{16}O$ carrier phase remains a mystery. None of the spinel crystals containing anomalous oxygen show any evidence of incorporated extraterrestrial material at a resolution of 200Å. Any extra-solar additive must have reacted with the spinel and lost its characteristic identity.

An alternate scenario is suggested by the observations of Al 1-15. The textural evidence is strongly suggestive of condensation, yet the mineralogy favors crystallization. One way to resolve this dilemma and at the same time supply $^{16}O$ to Allende is to form the spinels themselves elsewhere in an $^{16}O$-rich environment and then bring them to the Allende site. The first phase to condense (onto existing spinel) would be perovskite, followed by spinel and then melilite. This condensation sequence correctly accounts for the observed mineral relationships in Al 1-15.

References: