Trace elements in the Allende meteorite—IV.
Amoeboid olivine aggregates

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Abstract—INAA data for Ca, Sc, Hf, La, Ce, Sm, Eu, Tb, Yb, Lu, Os, Ir, Ru, Na, Cl, Br, Fe, Mn, Cr, Co, Au, As, and Sb are presented for ten amoeboid aggregates from the Allende meteorite. Only one lacks olivine. Seven of the remainder, as a group, have cosmic proportions of refractory lithophile and siderophile elements and appear to have formed when coarse-grained Allende inclusion material underwent partial reaction with a low-temperature nebular gas and mixture with FeO-rich olivine. The other two have highly fractionated abundances of refractory elements relative to one another compared to C1 chondrites, including Group II REE patterns, and probably formed by the mixing of fine-grained Allende inclusion material with FeO-rich olivine. Non-refractory siderophile components are also different in composition in each type of amoeboid olivine aggregate.

INTRODUCTION

IN A petrographic and electron microprobe study, GROSSMAN and STEELE (1976) described a class of inclusions from the Allende meteorite which they called 'amoeboid olivine aggregates'. On the basis of their beige color and lumpy appearance on slab surfaces, these were readily distinguished from the coarse- and fine-grained Ca-rich inclusions (GROSSMAN and GANAPATHY, 1975) found in the same meteorite. A fundamental mineralogical difference was also noted by GROSSMAN and STEELE (1976). Olivine, Fo64 to Fo99, constitutes the bulk of the amoeboid aggregates, but this phase has never been identified unequivocally from a fine-grained inclusion and is found only rarely in coarse-grained inclusions, and then as Fo100. Despite this major distinction, some mineralogical similarities between the three types of inclusions are noteworthy. Nepheline and sodalite are common in amoeboids and fine-grained inclusions, but are distinctly less abundant in coarse-grained inclusions. Spinel, perovskite, Ti,Al-rich pyroxene and anorthite, phases characteristic of coarse-grained inclusions, are also present in the amoeboids, often as ragged clumps of tiny grains.

Using mineralogical, textural and isotopic data, GROSSMAN and STEELE (1976) concluded that amoeboid olivine aggregates were formed when refractory condensates like those in coarse-grained inclusions reacted with the solar nebular gas at relatively low temperatures and became mixed with low-temperature condensates such as FeO-rich olivine. In this paper, we test this hypothesis by performing trace element analyses of amoeboids by INAA. Data collected for coarse- and fine-grained inclusions by the same technique in previous papers in this series (GROSSMAN and GANAPATHY, 1976a,b) can be used in comparing the amoeboids to these other types of inclusions.

SAMPLES

Samples used in this study were identified on slab surfaces of the Allende meteorite on the basis of their similarity in color and texture to 23 amoeboid olivine aggregates studied previously in this laboratory by microprobe techniques (GROSSMAN and STEELE, 1976). All samples were excavated from slabs in a clean room with stainless steel dental tools while viewing them with a binocular microscope. The largest amoeboids found were selected for analysis in order to maximize sample size and minimize the potential contamination of amoeboid material with surrounding, unwanted matrix. Samples weighing from only 2–8 mg were obtained from aggregates measuring 4–9 mm in length and 2–3 mm in width. Estimates of matrix contamination, made by visual inspection of sample powders, are less than 1% for all samples except for sample 2 which could contain as much as 5% matrix material.

In order to identify the minerals present in these samples, X-ray patterns were obtained from splits of their powders. Results are shown in Table 1, where all phases identified on the basis of at least one strong, characteristic, unambiguous line are listed as definitely present and those indicated by only a single weak line are listed as possibly present. Except for sample 4, all contain olivine and spinel. In addition, most contain nepheline and/or sodalite. Melilite, clinopyroxene and plagioclase are possible constituents of every amoeboid, but in no case could identification of these phases be made with certainty. The mineralogical composition of sample 4 is different from all the others. Only spinel and grossular could be identified from its powder pattern. A polished thin section was made of two

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chips of this sample, totalling 0.45 mm², in order to obtain more information about its mineralogy. Although this material was very fine-grained and took a poor polish, electron microprobe analysis showed that andradite, several Fe-rich, Ti,Al-pyroxenes, an Al-rich hedenbergite, a Ca-rich nepheline and grossular are present. The absence of olivine from sample 4 implies that this inclusion should not be classed with the amoeboid olivine aggregates. Hereafter, it will be referred to simply as an amoeboid aggregate or as an 'unclassified' inclusion.

EXPERIMENTAL

All samples were weighed into pre-cleaned, supersilica tubes, weighing approx 1 g, which were then sealed, washed again in hot HNO_3 and weighed. Separate chemical standards were used for each of Br, Os, Ru, Ir, and Au. These were prepared in essentially the same way as in KEAYS *et al.* (1971) and micro-pipetted into the same type of supersilica tube used for the samples. Reagent grade $CaCl_2$ powder was weighed into another tube and used as a standard for Ca and Cl. Similarly, 12.07 mg of the 'standard pot', SP, (PERLMAN and ASARO, 1969) were placed in another tube and used as the standard for all other elements. Together with an empty tube used as a blank, all samples and standards were irradiated simultaneously for 1 hr at a thermal neutron flux of $5 \times 10^{12}\, \text{n cm}^{-2}\, \text{sec}^{-1}$ in the isotope tray of the CP-5 reactor at Argonne National Laboratory. All supersilica tubes were washed in hot HNO_3 prior to counting which began within 3 hr of the end of the irradiation. Na, Mn and Cl were determined from spectra resulting from counting periods of 300–600 sec.

The blank, standards and samples underwent a second irradiation for 3 days in the VT-25 position of the vertical thimble of the same reactor at a thermal neutron flux of $3 \times 10^{13}\, \text{n cm}^{-2}\, \text{sec}^{-1}$. After the sample tubes were washed in hot HNO_3, all samples were counted within a period of 7 days, beginning 2 days after the end of the irradiation. Thus, Br, La, Sm, Au and, in some samples, Ca and Yb were determined in counting times of $1-2 \times 10^4$ sec. During the next month, samples were counted for $0.5-1.0 \times 10^5$ seconds each in order to obtain data for Lu, Fe, Co, Cr, Os, Ir, Ru, Sc, Hf, Ce, Eu, and Tb in all of them and Ca and Yb in those samples which had poor counting statistics for these elements in the previous series of counts.

All gamma-ray spectra were measured with the system described in GROSSMAN and GANAPATHY (1976a). The stability of this counting system was monitored by measuring a standard ^{137}Cs source. Its count rate was found to vary by only ±0.75% during the course of the above experiment. Monitoring of the energy vs channel calibration revealed a maximum drift equivalent to ±0.4 keV over a period of several months.

A significant Cl blank was suspected from data collected after the first irradiation. Consequently, a third irradiation

was performed in the isotope tray at a flux of 5×10^{12} $\text{n cm}^{-2}\, \text{sec}^{-1}$ for 30 min in order to determine the Cl content of the supersilica sample tubes. Five empty tubes, weighing approximately one gram each, were made from the same batch of tubing as the normal sample tubes, were washed in an identical fashion to them and were irradiated along with a $CaCl_2$ standard. Starting 4.5 hr after the irradiation, each tube was counted for 10 min on a Ge(Li) detector at Argonne.

Spectra were read out on magnetic tape and also on a high-speed printer. All data processing was performed manually on a programmable desk calculator. The radionuclides used for the determination of each element as well as the energies of the analytical peaks and the half-lives employed in this work are listed in Table 2. Also indicated is whether SP or a chemical standard was used for each element and, when the former was employed, the concentration of that element in SP. These data come from the work of PERLMAN and ASARO (1971), except for Tb whose concentration in SP was determined against BCR-1 in the course of the experiment described in GROSSMAN and GANAPATHY (1976a, b). The Lu data were checked for contributions from Au and Yb in the same way as in GROSSMAN *et al.* (1977). No Au corrections were found to be necessary for standard or samples and the corrections for Yb were less than one percent for all samples. Similarly, we looked into the possibility of interference with the 103.2 keV ^{153}Sm line by 103.8 keV X-rays of Pu arising from decay of ^{239}Np which, in turn, stems from neutron capture on ^{238}U. From data collected in a previous irradiation for SP and BCR-1, two standards with well-known Sm and U contents and widely-differing U/Sm ratios, the ratio of ^{239}Np counts at 106.1 keV to those of Pu at 103.8 keV was calculated and used to correct the ^{153}Sm data in this experiment. A 3.7% correction was found to be necessary for SP, the Sm standard, but no ^{239}Np peak was found at 106.1 keV in any of the samples, indicating a correction of <0.2%.

RESULTS

As a result of the experiment on the five empty sample tubes, we found a mean Cl concentration of 27.4 ± 1.4 ppm in the supersilica from which they are made, including one value of 32.3 ± 3.5 ppm. Such concentrations lead to very large Cl blank corrections to the total Cl activity measured in the samples, amounting to 48–78%. The Cl data in this paper and those for coarse- and fine-grained inclusions in GROSSMAN and GANAPATHY (1975) have been corrected accordingly. Except for Br, which is discussed later, and Cl, the blank corrections for all elements were well below 1% of the amount present in all cases in this study.

Data for all elements determined in this study are presented in Table 3. Uncertainties quoted are based on 1σ statistics for samples and standards and for all other data used in making corrections for interferences and blanks.

Table 1. Mineralogy of samples analyzed in this study, as deduced from X-ray powder patterns*

Sample	Olivine	Nepheline	Sodalite	Melilite	Spinel	Clinopyroxene	Plagioclase	Grossular
1	X	O		O	X	O	O	
2	X	X		O	X	O		
3	X	X		O	X	O	O	
4	O	O	O	O	X	O	O	X
5	X	O		O	X	O	O	
6	X	O	X	O	X	O	O	
7	X	X		O	X	O	O	
8	X	X		O	X	O	O	
9	X	O		O	X	O	O	
10	X	X		O	X	O	O	

* X denotes definitely present; O denotes possibly present; blank denotes not detected.

Table 2. Half-lives, analytical peaks and standard information for elements determined in this work

Nuclide	Half-life[2]	Energy (keV)[3]	Standard	Element Concentration in Standard (ppm unless otherwise indicated)[4]
^{76}As	26.32 h	559.5	S?	30.8 ±2.2
^{198}Au	2.696 d	411.8	Chem	
^{82}Br	35.30 h	554.3	Chem	
^{47}Ca	4.538 d	1297.1	Chem	
^{141}Ce	32.5 d	145.4	SP	80.3 ±3.9
^{38}Cl	0.622 h	1642.4	Chem	
^{60}Co	5.263 y	1332.5	SP	14.06±0.15
^{51}Cr	27.72 d	320.1	SP	115.1 ±3.8
^{152}Eu	12.7 y	1408.0	SP	1.291 ±0.034
^{59}Fe	45.1 d	1099.2	SP	1.017 ±0.012%
^{181}Hf	42.4 d	133.0	SP	6.23±0.44
^{192}Ir	74.02 d	468.1	Chem	
^{140}La	40.22 h	1596.4	SP	44.90±0.45
^{177}Lu	6.71 d	208.4	SP	402±36 ppb
^{56}Mn	2.576 h	846.6	SP	40.9 ±0.5
^{24}Na	15.0 h	1368.5	SP	2580±40
^{191}Os	15.4 d	129.4	Chem	
^{233}Pa[1]	27.0 d	311.9	SP	13.96±0.39 (Th)
^{103}Ru	39.35 d	497.1	Chem	
^{124}Sb	60.20 d	1691.0	SP	1.71±0.05
^{46}Sc	83.8 d	889.3	SP	20.55±0.33
^{153}Sm	46.7 h	103.2	SP	5.78±0.12
^{182}Ta	1f5.0 d	1189.1	SP	1.550±0.044
^{160}Tb	72.3 d	1177.9	SP	0.74±0.03[5]
^{175}Yb	100.6 h	396.3	SP	2.80±0.36

[1] This nuclide was used for the determination of Th.

[2] Half-lives are taken from the most recent entry for each nuclide in *Nuclear Data Sheets* (Sept. 1977 and earlier).

[3] BOWMAN and MCMURDO (1974).

[4] Except for Tb, concentrations of elements in SP are taken from PERLMAN and ASARO (1971).

[5] See text for source of Tb data in SP.

The accuracy of the data presented herein can not be tested in the usual fashion as no well-known standards other than the irradiation monitors were included in these experiments. Furthermore, data for these samples can not be checked against those of other workers since none of the Allende inclusions whose compositions have appeared in the literature have published petrographic or mineralogical descriptions matching those of amoeboid olivine aggregates. Aside from Br, As, Sb, and Th, however, all elements determined in this work have been determined in this laboratory previously under the same irradiation and counting conditions and using the same standards as in these experiments (GROSSMAN and GANAPATHY, 1975; GROSSMAN and GANAPATHY, 1976a, b; GROSSMAN et al., 1977). In those studies, internal checks were possible and agreement with literature data was satisfactory to excellent in all cases. In the case of Sm, GROSSMAN and GANAPATHY (1976a) obtained values for BCR-1 which were 4–8% lower than literature data. This discrepancy vanishes when a correction for U interference similar to that described above is applied to those data.

Unpublished data for As, Th, and Sb have been obtained in this laboratory, using the same standard as that in the present study. Comparison of data for BCR-1 from those studies with literature data for that standard is a useful test of our ability to determine these three elements. Our value of 0.7 ± 0.1 ppm As compares favorably with 0.70, the 'magnitude' arrived at by FLANAGAN (1973). For Th, we obtained 6.05 ± 0.04 and 6.09 ± 0.02 ppm in two separate irradiations, data which are in excellent agreement with the recommended value of 6.0 ppm (FLANAGAN, 1973). In three separate irradiations, we obtained values of 579 ± 17, 579 ± 11 and 601 ± 8 ppb for Sb, which are in good agreement with the measurement of KEAYS et al. (1974), 550 ± 60 ppb.

DISCUSSION

Refractory siderophile elements

As can be seen in Table 3, most amoeboid olivine aggregates contain unusually high concentrations of Os, Ir, and Ru, several ppm of each. The Os and Ir contents are plotted in Fig. 1, along with data for these elements in nine coarse-grained, Ca-rich Allende inclusions (GROSSMAN and GANAPATHY, 1976a). In that paper, it was noted that Os and Ir are strongly correlated with one another in coarse-grained inclusions and that their concentrations in them fall along

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Table 3. Concentrations[1] of all elements determined in the samples

Sample	Sample Size (mgm)	Ca (%)	Sc	Hf	La	Ce	Sm	Eu	Tb	Yb	Lu	Os
1	1.63	3.15 ±.14	54.30 ±.04	0.571 ±.081	1.85 ±.04	6.10 ±.34	1.21 ±.01	0.174 ±.012	0.161 ±.063	0.868 ±.078	0.136 ±.006	2.56 ±.07
2	1.24	1.41 ±.30	29.76 ±.05	0.56 ±.12	2.00 ±.06	2.94 ±.78	0.290 ±.015	0.099 ±.017	<0.25	0.330 ±.082	0.123 ±.015	1.99 ±.12
3	5.92	4.42 ±.33	26.58 ±.02	0.462 ±.051	1.04 ±.04	2.23 ±.23	0.636 ±.011	0.250 ±.007	0.152 ±.045	0.855 ±.062	0.121 ±.012	1.52 ±.06
4	3.91	17.7 ±.6	113.53 ±.06	1.66 ±.09	4.18 ±.08	11.4 ±.5	2.65 ±.02	0.978 ±.016	0.562 ±.062	2.75 ±.16	0.432 ±.024	5.53 ±.11
5	2.08	0.80 ±.15	10.46 ±.02	0.170 ±.037	0.446 ±.029	1.19 ±.20	0.244 ±.018	0.120 ±.008	<0.17	0.256 ±.052	0.0409 ±.0074	0.714 ±.058
6[2]	2.41	6.30 ±.26	22.36 ±.02	<0.068	8.97 ±.11	15.8 ±.3	4.38 ±.03	0.329 ±.010	0.605 ±.048	0.660 ±.060	<0.015	<0.12
7[3]	8.07	2.38 ±.17	12.62 ±.01	<0.024	2.26 ±.03	5.15 ±.09	1.422 ±.008	0.117 ±.003	0.200 ±.019	0.242 ±.029	<0.0067	<0.047
8	7.50	2.49 ±.09	18.62 ±.01	0.287 ±.027	0.892 ±.033	1.89 ±.14	0.432 ±.013	0.182 ±.004	0.077 ±.032	0.443 ±.044	0.072 ±.010	1.15 ±.04
9	2.01	3.01 ±.19	16.73 ±.02	0.299 ±.039	0.811 ±.053	1.80 ±.21	0.404 ±.036	0.146 ±.007	<0.13	0.532 ±.075	0.044 ±.020	0.983 ±.065
10	5.78	5.15 ±.18	34.54 ±.03	0.518 ±.056	1.35 ±.03	3.96 ±.31	0.864 ±.010	0.351 ±.008	0.150 ±.049	0.886 ±.047	0.208 ±.039	1.55 ±.10

[1] All upper limits are based on 2σ counting statistics.
[2] Sample 6 also contains 203 ± 30 ppb Ta and 438 ± 38 ppb Th.
[3] Sample 7 also contains 109 ± 13 ppb Ta and 185 ± 14 ppb Th.

a line whose slope is given by the ratio of their abundances in Cl chondrites, as can be seen in Fig. 1. It is also apparent from Fig. 1 that Os and Ir are strongly correlated with one another in seven amoeboid olivine aggregates and in the unclassified sample 4 and that data points for these samples fall along the same line as those for coarse-grained inclusions. Although there is some overlap between the two sets
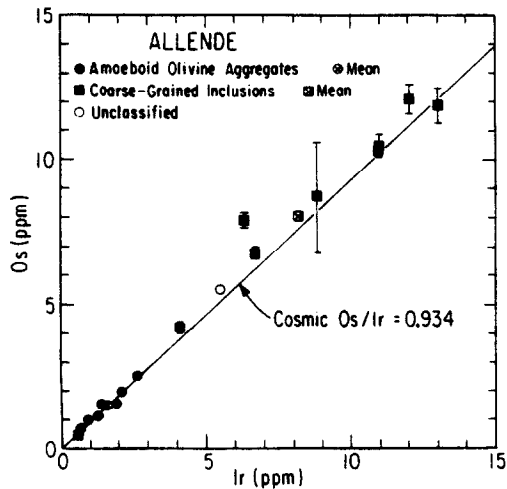

Fig. 1. Osmium and iridium contents of seven amoeboid olivine aggregates are lower than those of Allende coarse-grained inclusions, but plot along the same line whose slope equals the cosmic Os/Ir ratio.

of data points, there is a distinct tendency for amoeboid olivine aggregates to have lower Os and Ir contents than coarse-grained inclusions, as can be seen from the positions of their mean concentrations. The Os and Ir contents of the unclassified amoeboid aggregate, sample 4, are intermediate between those of the average coarse-grained inclusion and the average amoeboid olivine aggregate. A simple interpretation of these data is that the same refractory siderophile condensate components are present in the olivine amoeboids as in the coarse-grained inclusions, but that they are less abundant in the former than in the latter by a factor of approx 5.4.

The data for samples 6 and 7 are not plotted in Fig. 1. The upper limits to their Os contents are less than the lowest Os value reported for any coarse-grained inclusion studied by GROSSMAN and GANAPATHY (1976a) and less than any other amoeboid olivine aggregate reported here. Their Ir contents are also extremely low, several hundred times lower than the average coarse-grained inclusion and more than a factor of 20 lower than the lowest value found in any of the other olivine amoeboids. In fact, the Ir contents of these two samples are comparable to those of the so-called Group II fine-grained Allende inclusions (MARTIN and MASON, 1974), noted for their exceptionally low refractory siderophile element contents (GROSSMAN and GANAPATHY, 1976b).

If the Ru data in Table 3 are plotted against either the Os or Ir concentrations, graphs very similar to

studied in this work. (Values in ppm unless otherwise indicated)

Ir	Ru	Na (%)	Cl (%)	Br	Fe (%)	Mn (%)	Cr	Co	Au (ppb)	As	Sb
2.59 ±.03	4.68 ±.43	0.412 ±.010	0.79 ±.15	0.73 ±.25	8.29 ±.03	0.0563 ±.0007	1124 ±3	59.4 ±.2	106 ±3	3.09 ±.13	0.245 ±.057
2.04 ±.02	2.57 ±.67	0.930 ±.017	1.08 ±.20	0.65 ±.25	16.41 ±.06	0.184 ±.002	1411 ±4	107.0 ±.4	123 ±3	1.25 ±.22	0.288 ±.086
1.43 ±.01	2.08 ±.27	1.82 ±.02	0.186 ±.047	0.78 ±.20	10.30 ±.03	0.0829 ±.0009	1395 ±4	51.8 ±.2	237 ±3	1.43 ±.21	<0.069
5.44 ±.05	8.01 ±.60	0.912 ±.011	0.703 ±.084	12.1 ±.4	4.81 ±.02	0.0592 ±.0006	394 ±2	44.1 ±.2	88.8 ±4.6	1.01 ±.30	<0.15
0.641 ±.007	0.76 ±.28	0.646 ±.011	0.38 ±.15	<0.90	18.74 ±.06	0.157 ±.002	2195 ±6	115.5 ±.3	130 ±3	2.97 ±.49	0.152 ±.042
0.0281 ±.0019	<0.58	3.09 ±.03	1.09 ±.11	32.7 ±.9	6.22 ±.02	0.0458 ±.0006	2037 ±5	25.3 ±.1	26.3 ±2.8	1.96 ±.76	<0.087
0.00759 ±.00067	<0.21	1.61 ±.01	0.219 ±.076	2.55 ±.16	8.62 ±.03	0.0811 ±.0008	1491 ±4	20.66 ±.06	12.1 ±1.1	0.58 ±.13	0.097 ±.014
1.26 ±.01	1.80 ±.17	1.08 ±.01	<0.16	0.47 ±.23	9.18 ±.03	0.0649 ±.0007	1029 ±3	89.9 ±.2	384 ±3	8.1 ±1.5	0.248 ±.023
0.898 ±.009	1.63 ±.24	1.03 ±.02	<0.50	<1.3	14.74 ±.05	0.157 ±.002	1578 ±4	149.2 ±.3	228 ±5	2.87 ±.44	0.273 ±.037
1.91 ±.02	2.82 ±.36	2.09 ±.02	<0.26	3.19 ±.26	7.54 ±.03	0.0661 ±.0007	843 ±2	53.8 ±.2	124 ±2	1.55 ±.20	<0.086

Fig. 1 are produced and the conclusions drawn are the same. Ru is correlated strongly with both of these elements: the data points fall along lines having slopes equal to the cosmic ratios of Ru to the respective element and Ru concentrations in amoeboid olivine aggregates are significantly lower than those in coarse-grained inclusions. The Ru content of sample 4 is again intermediate between the two types of inclusions and upper limits to the Ru concentrations in samples 6 and 7 are lower than the lowest values seen for other olivine amoeboids studied herein.

Sc and Hf

GROSSMAN and GANAPATHY (1976a) noted that Sc and Hf are strongly correlated in coarse-grained, Ca-rich inclusions in Allende and that, when the concentrations of these two elements are plotted against one another, the data points scatter about a line whose
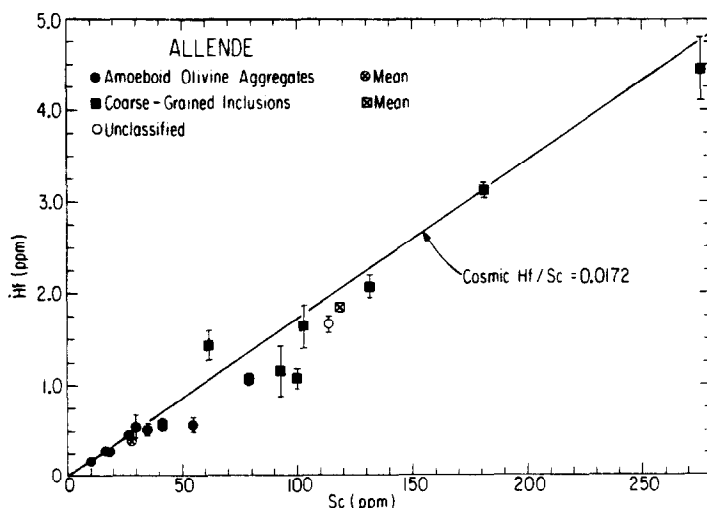

Fig. 2. Hafnium and scandium contents of seven amoeboid olivine aggregates are lower than those of Allende coarse-grained inclusions, but plot along the same line whose slope equals the cosmic Hf/Sc ratio.
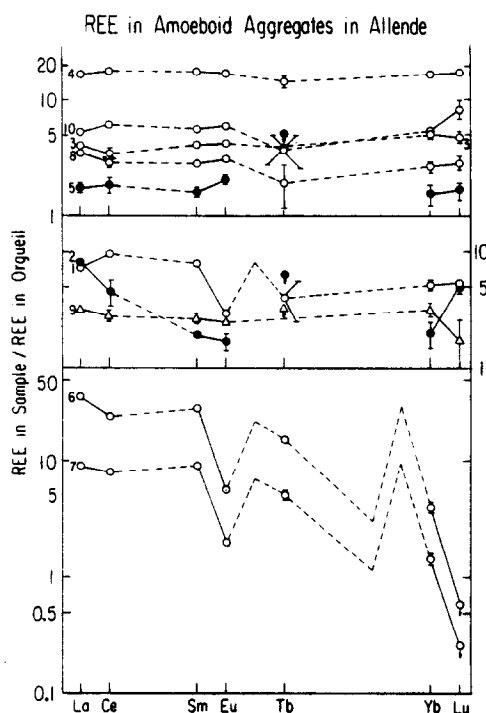
Fig. 3. Most amoeboid olivine aggregates have relatively flat REE patterns, except for small La/Ce, Sm/Eu, and Yb/Lu fractionations. They are very similar to those of Allende coarse-grained inclusions, but the absolute levels of REE are lower in the amoeboids. On the other hand, samples 6 and 7 have the strikingly fractionated REE patterns typical of Allende Group II fine-grained inclusions. Arrows indicate 2σ upper limits.

slope equals the ratio of these two elements in Cl chondrites. This is shown in Fig. 2, in which the data for eight of the amoeboid aggregates studied herein are also plotted. It is apparent that the olivine amoeboids plot along an extension of the trend exhibited by the coarse-grained inclusions, with the Sc and Hf concentrations in the former significantly lower than those in the latter, similar to the case of the refractory siderophiles. The unclassified sample 4 again plots much closer to the coarse-grained inclusions than do the olivine amoeboids. The data are consistent with the idea that the same Sc- and Hf-bearing refractory condensate components are present in the amoeboids as in coarse-grained inclusions, but that they are more abundant in the latter than in the amoeboids.

Again, the data for samples 6 and 7 have not been plotted. The upper limits to their Hf concentrations are much lower than the Hf contents of coarse-grained inclusions reported by GROSSMAN and GANAPATHY (1976a) and those of the other amoeboid olivine aggregates studied herein. They are consistent, however, with unpublished RNAA data from this laboratory for Hf in fine-grained inclusions. The Sc contents of these samples are lower than those of all the coarse-grained inclusions studied by GROSSMAN and GANAPATHY (1976a), within the range of those of the fine-grained inclusions reported by GROSSMAN

and GANAPATHY (1976b) and at the low end of the range of those of the other olivine amoeboids studied herein.

Rare earth elements

Data are shown in Fig. 3 for La, Ce, Sm, Eu, Tb, Yb, and Lu in ten amoeboid aggregates. The Cl data used for REE normalization were taken from NAKAMURA (1974), except for Tb whose concentration was that derived by GROSSMAN and GANAPATHY (1976a). The shapes of the REE patterns for samples 1, 3, 5, 8, 9, and 10 are very similar to those typical of coarse-grained, Ca-rich inclusions in Allende (MARTIN and MASON, 1974; CONARD et al., 1975; GROSSMAN and GANAPATHY, 1976a; GROSSMAN et al., 1977). They are relatively flat and commonly show small, but significant, positive or negative deviations from chondritic La/Ce, Sm/Eu and Yb/Lu ratios. The calculations of BOYNTON (1975) have shown clearly how Eu can fractionate from Sm and Yb from Lu during condensation. All features of the REE patterns of bulk, coarse-grained inclusions were probably produced during condensation of the REE from the solar nebula. The major difference between these REE patterns and those of coarse-grained inclusions is in the absolute levels of REE. The amoeboid olivine aggregates are significantly depleted in REE relative to coarse-grained inclusions, although still enriched in them by factors of two to ten relative to Cl chondrites. Sample 2 has a very unusual REE pattern for an Allende inclusion. Enrichments drop steadily from La to Ce to Sm and Eu and rise sharply from Yb to Lu in this sample. Sample 4 has a relatively flat REE pattern and, as in the case of its Os, Ir, Ru, Sc, and Hf contents, the absolute levels of REE are much closer to those of coarse-grained inclusions than are those of the amoeboid olivine aggregates. These aggregates contain the same REE-bearing condensate components as the coarse-grained inclusions, but in lower concentrations than the latter. This supports the idea expressed above that both types of inclusions contain the same Sc- and Hf-bearing components, since GROSSMAN et al. (1977) concluded that Sc, Hf, and the bulk of the REE entered the coarse-grained inclusions together in the same condensate phases.

Samples 6 and 7 are again exceptional. Their REE patterns are unlike those of the other olivine amoeboids, but their large negative Eu anomalies, high Yb/Lu ratios and high concentrations of light REE, particularly in sample 6, are all characteristic features of the remarkably fractionated REE patterns typical of the Group II fine-grained inclusions in Allende (TANAKA and MASUDA, 1973; MARTIN and MASON, 1974; CONARD et al., 1975; GROSSMAN and GANAPATHY, 1976b). Consequently, in the dashed parts of the REE patterns for these two samples in Fig. 3, the discontinuities at elements not determined in this study are inferred from the shapes of published, full Group II patterns.

Table 4. Refractory elements in amoeboid olivine aggregates and coarse-grained inclusions. (Values in ppm unless otherwise indicated)

Element	Mean Concentration in 7 Amoeboid Olivine Aggregates	Mean Concentration in 9 Coarse-Grained Inclusions	Concentration in Aggregates ÷ Concentration in Inclusions
Ca	2.92 ± 0.58%	17.2 ± 1.8%	0.170 ± 0.038
Sc	27.28 ± 5.47	118.3 ± 23.8	0.231 ± 0.066
Hf	0.410 ± 0.059	1.84 ± 0.41	0.223 ± 0.059
La	1.20 ± 0.22	4.24 ± 0.43	0.283 ± 0.059
Ce	2.87 ± 0.63	13.7 ± 2.2	0.209 ± 0.057
Sm	0.583 ± 0.132	2.80 ± 0.31	0.208 ± 0.052
Eu	0.189 ± 0.033	1.13 ± 0.07	0.167 ± 0.031
Tb	0.135 ± 0.020	0.60 ± 0.12	0.225 ± 0.056
Yb	0.596 ± 0.102	2.7 ± 0.3	0.221 ± 0.045
Lu	0.106 ± 0.022	0.47 ± 0.08	0.226 ± 0.061
Os	1.50 ± 0.24	8.1 ± 1.3	0.185 ± 0.042
Ir	1.54 ± 0.26	8.16 ± 1.36	0.189 ± 0.045
Ru	2.33 ± 0.46	10.5 ± 1.7	0.222 ± 0.057
		Mean	0.212 ± 0.029

Origin of the aggregates

GROSSMAN and STEELE (1976) showed that olivine, ranging in composition from Fo64 to Fo99, is the major constituent of the amoeboid olivine aggregates. The aggregates are constructed of subspherical lumps of micron-sized crystals of olivine, nepheline, sodalite, Ca-rich, Al-rich and Ti-rich pyroxenes, spinel, anorthite and perovskite surrounded by coarser-grained olivine. Similar observations have been made by WARK (1978). GROSSMAN and STEELE (1976) proposed that the aggregates formed when high-temperature condensates like those in the coarse-grained Allende inclusions, spinel, perovskite, anorthite, and the pyroxenes, were exposed to the nebular gas at lower temperatures, resulting in their reaction with the vapor to form nepheline and sodalite and in their mixture with FeO-rich olivine grains. That these aggregates have never been molten seems to be supported by their conglomeratic structures and the lack of equilibration of the compositions of adjacent mineral grains (GROSSMAN and STEELE, 1976) and the heterogeneous distribution of oxygen isotopes between coexisting phases (CLAYTON et al., 1977).

Thus far in this paper, we have seen from relative abundances of refractory trace elements that the same trace condensate components appear to be present in some of the amoeboid olivine aggregates as in coarse-grained inclusions. The question is whether or not the major high-temperature condensate minerals carried the refractory trace elements into the amoeboids.

The refractory component

Table 4 shows the mean concentration of each refractory element determined in the samples studied here and the standard error of the mean, excluding samples 4, 6, and 7. Also shown are the mean concentrations of the same elements in the population of nine coarse-grained inclusions studied by GROSSMAN

and GANAPATHY (1976a) and GROSSMAN et al. (1977) and, in the final column, the mean concentrations in the olivine amoeboids divided by their respective mean concentrations in coarse-grained inclusions. This simple calculation shows that depletion factors for all refractory elements determined in this group of seven amoeboid olivine aggregates relative to coarse-grained inclusions are indistinguishable from one another, having a mean value of 0.212 and a standard deviation of an individual of ±0.029. This conclusion is illustrated graphically in Fig. 4. All refractory elements are thus diluted to the same extent in the olivine amoeboids relative to their abundances in the coarse-grained inclusions, regardless of their siderophile or lithophile character. Because refractory lithophiles are unfractionated relative to refractory siderophiles compared to the cosmic abundances in the population of coarse-grained inclusions (GROSSMAN and GANAPATHY, 1976a; GROSSMAN et al., 1977), this observation implies that they are in cosmic proportion to each other in the group of amoeboid olivine aggregates as well. This is yet another important chemical characteristic in common to both types of inclusions.

Ca is the only refractory major element determined in this study. Assuming that the bulk of the Ca in amoeboid olivine aggregates resides in the Ca-rich phase assemblages equated with high-temperature condensates by GROSSMAN and STEELE (1976) and that the major element compositions of these assemblages are identical to those of Allende coarse-grained inclusions, the depletion of Ca in the olivine amoeboids implies that they contain an average of 17.0 ± 3.8% coarse-grained inclusion material, diluted by the addition of about 83% lower-temperature phases. The important point is that the depletion factor for the major high-temperature phases is indistinguishable from the mean depletion factor for all refractory elements determined here, 0.212 ± 0.029. The implica-
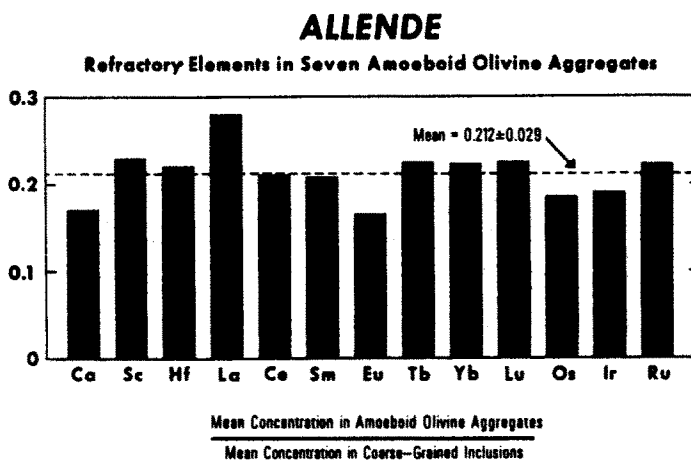
Fig. 4. Refractory elements are unfractionated relative to each other in seven amoeboid olivine aggregates, as a group, compared with coarse-grained Allende inclusions. The amoeboids contain about 21% coarse-grained inclusion material and 79% refractory-free condensates.

tion is thus very strong that refractory major elements and refractory trace elements entered the inclusions together, acting as a single component, and that that component had the same refractory element composition, on the average, as the coarse-grained Allende inclusions.

It would appear then that fine particles of high-temperature condensates did not always accumulate to form mm- to cm-sized coarse-grained inclusions. One possibility is that the amoeboids formed in a separate region of the nebula from the coarse-grained inclusions, one where the gas phase was supersaturated with refractories which ultimately condensed simultaneously with feldspathoids and FeO-rich olivine at temperatures below 1000K. This model is considered unlikely because of its difficulty in accounting for the absence from the amoeboids of metallic iron, which would also have condensed in abundance under these conditions. We prefer, instead, alternative explanations involving equilibrium condensation in which different phases condense at different times, allowing fractionation of some components from others, such as metallic iron from silicates, by grain-gas separation mechanisms. In the region of the nebula where the amoeboid olivine aggregates formed, perhaps the refractory condensates remained unaccreted until metallic iron had been lost and the gas temperature fell into the range 500–800K where FeO-rich olivine becomes stable at 10^{-3}atm total pressure. Another possibility is that the small particles of refractory condensates found in the amoeboids are actually the debris of once-larger, coarse-grained inclusions which underwent collisions after metallic iron had been lost.

Using the mean enrichment factor for all refractory elements, the amoeboid olivine aggregates contain about 21.2% coarse-grained inclusion material and 78.8% lower-temperature components. An independent estimate of this fraction is provided by the data of WARK (1978). He used broad beam electron micro-probe analysis to determine the bulk chemical compositions of inclusions from Allende whose petrographic descriptions are like those studied herein and which he called 'Type AO' inclusions and 'amoeboid olivines'. He found an average of 0.22% TiO_2, 5.1% Al_2O_3 and 3.4% CaO in five aggregates. Using unpublished INAA data from this laboratory, we have divided each of these concentrations by the mean concentration of the same element in a group of eight coarse-grained inclusions. The results, 0.15, 0.15, and 0.13, respectively, suggest that the coarse-grained inclusion component constitutes 14–15% of the aggregates studied by WARK (1978), a value similar to that in the present study.

Samples 6 and 7

While most amoeboid olivine aggregates contain a refractory component which seems to be identical in chemical composition to coarse-grained inclusions, we have seen that samples 6 and 7 have REE patterns shaped like those of Group II fine-grained inclusions. Sample 6 is much higher in refractories than sample 7, but the Ca, Sc, REE, and Ir contents of both lie within the very wide concentration ranges for these elements in fine-grained inclusions (GROSSMAN and GANAPATHY, 1976b). The Th contents of these samples, listed in the footnote to Table 3, are within the range of Th concentrations in Group II fine-grained inclusions given by MARTIN and MASON (1974). The Ta content of sample 7 lies just below the range of Ta contents found in fine-grained inclusions by GROSSMAN and GANAPATHY (1976b), but that of sample 6 lies within it. There is no convincing evidence for the presence of olivine in the fine-grained inclusions studied by GROSSMAN and GANAPATHY (1976b), but olivine is definitely present as a major constituent in samples 6 and 7. Actually, a third inclusion like these has already been studied in this laboratory, sample 15 of GROSSMAN and GANAPATHY (1976b). Its composition is shown therein. During

sampling, it was mistakenly thought to be a fine-grained inclusion from its appearance on a slab surface of Allende but, as mentioned in that paper, its texture, color, and mineralogy are very similar to those of amoeboid olivine aggregates. Like samples 6 and 7, it has a Group II REE pattern. Its levels of Sc, La, Sm, Tb, Dy, and Yb are within the concentration ranges for fine-grained inclusions and its levels of Ca, Ta, Ce, Eu, and Ir lie below the ranges in those inclusions.

It is significant that the concentrations of all refractory elements in these three samples are below their respective maximum concentrations in fine-grained inclusions. This raises the possibility that these three amoeboid olivine aggregates are simply mixtures of fine-grained inclusion material with olivine. If true, there should then be two mineralogical varieties of amoeboids, one in which olivine is mixed with phases typical of coarse-grained inclusions and the other in which it is mixed with the phases of fine-grained inclusions. It would be difficult to tell these apart mineralogically, especially if the coarse-grained inclusion material had been partially altered in the nebula to nepheline, sodalite and grossular. According to petrographic studies (ALLEN et al., 1978), this definitely happened to those coarse-grained inclusions which accreted prior to condensation of forsterite and is even more likely to have happened to that portion of coarse-grained inclusion material that remained unaccreted long enough to form the amoeboids. The only mineralogical difference between the proposed two types of amoeboids would then be the presence of melilite in the type made from coarse-grained inclusion material. Because of dilution by olivine, this would usually be a minor phase in the amoeboids (2–12%) and could easily be overlooked in any but the most detailed petrographic studies, especially considering the small grain sizes. Thus, even though GROSSMAN and STEELE (1976) did not report two varieties of amoeboids, such types may exist, as an exhaustive search for this critical phase was not made in each amoeboid in that study. Furthermore, the X-ray data in Table 1 of this study are too insensitive to tell if two types of amoeboids are present. Phases expected in both types of inclusions are either definitely present (spinel) or possibly present (pyroxene, anorthite, nepheline, sodalite) in every amoeboid. Melilite, characteristic of coarse-grained inclusions only, may or may not be present in each. Perovskite and grossular could be present in small amounts in each amoeboid without being detected in powder patterns among the other phases in this mixture.

Estimating the fraction of fine-grained inclusion material in the three amoeboids discussed above is much more difficult than the previous, analogous estimation of the fraction of coarse-grained inclusion material in the first seven amoeboids. Division of the mean concentration of each refractory element in the three amoeboid olivine aggregates by its mean concentration in the nine fine-grained inclusions of

GROSSMAN and GANAPATHY (1976b) results in widely varying ratios for different elements. This is probably due to the enormous concentration ranges for these elements in both types of inclusions, to the fact that different refractory elements are severely fractionated from one another in some inclusions or amoeboids relative to others, and to the small numbers of inclusions being averaged. The best estimate that can be made from these data, however, is that these amoeboid olivine aggregates contain from 30 to 60% fine-grained inclusion material. Hereafter, these three samples will be referred to as the fractionated type of amoeboid olivine aggregate and the others, excluding sample 4, will be called the unfractionated type, in allusion to the relative abundances of refractory elements found in each.

Nebular processes

GROSSMAN et al. (1977) showed that 21 refractory elements have nearly the same enrichment factor, 17.5 ± 0.4, in coarse-grained inclusions, as a group, relative to Cl chondrites. They attributed this to virtually total condensation and accretion of each refractory element into the coarse-grained inclusions, thought to represent the first 5.7% of chondritic matter to condense from a cooling gas of solar composition. While individual coarse-grained inclusions exhibit relatively small REE fractionations, the REE patterns of fine-grained Allende inclusions are strikingly and severely fractionated. BOYNTON (1975) showed how the shape of a Group II REE pattern in a fine-grained inclusion could be explained if that inclusion condensed after prior removal of the most refractory REE in a higher-temperature condensate. In that model, the removed material must contain the bulk of each of the most refractory heavy REE, such as Er and Lu, and a very small fraction of the more volatile light REE, such as La and Sm. GROSSMAN and GANAPATHY (1976b) also concluded that the fine-grained inclusions condensed after an earlier, higher-temperature condensation event, that which produced the coarse-grained inclusions. Assuming that the REE are in cosmic proportion to one another in the Allende meteorite and that the bulk of the REE in Allende reside in the coarse- and fine-grained inclusions, they proposed that fine-grained inclusions formed from those refractories which failed to accrete into coarse-grained inclusions and that only a very small fraction of each of the refractory elements was present in the fine-grained inclusions. Analyses of large samples of a homogenized, four kilogram bulk sample of Allende by many different investigators (ALLEN, to be published; BECKER et al., to be published; MORRISON et al., to be published; NAKAMURA and MASUDA, to be published; SHOWALTER et al., to be published) now show, however, that the Allende meteorite does *not* contain REE in the same proportions as Orgueil, but instead has a fractionated REE pattern, with light REE slightly more enriched than many of the heavy REE. Assuming that the solar

nebula initially contained REE in Cl proportions to one another everywhere, this observation implies that condensation and accretion of REE into the Allende parent body was an open-system process. It may very well be that fine-grained inclusions do *not* contain refractory components complementary to those in coarse-grained inclusions and, therefore, do *not* contain only a tiny fraction of the total REE in Allende. Rather, fine-grained inclusions may be complementary to some high-temperature component that was not sampled by Allende and that condensed, together with fine-grained inclusions, in a different region of the nebula from the coarse-grained ones.

The coexistence of coarse- and fine-grained inclusions in Allende means that its parent body sampled condensates from different nebular regions during accretion. The coexistence of two kinds of amoeboid olivine aggregates whose refractory components are equivalent to each of these types of inclusions leads to some interesting inferences about solar nebular processes. The finely-divided refractory components now intimately mixed with fine-grained olivine originated either as fine particles which failed to accrete into coarse- and fine-grained inclusions or as the debris from broken, once-larger inclusions. Basically, there are two possibilities. Either the olivine in the amoeboid aggregates all condensed in one region or it condensed in both the formation site of the coarse-grained inclusion material and that of the fine-grained inclusion material.

In the first case, both types of refractory-bearing materials had to mix and accrete with the same olivine to form the two kinds of amoeboid olivine aggregates. Unless each type of refractory material did so at a different time and/or portion of the same olivine-rich region, composite inclusions, containing both coarse- and fine-grained inclusion material, could have formed, with or without olivine. Such inclusions may exist in Allende, but have not yet been recognized.

In the second case, it is difficult to understand the origin of the FeO-rich olivine in the formation region of the fine-grained inclusions. All the chemical evidence points to the accretion of most coarse-grained inclusions at a temperature above the forsterite condensation temperature. It is thus easy to see how finely-subdivided equivalents of these inclusions could have remained suspended in the nebula while temperatures fell into the range where forsterite condensed and became FeO-rich and until they mixed with this olivine to form the amoeboids, even though no olivine occurs in most coarse-grained inclusions. GROSSMAN and GANAPATHY (1976b) pointed out, however, that the fine-grained inclusions contain Na-rich components which condensed below the forsterite condensation temperature and that the absence of forsterite from them implies that it was removed from this region of the nebula prior to accretion of the fine-grained inclusions. Either the finely-subdivided equivalents of these inclusions were reunited

with the lost forsterite after it became FeO-rich or a second stage of olivine condensation took place prior to formation of the fractionated type of amoeboids.

Non-refractory lithophiles

Assuming that the bulk of the Cl in amoeboid olivine aggregates is contained in sodalite, the amount of this phase in each aggregate can be estimated from the Cl data in Table 3 and microprobe analyses of sodalite in the amoeboids by GROSSMAN and STEELE (1976). This calculation suggests sodalite contents ranging from <2.8 to 19.4%. In particular, values of 14.0 and 19.1% are obtained for samples 1 and 2, respectively. Such high sodalite contents should have been detected in the X-ray patterns of these two samples, but were not (Table 1), perhaps partly due to sample heterogeneity. In the case of five aggregates, including samples 1 and 2, the computed amounts of sodalite require more Na than is known to be present. This discrepancy is probably due to the poor quality of the Cl data. In correcting these data for Cl in the silica irradiation vials, blank corrections of 48–78% had to be made. Clearly, relatively small variations in the Cl contents of the vials beyond the 1σ limits used to compute the total errors in the Cl data will lead to much larger uncertainties than those quoted in Table 3 and, in some cases, even larger blank corrections than have been made.

If we assume that all Na in the amoeboid olivine aggregates is concentrated in nepheline, the amount of this phase in each sample can be estimated from the microprobe data of GROSSMAN and STEELE (1976). Because that work and X-ray powder data herein show that sodalite is also present, these will be upper limits to the nepheline contents. From these, an upper limit to the amount of Ca contributed to the aggregates by feldspathoids can be obtained, because microprobe data show that, in the amoeboids, nepheline contains more Ca (1.77%) than does sodalite (0.34%) (GROSSMAN and STEELE, 1976). The calculation shows that the average unfractionated type of amoeboid olivine aggregate contains <9.06% nepheline and that <0.16% Ca is accounted for by feldspathoids. In addition, unpublished data obtained in the course of the work described by GROSSMAN and STEELE (1976) show that olivine in the aggregates contains an average of 0.20% Ca. After subtracting the mean content of the coarse-grained inclusion component estimated above and the approximate amount of feldspathoids estimated here from 100%, we calculate a mean olivine content of about 70%. Thus, olivine accounts for another 0.14% Ca in the unfractionated type of amoeboid. The total Ca contributed to these aggregates by the feldspathoids and olivine is thus <0.30 or <10.3% of the total Ca. In the discussion of Table 4, it was assumed that the bulk of the Ca in the unfractionated type of amoeboid is present in the high-temperature condensate fraction. The calculation performed here shows that this assumption was justified. The ratio of Ca due to the

Table 5. Non-refractory siderophile elements in different types of amoeboid olivine aggregates and Allende inclusions. (Values in ppm unless otherwise indicated)

Element	Amoeboid Olivine Aggregates		Allende Inclusions	
	Unfractionated Type	Fractionated Type	Coarse-Grained	Fine-Grained
Co	89.5 ± 13.9	19.0 ± 4.2	50.9 ± 20.9	29.0 ± 4.2
Au (ppb)	190 ± 38	15.8 ± 5.3	204 ± 82	17 ± 4
As	3.04 ± 0.90	1.27 ± 0.69	2.0	
Sb	0.241 ± 0.024	0.097		

high-temperature fraction in the average unfractionated type of amoeboid olivine aggregate to Ca in the average coarse-grained inclusion is <0.170 and >0.152 ± 0.038. Even the lower limit is indistinguishable from 0.212 ± 0.029, the mean ratio for all refractory elements. It should also be noted that the Ca now in feldspathoids was probably derived from the high-temperature condensates anyway, since the latter were the precursor phases which reacted with the nebular gas at low temperatures to form the feldspathoids, according to condensation calculations (GROSSMAN, 1972).

Br contents of the aggregates are relatively high, comparable in many cases to the levels for bulk C3 chondrites (REED, 1971) and, in the cases of samples 4 and 6, sometimes in excess of these by large factors. Blank corrections due to Br in the irradiation vials were smaller than for Cl, amounting to <5% for half the samples, but as high as 38% and 46% for samples 1 and 2, respectively. Sample 6 is the highest in Br and the only one in which sodalite was positively identified in the powder pattern. Br may have condensed from the nebula in sodalite in whose crystal structure it can substitute for Cl.

The mean Fe content of the aggregates, excluding sample 4, is 11.12 ± 1.47%. The mean composition of the 463 olivine grains in 18 different aggregates analysed by GROSSMAN and STEELE (1976) is Fo 83.01 ± 0.38, corresponding to a mean Fe content of 12.53 ± 0.26%. Using this composition and the mean olivine content of the aggregates estimated above (70%), the olivine contributes 8.77% Fe to the aggregates, a value somewhat less than the total iron in them. The difference is probably due to the FeO revealed by the electron microprobe in other components of the aggregates, such as spinel, pyroxene and feldspathoids.

The average Mn content in the fractionated type of amoeboids is higher than in fine-grained inclusions and that in the remaining amoeboids is much higher than the mean for coarse-grained inclusions. This indicates that olivine is the major Mn carrier and that Mn may have condensed in this phase. Cr is also higher in both types of amoeboid olivine aggregates than in their corresponding types of Allende inclusions.

Non-refractory siderophiles

Table 5 summarizes data for the mean concentrations of non-refractory siderophile elements in amoeboid olivine aggregates of the unfractionated and fractionated type and in coarse- and fine-grained inclusions. Data for Co and Au are taken from GROSSMAN and GANAPATHY (1976a) for coarse-grained inclusions and from GROSSMAN and GANAPATHY (1976b) for fine-grained inclusions. The As value for coarse-grained inclusions is a single determination by WÄNKE et al. (1974). GROSSMAN and GANAPATHY (1976b) pointed out the depletion of siderophiles in fine-grained inclusions relative to coarse-grained ones which can be seen easily from the Co and Au data on this table. A parallel depletion of siderophiles in the fractionated type of amoeboids relative to the unfractionated type can also be seen for all four elements in Table 5, ranging from nearly a factor of ten for Au to only a factor of 2.5 for As and Sb. The temptation is to try to explain these observations by having the refractory components of the amoeboid olivine aggregates contribute the bulk of the siderophiles, i.e. fine-grained inclusion material for the fractionated type of amoeboid and coarse-grained inclusion material for the others. If this were the case, however, the fractionated type of amoeboid would be a factor of 2–3 lower in siderophiles than fine-grained inclusions and the unfractionated type a factor of 5 lower than coarse-grained inclusions because of the dilution by olivine. Instead, we find that the levels of non-refractory siderophiles in the different types of amoeboids are similar to, or even greater than, the concentrations in their corresponding types of inclusions. From what is already known about the amounts of coarse- and fine-grained inclusion material in the different types of amoeboids, there seems to be no escape from the conclusion that there are additional components contributing to the total inventory of non-refractory siderophiles and that the additional components for the fractionated type of amoeboid must contain substantially less Co and Au than those for the unfractionated type.

Sample 4

The mineralogical composition of this sample is described above, in the Samples section, and is reminiscent in some ways of the fine- and ultrafine-grained Type A CAI bodies of WARK and LOVERING (1977), except for the presence of andradite in and absence of olivine from our sample. Because of the poor quality of our polished section, however, it is impossible to tell whether it is composed of the same, zoned, rounded bodies as those of Wark and Lovering or

whether a number of phases described by them, such as perovskite and anorthite, are present in our sample. In addition, the pyroxenes in our sample are often much richer in FeO, 3.7–19.5%, than those listed by Wark and Lovering. It appears to contain the same refractory trace element components as normal Allende coarse-grained inclusions and is rich in halogens. It could be an assemblage of fine particles of very heavily altered coarse-grained inclusion material. Alternatively, it may be related in some way to those assemblages described by Wark and Lovering, in which case it obviously has a more complex origin.

CONCLUSIONS

Two types of amoeboid olivine aggregates have been discovered in the Allende meteorite, which differ significantly in the chemical compositions of the refractory components which are mixed with their olivine. One type contains cosmic relative proportions of refractory elements, like coarse-grained Allende inclusions. The other is characterized by abundances of refractory elements which are highly fractionated relative to one another compared to Cl chondrites. This fractionation pattern, including that of the REE, is very similar to that of Group II fine-grained Allende inclusions. Apparently, fractions of coarse- and fine-grained inclusion material remained finely subdivided and suspended in their separate formation locations in the nebula until the gas temperatures fell to the point where FeO-rich olivine became stable and then accreted with this olivine to form the amoeboids.

REFERENCES

ALLEN J. M., GROSSMAN L., DAVIS A. M. and HUTCHEON I. D. (1978) Mineralogy, textures and mode of formation of a hibonite-bearing Allende inclusion. In *Proc. Ninth Lunar Planet. Sci. Conf., Geochim. Cosmochim. Acta Suppl.* 10, pp. 1209–1233. Pergamon Press.
ALLEN R. O., JR. (to be published) Trace element analysis of Allende meteorite reference material. In *Allende Meteorite Reference Sample* (eds E. Jarosewich and R. S. Clarke, Jr.). Smithson, Contrib. Earth Sci.
BECKER R., KOLLER P., MORSCHL P., KIESL W. and HERMANN F. (to be published) Determination of trace elements by NAA in the Allende-reference-meteorite. In *Allende Meteorite Reference Sample* (eds. E. Jarosewich and R. S. Clarke, Jr.). Smithson, Contrib. Earth Sci.
BOWMAN W. W. and McMURDO K. W. (1974) Radioactive-decay gammas ordered by energy and nuclide. *At. Data Nucl. Data Tables* 13, 89–292.
BOYNTON W. V. (1975) Fractionation in the solar nebula:

condensation of yttrium and the rare earth elements. *Geochim. Cosmochim. Acta* 39, 569–584.
CLAYTON R. N., ONUMA N., GROSSMAN L. and MAYEDA T. K. (1977) Distribution of the pre-solar component in Allende and other carbonaceous chondrites. *Earth Planet. Sci. Lett.* 34, 209–224.
CONARD R. L., SCHMITT R. A. and BOYNTON W. V. (1975) Rare-earth and other elemental abundances in Allende inclusions (abstract). *Meteoritics* 10, 384–387.
FLANAGAN F. J. (1973) 1972 values for international geochemical reference samples. *Geochim. Cosmochim. Acta* 37, 1189–1200.
GROSSMAN L. (1972) Condensation in the primitive solar nebula. *Geochim. Cosmochim. Acta* 36, 597–619.
GROSSMAN L. and GANAPATHY R. (1975) Volatile elements in Allende inclusions. In *Proc. Sixth Lunar Sci. Conf., Geochim. Cosmochim. Acta Suppl.* 6, pp. 1729–1736. Pergamon Press.
GROSSMAN L. and GANAPATHY R. (1976a) Trace elements in the Allende meteorite—I. Coarse-grained, Ca-rich inclusions. *Geochim. Cosmochim. Acta* 40, 331–344.
GROSSMAN L. and GANAPATHY R. (1976b) Trace elements in the Allende meteorite—II. Fine-grained, Ca-rich inclusions. *Geochim. Cosmochim. Acta* 40, 967–977.
GROSSMAN L., GANAPATHY R. and DAVIS A. M. (1977) Trace elements in the Allende meteorite—III. Coarse-grained inclusions revisited. *Geochim. Cosmochim. Acta* 41, 1647–1664.
GROSSMAN L. and STEELE I. M. (1976) Amoeboid olivine aggregates in the Allende meteorite. *Geochim. Cosmochim. Acta* 40, 149–155.
KEAYS R. R., GANAPATHY R. and ANDERS E. (1971) Chemical fractionations in meteorites—IV. Abundances of fourteen trace elements in L-chondrites; implications for cosmothermometry. *Geochim. Cosmochim. Acta* 35, 337–363.
KEAYS R. R., GANAPATHY R., LAUL J. C., KRÄHENBÜHL U. and MORGAN J. W. (1974) The simultaneous determination of 20 trace elements in terrestrial, lunar and meteoritic material by radiochemical neutron activation analysis. *Anal. Chim. Acta* 72, 1–29.
MARTIN P. M. and MASON B. (1974) Major and trace elements in the Allende meteorite. *Nature* 249, 333–334.
MORRISON G. H., POTTER N. M., ROTHENBERG A. M., GANGADHARAM E. V. and WONG S. F. (to be published) Multielement analysis of Allende meteorite. In *Allende Meteorite Reference Sample* (eds. E. Jarosewich and R. S. Clarke, Jr.). Smithson. Contrib. Earth Sci.
NAKAMURA N. (1974) Determination of REE, Ba, Fe, Mg, Na and K in carbonaceous and ordinary chondrites. *Geochim. Cosmochim. Acta* 38, 757–775.
NAKAMURA N. and MASUDA A. (to be published) Rare earth elements in the Allende reference material. In *Allende Meteorite Reference Sample* (eds. E. Jarosewich and R. S. Clarke, Jr.). Smithson. Contrib. Earth Sci.
NUCLEAR DATA SHEETS (Sept. 1977 and earlier). Edited by Nuclear Data Group, Oak Ridge National Laboratory, Oak Ridge, TN.
PERLMAN I. and ASARO F. (1969) Pottery analysis by neutron activation. *Archaeometry* 11, 21–52.
PERLMAN I. and ASARO F. (1971) Pottery analysis by neutron activation. In *Science and Archaeology* (ed. R. H. Brill), pp. 182–195. MIT.
REED G. W., JR. (1971) Bromine. In *Handbook of Elemental Abundances in Meteorites* (ed. B. Mason), pp. 279–284. Gordon & Breach.
SHOWALTER D. L., WAKITA H., SMITH R. H. and SCHMITT R. A. (to be published) Abundance of the 14 REE (rare earth elements) and 12 other major, minor and trace elements in Allende Meteorite Reference Material (AMRM). In *Allende Meteorite Reference Sample* (eds. E. Jarosewich and R. S. Clarke, Jr.). Smithson. Contrib. Earth Sci.

TANAKA T. and MASUDA A. (1973) Rare-earth elements in matrix, inclusions and chondrules of the Allende meteorite. *Icarus* **19**, 523–530.

WÄNKE H., BADDENHAUSEN H., PALME H. and SPETTEL B. (1974) On the chemistry of the Allende inclusions and their origin as high temperature condensates. *Earth Planet. Sci. Lett.* **23**, 1–7.

WARK D. A. (1978) Early solar system stratigraphy: the condensation sequence from Allende to chondrites, and the origin of chondrules. In *Lunar and Planetary Science* IX, pp. 1208–1210. The Lunar and Planetary Institute.

WARK D. A. and LOVERING J. F. (1977) Marker events in the early evolution of the solar system: Evidence from rims on Ca-Al-rich inclusions in carbonaceous chondrites. In *Proc. Eighth Lunar Sci. Conf., Geochim. Cosmochim. Acta Suppl.* **8**, pp. 95–112. Pergamon Press.