VOLATILE-RICH CHONDRULES IN THE ALLENDE METEORITE

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Abstract: A new type of chondrules in the Allende meteorite is rich in volatile elements and shows porphyritic textures similar to terrestrial basalts. This unique type is termed Type V to supplement H. Y. MCSWEEN's (Geochim. Cosmochim. Acta, **41**, 1843, 1977) classification of chondrules in carbonaceous chondrites.

The Type V chondrules form a continuous trend with the Type I and II chondrules in the (Na+K)-(Al)-(Si) and (Na+K)-(Al+Ca)-(Mg+Fe) ternary systems. Type IV is plotted between Type V and CAI's. These compositional features of the different types of chondrules suggest that Type V was resulted from a fractionation process in the precusor materials of the Allende meteorite.

1. Introduction

MCSWEEN (1977) classified the chondrules in the CO and CV carbonaceous chondrites into Types I, II, III and IV by their mineralogy and textures (Table 1). According to him, most of the chondrules of the Allende (CV3) meteorite are classified into the granular olivine chondrules of Type I, and the porphyritic or barred olivine chondrules of Type II. The excentroradial pyroxene chondrules of Type III are absent, and the anorthite-spinel-diopside-melilite chondrules of Type IV are rare. However, CLARKE *et al.* (1970) reported a unique chondrule rich in volatile elements from the Allende meteorite which was not included in MCSWEEN's classification.

In the present study of the Allende meteorite, a number of chondrules resembling the chondrules described by CLARKE *et al.* (1970) in composition have been found. To

Table 1. Petrologic classification of the five types of chondrules, Types I–IV from MCSWEEN, (1977) and Type V from this study.

Type	Distinguishing characteristics
I	Granular olivine (Fo_{90-100})±pyroxene±spinel ±opaque minerals in clear glassy mesostatis
II	Porphyritic or barred olivine (Fo_{50-85}) +Cr-rich hercynite in brown glassy mesostasis
III	Excentroradial pyroxene (En_{90-100})+glass generally smaller than other chondrule types
IV	Usually anorthite, spinel, diopside, melilite ±glass molded into well rounded chondrules
V	Porphyritic enstatite, augite±clinoenstatite no plagioclase in alkali rich glassy mesostasis

elucidate the formation processes of these chondrules, the textures and the bulk compositions of the new type chondrules have been examined and compared with those of McSween's Types I to IV and calcium-aluminum-rich inclusions (CAI's) in the Allende meteorite.

2. Experimental

About seventy chondrules and CAI's in the Allende meteorite have been examined under an optical microscope. They are distributed in six polished thin sections within a total area of 5.5 cm^2.

Bulk compositions of the chondrules were analyzed by an electron probe microanalyzer (EPMA) of JEOL 50A using wavelength dispersive techniques. Operating conditions were 15 kV accelerating voltage and a beam current of 2.0×10^{-8} A. A defocussed beam of 30 μm in diameter was slowly moved on the surface of the chondrules by hand. The counting times were 100 or 200 s, depending on the size of the chondrules. Nine elements, measured three at a time, were analyzed for each chondrule. Chlorine was measured by energy dispersive analysis only. In scanning the beam over the specimens, opaque minerals and polishing defects were avoided as much as possible in the same manner as by Ikeda (1980). The analytical sums of the analyses were commonly less than 100% due to the roughness of the polished surface of the chondrules. The correction for the X-ray intensities was made by Bence and Albee (1968)'s method. The correction coefficients for the bulk compositions are taken from Ikeda (1980).

Glass portions of the chondrules were analyzed by a broad beam of 30 μm in diameter without scanning. In some chondrules, the glass analyses were performed by energy dispersive techniques (JEOL-T200 and Hitachi EDX-S550).

3. Results and Discussions

The bulk compositions of the chondrules and CAI's are listed in Table 2. These results combined with our petrographic examinations indicate that the Type I and II chondrules are abundant, the Type III chondrules are absent and the Type IV chondrules are rare in the Allende meteorite, in agreement with McSween (1977).

Among the seventy chondrules, about one-seventh are rich in volatile elements such as alkali cations. Though some of them are of the Type IV chondrules with plagioclase phenocrysts, others are unique in texture and mineralogy as described below in comparison with the chondrules of McSween's types (Table 1). Therefore, these chondrules are reasonably considered to form a new type which is not included in McSween's classification for the chondrules in the carbonaceous chondrites. We propose the name Type V chondrules for these objects, to conform with an supplement McSween's (1977) classification.

3.1. *Type V chondrules*

The chondrules of Type V have irregular shapes with variable sizes of about 0.3–2 mm. As observed in the photomicrographs (Figs. 1a–1h) of the Type V

Table 2. Bulk compositions of the chondrules and CAI's of the Allende meteorite.

(a) Type I and II chondrules

No.	0202	0203	0204	0205	0206	0207	0208	0209
SiO_2	38.0	36.3	40.5	37.5	27.0	33.5	37.2	35.5
Cr_2O_3	0.4	0.5	0.9	0.4	0.7	0.1	0.5	0.7
CaO	1.0	0.7	1.9	1.3	2.0	3.2	5.4	2.0
Al_2O_3	1.5	1.1	2.6	1.7	1.6	1.9	4.6	1.7
TiO_2	0.1	0.1	0.2	0.1	0.1	0.1	0.3	0.1
MgO	51.7	48.9	32.9	36.5	31.6	23.8	37.2	34.7
FeO	5.7	7.7	16.0	20.5	19.8	24.4	9.5	15.5
Na_2O	0.3	0.2	0.8	0.4	0.3	1.6	0.6	0.6
K_2O	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	98.7	95.6	95.9	98.8	83.2	89.4	95.5	91.0

No.	0210	0211	0212	0214	0215	0401	0402	0403
SiO_2	36.9	35.8	31.8	28.0	40.3	49.6	47.6	38.8
Cr_2O_3	0.7	0.8	0.8	0.6	0.9	1.0	1.0	0.4
CaO	1.4	2.2	1.9	3.2	2.4	1.9	1.9	1.1
Al_2O_3	1.8	2.5	1.3	3.2	4.2	3.4	2.2	1.4
TiO_2	0.2	0.2	0.1	0.2	0.3	0.2	0.1	0.1
MgO	35.9	27.7	29.2	30.4	36.5	35.0	29.1	45.2
FeO	17.0	18.3	11.8	13.3	9.6	5.6	11.4	9.1
Na_2O	0.7	0.5	0.4	0.9	1.5	1.2	0.8	0.8
K_2O	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.2
Total	94.9	88.2	77.4	79.7	95.9	98.3	94.5	97.0

No.	0404	0405	0406	0407	0408	0409	0410	0411
SiO_2	39.9	43.2	39.1	38.3	42.3	37.5	44.5	43.3
Cr_2O_3	0.9	0.5	0.6	1.0	0.5	0.9	0.6	0.6
CaO	3.4	1.7	1.6	1.5	1.6	1.8	2.5	1.8
Al_2O_3	2.2	1.9	1.5	2.9	2.5	4.2	2.7	3.0
TiO_2	0.2	0.1	0.1	0.1	0.1	0.1	0.2	0.2
MgO	32.9	43.4	41.4	32.9	43.6	31.8	38.3	43.5
FeO	14.9	8.1	11.8	18.0	8.3	18.9	10.1	5.7
Na_2O	0.5	0.5	0.4	0.4	0.8	1.2	0.6	0.8
K_2O	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	95.0	99.4	96.7	95.3	99.9	96.5	99.5	99.0

No.	0412	0413	0414	0415	0502	0503	1202	1203
SiO_2	41.5	37.9	39.3	41.7	33.3	38.6	34.5	32.1
Cr_2O_3	0.9	0.8	0.8	0.8	0.9	0.7	0.4	1.1
CaO	2.5	1.1	2.0	1.2	1.5	1.3	1.2	1.2
Al_2O_3	4.3	1.4	2.6	1.8	1.4	1.1	1.9	1.5
TiO_2	0.3	0.1	0.2	0.2	0.1	0.1	0.1	0.1
MgO	38.8	38.8	37.0	41.9	33.7	43.4	38.7	26.6
FeO	10.0	17.4	16.1	12.4	14.5	10.4	14.6	25.2
Na_2O	1.1	0.3	0.4	0.5	0.6	0.1	0.7	0.1
K_2O	0.2	0.1	0.0	0.1	0.1	0.0	0.1	0.0
Total	99.7	98.1	98.6	100.7	86.2	95.8	92.4	88.2

Table 2 (continued).

No.	1205	1206	1301	1302	1305	1306	1307	1308
SiO_2	42.5	37.9	52.9	49.5	44.6	39.1	37.2	40.1
Cr_2O_3	0.9	0.6	1.2	1.5	0.9	0.5	0.9	1.0
CaO	2.3	2.3	4.1	1.7	4.4	0.6	2.4	2.1
Al_2O_3	3.3	2.7	3.9	1.9	6.0	1.8	2.0	3.1
TiO_2	0.2	0.2	0.3	0.2	0.2	0.2	0.2	0.3
MgO	40.3	32.0	29.5	28.1	33.4	43.5	25.6	38.8
FeO	8.9	11.5	3.4	10.2	4.3	8.0	16.6	5.9
Na_2O	1.0	0.8	0.6	0.5	0.6	0.6	0.7	1.4
K_2O	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.2
Total	99.8	88.4	96.2	94.3	94.7	94.4	85.9	93.0

No.	1801	1802	1803	1804	1805	1806	1807
SiO_2	38.3	34.7	33.1	41.0	37.7	44.0	41.5
Cr_2O_3	1.3	1.1	1.2	0.9	1.0	0.7	0.8
CaO	1.6	2.0	1.3	1.6	1.6	1.6	1.5
Al_2O_3	2.2	2.6	1.5	2.3	1.9	2.6	2.7
TiO_2	0.2	0.2	0.1	0.3	0.1	0.2	0.2
MgO	30.5	35.2	30.0	34.0	39.9	40.2	37.1
FeO	15.0	19.1	24.4	13.0	18.6	11.1	13.1
Na_2O	0.6	0.5	0.3	0.5	0.3	0.7	0.6
K_2O	0.1	0.1	0.0	0.1	0.0	0.1	0.1
Total	89.6	95.5	92.0	93.7	101.1	101.2	97.4

(b) Type IV chondrules

No.	0416	0417	0501	1209	1808	1810
SiO_2	31.9	34.5	39.5	41.6	32.8	36.8
Cr_2O_3	0.8	0.7	0.5	0.6	3.9	0.9
CaO	7.3	8.3	12.5	8.9	13.0	3.9
Al_2O_3	21.7	13.0	10.6	18.0	22.2	20.7
TiO_2	0.5	0.8	0.7	0.4	1.2	0.2
MgO	17.5	27.2	13.5	16.2	12.9	18.0
FeO	4.5	4.3	2.5	6.7	5.8	9.9
Na_2O	3.8	2.6	2.2	4.6	3.1	4.5
K_2O	0.1	0.2	0.1	0.2	0.1	0.2
Total	88.2	91.5	82.1	97.3	94.8	95.2

(c) Type V chondrules

No.	0201	0213	0418	0504	1201	1204	1207	1208	1304	1809
SiO_2	37.8	30.6	39.8	34.0	37.0	38.1	36.1	33.6	27.9	44.9
Cr_2O_3	0.8	0.7	0.6	0.9	0.9	0.9	0.7	1.3	0.7	0.9
CaO	5.5	2.8	6.1	3.6	6.8	3.0	3.2	0.5	2.6	5.4
Al_2O_3	8.5	3.8	19.7	3.1	9.2	5.9	8.7	6.7	19.0	7.9
TiO_2	0.5	0.3	0.7	0.4	1.0	0.3	0.4	0.4	0.4	0.5
MgO	19.2	31.9	16.2	19.2	18.2	25.7	20.8	24.6	18.0	27.8
FeO	8.2	10.5	4.3	13.6	10.2	13.8	15.3	21.4	8.6	7.4
Na_2O	3.0	2.0	5.8	2.4	3.1	1.8	2.8	2.2	7.8	2.1
K_2O	0.3	0.1	0.2	0.2	0.3	0.1	0.4	0.3	0.2	0.1
Total	84.0	82.7	93.3	77.5	87.1	89.8	88.6	91.2	85.4	97.0

Table 2 (continued).

(d) Groundmass of type V chondrules

No.	1201GM	1207GM	1304GM	Type C*
SiO_2	33.8	39.4	41.7	40.2
Cr_2O_3	0.6	0.4	0.4	0.2
CaO	4.7	6.5	4.1	5.3
Al_2O_3	16.8	18.7	22.7	17.8
TiO_2	1.1	0.6	0.3	0.1
MgO	13.9	12.6	11.4	15.2
FeO	11.2	6.8	4.3	8.8
Na_2O	7.0	8.7	14.5	10.6
K_2O	0.7	0.5	0.2	0.6
Total	89.8	94.2	99.5	100.6

* Composition of the type C chondrule reported by CLARKE *et al.* (1970). Total contains 2.0 wt% of chlorine.

(e) CAI's

No.	12101	12102	12103	1303	1309	1310
SiO_2	30.1	27.8	33.0	29.6	30.1	30.8
Cr_2O_3	0.1	0.1	0.1	0.1	0.1	0.1
CaO	17.4	18.8	17.9	24.1	22.3	17.4
Al_2O_3	31.5	37.3	32.3	28.8	30.2	36.0
TiO_2	0.0	0.1	0.1	1.8	0.4	0.5
MgO	3.2	8.4	4.1	5.4	7.9	5.6
FeO	3.1	5.3	3.2	2.0	0.3	5.4
Na_2O	2.2	2.0	4.5	0.9	0.1	1.4
K_2O	0.0	0.0	0.0	0.0	0.0	0.9
Total	88.0	99.9	95.3	92.8	91.9	99.2

chondrules (Nos. 0201, 1201, 1207 and 1304 in Table 2c), they show a prophyritic texture similar to the terrestrial basalts and consists of phenocrysts of augite, enstatite, ±clinoenstatite, ±olivine and interstices of glass or microcrystals of the above-mentioned minerals.

Chondrule No. 0201 (Figs. 1a, 1b) is one of the typical examples of Type V, and has enstatite (20%), clinoenstatite (5%) and augite (7%) phenocrysts in a groundmass (68%) of glass and fine crystals of albite, sodalite and augite. No olivine crystals were found in this chondrule. The phenocrysts of enstatite are overgrown with well-defined rims of augite, and are columnar in shape, 50–80 μm in diameter and up to 350 μm in length (Fig. 2). Single crystals of augite are also observed as phenocrysts. Phenocrysts of clinoenstatite are subhedral in shape, and are on the order of 100 μm in size. Opaque minerals, approximately 50 μm in size, are observed within the chondrule and also at the boundary between the chondrule and the matrix.

The clinoenstatite phenocrysts contain only 1 mol% of the Fs and Wo components (Fig. 3). In the enstatite-augite phenocrysts, the Wo component of the core enstatite and the mantle augite is about 4 mol% and up to 43 mol%, respectively. The Fs content of both regions is only 1 mol%.

The groundmass is a homogeneous mixture of glass and microcrystals of augite,

Fig. 1. Photomicrographs of the Type V chondrules. The scale bars are 0.3 mm.

(a) and (b): Plane and crossed polarization photograph of No. 0201 chondrule. This chondrule shows the texture like a terrestrial basalt. Part of the photograph is enlarged in Fig. 2.

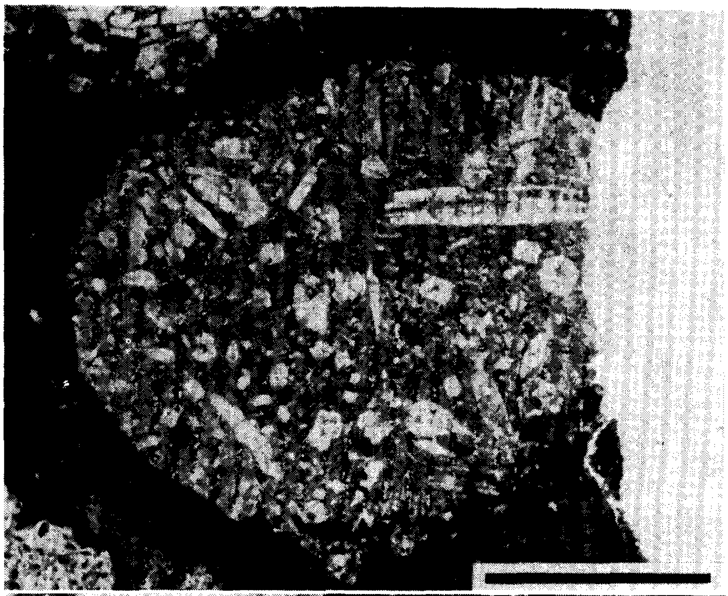


Fig. 1a.

Fig. 1b.

(c) and (d): Plane and crossed polarization photograph of No. 1201 chondrule. This condrule shows long and slender shape, but has typical texture of Type V chondrule. Phenocrysts are mostly augite, and dispersed in groundmass of glass or microcrystals.

Fig. 1c.

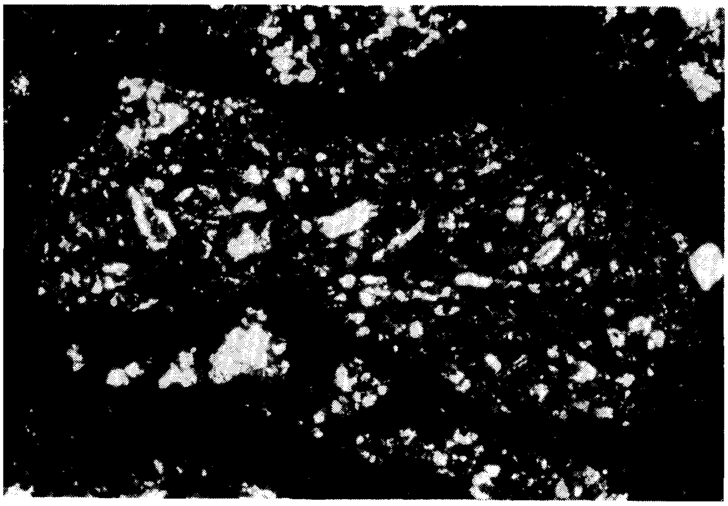


Fig. 1d.

(e) and (f): Plane and crossed polarization photograph of No. 1207 chondrule. This chondrule has relatively low alkali content. Phenocrysts are smaller than other chondrules and modal ratio of olivine is higher.

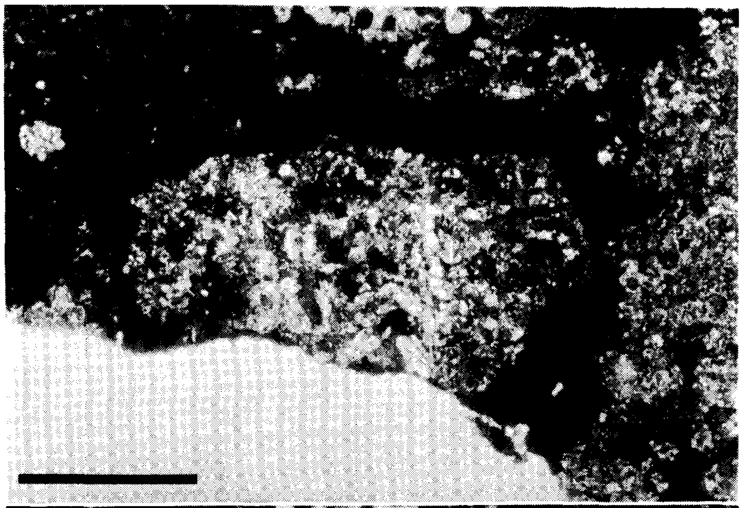


Fig. 1e.

Fig. 1f.

albite and sodalite. Most of the glass has a composition intermediate between albite and nepheline but some has that of sodalite. Chlorine is present in microcrystals of sodalite only in the groundmass of the Type V chondrules.

Among the chondrules of Type V, some have more irregular external forms and *(g) and (h): Plane and crossed polarization photograph of No. 1304 chondrule. Groundmass of this chondrule is almost alkali-rich glass. Alkali content of this chondrule is the highest among the Type V chondrules in this study. Phenocrysts are augite and olivine.*

Fig. 1g.

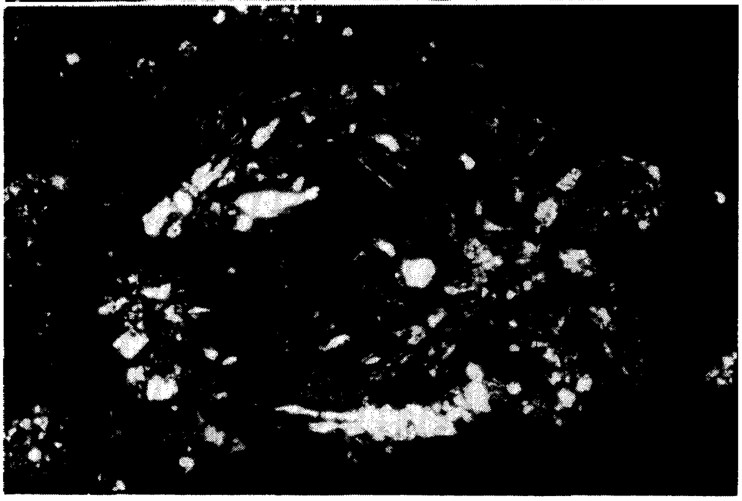
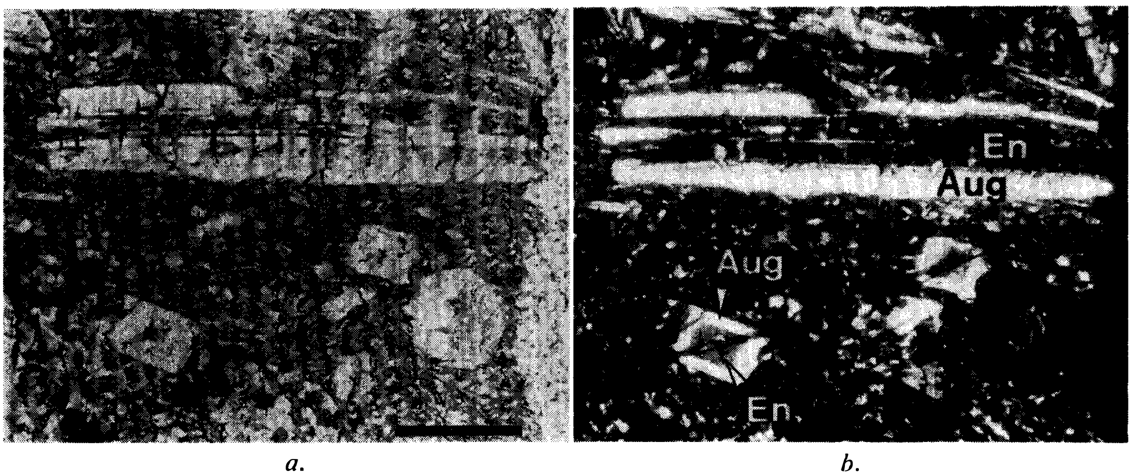
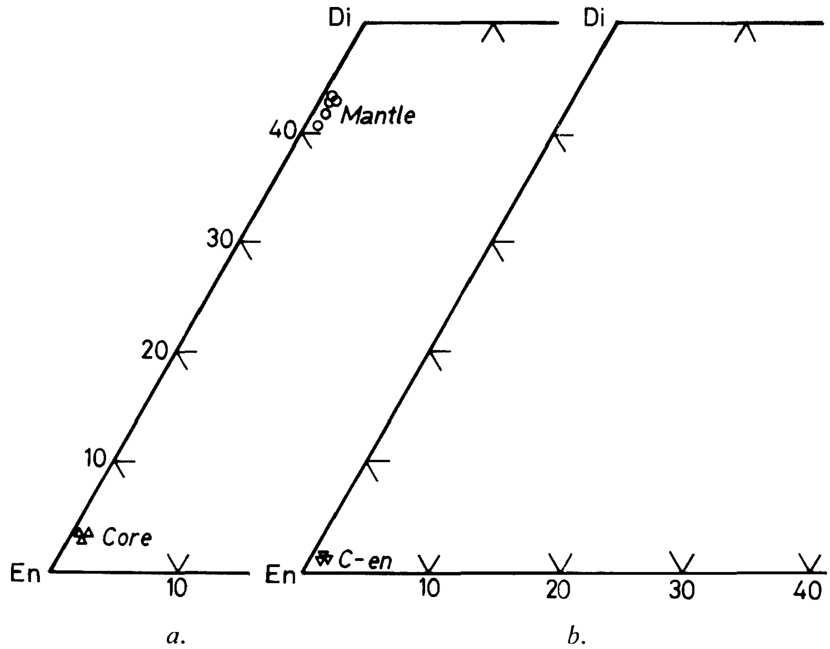


Fig. 1h.



a. *b.*

Figs. 2a, b. Enlarged optical micrograph of No. 0201 chondrule. The scale bar is 0.1 mm. The vertical and crossing sections of the pyroxene phenocrysts show that the phenocrysts are rectangular columns. In the rectangular pyroxene phenocrysts, the core enstatite is surrounded by augite of the same thickness as the core. Opaque minerals are metalsulfides. Groundmass is almost glass. Enstatite and augite are represented by En and Aug, respectively.



Figs. 3a, b. Chemical compositions of the pyroxene phenocrysts of a Type V chondrule plotted on the pyroxene quadrilateral. a) Enstatite-augite phenocrysts. The core is almost pure enstatite, and the mantle is almost iron-free augite. b) Clinoenstatite (C-en) phenocrysts.

smaller phenocrysts than the chondrule described above (Fig. 1). Others with lower contents of alkali cations have more olivine phenocrysts and less groundmass, though the textures of the groundmass are almost the same as above. The unique chondrule reported by CLARKE *et al.* (1970) which consists of only groundmass has a similar composition and texture to the groundmass of the Type V chondrules (Type C in Table 2d and Figs. 4 and 5). Thus, the chondrule reported by CLARKE *et al.* (1970) is regarded as a special case of the Type V chondrules which are generally prophyritic.

3.2. Bulk compositions of the chondrules

In order to obtain a clue to the formation process of the chondrules of Type V, their bulk compositions have been compared with those of the other types. To emphasize the characteristics of each type, bulk chondrule analyses are plotted on (Na+K)–(Al+Ca)–(Si+Mg+Fe) ternary diagrams in order to distinguish the volatile, refractory and major element components, respectively, of the different chondrule types.

In practice the data are plotted on the ternary diagrams of (Na+K)–(Al)–(Si) (Fig. 4) and (Na+K)–(Al+Ca)–(Mg+Fe) (Fig. 5) by atomic %. In these figures, the solar abundance (star) is also plotted as are the compositions of pure olivine (Ol), albite (Ab), nepheline (Ne) and anorthite (An). Because more than 75% of the total 64 chondrules are of Types I and II, the data of the Type I and II chondrules are only partially plotted in these figures for the purpose of clarification.

The compositions of Type V are plotted near the extrapolated line which starts from the Si (Fig. 4) or Mg+Fe apex (Fig. 5) through the compositions of Types I and II. The CAI's are almost free from alkali metals and are plotted close to the

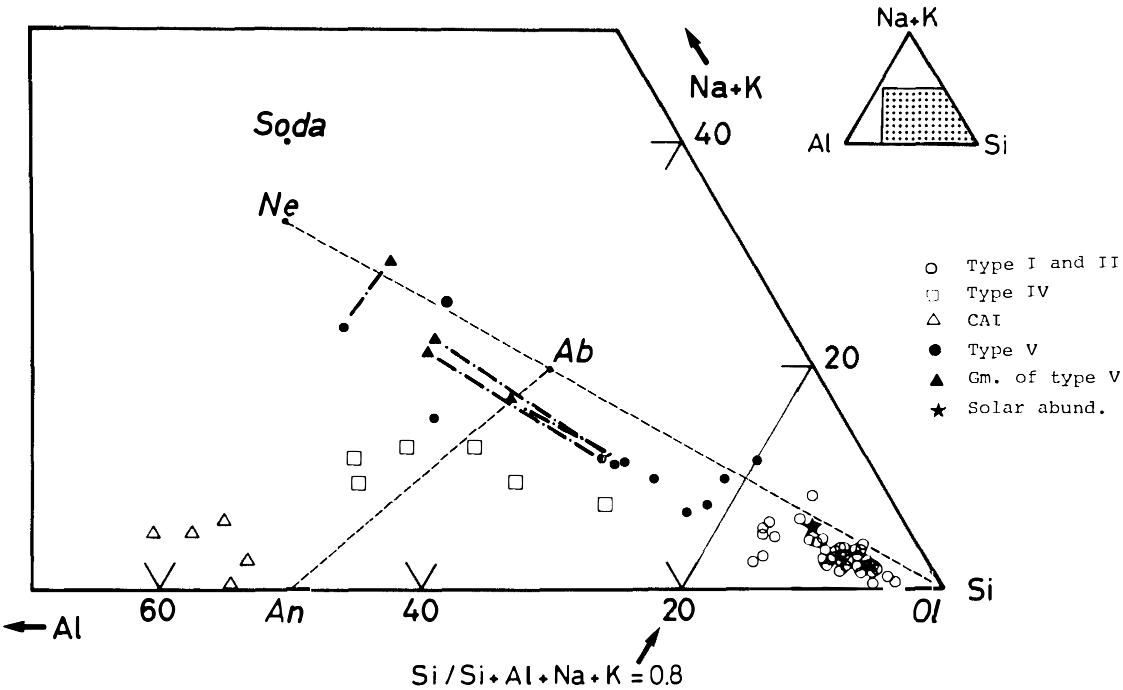


Fig. 4. *Atomic fractions of the chondrules in the Allende meteorite plotted in the (Na+K)–(Al)–(Si) triangle, where Ab, An, Ol, Ne, and Soda represent albite, anorthite, olivine, nepheline and sodalite, respectively. Dot-and-dashed lines represent the bulk-groundmass plots of the Type V chondrules. All the groundmasses and some of the Type V chondrules are plotted outside the Ab–An–Ol triangle. The boundary line of Si/(Si+Al+Na+K)=0.8 between Types I and II and Type V is shown by a solid line.*

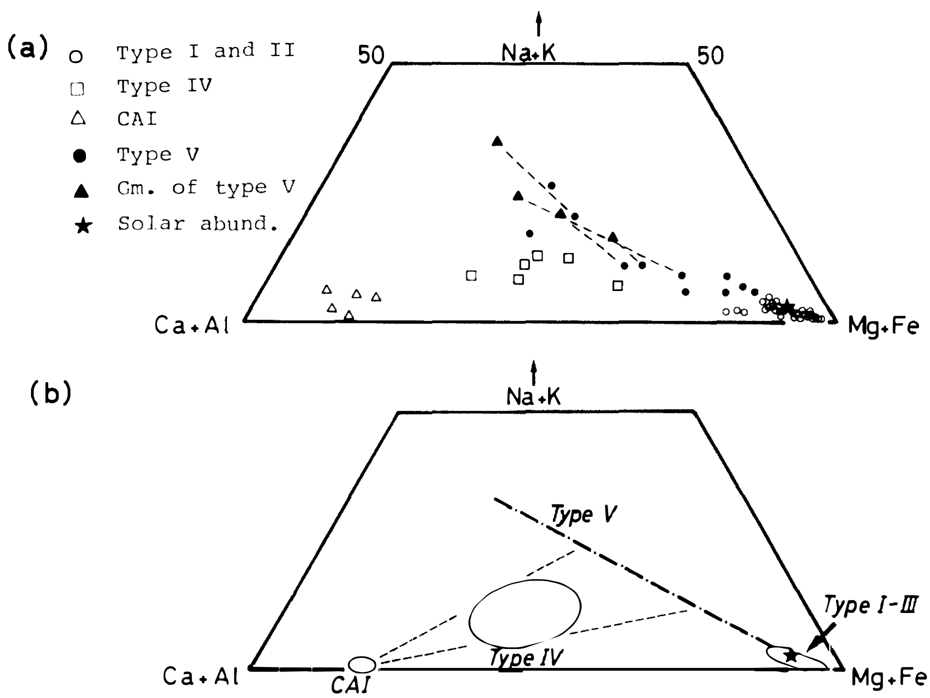


Fig. 5.a. Atomic fractions of the chondrules in the Allende meteorite plotted in the (Na+K)–(Ca+Al)–(Mg+Fe) triangle. The symbols and dot-and-dashed lines are the same as in Fig. 4.
b. Schematic drawing of Fig. 5a. Dot-and-dashed line from the Mg+Fe apex stands for the fractional trend.

base in the figures. Thus, six chondrules of Type IV and five CAI's are plotted in Figs. 4 and 5 in different areas from the straight line running through Types I, II and V. The distinction between Types I and II and Type V can be made by the boundary line of Si/(Si+Al+Na+K)=0.8 (Fig. 4). In Figs. 4 and 5a, the dot-and-dashed lines represent the bulk-groundmass assemblages of some Type V chondrules. Type IV chondrules are plotted between Type V and CAI's (Fig. 5b), implying a mixing of these objects.

The fact that Type I, II and V chondrules form a line starting from the Si or Mg+Fe ends can be explained by two different processes. The first is a mixing process of two end components in the multicomponent system, and the second is a fractionation process by olivine and/or pyroxene. In the first process, the materials with large amounts of volatile elements must have existed as one end component, implying that the Type V chondrules should be abundant, whereas, in fact, they are rather rare. Therefore, the fractionation process has probably operated to produce Type V probably from Type I and/or II. The enrichment of the volatile elements in the chondrules requires that the fractionation process had occurred keeping the volatile elements in a surrounding medium, before the accretion of the chondrules took place.

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