MORE EARLY SOLAR SYSTEM STRATIGRAPHY: COARSE-GRAINED CAI's.
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The Allende carbonaceous chondrite is an aggregate of various solid and liquid condensates whose order of condensation has been determined by observing which types consistently enclose others (1,2). This order is:
1. coarse-grained Ca-Al-rich inclusions (CAI's);
2. fine-grained CAI's;
3. ameboid olivine aggregates;
4. olivine and sulfide chondrules;
5. matrix. The order of formation of the different types of coarse-grained CAI's, however, is not clear. This is unfortunate since they are apparently the oldest known solar system materials and must hold many keys to an understanding of how the protosolar nebula condensed into the Sun and planets, and thus of how other stellar (and planetary) systems form.

Within the coarse-grained CAI's, the discovery of two composite Type B-in-Type A CAI's (Egg 3 and 3529,33) is of particular interest because this B-before-A order is inconsistent with the conventional wisdom in which the more Ca-Al-rich Type A CAI's would condense earlier than the Type B's (3). However, the stratigraphic observations below are unequivocal evidence that at least in two cases Type B condensed before Type A. Whether this order is generally true may be difficult to confirm since composite CAI's are rare. However, other observations are not inconsistent with a B-before-A order. Firstly, the consistent ordering of other Allende components implies that condensation was a one-way process and so it would be unusual if the only two known Type A and B composites actually ran against the normal trend. Secondly, the initial $^{26}$Al/$^{27}$Al of $\approx 2 \times 10^{-5}$ in a Type A CAI (4) compared to $\approx 5 \times 10^{-5}$ for some Type B CAI's (5) could result from later Type A condensation - or from different proportions of $^{26}$Al in the parent gas mixtures. This question is examined in an isotopic study (6) of 3529,33.

The coarse-grained inner CAI of the 3529,33 composite (Fig. 1) has the Type B Ti-Al-pyroxene (Tpx)/melilite (ak 4-70)/anorthite/spinel mineralogy. Its concentrically zoned structure of a 2-3 mm wide melilitic mantle (ak 4-35) surrounding a Tpx (9-12%TiO$_2$) and melilite (ak 30-70)-rich core mark it as subtype B$_1$ (7). An encircling spinel shell or "palisade" (18) separates it (Fig. 1) from the medium-grained, heavily altered outer CAI which has Type A melilite (ak 4-25)/spinel/perovskite mineralogy. This palisade is interpreted as the inner CAI's original first rim layer (9). This is supported by the change in the melilite from ak 20 to ak 4 in a 50 μm layer approaching the palisade a change typically observed below the rims of ordinary CAI's (7). By an extension of this idea the outer Type A melilite layer could be regarded simply as the thickened second rim layer. This idea is explored in a companion abstract (9).

Inner and outer CAI's are also distinguished by their different opaque contents: the inner CAI has the large Ni-Fe, Fe-Ni-S and complex Refractory/Platinum Metal (RPM) intergrowths typically found in Type B CAI's (10) whereas the outer CAI has the usual simple μm-sized nuggets of RPM alloys and Ni-Fe of Type A CAI's (10). The texture and zonation of the inner CAI probably resulted from inward crystallization of a liquid droplet. This cannot be so for the outer CAI whose metal nuggets are not randomly dispersed but vary from RPM-rich near the palisade to Ni-Fe-rich/RPM-poor towards the rim. This distribution, plus the uneven thickness of the Type A layer.
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(ranging from a barely discernible skin in some places to a 5 mm thick "blister" in others), are consistent with condensation as a solid. The fact that this Type A skin could easily be overlooked means that other composite CAI's may not yet have been recognized, and also warns against sampling too skimpily when making CAI thin sections.

The second composite, Egg 3, also has a coarse-grained Type B inner CAI composed of Tpx (5-11% TiO₂), melilitic (ak 31-64) spinel and anorthite, and is enclosed by a spinel palisade (Fig. 2). The outer Type A layer of melilitic (plus spinel and perovskite) differs in being recrystallized, finer-grained and more gehlenitic (ak 21-30) than that inside. In the inner CAI all opaques are Ni-rich: Ni-Fe metal, NiS and complex Ni/Fe/RPM bodies. In the outer CAI most opaques are small Ni-rich (55-95% Ni) nuggets of Ni/Fe/ RPM alloy which do not vary systematically in composition toward the rim as in 3529,33. Egg 3, an isotopically anomalous CAI, is further described in a companion abstract (11).

The unusual V, Mo, Fe, Ni and Ge chemistry found (11) in both parts of Egg 3 suggests that they both condensed under similar, relatively oxidizing conditions from the same reservoir. In contrast the parts of 3529,33 could have formed from different undepleted reservoirs on account of their high (initial) enrichments in refractory Rare Earth Elements (12) and RPM's, and greater overall chemical disparity. On the other hand the reservoir from which the Type A part of 3529,33 began to condense became depleted in RPM's before 3529,33's condensation ended. A similar pattern of early, inner RPM enrichment (i.e. Mason Group I) giving way to later RPM depletion (Group II) is found in a third composite Type A-in-Type A CAI, 3643, described in (13.).

Because Type A CAI's are richer in Ca and Al, and poorer in Mg, Si & Fe i.e. are more refractory than Type B's (7), the change from Type B to Type A condensation presumably required an increase in temperature or decrease in pressure, or both i.e. an increase in some (T/P) parameter. We speculate that this might perhaps have occurred downstream from an old and already much diluted supernova shock wave impacting into a dense molecular cloud (2). Behind such shock fronts, on time scales of 100's - 1000's of years and dimensions of several planetary systems, temperature and ionization decrease, particle density increases but pressure remains relatively constant (14).

Given sufficient supersaturation in cooler gas downstream from the shock, grains of the most refractory elements would nucleate and the largest of them drift inertially upstream against the gas as the shock was decelerated. Type B CAI's drifting up into hotter, less supersaturated gas could begin to condense crusts of Type A material. In this complicated, dynamically-evolving system the post-shock temperatures must eventually decrease, permitting the condensation of less refractory materials. Some such scenario as this would provide a source of 26Al and 16O, of isotopic fractionation by grain condensation and evaporation, of homogenization of the protosolar cloud by the shock (except perhaps for rare, incompletely mixed, isotopically anomalous pockets), of the observed unidirectional condensation sequence and of the migration of grains away from condensing gas.

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Fig. 1. Allende coarse-grained CAI inclusion 3529,33.  
Fig. 2. Allende coarse-grained CAI inclusion Egg 3.