THE FIRST STEP IN CAI RIM FORMATION: FLASH HEATING OR SUBSOLIDUS EVAPORATION ?

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Introduction: The oldest known solar system materials, Ca-Al-rich Inclusions (CAIs) in meteorites, hold clues to high temperature events in the early solar nebula. CAIs are enclosed in thin 'Wark-Lovering' (WL) rims which have the same ultra-refractory element abundance pattern (only ~4 times richer) as the underlying CAI [1]. The rims were thus derived from the outer CAI by volatilization of its more volatile constituents. The mechanisms proposed for volatilization are: (a) Flash Heating [2] (~3000K, 1-2 sec) or (b) Subsolidus Evaporation [3] (lower temperature, slower).

Which was it, (a) or (b) ? The answer is important, because if Flash Heating is a myth, then astrophysicists do not need to explain these extreme conditions. But if Flash Heating really happened, then it is telling us an important, challenging fact about the nebula.

In this work, we try to answer the question by examining the immediate subrim zone of CAIs for signs of the *melting* that Flash Heating would, and Subsolidus Evaporation would not, have produced. We avoided CAIs that were melted themselves during their formation, and studied a CAI that was an *unmelted* solid condensate, a so-called 'Fluffy Type A' (FTA) CAI [4], and two *incompletely melted* Type B2 CAIs [5].

To establish that these CAIs had experienced rim volatilization, we first analysed them and their rims to check that the rims were more enriched in ultra-refractory elements.

Analytical Technique: Analyses were performed using the RSES aperture-imaging 193nm laser ablation system, coupled to an Agilent 7500s quadrupole ICPMS [6]. Concentrations of initially 40, later 27, elements were measured using Ca as internal standard on a scan-by-scan basis and were standardized against NIST612 and USGS BCR2G. Checks were also made against a well-analysed synthetic 'Type B CAI'. Analyses were generally within 10-15% of the known compositions, more than adequate for this work.

Because the Ca internal standard varies with depth in heterogeneous CAIs, the sum of major oxides measured by LA-ICPMS was normalized to total 100%. Early analyses used a 40μm circular laser spot, later changed to a rectangle 15 μm x 100 μm to analyse layers within the WL rims (thickness ~40 μm).

Since rims may be inclined, depth profiles were examined to discover if the beam passed out of the rim into matrix or subrim. Such analyses were discarded. Depth profiles also revealed the abundance of inclusions of perovskite and μm-sized refractory metal nuggets. The metal was, however, not amenable to accurate analysis because it reflects laser light and reduces ablation efficiency.

Results: Due to space limitations, data is presented as graphs for representative Rare Earth Elements (REE), Zr, Ca & Sr only.
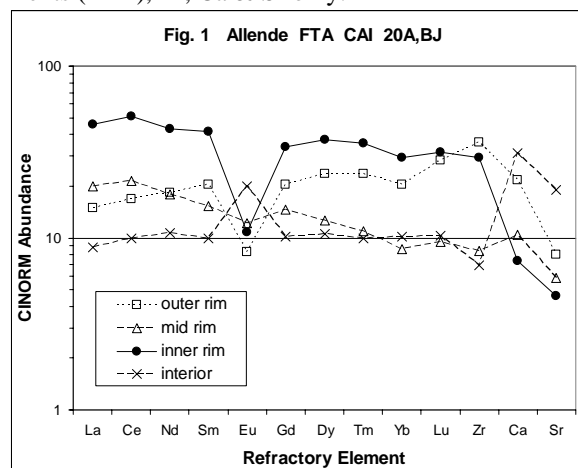

Fig. 1 Allende FTA CAI 20A,BJ

Fig.1 (above) shows the data for Allende solid condensate FTA CAI 20A,BJ composed mainly of melilite with spinel & perovskite inclusions. The abundances of ultra-refractory REE & Zr are typically 4-5 times higher in the inner rim (where the main host perovskite is concentrated) than in the CAI interior, indicating that the outer CAI experienced a high temperature volatilization event [1]. Eu, Ca & Sr are only moderately refractory and were partly volatilized, depleting them in rim relative to CAI. The data also show fractionation between the outer pyroxene rim layer and the inner, perovskite-bearing rim layer, due to pyroxene's preference for smaller, heavy REE ions.

Although the subrim melilite shows the effect of the high temperature during rim volatilization (being zoned [7] from ~ ak15 100 μm below the rim to ~ak4 at the rim), it shows no sign of having been melted. The evidence [7] against melting of the subrim zone and CAI as a whole includes:- (a) the complex outline of the rim, (b) the presence of voids between melilite crystals, (c) the absence of concentric zonation in the CAI, with melilite crystal compositions being randomly distributed, and (e) the reverse zoning within melilite crystals, whose exteriors are *less* akermanitic

than the cores, opposite to the trend expected from melt crystallization.

Fig. 2   Allende Type B2 CAI 20B,A
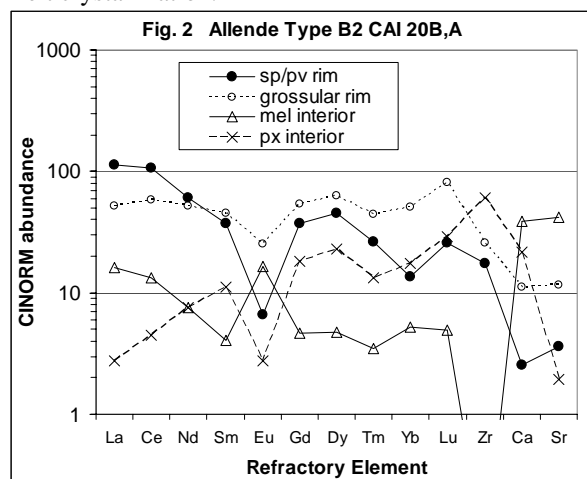
In Allende CAI 20B,A (Fig.2) the perovskite, spinel, and grossular (altered melilite) rim layers have average abundances of refractory elements about 5-8 x the average abundances in the melilite & pyroxene interior (except for depletions of Eu, Ca & Sr, as for 20A,BJ). The outer CAI therefore experienced high temperature volatilization.

CAI 20B,A is of Type B2. Such CAIs have an un-zoned distribution of major Ti-Al pyroxene, melilite and anorthite, ~constant melilite (high ak 40-65) and pyroxene (low TiO_2 4-6%) compositions, presence of spinel framboids, and the WL rims are not clearly layered, beginning with a semi-continuous band of separate spinel grains [7]. These properties are argued [5] to result from crystallization of *incompletely melted* material. Most importantly, there is no evidence for a subrim melt zone of different texture and mineral chemistry from the rest of the CAI.

Fig. 3   Efremovka Type B1/B2 CAI E69
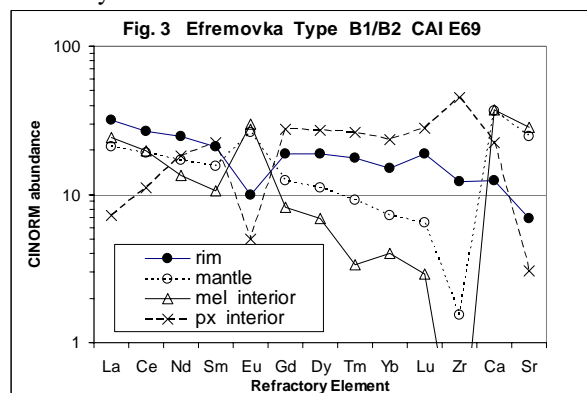
The rim of CAI E69 (Fig.3) has from 1.5-3 x the abundances of refractory elements of the melilite mantle (except for depletions of Eu, Ca & Sr as before). The mantle is in turn more enriched than the average of the interior melilite & pyroxene. This is again evidence that the skin of E69 experienced volatilization.

CAI E69 has some features of Type B2 (not strongly zoned, with some pyroxene crystals close to the rim, and the rim is poorly layered, with a dense band of spinel grains and intervening silicates). It also has some Type B1 features (mantle of melilite almost free of spinel inclusions). While the mantle is evidence of crystallization from melt [8], the probability is that melting occurred during formation of the primary CAI rather than during rim volatilization, for which there are no clear signs (e.g. no subrim layer of acicular hibonite crystals, seen in many Type B1 CAIs).

Conclusions: We have shown above that the three selected CAIs have rims that are more strongly enriched in refractory elements than the underlying CAI. This is evidence that the CAIs experienced high temperature volatilization.

We have presented observations from the texture and mineral chemistry of the subrim zone immediately below the rim that strongly suggest that this zone was not melted during the rim volatilization event. This is evidence against an intense 'Flash Heating' which would probably have melted at least some material below the rim. We therefore conclude that the ultra-refractory enrichment of rims is unlikely to have been produced by 'Flash Heating' …. and hence that the competing model of 'Subsolidus Vaporization' is more probable.

References:

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