Amoeboid olivine aggregates in the Allende meteorite

Lawrence Grossman

Department of the Geophysical Sciences and Enrico Fermi Institute, The University of Chicago, Chicago, Illinois 60637, U.S.A.

and

Ian M. Steele

Department of the Geophysical Sciences, The University of Chicago, Chicago, Illinois 60637, U.S.A.

Abstract—Greyish-brown, irregularly-shaped aggregates composed predominantly of olivine make up $\sim 2\%$ of the Allende meteorite by volume. Many of the aggregates are constructed of subspherical lumps of micron-sized crystals of olivine, pyroxene, nepheline and sodalite surrounded by coarser-grained olivine. Rarely, anorthite, spinel and perovskite are also present. The olivine ranges in composition from Fo64 to Fo99. Pyroxenes range from aluminous diopside to hedenbergite to very Al-rich and Ti-Al-rich varieties. The nepheline contains $1 \cdot 6 - 2 \cdot 4\%$ K_2O and $1 \cdot 6 - 5 \cdot 2\%$ CaO but the sodalite is significantly poorer in these elements. The spinel contains $2 \cdot 1 - 13 \cdot 4\%$ FeO. Textural information and oxygen isotopic data suggest that the aggregates are composed of primary, solid condensates from the solar nebula. The perovskite, spinel and Ti-Al-rich pyroxenes are the remains of high-temperature condensates but the olivine compositions and the presence of feldspathoids indicate that some of the grains continued to react with the solar nebular vapor in the temperature range $500-900°K$.

INTRODUCTION

THE C3 CHONDRITES are thought to be composed of materials that condensed directly from the vapor of the solar nebula over a wide temperature range. Many of the different petrographic units found inside these chondrites are accumulations of minerals which represent samples of the condensate at different stages of the cooling of the nebula. Thus, detailed petrographic, chemical and isotopic studies of discrete classes of textural units in a meteorite such as Allende may expose a wealth of information about nebular evolution and the chemical components available to the accreting planets.

A substantial amount of petrographic information is now available about the high-temperature condensates in Allende (FUCHS, 1969, 1971; CLARKE et al., 1970; GROSSMAN, 1975) but relatively little is known about the other components which are present. This paper presents the results of a petrographic and mineralogical study of a class of aggregates in Allende which appears to have stopped reacting with the nebula at temperatures much lower than the Ca-Al-rich inclusions.

PROCEDURE

Sampling

The objects described in this paper were found in the same thin sections cut from slabs of the Allende stones described in GROSSMAN (1975). Although these objects are present in 80% of the 30 polished thin sections described

in GROSSMAN (1975), the analyses discussed here are from 23 aggregates in only 10 of those thin sections. The labelling of textural units is the same here as in GROSSMAN (1975), e.g. TS8 F1 means feature number 1 in thin section number 8.

Analytical

All analyses were obtained with an ARL electron microprobe operated at 15 kV and with a focused beam. Standards included synthetic glasses and oxides and natural minerals chosen to minimize differential matrix effects. Using wavelength dispersion, we performed olivine analyses by obtaining count rates for Mg, Fe, and Ca with a beam current of $0 \cdot 25 - 0 \cdot 35 \mu A$. The computer program PYX-OL-FELD (unpublished) was used for drift and matrix corrections. This program calculates SiO_2 by difference from 100% and applies the BENCE–ALBEE (1968) correction procedure with alpha values of ALBEE and RAY (1970). Analyses were accepted if the calculated formulae had between $1 \cdot 88$ and $2 \cdot 07$ Mg + Fe + Ca and between $0 \cdot 97$ and $1 \cdot 07$ Si atoms based on $4 \cdot 0$ oxygens. Analyses of known olivine compositions are accurate to $\pm 2\%$ absolute.

A Nuclear Semiconductor AUTOTRACE energy dispersive system on-line with a PDP-8 computer was used for analysis of other phases. Data reduction followed closely the procedure outlined by REED and WARE (1973) using computer programs slightly modified from those supplied by N. Ware. To minimize sodium loss from nepheline and sodalite, a beam current of about 5 nA and a counting interval of 1 min were used. Under these conditions, the observed sodium loss was less than 3% of the amount present. For other phases these parameters were increased to 50 nA and 2 min, respectively. The accuracy, based on analysis of known compositions, is estimated to be within $\pm 3\%$ of the amount present for concentrations above 5% and within $\pm 5\%$ for lower concentrations. Larger errors can be expected between 1% and the limit of detection

(0·2%). Larger errors are present for K and Cl because of incomplete pulse pile-up rejection.

PETROGRAPHY AND MINERAL CHEMISTRY

Description

Two amoeboid aggregates are shown in Figs. 1a and 1b as they appear on slab surfaces. They are highly irregular in shape, greyish-brown in color and 1–10 mm in longest dimensions. Their most characteristic feature is the presence of elongated protuberances which, themselves, have lobate appendages. Closer inspection reveals that the aggregates consist of rounded polycrystalline lumps which average ∼0·1 mm in diameter These, in turn, are composed of grey translucent grains having a glassy luster and a much finer-grained, whitish material. Olivine is the only mineral detected in X-ray powder patterns of bulk inclusions and of samples of these different textural components. Rarely, pink spinel-rich areas are visible on slab surfaces. These amoeboid aggregates seem to make up about 2% by volume of the Allende stones studied here but we have seen other stones in which both their frequency and size are considerably greater than in ours.

Examination of thin sections (Figs. 1c–1f) reveals that the amoeboids are exceedingly fine-grained. Large regions are so fine-grained that they are dark in transmitted light while adjacent, translucent areas in the interiors of these aggregates consist of clusters of 1–5 μm grains. Electron probe analyses of fine-grained areas reveal the presence of feldspathoids, pyroxene and olivine. Coarse-grained patches are dominantly olivine. Particularly noticeable is the coarsening of grain size in zones surrounding the inclusions and in narrow rims surrounding irregular lumps on the edges and in the insides of the aggregates. The coarse material is dominantly olivine.

Olivine

Figure 2a is a histogram of olivine compositions of 463 randomly selected points in 18 amoeboid aggregates from 10 polished thin sections. These are analyses of both single olivine crystals > 1 μm in size and monomineralic areas of finer-grained olivine. The distribution of analyses stretches from Fo64 to Fo99 and contains a relatively flat, broad peak between Fo73 and Fo93. Most individual aggregates show similar distributions although one, TS8 Fl, shows a peak at Fo97 and several others contain a large proportion of analyses between Fo64 and Fo73. Usually, little difference in olivine composition is observed between the core and the rim of an aggregate, although one aggregate has core olivines in the range Fo90 to Fo95 and rim olivines containing Fo80.
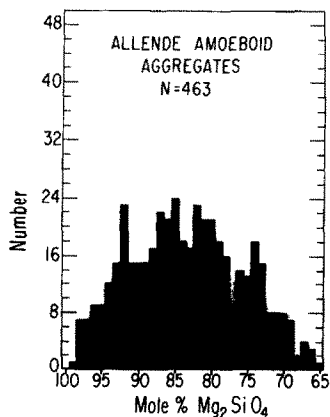
In this paper, chondrules are defined as objects containing unambiguous textural evidence of being the solidification products of rapidly-crystallized molten droplets, i.e. they must be composed of glass and/or porphyritic, barred or radiating crystalline materials. The amoeboid aggregates discussed here do not fall into this textural category. CLARKE et al. (1970) gave a very accurate description of an amoeboid aggregate but they classified it as a 'type c Ca–Al-rich chondrule'. In order to investigate further the distinction between chondrules and these aggregates, we determined the compositions of olivines in 325 randomly-selected spots inside chondrules in 12 Allende thin sections at an approximate sampling rate of 5 spots per chondrule and 5 chondrules per section. The results are shown in the histogram in Fig. 2b from which it is clear that there is a marked contrast in olivine compositions between the chondrules and the aggregates in Fig. 2a. The olivine composition histogram for chondrules is peaked at Fo100, drops steeply to Fo90 and has a low tail stretching out to Fo76. Clearly, the aggregates can be distinguished from the chondrules on the basis of mineral chemistry as well as petrography. CLARKE et al. (1970) also presented a histogram of chondrule olivine compositions. It is peaked at Fo100 but a large proportion of the data are in a long tail stretching out to Fo55, suggesting that their histogram contains a significant number of analyses from amoeboids in addition to chondrules.

Feldspathoids

In the course of the olivine determinations, the count rates for Al and Ca were monitored routinely. In the case of the amoeboids, many of the analyzed spots did not yield olivine or Al-free pyroxene stoichiometry. These areas were often quite rich in Al and/or Ca. Because of the very fine-grained nature of the aggregates, little mineralogical information can be gained by optical examination. For this reason, sets of X-ray scanning photos were taken of selected regions in several aggregates in an attempt to identify the phases present and study their spatial distribution. An example is shown in Fig. 3. Patches of several different phases other than olivine are visible. Two are Na–Al-rich silicates and one of these also contains Cl. GROSSMAN (1974) proposed that these minerals are nepheline and sodalite, respectively, on the basis of such photos and an X-ray powder pattern of the <3·08 density fraction separated from an aggregate by N. Onuma. Other Na-free, Ca–Al-rich phases are also present. The photographs are deceptive in the sense that the feldspathoid grain size often appears to be in the range 10–20 μm. In reality, these are polycrystalline areas in which individual grains average less than 1 μm in size.
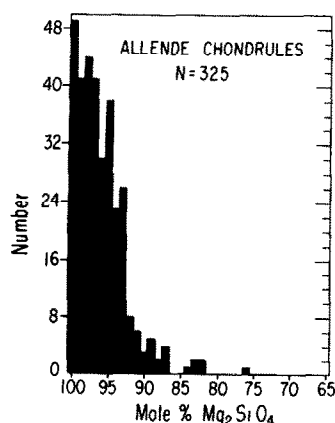

Fig. 2. a. Histogram of olivine compositions from 18 amoeboid aggregates in the Allende meteorite.
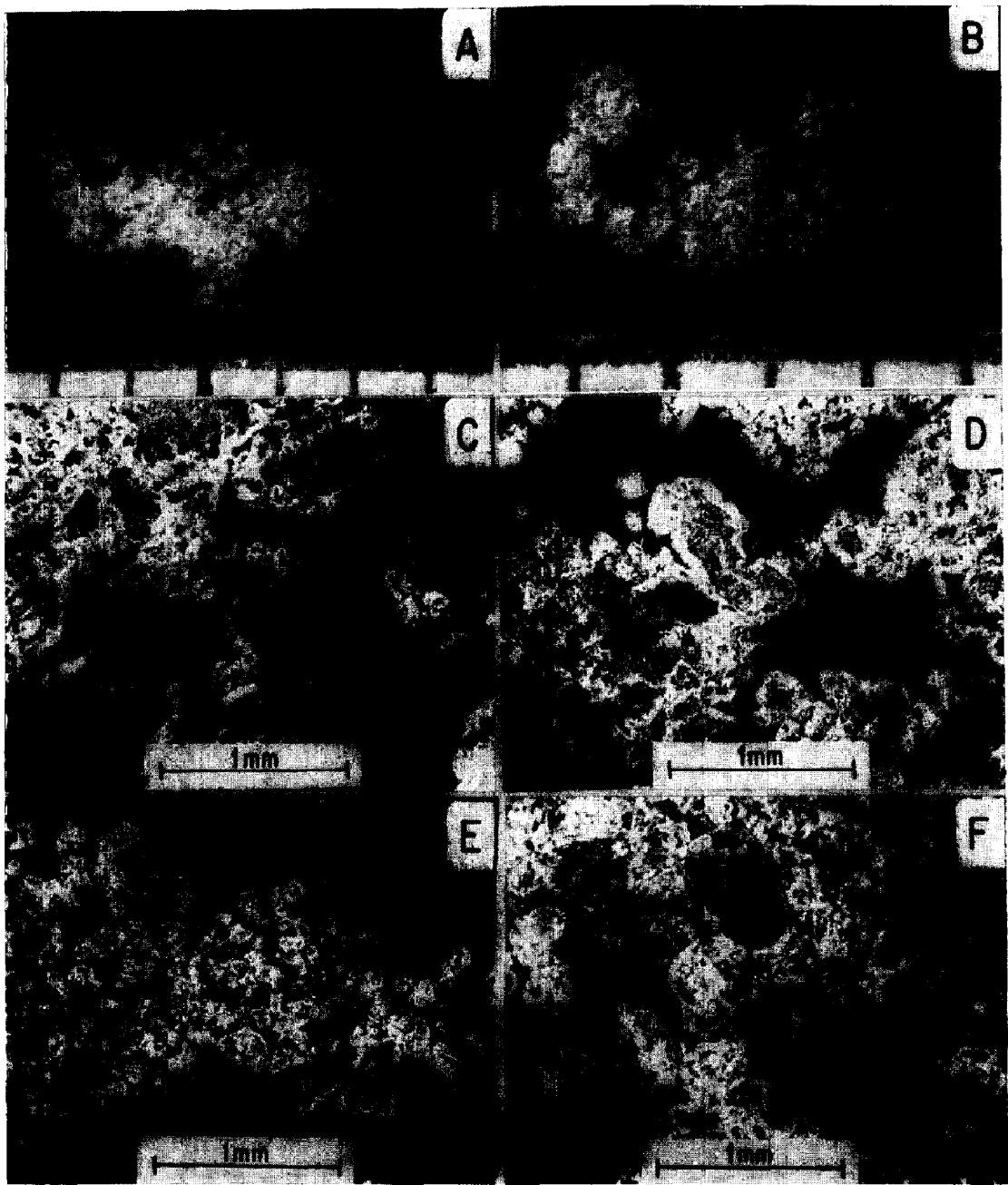b Histogram of olivine compositions from approximately 60 chondrules in the Allende meteorite.

Fig. 1. a and b. Amoeboid aggregates as they appear on slab surfaces of the Allende meteorite. Note their irregular shapes. Scale calibrated in mm. c–f. Amoeboid aggregates in thin section, transmitted light. Dark regions are opaque and fine-grained. Bright areas are transparent and coarse-grained. c and d. TS11 F1. Note the lobate margins. Bright rims and bright interior patches are coarse olivine. Dark regions are composed of fine-grained olivine, feldspathoids and pyroxenes. Darkest region in the aggregate in c is spinel-rich. e. TS19 F2. Composed of irregular lumps, each of which contains a core of fine-grained olivine, feldspathoids and pyroxenes and a rim of coarse-grained olivine. f. TS8 F2 is the dark sphere which is embedded in TS8 F1, an amoeboid aggregate. TS8 F2 contains very fine-grained feldspathoids, pyroxenes and anorthite. Its bright rim contains diopsidic pyroxene and olivine.
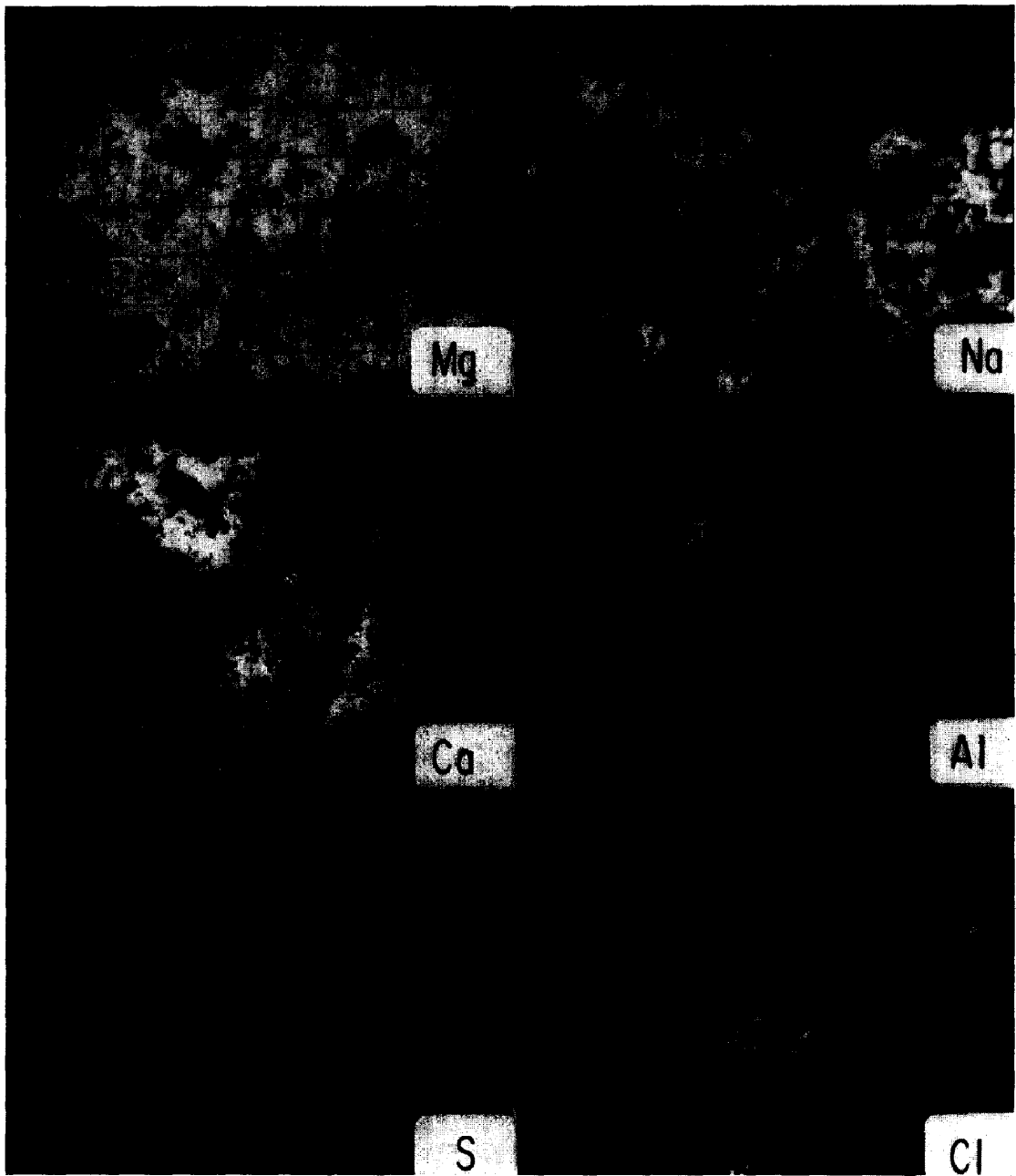
Fig. 3. X-ray scanning photographs of a typical region of TS11 F1, 200 μm × 160 μm in size. High-Mg areas are rich in olivine and pyroxene. Low-Mg areas are rich in feldspathoids. High Ca contents mark the presence of pyroxenes. Na–Al-rich areas without Cl contain nepheline; those with Cl contain sodalite. Individual grains of feldspathoids rarely exceed 1 μm in size.

Table 1 shows nepheline analyses from several different aggregates. Because of the small grain size, even the use of a 1 μm spot cannot completely avoid the inclusion of small amounts of adjacent, unwanted phases in the analytical volume. The analyses shown are considered the best of a large number of analyses because they appear to be the least contaminated by nearby minerals on the basis of their Mg contents. They are similar to terrestrial nephelines in that they contain slightly more Si and less Al ions than is represented by the ideal formula, $NaAlSiO_4$ (DEER et al., 1963). Also the cation sum, Na + K + 2Ca, lies between 7 and 8 as is the case for terrestrial nephelines but the K_2O contents are somewhat lower in the meteoritic ones. The 1·5% K reported by CLARKE et al. (1970) from nepheline inside a 'type c chondrule' is in good agreement with the data in Table 1. The CaO contents of the Allende nephelines are, however, distinctly higher than their terrestrial counterparts. Although considerable quantities of CaO can dissolve in this phase, terrestrial samples usually contain less than 1 wt% either because they form in CaO-poor environments or because they compete with phases possessing a greater affinity for CaO. The presence of 2-5 wt% CaO in the Allende nepheline may indicate that it formed by reaction of a CaO-rich precursor.

Sodalite compositions are shown in Table 2. Again, these are the analyses which appear to be the least contaminated by adjacent phases. In some there is a tendency toward more Al and less Si ions than in the ideal formula, $Na_8Al_6Si_6O_{24}Cl_2$. The CaO contents are slightly higher and the K_2O contents lower than in terrestrial sodalite. Again the low K_2O contents agree with the data of CLARKE et al. (1970) who reported <0·1% K in sodalite from a 'type c chondrule'. The numbers of Na and Cl ions are both lower than in the ideal formula and correlations exist between Na and Cl and between Cl and the cation sum Na + K + 2Ca. Substitution of OH or F could possibly account for the Cl deficiency but this cannot explain the correlated Na depletions and is therefore considered unlikely. Another possibility is that these analyses actually represent the compositions of very fine-grained intergrowths of nepheline and sodalite. This is also thought to be unlikely because it would imply that not a single grain of pure sodalite larger than 1 μm was found. Rather, we believe that the sodalite in the aggregates is simply deficient in both Na and Cl.

Pyroxenes

The Ca-rich areas in Fig. 3 are made up largely of pyroxene, a common constituent of many of the aggregates. Representative compositions, selected from a larger number of analyses because they conform most closely to pyroxene stoichiometry, are shown in Table 3. Other attempts at analyzing pyroxenes failed because of the fine grain size and the overlap of the beam with adjacent phases. Also shown in Table 3 are the numbers of cations on the basis of 6 oxygens where all Al in excess of that required to fill the tetrahedral sites is counted among the octahedral cations. Also calculated and listed is the atom % that each of Mg, Fe and Ca represent of the sum of the divalent cations.

All the pyroxenes are rich in CaO, which ranges from 14·0 to 26·5%. Some pyroxenes contain less than 2% Al_2O_3 (columns 1 and 2) and range in composition from diopside to hedenbergite. Most of the pyroxenes, however, are rich in Al_2O_3 and have high MgO/FeO ratios. In the final three columns are some analyses which contain exceptionally high Al_2O_3. If these are truly pyroxenes, their Al_2O_3 contents would be the highest ever reported in nature. Analyses 6-8 come from such fine-grained regions that it is impossible to tell if they are crystalline or if they are glasses which just happen to have pyroxene stoichiometry. Analysis 7 comes from TS8 F2, the fine-grained spherical object shown in Fig. 1f. The optical properties of TS8 F2 vary from opaque to isotropic to weakly birefringent from place to place. This, together with its spherical shape, suggests that it is a partially devitrified glass sphere. Analysis 7, with the highest Al_2O_3 content of all, may be a glass or, alternatively, a mineral having pyroxene stoichiometry which formed by devitrification. This could also apply to analyses 2 and 5, which also come from TS8 F2. There is no special reason, however, to believe that analyses 6 and 8 have similar explanations. They are from TS8 F1, the amoeboid aggregate which encloses TS8 F2. Analysis 8 is very similar to the compositions of many Ti–Al-rich pyroxenes in the Ca–Al-rich white inclusions in this meteorite, but its Al_2O_3 content is substantially higher (MASON, 1974; GROSSMAN, 1975).

Other phases

Plagioclase and spinel are occasionally found as tiny grains or clumps of tiny grains in pyroxene-rich areas.

Table 1. Analyses of nephelines from amoeboid aggregates in Allende

	TS11 F1	TS19 F3	TS11 F1	TS19 F3	TS11 F3	TS8 F5	TS8 F2	TS8 F7	TS8 F1	TS8 F2
SiO_2	43.8	43.7	43.9	43.4	44.4	43.9	43.1	43.0	43.5	43.3
TiO_2	–	–	–	–	–	–	0.2	–	–	–
Al_2O_3	34.9	35.0	33.7	35.4	36.2	34.7	35.3	35.9	33.5	34.7
FeO	1.0	1.37	1.35	0.3	0.5	0.6	–	0.3	0.7	0.3
MgO	0.3	0.5	0.6	–	–	0.4	0.4	–	0.6	–
CaO	2.0	2.1	1.66	2.2	1.59	2.0	3.3	2.1	2.6	5.2
Na_2O	18.4	18.3	17.6	17.6	17.9	17.2	17.2	16.3	15.8	14.0
K_2O	2.1	2.0	1.9	2.1	2.0	–	1.9	2.4	1.6	1.6
SO_3	0.3	0.3	–	–	0.2	–	0.2	0.3	–	0.2
Cl	0.1	–	–	–	–	–	–	0.1	–	–
Total	102.9	103.3	100.7	101.0	102.8	98.8	101.6	100.4	98.3	99.3
Numbers of ions on the basis of 32 oxygens										
Si	8.15	8.12	8.30	8.15	8.18	8.31	8.07	8.13	8.35	8.23
Al	7.67	7.65	7.50	7.84	7.88	7.75	7.79	8.00	7.58	7.79
Fe	0.15	0.21	0.21	0.05	0.08	0.09	–	0.05	0.11	0.04
Mg	0.08	0.13	0.17	–	–	0.10	0.11	–	0.17	–
Ca	0.40	0.42	0.34	0.45	0.31	0.41	0.66	0.43	0.54	1.06
Na	6.63	6.59	6.45	6.42	6.41	6.31	6.26	5.97	5.86	5.16
K	0.50	0.48	0.46	0.50	0.46	0.01	0.45	0.57	0.39	0.38
Na+K+2Ca	7.93	7.91	7.59	7.82	7.49	7.14	8.03	7.40	7.33	7.66

Table 2. Compositions of sodalites in amoeboid aggregates from
Allende

	TS8 F1	TS11 F1	TS8 F1	TS8 F7	TS8 F2	TS8 F6	TS11 F4
SiO_2	37.3	37.1	36.8	38.0	34.8	36.7	37.9
TiO_2	-	-	-	-	-	-	-
Al_2O_3	31.7	31.5	33.3	33.3	35.2	31.5	31.5
FeO	0.9	0.3	-	0.6	0.6	1.47	0.9
MgO	-	-	-	-	0.3	0.6	0.4
CaO	0.4	-	0.2	0.6	-	0.9	1.21
Na_2O	24.1	23.4	23.6	23.0	22.4	21.7	21.4
K_2O	-	-	-	-	-	-	0.1
S	-	-	0.2	-	-	-	-
Cl	5.8	6.0	6.0	5.5	5.6	5.4	5.1
	100.2	98.3	100.1	101.0	98.9	98.3	98.5
O≡Cl,S	1.3	1.4	1.5	1.2	1.3	1.2	1.2
Total	98.9	96.9	98.6	99.8	97.6	97.1	97.3

Numbers of ions on the basis of the 21(O) in the $3Al_2O_3 \cdot 6SiO_2$ framework

Si	6.00	6.00	5.84	5.91	5.54	5.98	6.05
Al	6.01	6.00	6.22	6.12	6.61	6.04	5.93
Fe	0.12	0.04	-	0.08	0.08	0.20	0.11
Mg	-	-	-	-	0.06	0.15	0.09
Na	7.51	7.34	7.26	6.93	6.91	6.86	6.65
Ca	0.06	-	0.03	0.10	-	0.16	0.21
K	-	-	-	-	-	-	0.02
Cl	1.58	1.64	1.61	1.44	1.50	1.49	1.39
S	-	-	0.06	-	-	-	-
Na+K+2Ca	7.63	7.34	7.32	7.13	6.91	7.18	7.09

Analyses are given in Table 4. The plagioclase is pure anorthite, reminiscent of the plagioclase compositions in the Ca–Al-rich inclusions in Allende. The plagioclase shown in the table is from TS8 F2 but, rarely, this phase is also found elsewhere in the aggregates. The high analytical sums for the spinels are due to the fact that the standards and the data reduction programs were optimized for silicate analysis. Greater errors are to be expected for oxides. Although one of the spinel analyses shows some contamination from a silicate, it is clear that spinels in the aggregates show a wide range of FeO/MgO ratios. One unusual, ragged, spinel-rich region, 60 μm in diameter, was encountered in the center of an aggregate. It contained perovskite in grains so small, however, that no analyses could be obtained which were not seriously contaminated with spinel.

DISCUSSION

Evidence for direct condensation

The amoeboid olivine aggregates are a distinct petrographic component in the Allende meteorite, identifiable on the basis of appearance and mineralogy. Their irregular shape, the absence of glass and

Table 3. Pyroxenes in amoeboid aggregates in Allende

	(1) TS8 F1	(2) TS8 F2	(3) TS19 F3	(4) TS8 F1	(5) TS8 F2	(6) TS8 F1	(7) TS8 F2	(8) TS8 F1
SiO_2	49.0	53.8	56.0	51.5	51.3	37.9	29.7	32.0
TiO_2	-	-	1.22	0.4	-	-	-	7.5
Al_2O_3	-	1.59	2.8	6.4	8.4	31.9	45.4	27.0
FeO	25.4	0.3	0.9	0.3	0.5	1.85	3.0	1.40
MgO	3.2	18.7	22.8	16.7	16.5	3.2	5.7	7.7
CaO	23.2	24.3	18.7	25.2	24.9	26.5	14.0	24.7
Na_2O	-	-	-	-	-	0.3	0.3	-
K_2O	-	-	0.1	-	-	-	0.1	-
Total	100.8	98.7	102.5	100.5	101.6	101.7	98.2	100.3

Numbers of ions on the basis of 6 oxygens

Si	1.97	1.96	1.93	1.85	1.82	1.36	1.07	1.19
Al	-	0.04	0.07	0.15	0.18	0.64	0.93	0.81
	1.97	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Al	-	0.03	0.04	0.12	0.17	0.71	1.00	0.37
Ti	-	-	0.03	0.01	-	-	-	0.21
Mg	0.19	1.02	1.17	0.90	0.87	0.17	0.31	0.43
Fe	0.86	0.01	0.03	0.01	0.01	0.06	0.09	0.05
Ca	1.00	0.95	0.69	0.97	0.95	1.02	0.54	0.98
Na	-	-	-	-	-	0.02	0.02	-
K	-	-	0.01	-	-	-	0.01	-
	2.05	2.01	1.97	2.01	2.00	1.98	1.97	2.04
Mg	9.3	51.5	61.9	47.9	47.5	13.6	33.0	29.5
Fe	42.0	0.5	1.6	0.5	0.5	4.8	9.6	3.4
Ca	48.7	48.0	36.5	51.6	52.0	81.6	57.4	67.1

Table 4. Anorthite and spinel from amoeboid aggregates

	TS8 F2	TS11 F1	TS8 F1
SiO₂	43.0	-	2.3
TiO₂	-	0.4	0.4
Al₂O₃	37.1	68.5	71.2
FeO	-	13.4	2.1
MgO	-	19.6	26.3
CaO	19.3	-	1.37
Na₂O	-	-	-
K₂O	-	-	0.1
Total	99.4	101.9	103.8
Numbers of ions on the basis of 8 oxygens			
Si	2.00	-	0.10
Al	2.00	3.98	3.86
Ti	-	-	0.02
Mg	-	1.44	1.80
Fe	-	0.56	0.08
Ca	0.96	-	0.06
Na	-	-	-
K	-	-	-

of barred or radiating crystalline structures indicates that they should not be thought of as chondrules in the usual sense of the word. Indeed, there is no particular reason to assume that they were ever molten. They appear to be aggregates of rounded lumps of fine-grained olivine, pyroxene and feldspathoids, each of which is surrounded by coarse-grained olivine. It is difficult to imagine how such aggregates could have formed by the crystallization of a liquid. This is especially true of the one shown in Fig. 1e which resembles a conglomerate more than it does an igneous rock.

GROSSMAN (1974) and CLAYTON et al. (in preparation) presented some oxygen isotopic data which bear on the question of liquid origin. A single amoeboid aggregate was split into two density fractions using heavy liquids. X-ray diffraction showed that the >3·08 density fraction was dominated by olivine but the <3·08 density fraction contained several tens of per cent nepheline and sodalite in addition to olivine. The oxygen isotopic compositions of the two fractions were found to lie on the mixing line between terrestrial oxygen and the exotic, O^{16}-rich component. Moreover, the two fractions contain different amounts of the exotic component, with the dense fraction having a $\delta O18$ of $-14·47‰$ relative to SMOW and the feldspathoid-rich fraction having a δO^{18} of $-7·84$. Had the aggregates ever been molten, the oxygen isotopic compositions of the phases which crystallized from the liquid would have approached equilibrium with one another, thus destroying any pre-existing isotopic heterogeneity. In that case, the isotopic compositions of the olivine and feldspathoids would be much closer to one another and would lie on a line having a slope of 1/2 on a graph of δO^{17} vs δO^{18},

instead of on the mixing line which has a slope of unity. If the isotopic heterogeneity was indeed produced in the meteoritic phases as they condensed from the nebula (CLAYTON et al., 1973, 1975), it implies that the amoeboid aggregates were not molten during or since the condensation of their constituent phases.

Equilibration temperature

Assuming a primary condensation origin for these aggregates, we can go on to consider the conditions under which they condensed. According to updated theoretical calculations (GROSSMAN, in press) forsterite condensed from the nebula at 1430°K at a total pressure of 10^{-3} atm, thereby removing virtually all of the Mg and about 60% of the Si from the vapor. The remaining Si was later consumed in the reaction of forsterite with the vapor to form enstatite at about 1355°K. The nebular gas was so reducing at high temperatures that metallic nickel–iron was in equilibrium with the gas when forsterite first condensed. The forsterite contained less than 1 mole % FeO until the temperature fell to 800°K, where the H_2O/H_2 ratio began to rise from $\sim 5·8 \times 10^{-4}$ to $\sim 1·6 \times 10^{-3}$ at 700°K. Correspondingly, the fayalite content of the olivine in equilibrium with the gas rose from 0·5 mole % at 800°K to 32 mole % at 500°K, and the ratio of olivine to pyroxene increased (GROSSMAN, 1972). According to this model, most of the olivines in the amoeboid aggregates stopped equilibrating with the nebula between 650° and 500°K. LARIMER and ANDERS (1967) discussed the kinetics of this reaction in the solar nebula. It is apparent from their calculation that grains of this size could equilibrate with the gas at this temperature in 10–100 years if volatile, iron-containing gaseous species became stable, as was likely the case.

Condensation of alkali metals

One of the major unsolved problems in the chemistry of the nebula is the behavior of the alkali metals during condensation. GROSSMAN (1972) calculated that anorthite would have formed in the nebula at 1362°K by the reaction of previously-condensed spinel and diopside. At that time it appeared that the alkalies condensed by forming solid solutions with this anorthite in the temperature range 1200–1000°K and that no other alkali-bearing phases were stable until much lower temperatures. Of all the condensate phases reported in GROSSMAN (1972), however, anorthite has the greatest uncertainty in its condensation temperature because it is exceedingly sensitive to the presence or absence of other phases and to their temperatures of appearance. In particular, had anorthite not condensed at a higher temperature than enstatite, 1349°K, in those computations, it would not have condensed at all because of the massive depletion of gaseous SiO during enstatite condensation. In fact, later computations (GROSSMAN, in press) based on improved abundance estimates (CAMERON, 1973a) and

updated thermodynamic data show precisely this effect. Although the cumulative effect of the changes in these input parameters produced no changes in the rest of the condensation sequence, the spinel–diopside reaction to produce anorthite no longer occurred above the condensation point of enstatite, thus eliminating anorthite as a possible condensate. This was largely due to newer thermal data for spinel (*JANAF Tables*, 1972) which made it 3 kcal/mole more stable than in ROBIE and WALDBAUM (1968) whose data were used in GROSSMAN (1972). More recently, THOMPSON (1975) suggested a correction to the data for anorthite making it 5·8 kcal/mole more stable than in Robie and Waldbaum and, as a result, it is conceivable that anorthite could again appear in the condensation sequence. Because anorthite condensation is so extremely sensitive to the exact composition of the vapor, the presence or absence of anorthite in actual condensate assemblages may have been controlled by slight departures from equilibrium, regardless of the precise values of the thermodynamic data. In the absence of anorthite, how would the alkali metals have condensed from the nebula? Perhaps the amoeboid aggregates are important clues that the alkalies condensed as nepheline and sodalite.

It is certain that feldspathoids could not have coexisted in equilibrium with the nebular vapor at temperatures greater than 1100°K. Although it has not yet been shown by thermodynamic calculations, it does seem possible that such phases could be stable below ~900°K. In this case, they would have to form by the reaction of gaseous alkalies with pre-existing silicates because at equilibrium no silicon would have been left in the vapor at these temperatures.

GROSSMAN *et al.* (1975) presented some compelling textural evidence for the condensation of feldspathoids in a fine-grained pink inclusion in Allende, although some of the alkalies in such inclusions must be of later origin (GRAY *et al.*, 1973; GROSSMAN and GANAPATHY, 1975). At the same time, there is also some meteoritic evidence for the condensation of anorthite—its presence in the coarse, Ca–Al-rich inclusions. Much of this anorthite, however, was isolated in the interiors of these inclusions at the time the alkalies condensed and was unable to exchange with them.

Origin

Many of the phases observed in the amoeboid aggregates condensed at much higher temperatures than the feldspathoids. Ca–Al-rich and Ca–Al–Ti-rich pyroxenes have been found elsewhere in meteorites only as constituents of refractory condensate inclusions in Allende and other C3 chondrites. This is also true of spinel–perovskite assemblages. Remains of these high-temperature phases are recognizable as individual grains or inclusions inside the amoeboid aggregates, although these pyroxenes and spinels are sometimes considerably richer in FeO than their counterparts in most of the Ca–Al-rich aggregates

(GROSSMAN, 1975). It is concluded that the perovskite, spinel, olivine and pyroxenes condensed from the nebula in the temperature range 1400–1600°K and that some of these grains continued to equilibrate with the nebular vapor as it cooled to 500–650°K where FeO was able to dissolve in them. At some temperature below ~900°K some of the Ca–Al-rich silicate particles began to react with gaseous Na-, K- and Cl-bearing molecules to form nepheline and sodalite. Micron-sized grains of all these phases then began to stick to one another, forming the subspherical clumps so conspicuous in Fig. 1. Before these accreted together to form the aggregates, however, they were each coated by a thin layer of coarser-grained olivine. This late growth of olivine implies that the aggregates are not simply the result of single-stage, closed system condensation. In that case, all the Mg and Si would have been removed from the vapor at much higher temperatures (1300°K), leaving none to condense as coatings on the feldspathoid-rich clumps at 500°K. Rather, the olivine overgrowths suggest that, after the clumps formed, they were exposed to a fresh source of gas containing uncondensed Mg and Si and that olivine condensed from this gas on to the clumps which later formed the aggregates. This gas was either supercooled or it was not hot for a long enough period of time to evaporate the earlier-formed clumps.

Chondrule formation

The partly devitrified glass sphere, TS8 F2, is also surrounded by a thin olivine rind which is clearly visible in Fig. 1f. Tables 1–3 show that all the phases characteristic of the amoeboid aggregates are also present inside the sphere, probably as devitrification products. The bulk composition of the sphere must therefore be rather similar to that of the aggregates. It is concluded that some of the fine-grained clumps were melted occasionally, forming liquid droplets which cooled rapidly, quenching to glassy spheres. The evidence from TS8 F2 shows that it, too, was coated by a late overgrowth of olivine before being incorporated into the amoeboid aggregate, TS8 F1. These observations thus strongly support the contention that at least some meteoritic chondrules were formed in the nebula as suggested by WHIPPLE (1972) and CAMERON (1973b), rather than in the regolith of a large solid body.

CONCLUSION

Evidence from textural relations and oxygen isotopic measurements suggests that the amoeboid aggregates in Allende are primary condensates from the vapor of the solar nebula. Although vestiges of high-temperature condensates are present in the form of spinel, perovskite and Ti–Al-rich pyroxenes, the olivine compositions and the presence of the feldspathoids indicate that much of the material in the aggregates continued to react with the vapor in the

temperature range 500–900°K. The Allende meteorite is a mixture of different classes of petrographic units, each of which appears to have stopped equilibrating with the nebular vapor in a different temperature range.

REFERENCES

ALBEE A. L. and RAY L. (1970) Correction factors for electron probe microanalysis of silicates, oxides, carbonates, phosphates, and sulfates. *Anal. Chem.* **42.** 1408–1414.
BENCE A. E. and ALBEE A. L. (1968) Empirical correction factors for the electron microanalysis of silicates and oxides. *J. Geol.* **76.** 382–403.
CAMERON. A. G. W. (1973a) Abundances of the elements in the solar system. *Space Sci. Rev.* **15.** 121–146.
CAMERON A. G. W. (1973b) Accumulation processes in the primitive solar nebula. *Icarus* **18.** 407–450.
CLARKE R. S., JR., JAROSEWICH E., MASON B., NELEN J., GÓMEZ M. and HYDE J. R. (1970) The Allende, Mexico, meteorite shower. *Smithson. Contrib. Earth Sci.* No. 5.
CLAYTON R. N., GROSSMAN L. and MAYEDA T. K. (1973) A component of primitive nuclear composition in carbonaceous meteorites. *Science* **182.** 485–488.
CLAYTON R. N., GROSSMAN L., MAYEDA T. K. and ONUMA N. (1975) Heterogeneities in the solar nebula. In *Proceedings of the Soviet–American Conference on the Cosmochemistry of the Moon and Planets*, in press.
CLAYTON R. N., ONUMA N., GROSSMAN L. and MAYEDA T. K. (in preparation) Oxygen isotope abundances in separated phases from the Allende meteorite.
DEER W. A., HOWIE R. A. and ZUSSMAN J. (1963) *Rock-Forming Minerals* 1 ol. 4. *Framework Silicates.* 435 pp. Longmans & Green.

FUCHS L. H. (1969) Occurrence of cordierite and aluminous orthoenstatite in the Allende meteorite. *Amer. Mineral.* **54.** 1645–1653.
FUCHS L. H. (1971) Occurrence of wollastonite, rhönite, and andradite in the Allende meteorite. *Amer. Mineral.* **56.** 2053–2067.
GRAY C. M., PAPANASTASSIOU D. A. and WASSERBURG G. J. (1973) The identification of early condensates from the solar nebula. *Icarus* **20.** 213–239.
GROSSMAN L. (1972) Condensation in the primitive solar nebula. *Geochim. Cosmochim. Acta* **36.** 597–619.
GROSSMAN L. (1974) Amoeba-shaped olivine aggregates: a new type of inclusion in the Allende meteorite (Abstract). *Meteoritics* **9** 348 349.
GROSSMAN L. (1975) Petrography and mineral chemistry of Ca-rich inclusions in the Allende meteorite. *Geochim. Cosmochim. Acta* **39,** 433–454.
GROSSMAN L. (in press) Chemical fractionation in the solar nebula. In *Proceedings of the Soviet–American Conference on the Cosmochemistry of the Moon and Planets.*
GROSSMAN L., FRULAND R. M. and McKAY D. S. (1975) Scanning electron microscopy of a pink inclusion from the Allende meteorite. *Geophys. Res. Lett.* **2.** 37–40.
GROSSMAN L. and GANAPATHY R. (1975) Volatile elements and high-temperature condensation. In *Lunar Science VI.* pp. 318–320. Lunar Science Institute, Houston.
JANAF Thermochemical Tables (1972) Supplement No. 37. Thermal Research Laboratory. Dow Chemical Company, Midland, Michigan.
LARIMER J. W. and ANDERS E. (1967) Chemical fractionations in meteorites—II. Abundance patterns and their interpretation. *Geochim. Cosmochim. Acta* **31.** 1239–1270.
MASON B. (1974) Aluminum-titanium-rich pyroxenes, with special reference to the Allende meteorite. *Amer. Mineral.* **59.** 1198–1202.
REED S. J. B. and WARE N. G. (1973) Quantitative electron microprobe analysis using a lithium drifted silicon detector. *X-Ray Spectrometry* **2,** 69–74.
ROBIE R. A. and WALDBAUM D. R. (1968) Thermodynamic properties of minerals and related substances at 298·15°K (25·0°C) and one atmosphere (1·013 bars) pressure and at higher temperatures. *U.S. Geol. Surv. Bull.* **1259.**
THOMPSON A. B. (1975) Gibbs energy of aluminous minerals. *Contrib. Mineral. Petrol.* **48,** 123–136.
WHIPPLE F. L. (1972) On certain aerodynamic processes for asteroids and comets. In *From Plasma to Planet.* (editor A. Elvius). pp. 211–232. Almqvist & Wiksell.