

# Chemical Composition of an Unusual Xenolith of the Allende Meteorite

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*Dedicated to Prof. Heinrich Wänke on the occasion of his 60th birthday*

The chemical composition of an unusual xenolith (All-AF) from the Allende meteorite was determined by neutron activation and x-ray fluorescence analyses. The xenolith is similar in bulk composition to Allende, but has large excesses in some moderately volatile trace elements, such as Na, K, Au, Sb etc. Some of these elements show considerable variations in other components of Allende, suggesting inhomogeneous distribution in Allende. However, elements of higher volatility, such as Zn and Se have concentrations typical of bulk Allende and other type 3 carbonaceous chondrites. Therefore, All-AF must have formed from the same reservoir as bulk Allende.

All-AF has uniform grain size and does not, and did never, contain chondrules. The low content of volatile elements, therefore cannot be ascribed to loss of volatiles during the chondrule forming process. It is a characteristic of the Allende reservoir. The chemical composition of related dark inclusions (DIs) in Allende is different from All-AF. Dark inclusions may have formed by separation of fine grained material in the early solar nebula while All-AF resembles bulk Allende material that was never subject to chondrule formation. Both, dark inclusions and All-AF have oxygen isotopic compositions which plot at the upper end of the  $\delta^{18}\text{O}$  vs.  $\delta^{17}\text{O}$  correlation, suggesting extensive oxygen exchange with ambient gas.

## Introduction

In a companion paper texture and mineralogy of a large cm-sized xenolith (All-AF) of the Allende meteorite is discussed [1]. The xenolith shows some textural similarity to the well known dark inclusions (DIs) of Allende [2], as both, All-AF and dark inclusions do not contain chondrules and both have uniform grain size, quite different from any bulk Allende sample containing a mixture of fine grained matrix and coarse grained chondrules, inclusions and mineral fragments. The absence of chondrules and other coarse grained lithologies in dark inclusions and in All-AF, either reflects extensive reworking of bulk Allende material in a parent body [3], or indicates the absence of coarse grained components during accretion in the solar nebula [4]. The chemical composition of dark inclusions suggests the second alternative. The comparatively low content of refractory elements, the high abundances of total Fe and other chemical properties indicate that chondrules, coarse-grained Ca, Al-inclusions (CAIs) and large fine-grained aggregates were

absent when DIs formed. The absence of fine-grained spinel-rich aggregates from the formation region of DIs is inferred from the low abundances of Na, K, Cl etc. in dark inclusions [4].

It is the purpose of this paper to better define the relationship of All-AF to other Allende components, in particular to DIs, by studying the abundances of major and trace elements in the xenolith fragment. Chemical analyses of a large dark inclusion were obtained for comparison. A more extensive set of chemical data on DIs was reported recently [4]. A preliminary report of the All-AF data was given some time ago [5]. In addition, isotopic compositions of oxygen and silicon in All-AF were determined by R. N. Clayton and T. K. Mayeda from the University of Chicago.

The origin of AF will be investigated in the light of these data: Is AF reworked Allende material i.e. is it the result of processes that occurred on the Allende parent body or did it form independently, unrelated to other Allende components, under different nebular conditions? To be able to distinguish between these two processes is a necessary prerequisite for better understanding the formation and origin of chondritic meteorites.

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Table 1. Chemical composition of Allende xenolith All-AF.

	Sample A 102.4 mg	Sample B 311.4 mg	Allende dark incl. 264.6 mg	St. dev.	Allende bulk	Sample A/ Allende bulk
%						
Mg	15.50 <sup>a</sup>		13.98 <sup>a</sup>	3	14.83 <sup>c</sup>	1.05
Al	2.36 <sup>a</sup>		1.19 <sup>a</sup>	3	1.74 <sup>c</sup>	1.36
Si	16.16 <sup>a</sup>		14.87 <sup>a</sup>	3	16.03 <sup>c</sup>	1.01
Ca	1.34 <sup>a</sup>	1.56	1.70 <sup>a</sup>	3	1.84 <sup>c</sup>	0.73
Ti	0.06 <sup>a</sup>		0.08 <sup>a</sup>	3	0.09 <sup>c</sup>	0.67
Fe	21.97	23.70	26.32	3	23.57 <sup>c</sup>	0.93
ppm						
Na	7 270	4 940	770	3	3 400 <sup>c</sup>	2.14
P	1 140 <sup>a</sup>		1 510 <sup>a</sup>	5	1 047 <sup>c</sup>	1.09
Cl	540		240 <sup>b</sup>	20	290 <sup>c</sup>	1.86
K	781	566	85 <sup>b</sup>	5	289 <sup>d</sup>	2.70
Sc	10.7	9.8	9.7	3	11.5 <sup>d</sup>	0.93
Cr	3 780	3 650	2 530	3	3 580 <sup>d</sup>	1.06
Mn	1 804	1 660	2 050	3	1 472 <sup>d</sup>	1.23
Co	785	675	706	3	640 <sup>d</sup>	1.23
Ni	17 900	16 500	16 300	4	13 500 <sup>d</sup>	1.33
Cu	140	174		25	125 <sup>d</sup>	1.12
Zn	124	139	160	10	110 <sup>c</sup>	1.13
Ga	6.3	7.0	8.3	10	6.1 <sup>d</sup>	1.03
As	6.8	4.3	1.8	5	1.33 <sup>d</sup>	5.11
Se	5.7	6.9	9.1	12	8.6 <sup>d</sup>	0.66
Br	10.7	1.1 <sup>b</sup>	0.87	5	1.6 <sup>d</sup>	6.69
Ru	1.9	1.2	1.4	25	1.07 <sup>e</sup>	1.78
Sb	0.44	0.25	0.13	10	0.083 <sup>f</sup>	5.30
La	0.5	0.48	0.39	10	0.52 <sup>d</sup>	0.96
Ce	1.4	1.2	1.4	20	1.33 <sup>d</sup>	1.05
Nd	1	0.9		20	0.99 <sup>d</sup>	1.01
Sm	0.31	0.3	0.24	4	0.34 <sup>d</sup>	0.91
Eu	0.12	0.11	0.083	12	0.11 <sup>d</sup>	1.09
Dy	0.52	0.5		15	0.42 <sup>d</sup>	1.24
Yb	0.33	0.32	0.27	12	0.30 <sup>d</sup>	1.10
Lu	0.052	0.049	0.039	10	0.052 <sup>d</sup>	1.00
Hf	0.2	0.19	0.16	20	0.21 <sup>d</sup>	0.95
Re	0.092	0.066		10	0.064 <sup>d</sup>	1.44
Os	1.1	0.86	0.75	6	0.75 <sup>d</sup>	1.47
Ir	0.98	0.78	0.72	3	0.74 <sup>d</sup>	1.32
Pt	2.7	2.2		15	1.64 <sup>e</sup>	1.65
Au	2.45	1.43	0.144	3	0.15 <sup>d</sup>	16.33
Hg	2.9	4.8	<0.2	10	0.035 <sup>d</sup>	82.86

<sup>a</sup> XRF-data. – <sup>b</sup> Accuracy reduced by a factor of two. – <sup>c</sup> Jarosewich *et al.* [26]. – <sup>d</sup> Average of 4 Allende samples, this laboratory. – <sup>e</sup> Calculated from CI-ratios. – <sup>f</sup> Kallemeyn and Wasson [27].

## Samples, Methods and Results

Two bulk samples, 102.4 mg and 311.4 mg, were analysed by instrumental neutron activation analysis (INAA). Samples were irradiated for six hours at a neutron flux of  $7 \times 10^{11}$  n/cm<sup>2</sup> sec in a TRIGA-reactor. Countings on large Ge(Li)-detectors began immediately after the end of bombardement. Samples were counted at least five times with increasingly longer durations. Peak deconvolution was done according to

the procedures described by Kruse [6]. Results of the analyses are given in Table 1. The 102.4 mg aliquot was, after counting, used for XRF-analysis, according to procedures by Palme and Jagoutz [7]. Results of this analysis are included in Table 1. A 57.7 mg subsample C of sample B (311.4 mg) was analysed for siderophile elements by the metal extraction method [8]. Results are given in Table 2.

Additional small subsamples from the fragment were hand-picked. A sulfide-rich, a metal-rich and a

Table 2. Siderophiles in Allende xenolith AF.

	Sample C 57.7 mg (1)	Sample A 102.4 mg (2)	Allende bulk (3)	Sample C norm. to All. bulk
Co ppm	548	785	641	0.85
Ni ppm	12 800	17 900	15 050	0.85
Cu ppm	60	140	106	0.57
As ppm	6.23	6.8	1.5	4.15
Mo ppm	1.24		1.51	0.82
Ru ppm	1.4		1.1	1.27
Pd ppm	1.53		0.705 <sup>a</sup>	2.17
Sb ppb	250	440	80	3.13
W ppb	120		148	0.81
Re ppb	62	92	68	0.91
Ir ppb	794	980	811	0.98
Pt ppb	2 590	2 700	1 500	1.73
Au ppb	1 890	2 450	107	17.66

(1) By metal extraction. – (2) See Table 1. – (3) Palme and Rammensee (unpublished data). – <sup>a</sup> Takahashi *et al.* [28].

Ca, Al-rich sample were analysed by INAA. Results of these analyses are given in Table 3. Analytical results of a large dark inclusion (DI) are presented in Table 1.

Oxygen and silicon isotopic compositions were determined on a single few mg chunk of All-AF. Analyses were made by T. K. Mayeda and R. N. Clayton at the University of Chicago, applying routine procedures. Results are shown in Table 4.

### Chemical Composition of All-AF

#### Major Elements

From Table 1 it is apparent that the major element composition of AF is not very different from bulk Allende. The Mg/Si ratio of 0.96 is within error limits identical to that of Allende (0.93), but significantly different from the CI-ratio of 0.87. The total Fe contents of the two large AF samples are 21.97% and 23.70%, very similar to 23.57% for bulk Allende, but different from DIs which have higher Fe-contents, from 26 to 30% (see Table 1 and [4]). Major differences between bulk Allende and All-AF are, however, found for Ca, Al and Ti, as will be discussed later.

#### Refractory Elements

Refractory trace elements (Sc, REE, Hf etc.) have surprisingly uniform CI-enrichment factors in All-AF (Figure 1). The two samples A and B differ only slightly. Refractory metals (Ir, Os etc.), show a similar behaviour, fragment A being comparatively more enriched in refractory metals than in refractory

Table 3. Results of INAA-analyses of subsamples of All-AF.

	Sample D Ca, Al-rich 3.83 mg	Sample E 1.14 mg	Sample F sulf.-rich 0.39 mg	Accuracy
‰				
Ca	7.42	10.5 *		10
Fe	33.5	24.3	32	3
ppm				
Na	6520	5200	6100	3
Cl	470			20
K	702	535	740	10
Sc	71.4	11.9	1.7 *	5
Cr	280	910	1470	5
Mn	770	1070	1023	3
Co	170	170	1400	5
Ni	2430	4470 *	27 600	5
Cu	<400	<200	510	5
Zn	100	<50		25
Ga	4.7	4.3	4.7	20
As	0.9	1.58 *	1 *	12
Se	14.3		25	20
Br	4.7 *		32	5
Ru	7.7			20
La	2.5	3.44	<1.4	7
Ce	13.2	14		20
Sm	1.81	2.26	<0.1	4
Eu	0.88	0.52	<0.03	4
Tb	0.46			30
Dy	3.01	1.4	<0.2	10
Ho	0.6			20
Yb	1.47	0.97 *	<0.03	10
Lu	0.34	<0.1		15
Hf	1.6	<1.5		15
Ta	<0.4			
W	<0.7			
Re	0.43			15
Os	4.98			10
Ir	4.72	0.15 *	<0.1	5
Pt	10			25
Au	0.301	0.457	0.032 *	5
Hg	4.7 *		70	5
Th	1.97			15

\* Accuracy reduced by a factor of two.

Table 4. Oxygen and silicon isotopic composition of All-AF.

$\delta^{17}\text{O}$	1.01	$\delta^{29}\text{Si}$	−0.19
$\delta^{18}\text{O}$	5.69	$\delta^{30}\text{Si}$	−0.24

lithophiles. The data for a small subsample D of 3.83 mg (Fig. 1, Table 3) indicate a more fractionated pattern of refractory elements. The generally high content of refractories speak for a Ca, Al-rich precursor with a somewhat fractionated pattern, similar to those found in Ca, Al-inclusions from Allende. Sample E (1.14 mg, Table 3) is even more fractionated. The high content of light REE (e.g. La), the low concentrations of the refractory lithophile elements Sc, Lu and Hf as

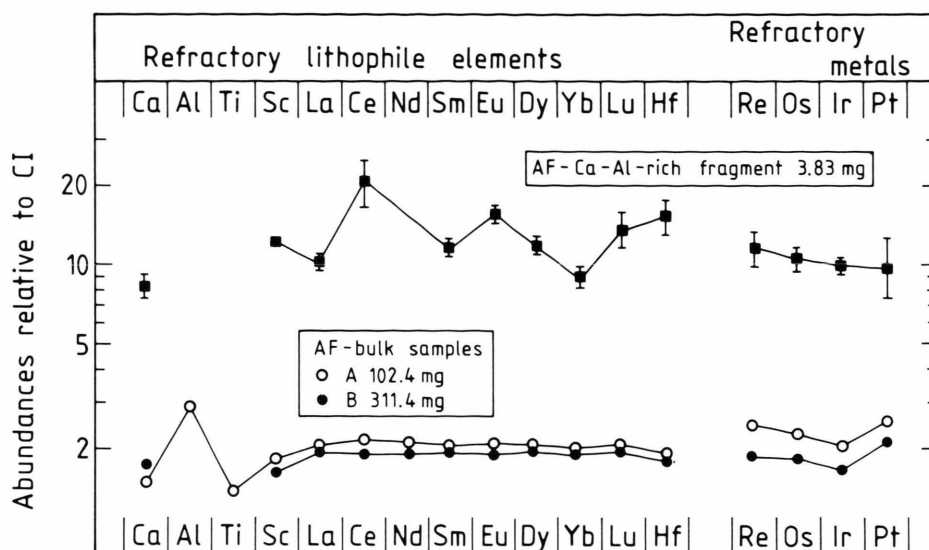


Fig. 1. Refractory elements in two bulk samples and a Ca-Al separate of Allende xenolith All-AF. Elements are normalized to CI-abundances. The major elements Ca, Al and Ti are more variable than the REE and Sc, presumably because they are more susceptible to alteration than the host phase of the REE and Sc.

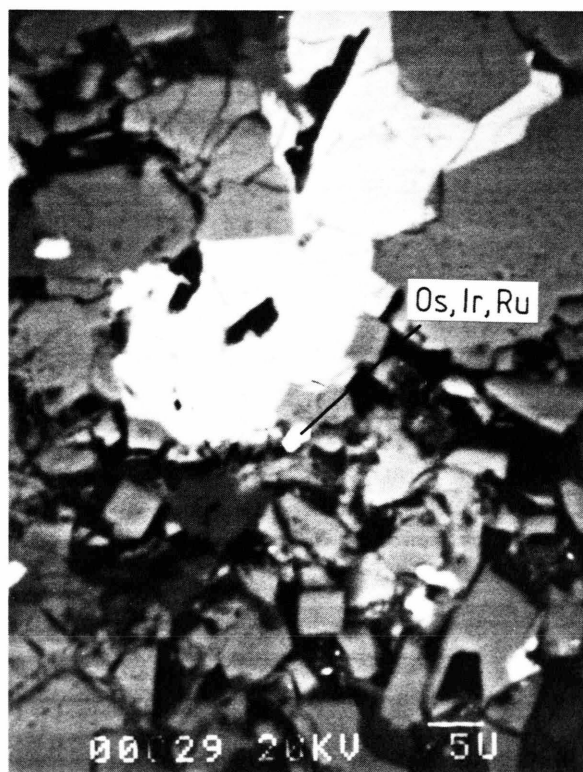


Fig. 2. A Os, Ir, Ru nugget (bright grain in center) between sulfide and olivine. In the upper right, large grains of andradite. SEM picture (back scattered electrons).

well as the low abundances of refractory metals (Ir etc.) are typical of frequently found fine-grained, spinel-rich Allende inclusions with a group II pattern of REE [9]. It therefore appears that the All-AF-precursor material contained refractory-rich components similar to those found in bulk Allende samples.

A polished section of sample D showed the presence of large (5  $\mu\text{m}$ ) grains of perovskite associated with sulfides containing andradite and ilmenite. Several refractory metal-rich nuggets were encountered. Figure 2 is an example of an Os, Ir, Ru-rich grain. Two occurrences of  $\text{BaSO}_4$  were found in the same section. These observations indicate the presence of a refractory rich precursor material that was extensively altered at lower temperatures, resulting in sulfide-andradite assemblages described by Kurat *et al.* [1].

CI-normalized refractory elements of DIs and of fragment All-AF are compared in Figure 3. As noted by Bischoff *et al.* [4] DIs have somewhat lower abundances of all refractory elements than bulk Allende, except for Ca which is higher in DIs. The two All-AF samples, however, have approximately similar refractory element abundances as bulk Allende (Ir, Sc and La in Figure 3). Obvious exceptions are the refractory major elements Ca and Al (Figure 3). The low Ca of All-AF and its high Al leads to an unusual Ca/Al-ratio of 0.57 compared to the chondritic ratio of 1.1. The



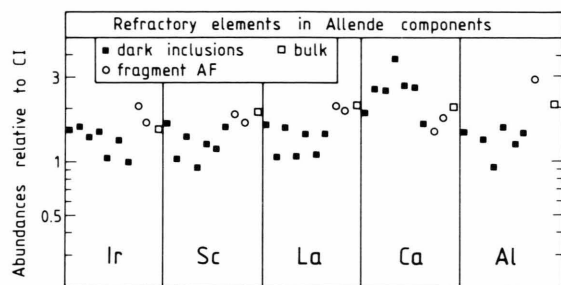


Fig. 3. Refractory elements in All-AF and Allende dark inclusions (DIs). AF has similar refractory element contents as bulk Allende, while DIs are lower except for Ca. Data for DIs [4].

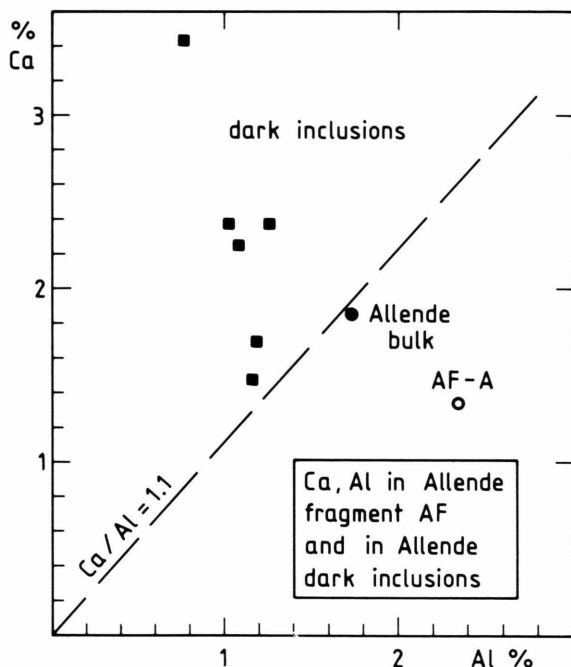


Fig. 4. Ca-Al in dark inclusions is complementary to that of All-AF. Data for DIs: [4].

difference between DIs and fragment AF with respect to the Ca/Al-ratio is very obvious from Figure 4. The low Al contents of DIs reflects their low modal abundances of Al,Na-silicates [4]. DIs are, therefore, rather low in Na. The high Al content of AF, on the other hand, is accompanied by a high Na content.

Nepheline ( $\text{NaAlSi}_3\text{O}_8$ ) is indeed the major carrier of Na in AF. If Na were exclusively sited in nepheline it would lock up 0.73% Al, according to its Na-content. This would be more than enough to account for the excess Al in All-AF relative to bulk Allende. It is, however, also clear that a major fraction of Al must be

contained in other phases. As discussed by Kurat *et al.* [1], olivine of All-AF contains unusually large amounts of Al. With an estimated average of 0.7% Al in AF-olivine [1] about 30% of the Al would reside in olivine (assuming 100% olivine in AF). With a similar fraction in nepheline one would still have to account for nearly 1% Al which must then be distributed among minor phases, such as, fassaite, sulfide-andradite-aggregates and diopside.

Since olivine contains on the average only about 0.15% Ca, the bulk of this element is contained in other phases: andradite and Ca-rich pyroxenes (diopside, salite).

The amount of REE in AF is about the same as in bulk Allende. However, no typical REE-carriers are present in All-AF except some altered CAIs. Glass, the REE-carrier of chondrules, is absent. Phosphate, another possible REE-carrier, is only found in association with altered CAIs and some relict perovskite associated with them. Also, the bulk P-content of All-AF is not unusually high (Table 1). The same CI-enrichment factors of REE and other refractory elements, not associated with REE (e.g. Sc) speak against a trace mineral as a major REE-carrier. One has to conclude that a major fraction of the REE is associated with olivine. Recent SIMS measurements indeed demonstrated the presence of REE in olivine of AF [10]. A close relationship between olivine and refractory lithophile elements was also found from the analyses of individual forsterite grains from Allende [11]. None of the analysed forsterite grains was free of REE.

It is remarkable that the REE, generally considered to be incompatible, show a more regular behaviour than Ca and Al. This demonstrates that the bulk of the REE is not associated with major Ca- and Al-bearing phases in DIs and in AF and presumably also in the Allende matrix. Initially the REE may well have condensed together with Ca and Al in close association with forsterite. During alteration (gas-solid interaction), however, Al and particularly Ca were much more mobile than the REE. Igneous fractionation can be excluded. It would produce exactly the opposite trend: Large fractionations of REE from each other and from Sc and comparatively smaller variations in Ca and Al.

#### *Chromium, Moderately Volatile and Volatile Elements*

Figure 5 is a plot of Cr vs. Fe of bulk Allende, DIs and All-AF. It can be shown that all carbonaceous

chondrites have similar Fe/Cr-ratios of about 65–70. Both All-AF samples are in this range, the larger of the analysed samples has, within error limits, the same ratio as bulk Allende (Figure 5). Dark inclusions, however, have higher Fe contents and most of them also lower Cr-content than bulk Allende or All-AF. Allende chondrules have, on the other hand, similar or higher Cr contents than bulk Allende [12, 13]. Low Cr-contents in DIs therefore support the conclusion of Bischoff *et al.* [4], that chondrules were absent when

dark inclusions accreted. The high Cr in AF would then suggest that the fragment should have sampled chondrules or the precursors of chondrules. Textural and mineralogical observations by Kurat *et al.* [1] showed that All-AF is free of chondrules, it contains lithologies that may best be described as unmelted chondrule precursors.

Figure 6 is a plot of moderately volatile elements in AF and in bulk Allende normalized to CI and arranged in order of decreasing condensation temperatures. Large deviations from the Allende bulk chemistry are found for some elements. Gold, for example, is enriched in sample A by more than a factor of ten. Other metals with similar volatilities, such as Pd, As and Sb, are also enriched, although to a lesser extent. In constructing Fig. 6 we used data from fragment A (Table 1) and additional data from the analysis by the metal extraction technique (Table 2), which gave a lower Au content than that of sample A. It is therefore likely that the corresponding enrichment factors for Pd and Sb in sample A would be higher than those plotted in Figure 6. Besides these metals there is considerable enrichment in All-AF of some moderately volatile lithophile elements, such as K, Na, and Br. The enrichment factors for sample B are in all cases lower than those for A, although concentrations are still above the bulk Allende level. Clearly excesses of moderately volatile elements are inhomogeneously distributed within the All-AF fragment. What is the reason for these enrichments? Either a component rich in Au, As, Na etc. was mobilized in the parent body or the high concentrations of these elements

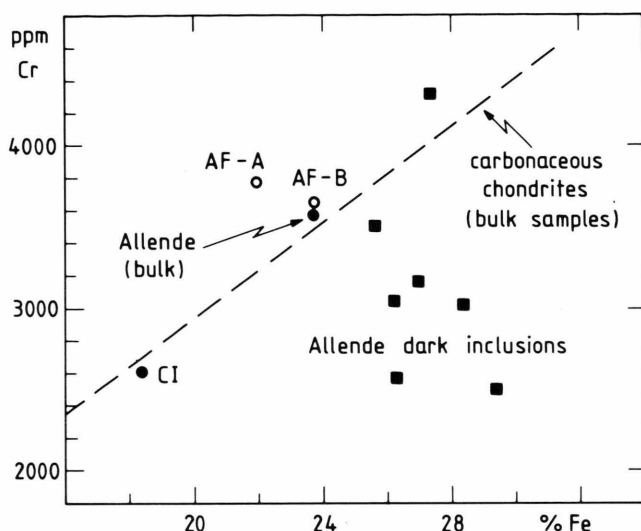


Fig. 5. Dark inclusions are higher in Fe and lower in Cr than bulk Allende. All-AF is similar to bulk Allende. Data for DIs [4].

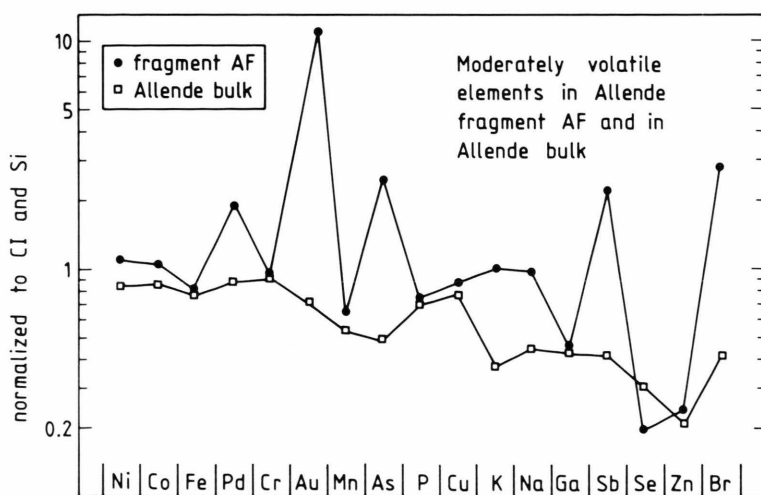


Fig. 6. Moderately volatile elements in All-AF. Huge enrichments of Au, As, Sb and Br, and high contents of Na and K are characteristic of xenolith All-AF.

were established in the solar nebula during condensation, prior to accretion.

The available textural and chemical evidence, discussed in Kurat *et al.* [1] clearly favours the second possibility. Mobilization by reheating can be excluded because elements more mobile than those enriched in AF have essentially “normal” Allende-abundances. The contents of Zn and Se in All-AF are typical of CV-meteorites in general (Figure 7). Both elements are diagnostic for type 3 carbonaceous chondrites. H-chondrites, for example, have similar Se contents as CV-chondrites, but significantly lower Zn abundances [14]. Any heating process of Allende material would lead to comparatively larger losses of Se and Zn than of Au and Na. However Se and Zn concentrations are surprisingly uniform in Allende bulk samples and in a variety of Allende components, such as dark inclusions and All-AF. Hence, selective mobilization of Au and Na by thermal events on the parent body seems unlikely.

A liquid that would transport Au, As, Na and K can be excluded. There is not a single textural or mineralogical observation in support of this possibility. No hydrous phases have been observed in AF, no depositions that would be indicative of the action of a fluid phase. Furthermore, it is very unlikely that Na and Au would be mobilized in a common process. It is more likely that reactions of gaseous Na, K, Cl and Br with solid Al-silicates and gaseous moderately volatile metals (Au, Sb) with preexisting metallic carrier phases led to the enhancement of these elements. Both reactions could have occurred in the solar nebula at temperatures above the condensation temperatures of Se and Zn.

Enrichment of Na, K, Cl, and Br and also of Au and other moderately volatile elements in various components of Allende is not uncommon. CAIs, for example, are often enriched in these elements. This is particularly true for fine grained-spinel-rich inclusions (e.g. [15]). Because for their high surface area, they readily react with gaseous Na etc. Coarse-grained inclusions are predominantly enriched in volatiles on the outside, as there was not enough time for diffusion into the inclusion.

Occasionally, reactions with gaseous Zn, S (and Se) are recorded in refractory inclusions. However, extensive S-alteration, such as for example, recorded in the EGG-6 inclusion [16] is relatively rare. The range of temperatures where alteration of Allende components occurred was quite variable, extending in some cases

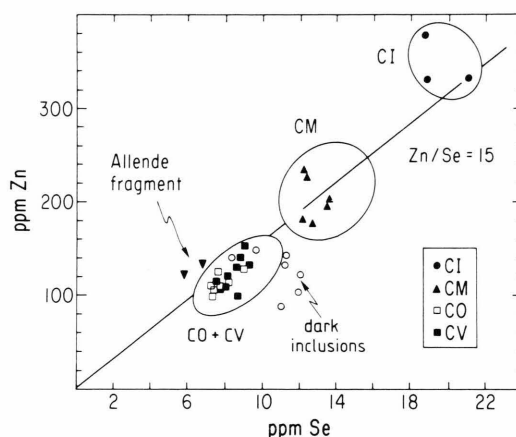


Fig. 7. Two rather volatile elements Se and Zn have typical Allende i.e. C3-chondritic abundances in All-AF. A similar observation was made for DIs [4]. Data for carbonaceous chondrites from Mainz (unpublished).

to rather low temperatures. Although the All-AF fragment did suffer extensive S-alteration it supposedly has “normal” (i.e. Allende-bulk) S-content, judging from the abundance of Se, an element closely associated with sulfide. This indicates that All-AF was not longer exposed to gaseous S as other Allende components or that the S-reservoir was a closed system.

The type of process that leads to enhancement of elements such as Na or Au is quite obvious in the alteration of Ca, Al-rich materials of Allende. There is, for example, an approximate correlation of Au and Na in coarse grained CAIs [17]. Fine grained CAIs have very high Na contents, but are low in Au, simply because they do not contain a host phase for Au, but abundant host phases for Na, Al-rich silicates [18].

It is now clear that the type of alteration discussed here is characteristic of the oxidized subgroup of the CV-chondrites, as defined by McSween [19]. The reduced subgroup is much less affected [18]. It is furthermore clear that the alteration must have occurred very early in the history of the solar system, as fine-grained inclusions contain large amounts of  $^{129}\text{Xe}$  [20].

There is some indication that elements much more volatile than Se and Zn have high abundances in All-AF. Rather high concentrations of Hg were found in all samples and separates from All-AF, while Hg concentrations were always below detection limit in bulk Allende samples. We have furthermore found one occurrence of HgS in a section of a sulfide-rich particle from All-AF. The significance of Hg data is, however, difficult to evaluate. We also have found high contents

of Hg in some of our analyses of carbonaceous chondrites, without any other element correlating with Hg.

One reviewer questioned the significance of high contents of Na, Au, Hg etc. and suggested that these elements may rather have been introduced by contamination. In this laboratory more than one hundred Allende samples have been analysed in the past 20 years. All samples were treated in the same way, including removal from Allende. Systematically low Na contents were found in *all* dark inclusions, no Hg was detected in any of them, despite two orders of magnitude lower sample sizes than analyzed bulk samples. Furthermore high Na contents in AF are supported by high modal abundance of nepheline [1]. Similar arguments can be applied to Hg. All samples and subsamples of AF contain some measurable amounts of Hg, while Hg contents were below detection limit in all dark inclusions.

### Oxygen Isotopic Composition of All-AF

In Fig. 8 the oxygen isotopic composition of All-AF and dark inclusions is shown in a  $\delta^{17}\text{O}$  vs.  $\delta^{18}\text{O}$  diagram. The data from dark inclusions were taken from Clayton *et al.* [21] and Bischoff *et al.* [4]. All-AF

belongs, together with two dark inclusions, to the Allende samples with the highest enrichment in  $^{18}\text{O}$  and  $^{17}\text{O}$  (Figure 8). The correlation through all dark inclusion points (including Allende matrix and All-AF) has a slope slightly less steep than that of the Allende mixing line [21]. In constructing this line we have connected the three Allende points with the highest  $\delta^{17}\text{O}$  and  $\delta^{18}\text{O}$  (Fig. 8) with those with the lowest  $\delta^{17}\text{O}$  and  $\delta^{18}\text{O}$  ( $-40$  and  $-41$ ). For the interpretation of the Allende mixing line it is assumed that material, originally high in  $\delta^{16}\text{O}$ , exchanged oxygen with a gaseous reservoir with an oxygen isotopic composition on the Allende mixing line, at or above the All-AF composition (Figure 8). The position of the dark inclusions along this line simply reflects their extent of oxygen equilibration with this reservoir [21]. The slight difference in slope between the Allende mixing line and the dark inclusion correlation line probably indicates contribution by a small chondrule-like component in the original DI-reservoir, as they are shifted in the direction of the isotopic composition of chondrules [21]. The absence of a chondrule component in DIs is evident from their texture and has been inferred from their composition. The extreme composition of All-AF and two dark inclusions shows a similar degree of equilibration with the gaseous oxygen reservoir and confirms the textural finding that All-AF has never had chondrules (see next chapter).

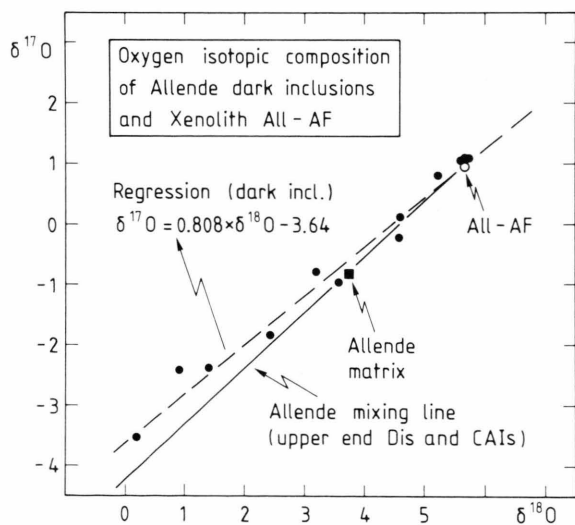


Fig. 8. Oxygen isotopic composition of All-AF and dark inclusions. A regression through DIs, All-AF and Allende matrix has a slightly different slope than the Allende mixing line. A possible reflection of a small chondrule component in DIs. All-AF and two DIs have the lowest  $\delta^{16}\text{O}$  of all Allende samples analysed so far. Data for DIs see [4], [17].

### Fragment AF and the Formation of Chondrules

Anders [23] and Larimer and Anders [24] have proposed that chondrules were formed by remelting of matrix. Rapid heating of matrix would lead to loss of volatile and moderately volatile elements from the chondrule melt. The bulk content of volatiles in carbonaceous and ordinary chondrites would thus be determined by the fraction of volatile-free chondrules in the meteorite. The depletions of Zn and Se (relative to CI) is, according to this model, simply the result of dilution of CI-like matrix with chondrules.

This model would predict CI-concentrations of all volatile elements for All-AF, since All-AF does not contain chondrules. The possibility that chondrules were originally present in All-AF and that any record of them has been erased by alteration can be discarded on textural and mineral chemical grounds, as extensively discussed in Kurat *et al.* [1]. In fact, All-AF has similar concentrations of the rather volatile elements,

Zn and Se, as bulk Allende and if All-AF does not contain chondrules and did never contain chondrules the depletion of Zn and Se cannot be the result of chondrule formation from initially volatile-rich matrix material. Similar arguments can be made for dark inclusions. Their Zn and Se contents are in the same range as those of All-AF and bulk Allende, respectively [4]. They consist largely of some type of fine-grained matrix material and lack chondrules.

It is therefore clear that depletion of volatile elements in Allende and related meteorites is a property of the reservoir from which these meteorites formed and has nothing to do with the formation of chondrules.

### Origin of Allende Xenolith All-AF

The similarity of the major and minor element composition of All-AF with bulk Allende indicates formation of All-AF from the same reservoir as bulk Allende. The major phase in All-AF and bulk Allende is FeO-rich olivine. However, the first olivine to condense from a gas of solar composition is forsterite, even at considerably more oxidizing conditions than those in a gas of solar composition [25]. Reaction of gaseous FeO with forsterite at lower temperatures may produce more fayalitic olivine [25]. Formation of chondrules must have occurred before conversion of forsterite to FeO-rich olivine, as chondrules are low in FeO. Once chondrules are formed, reaction with gaseous FeO will only result in FeO-rich chondrule rims, while the much smaller matrix olivines will completely react to fayalitic olivine. Texture and trace element data provide evidence that the All-AF olivines are not igneous in origin [1]. Recent analyses by SIMS showed, for olivine, an unusually high level of REE [10]. This level is broadly consistent with the level of REE found by INAA of FeO-poor forsterites [11]. Similarly the high content of Al in Allende forsterite and in AF-olivine is not compatible with crystallization from a melt. During formation of All-AF, Al-silicates were preferentially accreted, resulting in relatively high Al-contents of the fragment. At lower temperatures Na and K condensed to form nepheline and finally Cl and Br entered these phases

at still lower temperatures leading to the formation of sodalite.

The enhancement of some metals (Au, As, Sb) with similar volatilities to those of Na and K requires metal to be extensively exposed to the solar gas probably before condensation of S. After condensation of siderophiles, gaseous S reacted with the metal to form sulfides. Ni-rich metal and Ni-rich sulfide reflect the oxidising environment.

Low temperature alteration produced abundant andradite and resulted in the incorporation of Hg.

In contrast, the history of dark inclusions must have been quite different. As emphasized by Bischoff *et al.* [4] the dominant process appears to have been preferred sampling of fine grained matrix material. The lack of chondrules, CAIs and large fine-grained aggregates can be inferred from the chemical composition of these objects.

Both objects, DIs and AF have in common extensive reaction with the ambient oxygen gas environment, which is reflected in their oxygen isotopic composition at the upper end of the  $\delta^{17}\text{O}$ ,  $\delta^{18}\text{O}$  Allende correlation line.

It therefore appears that chemically similar but texturally rather different objects were formed from a single reservoir. Different physico-chemical conditions must have prevailed during formation of these lithologies from an initially hot solar gas. Processes on the Allende parent body did not significantly contribute in establishing the present texture and mineralogy of Allende and its clasts.

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