ARE CAI's CONDENSATES OR DISTILLATION RESIDUES?
EVIDENCE FROM A COMPREHENSIVE SURVEY OF FINE- TO MEDIUM-GRAINED INCLUSIONS IN THE ALLENDE C3(V) CARBONACEOUS CHONDRITE. Alan S. Kornacki, Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, and Department of Geological Sciences, Harvard University, 24 Oxford Street, Cambridge MA 02138.

Ca,Al-rich inclusions (CAI's) in carbonaceous chondrites have been the subject of unprecedented study since it was recognized that their refractory minerals probably formed at high temperature during the early history of the solar system (1). Research has been concentrated on coarse-grained CAI's (often, cm-sized objects with mm-sized mineral grains). Proponents of the equilibrium condensation model interpret some or all of these as primitive, high-temperature condensates from the cooling solar nebula (2). The preoccupation with coarse-grained CAI's has been such that an unbiased, detailed, comprehensive survey of all inclusions in a carbonaceous chondrite has never been made. The preliminary results of a survey of this type are reported here. They suggest that distillation of precondensed material was an important process in the early solar system.

The textures and mineralogy of 147 fine- to medium-grained inclusions in 16 polished thin sections of the Allende C3(V) carbonaceous chondrite were studied by optical and scanning electron microscopy. Individual mineral grains are generally smaller than 0.1 mm in these inclusions. This population, which makes up 5.3 vol % of the meteorite, excludes all chondrules, individual mineral grains, assemblages of opaque minerals, and fragments of any of the three previous types of objects. It includes all other objects with diameter ≥0.1 mm. In general, these correspond to those objects previously described as amoeboid olivine aggregates (3) or fine-grained CAI's (4).

The 147 inclusions studied can be classified into five types on the basis of their textures and mineralogy. Inclusions intermediate to these types are also present. Since the inclusions grade into one another, they appear to be a suite of related objects:

Type 1 inclusions (45 observed; 2.0 vol %) are aggregates that consist of rimmed pebbles, droplets, shards, and fragments of Ca,Al-rich minerals (such as Fe-bearing spinel, perovskite, hibonite, anorthite, grossular, andradite, diopside, hedenbergite, and Ti,Al-pyroxene); two feldspathoids (nepheline and sodalite); and olivine. These are set in a porous matrix of Fe-enriched olivine, diopside-pyroxene, and feldspathoids. Small amounts of (Fe,Ni) metal and sulfides, ilmenite, and chrome are present. Type 1 inclusions can be characterized as fine-grained, olivine-rich CAI's.

Type 2 inclusions (14 observed; 0.2 vol %) are invariably delicate, elongate inclusions that consist almost entirely of the porous, fine-grained olivine, pyroxene, and feldspathoid matrix of the Type 1 inclusions. Type 2 inclusions can be characterized as fine-grained, olivine-rich aggregates.

Type 3 inclusions (12 observed; 1.1 vol %) consist of long, convoluted strings of pebbles enriched in Ca,Al minerals. These are more coarse-grained than Types 1 and 2; this and their prominent banding contribute to give them a "wormy" appearance. The pebbles have cores of melilite+Mg-spinel+perovskite intergrowths rimmed by anorthite+grossular, several pyroxenes, feldspathoids, andradite, and olivine. Occasional grains of metal, sulfides, and ilmenite are found. Type 3 inclusions can be characterized as fine- to medium-grained, olivine-poor CAI's.
Type 4 inclusions (16 observed; 0.3 vol%) consist of individual Ca,Al-rich objects whose morphology and texture seem to indicate that they were once molten. These generally spherical objects have cores and rim sequences that closely match those of the Type 3 objects.

Type 5 inclusions (60 observed; 1.7 vol%) are relatively abundant, primarily fine- to medium-grained aggregates of recrystallized olivine with lesser amounts of pyroxene and feldspathoids and minor metal and sulfides. The olivine grains in these aggregates have forsteritic cores and Fe-enriched rims; grain boundaries form 120° junctions. Thick rims of Fe-enriched olivine commonly completely surround these inclusions. Most Type 5 inclusions have a vuggy texture that differs from the abundant, delicate pore space interstitial to the olivine "matchsticks" in the matrix of Types 1 and 2 inclusions (the other types of olivine-rich inclusions). Rimmed Ca,Al-rich droplets are found in 20% of the Type 5 inclusions. These droplets have textures and minerals that resemble those found in the nuggets and droplets common in Type 1 inclusions.

It is proposed that the fine- to medium-grained inclusions in Allende are not direct condensates from a cooling solar nebula. Rather, they are a suite of objects related by and recording various stages of the complex metamorphism, devolatilization, melting, and devitrification of precursor material that was perhaps chemically similar to the matrix of C2 chondrites.

The concept that precondensed material played an important role during the early evolution of the solar system is not a new one (5). Geochemical and petrological evidence that may be better explained by the episodic, incomplete metamorphism of volatile-rich solid material rather than by sequential condensation from a hot, turbulent nebula includes: [a] the apparent survival of incompletely-mixed presolar material in primitive meteorites, including Ne-E (6), s-process isotopes of Xe (7), and $^{26}$Al (8); [b] the widespread occurrence of $^{16}$O anomalies (9); [c] the occurrence in fine-grained inclusions of relatively volatile minerals [feldspathoids, ilmenite, and (Fe, Ni) metal and sulfides] interior to refractory minerals (perovskite, spinel, and melilite); [d] the occurrence in CAI interiors and rims of metamorphic minerals (including andradite, grossular, ilmenite, and Fe-bearing spinel) not predicted by thermodynamic calculations; and [e] the occurrence of Ca,Al-rich liquid droplets that were incorporated in fine-grained inclusions.

The progression of devolatilization may be best preserved in the abundant fine-grained, olivine-rich CAI's (Type 1 inclusions). Spinel+pyroxene-rich nuggets and fragments are set in an olivine+feldspathoid-rich matrix. These Ca,Al-rich nuggets and fragments may be remnants of the devolatilized precursor material. The fine-grained porous matrix may have recondensed from the cloud of volatiles that enveloped the refractory remnant. These two components were mixed to form the Type 1 inclusions.

The Ca,Al-rich nuggets now strung out as "wormy" Type 3 inclusions have relatively little matrix associated with them. Because Type 3 inclusions may consist primarily of refractory remnants, they seem to preserve a record of more efficient distillation. Volatiles did not recondense in the vicinity of these nuggets or were not later mixed with them. As a result, these inclusions are matrix-poor. The volatiles may have snowed out later and/or elsewhere to form the wispy, porous Type 2 inclusions (fine-grained, olivine-rich aggregates).
All five types of inclusions are rimmed. The rims observed in CAI's have been explained as the remnants of sequential condensation from and reaction with a cooling solar nebula (10). Rimmed textures are not common in rocks that crystallized from silicate melts. But the chemical composition of most silicate melts differs markedly from that of CAI's. The equilibrium condensation model does not predict the appearance of stable, Ca-Al-rich liquids in the nebula (11). However, there is textural evidence that Ca,Al-rich liquid droplets were commonly incorporated in Type 1 and Type 5 inclusions. Furthermore, individual droplets of this chemistry compose Type 4 inclusions. Rims of silicate minerals crystallized around cores of Si-poor, Al- and Ti-oxides (melilite, hibonite, spinel, perovskite, and ilmenite) in these droplets, as they did in coarse-grained CAI's.

Apparently, some Ca,Al-rich material partially or totally melted. Solids crystallized from these liquids, perhaps around unmelted seed crystals of minerals like perovskite, which acted as nucleation sites. Large droplets developed chilled margins of Ca,Al-rich glass; smaller droplets may have been glassy throughout. Heterogeneous nucleation and diffusion in these homogeneous glasses could have produced rim sequences and patchy, fine-grained textures when they devitrified (12). Type 1 inclusions appear to have incorporated some of these droplets. The Ca,Al-rich nuggets and fragments in Type 1 inclusions may be devitrified glasses. Type 3 inclusions may be strings of devitrified glass beads that partially fused together when they were hot, soft, and plastic. Type 4 inclusions could be independent droplets of these Ca,Al-rich liquids.

The abundant, medium-grained Type 5 inclusions appear to be recrystallized olivine-rich aggregates [Type 2 inclusions (?)]. If so, they may be polymetamorphic. Numerous vugs may have been produced by escaping volatile-rich vapors during a metamorphic episode. Recrystallization of this vapor could have produced the patches of feldspathoids and Fe-enriched rims. Although Type 5 inclusions may never have been melted, they did incorporate Ca,Al-rich droplets. At least one episode of solid-state metamorphism (recrystallization) is recorded by the 120° grain boundaries that characterize Type 5 inclusions.

Interestingly, no obvious coarse-grained CAI material was observed in any of the 16 thin sections, although a few of the Type 4 inclusions (those which appear to have once been molten) are more coarse-grained (\%0.1 mm) than the others. The apparent absence of coarse-grained CAI's in a large number of thin sections randomly prepared from several fragments of the Allende meteorite is noteworthy, especially since geochemical and petrological studies of coarse-grained CAI's have been used to draw important conclusions about the early history of the solar system (10,11,13). Fine- to medium-grained inclusions appear to outnumber coarse-grained CAI's by at least two orders of magnitude. These small objects comprise a significant component of the Allende meteorite and seem to record important processes that occurred in the early history of the solar system.