VOLATILE ELEMENTS AND HIGH-TEMPERATURE CONDENSATION, L. Grossman* and R. Ganapathy**, *Dept. of Geophysical Sciences and Enrico Fermi Institute, **Dept. of Geophysical Sciences, University of Chicago, Chicago, Ill. 60637.

For many years it was a common practice in cosmochemistry to attempt to model planetary compositions by mixing different meteorite types together in various proportions(1,2). More recently, several laboratories have begun to use the different petrographic units found inside primitive chondrites as end-member components in modelling the compositions of the planets. This has resulted from the realization that the different classes of mineral aggregates in the chondrites have their own separate, nebular origins. Specifically, a number of investigators (3,4,5) have proposed that the moon accreted from dust containing super-chondritic abundances of solar nebular high-temperature condensates similar to the Ca-Al-rich inclusions found in the Allende meteorite. While the moon and planets undoubtedly formed by the accumulation of mixtures of various nebular materials, this type of model suffers from incomplete knowledge of the myriad of chemical components actually present in the chondrites and a lack of understanding of their origins.

For example, let us consider the Ca-rich inclusions in the Allende meteorite which have become so important in models of lunar accretion. Two distinctly different classes of objects are included in this category and both have been rather loosely referred to as "high-temperature condensates." One type occurs as white, rounded, cm-sized objects containing mm-sized crystals of melilite with smaller grains of spinel and perovskite (6) or large grains of a Ti-Al-rich pyroxene with smaller crystals of spinel, melilite, anorthite and perovskite (7). The other type are exceedingly fine-grained, irregularly-shaped objects varying in color from white to pink to purple. They contain micron-sized crystals of spinel, pyroxene, grossular, nepheline and sodalite (7).

The coarse-grained inclusions are very similar in bulk chemical composition and mineralogy to mineral assemblages predicted in thermodynamic models to have condensed from the solar nebula at temperatures above 1400°K (8). Na_2O contents from 0.11% to 0.7% are present in the three coarse-grained inclusions whose bulk chemical compositions are reported in the literature (7, 9,10) and one of these also contains 0.1% Cl. The presence of these elements in such quantities is difficult to explain by condensation models because Na and Cl should have condensed from the solar nebula at much lower temperatures (1000-1100°K) than the Ca-Al-rich phases which make up the bulk of these inclusions.

In contrast, the fine-grained inclusions contain few phases predicted to condense at high temperatures. The two bulk chemical compositions in the literature (7,9) suggest some relationship between these and the coarse-grained inclusions because of the high CaO, Al_2O_3 and TiO_2 contents; however, these two fine-grained inclusions contain 1.1 and 4.1% Na_2O.

Lithophile and siderophile refractory trace elements are enriched relative to C1 chondrites by factors of 12 to 26 in the coarse-grained inclusions (9,10,11,12), supporting the proposal that they are high-temperature condensates. Tanaka and Masuda (12) found a fine-grained inclusion which is enriched in the light rare earths by a factor of $\sim$ 24 like the coarse-grained

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ones but, in contrast to them, the enrichment factors relative to Cl chondrites fall steeply to less than 1 for the heavy rare earths. Gray et al. (9) showed that the fine-grained inclusions are enriched in refractory Sr by only a factor of 3 to 4 relative to Cl's while the coarse-grained ones show the usual enrichment factor of ~ 20. Gray et al. (9) also found the concentration of Rb, a volatile, to be an order of magnitude higher in the fine-grained inclusions than the coarse-grained ones. Grossman (13) reported uniformly high concentrations of the refractory elements La, Sm, Eu, Yb, Sc and Ir and highly variable Na contents in 16 inclusions but no distinction on the basis of grain size was made in that study.

We have begun a systematic neutron activation study of the compositions of 10 coarse-grained and 10 fine-grained Ca-Al-rich inclusions in the Allende meteorite. All samples (2 to 20 mgm) were excavated from slab surfaces in a clean room using stainless steel dental tools and a stereoscopic microscope. Great pains were taken to avoid contamination from the surrounding matrix. Our data for Mn, Na and Cl are reported in Table 1. Mn should have condensed from the nebula between 1100 and 1200°K at equilibrium (8).

Mn, Na and Cl concentrations are consistently and substantially higher in the fine-grained inclusions than in the coarse-grained inclusions. These relatively volatile elements do not have negligible abundances even in the coarse-grained inclusions. Wänke et al. (10) noted that these elements were concentrated toward the outside of a coarse-grained inclusion and Grossman (6) reported Na and Cl enrichments in fine-grained, opaque areas found interstitially and in the outer zones of coarse-grained inclusions. Gray et al. (9) noted that the Na contents of fine-grained inclusions increased toward the outside. These observations suggest that the volatiles have a secondary origin. In contrast, an SEM study of a fine-grained inclusion (14) revealed it to be a cavernous aggregate of euhedral crystals, suggesting an origin by direct condensation from a vapor. Intergrown with the Ca-Al-rich phases are euhedral crystals of alkali-, Cl-bearing silicates, implying that some of the volatiles are primary, having condensed simultaneously with the more refractory elements in the fine-grained inclusions. These findings are in agreement with the data in (9) which show that the bulk of the Rb may have been incorporated by the fine-grained inclusions 4.6 b.y. ago and that more Rb may have been added to them in the last 3.6 b.y. The relatively recent addition of Rb had to take place inside the Allende parent body, long after condensation was over. This probably occurred during a mild metamorphic event which caused the redistribution of other volatile elements (Mn, Na, Cl) in addition to Rb and which affected both types of inclusions. The reason the fine-grained inclusions have higher volatile element contents is that they contain an additional complement of these elements which was emplaced during condensation.

The mineral assemblages, high volatile element contents and textural relations inside the fine-grained inclusions all indicate an origin by non-equilibrium condensation in which some volatile-containing phases co-crystallized with the refractories. These objects coexist in Allende with coarse-grained inclusions that resemble much more closely the predicted products of equilibrium condensation from the nebula. How these two kinds of inclusions

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Table 1. Volatile elements in Ca-rich Allende inclusions
(Values in ppm unless otherwise indicated; n.d.-not detected)

Sample		Mn	Na	Cl
Coarse-grained:	1	46.4±0.9	1287±10	n.d.
	2	182±4	620±15	n.d.
	3	22.5±0.5	1374±11	n.d.
	4	98±2	1523±19	n.d.
	5	79±2	1639±15	n.d.
	6	19±1	271±7	n.d.
	7	427±7	8329±55	n.d.
	8	20.4±0.6	903±7	n.d.
	9	72±2	4710±32	n.d.
	10	9.4±0.3	568±5	n.d.
Fine-grained:	11	383±6	1.40±0.01%	0.86±0.12%
	12	403±6	3.10±0.02%	1.17±0.15%
	13	374 ±7	5.14±0.03%	1.33±0.29%
	14	696±10	4.23±0.03%	1.72±0.24%
	15	898±13	1.08±0.01%	n.d.
	16	509±8	2.59±0.02%	0.87±0.27%
	17	161±3	1.89±0.01%	0.62±0.11%
	18	348±6	3.40±0.02%	0.33±0.19%
	19	865±13	3.09±0.02%	n.d.
	20	475±7	1.44±0.01%	n.d.
Bulk Allende		1528±21	3417±22	n.d.
BCR-1		1414±36	2.42±0.01%	n.d.

apparently formed in close proximity to one another is a mystery that demonstrates how little we really know about the chemistry of the nebula. The fact that these inclusions comprise only 5-10% of the Allende meteorite is a clue to how much information remains hidden in the primitive chondrites and how much our current models of planetary formation may change in the future as this information is revealed and interpreted.

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