

PETROLOGY OF CHONDRULES IN ALH-77015 (L3) CHONDRITE

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Abstract: Chondrules in ALH-77015 (L3) chondrite were studied petrographically. Size and bulk chemical composition of about one hundred chondrules were investigated with relation to their texture. There seems to be no relation between the size and the texture, and the texture is mainly controlled by chemical composition, especially SiO_2 , MgO and FeO contents. Another controlling factor, such as cooling rate, degree of supercooling or maximum temperature of heating, seems to be subordinate.

Two types of olivine grains, different in the occurrence and mineralogy, are contained in some porphyritic chondrules. One is thought to be a relic crystal which had already existed before chondrules formation, representing secondary origin of chondrules. It further shows a relative low temperature of heating and a short duration of melting at the time of chondrule formation.

1. Introduction

Chondrules show various textures, which should reflect the differences in physical and chemical conditions at the time of their formation. In order to elucidate the conditions, petrological studies including chemical analyses of chondrules and their constituent minerals were performed on ALH-77015 chondrite.

ALH-77015 chondrite is a typical “unequilibrated” chondrite, consisting of closely packed chondrules with various sizes, fragments of chondrules and minerals set in the brown to black opaque fine-grained matrix.

2. Classification of Chondrules

Chondrules are classified into four types according to their texture (Table 1). “Porphyritic” chondrules show various textures, such as euhedral olivine, anhedral olivine and euhedral pyroxene with or without inclusions of olivine. The abundances of crystals and metals vary greatly. Further subclassification of them based on the above features is difficult because the differences among them are gradual and can not be uniquely defined. In this paper, chondrules with crystals more than 90% are called “highly crystalline”. Pyroxene in the porphyritic chondrules always coexists with olivine and occurs as euhedral grains with or without olivine inclusions or as anhedral grains grown interstitially between olivine grains. Chondrules with pyroxene only is not observed in the porphyritic type of this chondrite.

Table 1. A comparison of classification of chondrules.

This study	DODD (1971, 1978)	McSWEEN* (1979)	EVENSEN <i>et al.</i> (1979)	SIMON and HAGGERTY* (1980)
Porphyritic [Crystals < 90% [Crystals > 90% (highly -crystalline) [Olivine [Olivine and pyroxene	Microporphyritic [Metal-poor [Metal-rich [Spherical, metal-rich [Pyroxene rich	Type I [Opaque-free [Opaque-mineral -bearing Type II	Porphyritic [Olivine [Olivine and pyroxene	Euhedral olivine Anhedral olivine Glassy/skeletal olivine
Barred	Barred	Type II	Barred	Barred
Radial	Excentroradial	Type III	Radiating-px, -ol and px Barred-px	Pyroxene-type
Glassy	Glassy Devitrified glass			

* For the chondrules in carbonaceous chondrites.

“Barred” chondrules are characterized by the parallel sets of elongated olivine in glass or devitrified groundmass. Rarely euhedral or anhedral olivine grains are present at the center of the chondrules. Width of the olivine bar varies from below 10 μm to more than 100 μm . Chondrules with narrow olivine bars resemble “radial” types. In this paper, chondrules with olivine bars are called “barred” type regardless of their width.

“Radial” type chondrules consist of fibrous to tabular pyroxene with small amounts of groundmass. Typical one shows a radial texture grown from a single point near the surface of the chondrule. Occasionally bundles of acicular or tabular crystals are interlocking. In this paper, “radial” chondrules are limited to those which have only pyroxene as crystalline phases. Radial chondrules contain extremely small amounts of groundmass compared with porphyritic or barred ones.

“Glassy” chondrules are glassy or devitrified ones and contain no observable crystals. Occasionally heterogeneous glassy chondrule is present, consisting of two portions of different color and chemical composition.

3. Analytical Methods

Three polished thin sections were made from sample ALH-77015 chondrite provided from the National Institute of Polar Research. A portion of the sample was used for wet chemical analysis. After microscopic observation, each chondrule,

and its constituent minerals and glass were analyzed with JEOL-5 and automated JEOL-733 electron probe microanalyzers. Minerals and glass were analyzed with a focused beam with 15 kV accelerating voltage and 0.2×10^{-7} A specimen current. The correction was made after BENCE and ALBEE (1968) and NAKAMURA and KUSHIRO (1970). Bulk chemical composition of chondrules was determined with a defocused beam of about 50 μm in diameter for 100 to 400 seconds. The correction for analyses of polyphase samples with a broad beam was made after IKEDA (1980).

4. Results

4.1. Size and texture of chondrules

Size distribution of chondrules in ALH-77015 in relation to their textures is shown in Fig. 1a and is compared with those in other chondrites (MARTIN and MILLS, 1976, 1978) in Fig. 1b. The figure shows nearly uniform size distribution regardless of textures; that is, chondrules with different textures are similar in size distribution, except for barred chondrules which have slightly smaller sizes. The distribution pattern of ALH-77015 resembles those of other chondrites, although the measurements were made in thin sections. The average apparent radius on the thin section is about 0.4 mm for all of them.

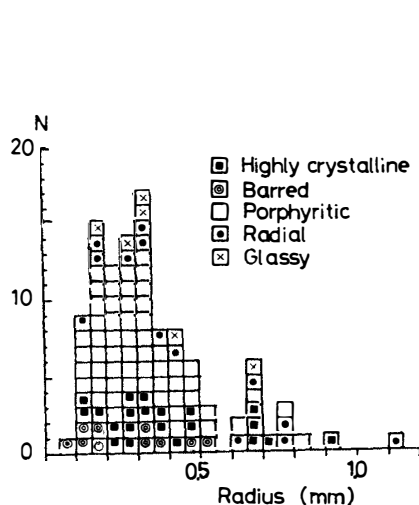


Fig. 1a. Size distribution of chondrules in ALH-77015 chondrite in relation to textures.

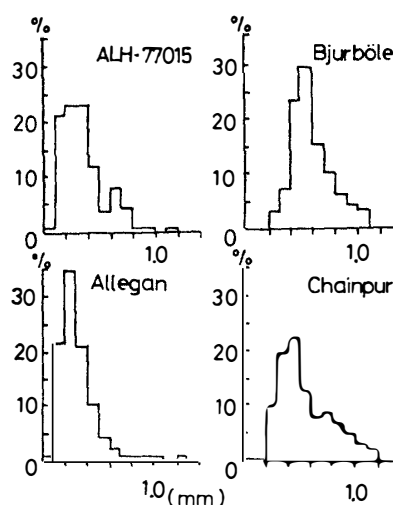


Fig. 1b. Size distribution of chondrules in four chondrites, ALH-77015 (L3, this study), Bjurböle (L4, MARTIN and MILLS, 1976), Chainpur (LL3, MARTIN and MILLS, 1976), Allegan (H5, MARTIN and MILLS, 1978). Measurement of ALH-77015 was made on thin sections, and the other observations were made on hand-picked samples under a binocular microscope.

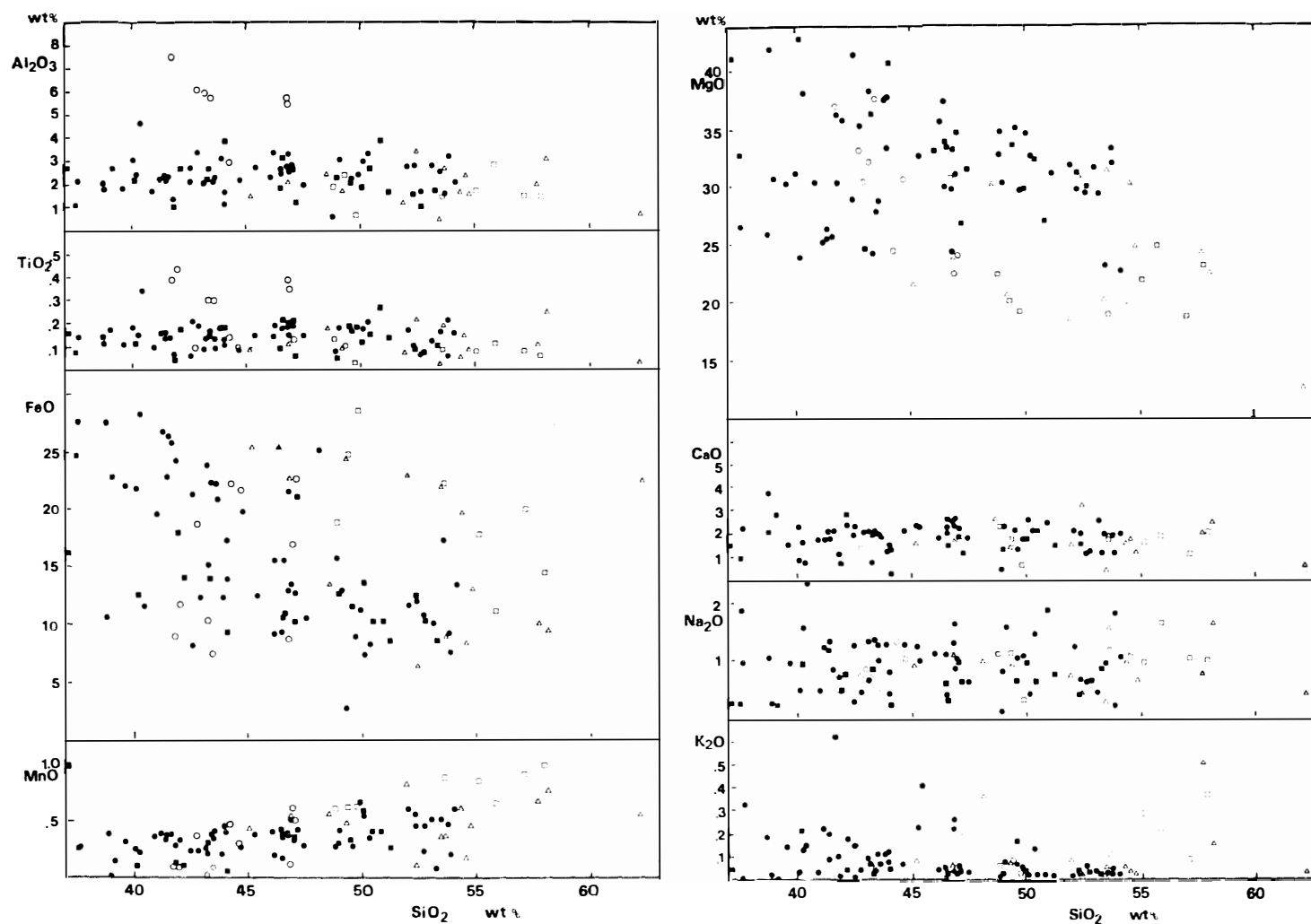


Fig. 2. Chemical composition of chondrules in relation to textures, plotted against SiO_2 . Symbols: closed circle, porphyritic; closed square, highly crystalline; open circle, barred; open square, radial; open triangle, glassy.

Table 2. Chemical composition of chondrules in ALH-77015 chondrite. Chondrules are grouped into textural types.

	Porphyritic														
	1	2	3	4	6	7	11	12	27	28	41	42	44	48	49
SiO ₂	43.64	41.83	52.69	53.80	53.15	43.21	42.57	44.72	42.88	40.96	41.64	49.68	50.17	45.42	38.74
Al ₂ O ₃	2.26	1.43	1.66	1.52	2.69	2.17	2.13	2.13	3.34	1.78	2.32	2.23	2.95	2.70	2.08
TiO ₂	0.11	0.01	0.08	0.07	0.13	0.10	0.07	0.10	0.19	0.11	0.14	0.17	0.18	0.16	0.13
FeO	20.78	24.09	10.88	9.43	10.10	23.75	21.05	19.71	12.27	19.51	25.73	8.89	7.38	12.43	27.63
MnO	0.35	0.29	0.25	0.21	0.51	0.28	0.34	0.29	0.25	0.36	0.38	0.28	0.55	0.39	0.38
MgO	28.78	30.25	29.50	32.95	31.57	24.67	28.83	30.48	35.11	30.17	25.70	34.92	34.59	32.55	26.02
CaO	1.96	1.25	1.24	1.25	2.50	2.13	2.07	2.20	2.16	1.81	2.11	1.34	2.66	2.29	2.05
Na ₂ O	1.31	0.79	0.68	0.26	0.47	1.38	1.31	1.30	0.48	0.49	0.86	1.08	0.41	1.04	1.07
K ₂ O	0.07	0.11	0.08	0.03	0.04	0.10	0.15	0.08	0.05	0.03	0.62	0.08	0.03	0.40	0.20
Total	99.26	100.05	97.05	99.52	101.17	97.76	98.53	100.99	96.73	95.19	99.50	98.66	98.92	97.38	98.30
	Porphyritic														
	50	53	54	56	57	58	60	63	65	66	68	69	70	71	73
SiO ₂	43.60	50.37	46.25	49.80	39.61	41.44	46.90	43.24	48.93	44.04	43.92	52.12	53.83	40.49	41.24
Al ₂ O ₃	2.18	3.23	3.23	2.48	1.82	2.37	2.48	2.18	0.63	1.06	3.14	2.69	3.15	1.76	2.24
TiO ₂	0.14	0.21	0.20	0.19	0.11	0.14	0.16	0.14	0.09	0.11	0.18	0.17	0.22	0.12	0.16
FeO	22.05	8.12	9.12	11.29	22.08	22.72	13.53	15.07	15.68	17.16	12.29	11.75	7.68	22.07	26.71
MnO	0.41	0.37	0.22	0.66	0.32	0.34	0.52	0.20	0.29	0.47	0.21	0.61	0.46	0.38	0.40
MgO	27.72	32.50	34.73	29.57	30.33	26.36	33.20	38.26	32.61	33.22	37.52	31.72	32.04	26.46	25.12
CaO	2.00	2.22	2.40	1.88	1.57	2.17	2.77	0.77	0.52	1.54	1.32	2.20	2.00	1.64	1.76
Na ₂ O	1.20	1.46	1.27	1.11	0.95	1.21	0.89	0.70	0.13	0.45	1.30	1.24	0.82	0.91	1.26
K ₂ O	0.12	0.13	0.23	0.06	0.14	0.21	0.05	0.08	0.02	0.13	0.13	0.03	0.05	0.05	0.23
Total	99.41	98.61	97.64	97.04	96.92	96.95	100.51	100.64	98.88	98.18	100.00	102.52	101.25	93.88	99.10

Petrology of Chondrules in ALH-77015 (L3) Chondrite

Table 2. (Continued).

		Porphyritic															
		74	75	78	81	82	88	89	90	91	92	93	98	99	101	104	
	SiO ₂	49.11	43.43	41.49	53.58	40.10	44.08	46.18	46.84	47.03	54.15	46.55	37.64	46.82	40.40	38.81	
	Al ₂ O ₃	3.05	2.73	2.20	2.59	3.12	1.62	2.30	3.31	2.79	2.13	2.44	2.10	2.76	4.56	1.89	
	TiO ₂	0.19	0.16	0.16	0.16	0.19	0.14	0.15	0.21	0.20	0.16	0.18	0.14	0.19	0.35	0.14	
	FeO	12.93	22.21	26.26	17.34	21.65	13.89	15.47	21.48	12.73	13.55	15.64	27.52	12.88	11.50	10.55	
	MnO	0.42	0.38	0.37	0.52	0.25	0.41	0.41	0.40	0.35	0.60	0.39	0.24	0.38	0.02	0.01	
	MgO	30.15	24.22	25.47	22.83	31.30	37.63	33.09	24.32	31.08	22.57	29.90	26.32	29.79	37.94	41.94	
	CaO	2.42	2.16	1.77	2.01	2.33	1.39	1.87	2.57	2.29	2.06	2.02	2.26	2.44	0.85	3.71	
	Na ₂ O	1.60	1.39	1.37	1.07	0.53	0.81	1.17	1.62	1.08	1.10	1.16	0.93	1.32	2.31	0.30	
	K ₂ O	0.09	0.04	0.10	0.34	0.03	0.08	0.05	0.26	0.30	0.02	0.02	0.32	0.22	0.15	0.02	
	Total	99.96	96.73	99.18	100.13	99.50	100.05	100.69	100.00	97.59	96.33	98.32	97.17	96.80	98.08	97.37	
		Porphyritic				Crystalline											
		106	107	108	110	5	10	13	18	29	30	43	45	46	47	52	
	SiO ₂	46.55	42.56	47.54	40.24	49.00	42.20	44.11	49.18	47.20	50.49	53.31	47.09	52.77	46.62	46.53	
	Al ₂ O ₃	2.58	2.63	1.96	2.44	2.29	2.67	3.74	1.74	1.16	2.61	1.66	2.58	0.99	3.07	1.82	
	TiO ₂	0.18	0.22	0.25	0.25	0.06	0.18	0.18	0.08	0.06	0.15	0.11	0.20	0.08	0.21	0.10	
	FeO	9.30	8.15	10.50	28.07	12.71	13.94	9.20	14.33	21.06	10.24	8.47	10.30	10.31	10.90	10.63	
	MnO	0.18	0.25	0.30	0.22	0.32	0.10	0.06	0.59	0.43	0.43	0.09	0.36	0.44	0.36	0.42	
	MgO	37.15	41.10	31.43	23.83	34.61	35.74	40.34	25.40	26.60	32.16	29.23	34.67	29.81	33.29	32.50	
	CaO	2.22	2.34	1.75	1.69	1.39	2.47	0.28	1.62	1.14	2.19	1.23	1.86	1.30	2.69	1.46	
	Na ₂ O	0.46	0.32	0.62	1.59	0.84	0.79	0.29	0.81	0.66	0.65	0.86	1.02	0.67	0.38	0.61	
	K ₂ O	0.03	0.01	0.03	0.13	0.03	0.05	0.05	0.07	0.04	0.03	0.06	0.06	0.04	0.03	0.06	
	Total	98.64	97.57	94.27	98.36	101.23	98.12	98.24	93.82	98.35	98.94	95.02	98.15	96.41	97.57	95.14	

Table 2. (Continued).

	Crystalline											Barred			
	59	67	72	80	85	94	97	100	102	103	105	9	25	38	39
SiO ₂	40.22	52.34	50.12	37.17	49.56	51.28	43.36	39.13	37.58	41.89	50.92	43.49	47.09	41.79	44.30
Al ₂ O ₃	2.21	1.52	1.80	2.65	2.17	1.69	2.21	2.62	1.12	1.02	3.80	5.65	2.28	7.44	2.89
TiO ₂	0.13	0.10	0.13	0.15	0.19	0.14	0.15	0.17	0.08	0.06	0.27	0.30	0.13	0.39	0.15
FeO	12.37	12.37	13.64	16.17	11.57	8.59	14.03	22.57	24.54	17.85	10.12	7.50	22.38	8.84	21.96
MnO	0.11	0.57	0.58	0.12	0.34	0.26	0.32	0.15	0.27	0.12	0.41	0.09	0.51	0.10	0.47
MgO	42.45	31.14	29.78	41.40	33.38	31.15	36.12	30.57	32.46	36.09	26.83	37.45	23.97	36.77	24.17
CaO	0.94	1.53	1.83	1.55	2.14	1.55	2.07	2.76	0.92	0.74	2.55	4.97	1.80	5.45	2.19
Na ₂ O	0.94	0.43	0.95	0.28	0.69	0.78	0.89	0.20	0.31	0.05	1.87	0.48	1.23	0.45	1.34
K ₂ O	0.21	0.04	0.04	0.04	0.16	0.03	0.03	0.00	0.00	0.00	0.03	0.06	0.20	0.05	0.11
Total	99.55	100.13	98.87	99.54	100.21	95.37	99.17	98.16	97.28	97.81	96.80	99.99	99.58	101.36	97.57
	Barred						Radial								
	40	55	84	86	87	96	21	22	23	26	31	34	35	36	37
SiO ₂	44.71	46.92	43.28	42.80	46.85	42.98	54.35	57.68	49.31	46.90	58.08	62.16	54.55	54.78	45.19
Al ₂ O ₃	1.19	5.41	5.90	1.50	5.69	6.07	1.62	1.84	1.73	2.12	3.02	0.65	2.28	1.43	1.49
TiO ₂	0.11	0.35	0.31	0.10	0.40	0.44	0.11	0.11	0.10	0.12	0.19	0.03	0.15	0.09	0.09
FeO	21.45	16.78	10.23	18.61	8.67	11.63	19.49	10.13	24.19	22.76	9.43	22.52	8.34	13.04	25.20
MnO	0.29	0.62	0.03	0.37	0.12	0.10	0.61	0.68	0.48	0.54	0.76	0.57	0.18	0.46	0.44
MgO	30.34	22.30	32.01	32.99	30.73	30.33	19.79	24.05	29.51	23.80	22.17	12.39	29.89	24.70	21.44
CaO	1.03	4.14	5.30	1.39	5.15	5.51	1.69	2.09	1.42	1.78	2.51	0.61	1.85	1.28	1.52
Na ₂ O	0.07	1.12	0.75	0.76	1.23	0.88	0.99	0.76	0.93	1.12	1.67	0.44	1.12	0.64	0.91
K ₂ O	0.01	0.08	0.05	0.15	0.11	0.05	0.06	0.50	0.08	0.07	0.15	0.03	0.04	0.04	0.08
Total	99.20	97.71	97.84	98.67	98.94	97.55	98.71	97.83	98.73	99.19	97.99	99.41	98.40	96.46	96.36

Table 2. (Continued).

	Radial					Glassy	
	51	61	62	64	109	24	32
SiO ₂	51.93	48.56	53.45	56.64	52.40	55.82	57.12
Al ₂ O ₃	1.22	2.43	0.41	2.61	3.31	2.78	1.47
TiO ₂	0.08	0.18	0.03	0.02	0.22	0.11	0.07
FeO	22.91	13.29	21.87	8.95	6.32	11.18	19.86
MnO	0.81	0.57	0.37	0.36	0.12	0.66	0.90
MgO	18.41	29.92	20.06	31.16	31.01	24.58	18.35
CaO	1.49	2.66	0.43	1.98	3.24	1.88	1.17
Na ₂ O	0.74	0.99	0.30	1.53	0.44	1.64	1.05
K ₂ O	0.08	0.36	0.03	0.06	0.03	0.21	0.09
Total	97.68	98.96	96.93	100.49	97.09	98.85	100.08

	Glassy					
	33	76	77	79	83	95
SiO ₂	49.38	49.78	55.14	57.86	53.64	48.87
Al ₂ O ₃	2.30	0.63	1.62	1.36	1.42	1.91
TiO ₂	0.11	0.04	0.08	0.07	0.09	0.11
FeO	24.67	28.41	17.69	14.55	22.28	18.80
MnO	0.63	0.63	0.84	0.97	0.87	0.60
MgO	19.92	19.01	21.64	22.84	18.77	22.25
CaO	1.82	0.70	1.63	2.04	1.87	2.43
Na ₂ O	1.12	0.33	0.96	1.01	1.17	1.16
K ₂ O	0.06	0.03	0.29	0.36	0.11	0.07
Total	100.05	99.54	99.89	101.04	100.22	96.19

4.2. Bulk chemical composition of chondrules

The bulk chemical compositions of chondrules in relation to textures are shown in Fig. 2 and are listed in Table 2. As shown in the figure, the FeO and MgO contents decrease with increasing SiO₂, though the tendency is not so clear as in the case of the "equilibrated" chondrites (NAGAHARA, 1979).

General relations between chemical composition and texture are as follows; (1) porphyritic chondrules have the widest range of variation, (2) SiO₂ contents of porphyritic chondrules (closed circle) and highly crystalline ones (closed square) vary from 37 wt% to 54 wt%, radial (open square) and glassy (open triangle) ones from 45 wt% to 62 wt%, and barred ones (open circle) from 42 wt% to 47 wt%, (3) barred chondrules are rich in Al₂O₃, TiO₂ and CaO, and poor in FeO and MgO, and (4) radial and glassy are rich in FeO and poor in MgO.

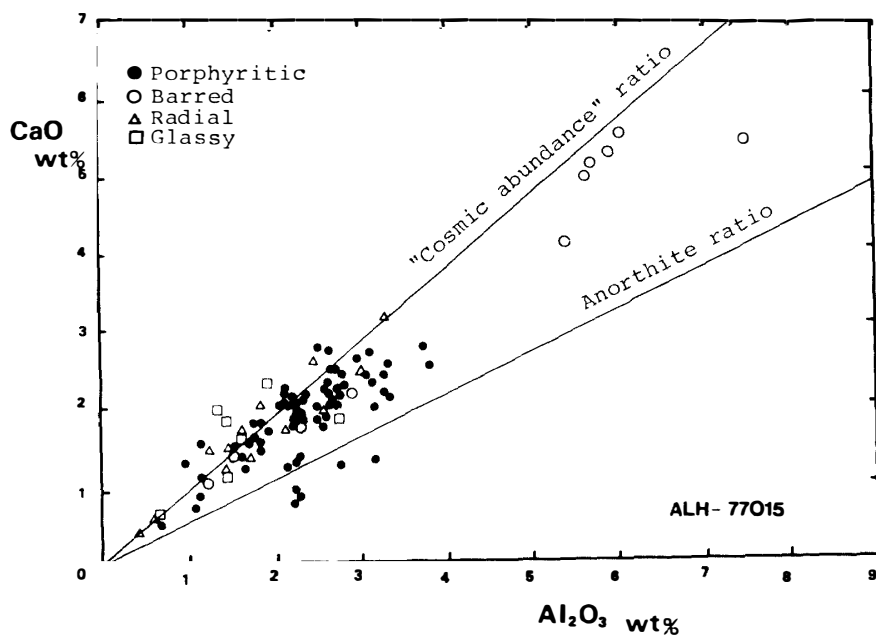


Fig. 3a. Relation between Al_2O_3 and CaO contents of chondrules.

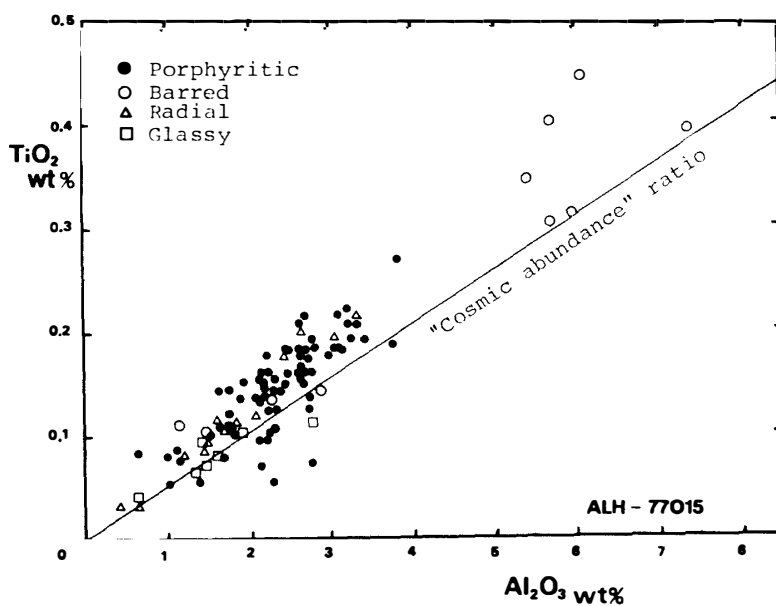


Fig. 3b. Relation between Al_2O_3 and TiO_2 contents of chondrules.

There are clear inter-elemental correlations between Al_2O_3 and CaO and between Al_2O_3 and TiO_2 for all types of chondrules (Fig. 3). These tendencies are similar to those observed in the chondrules in C3 chondrite (McSWEEN, 1977). Their ratios are close to those of the cosmic abundance of these elements. Figure 3 also shows

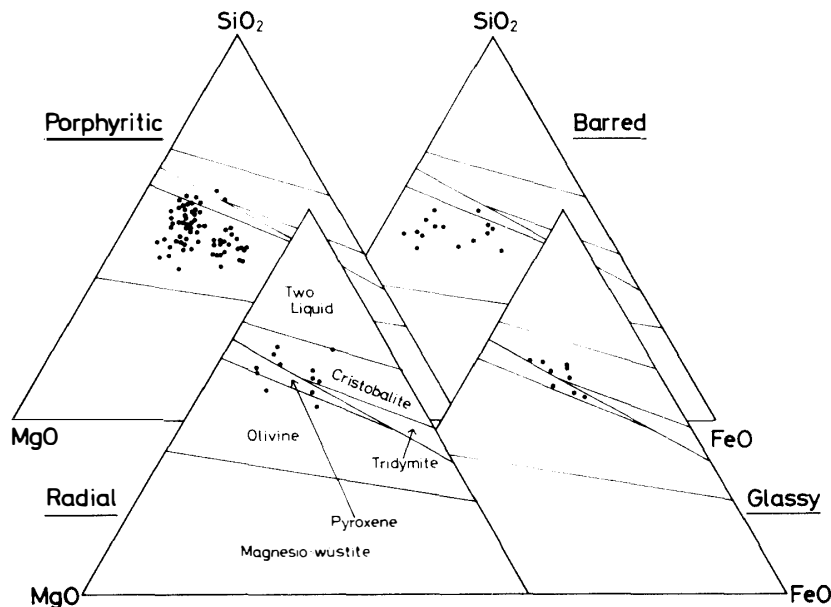


Fig. 4. $MgO:FeO:SiO_2$ ratio (wt%) of chondrules of different textures. The liquidus phase fields of this ternary system are from BOWEN and SCHAIERER (1935). "Porphyritic" contains highly crystalline ones.

that some of the barred olivine chondrules contain much higher Al_2O_3 , CaO and TiO_2 contents than the other types of chondrules. SIMON and HAGGERTY (1980) found the same fact in Allende (C3) chondrite. The Al_2O_3 and Na_2O contents in most chondrules show a weak positive correlation; however, the barred olivine chondrules with high Al_2O_3 and CaO contents show an inverse correlation.

Chondrules consist mainly of SiO_2 , MgO and FeO (about 90 wt% of each chondrule). The $SiO_2:MgO:FeO$ ratio (wt%) of chondrules of different textural types are shown in Fig. 4 with the liquidus phase field of the ternary system (BOWEN and SCHAIERER, 1935). Most of them are plotted in the liquidus field of olivine. A few in the pyroxene and cristobalite fields, are shifted in the olivine and pyroxene fields when the feldspar components are subtracted.

4.3. Two types of olivine within a single chondrule

Some chondrules contain two types of olivine (Fig. 5). One is dirty, large anhedral grains with many cleavages located near the center of the chondrule, and the other is clear small euhedral grains set around the former one. Usually clear olivine overgrows the dirty one. Among the clear olivine grains, pale brown to pale purple glass is present.

Two types of olivine show different chemical compositions. The former is usually uniform in composition (Figs. 6b, c) and occasionally it reveals "reverse" zoning with a MgO-rich rim and a FeO-rich core (Fig. 6a). On the contrary, the latter is richer

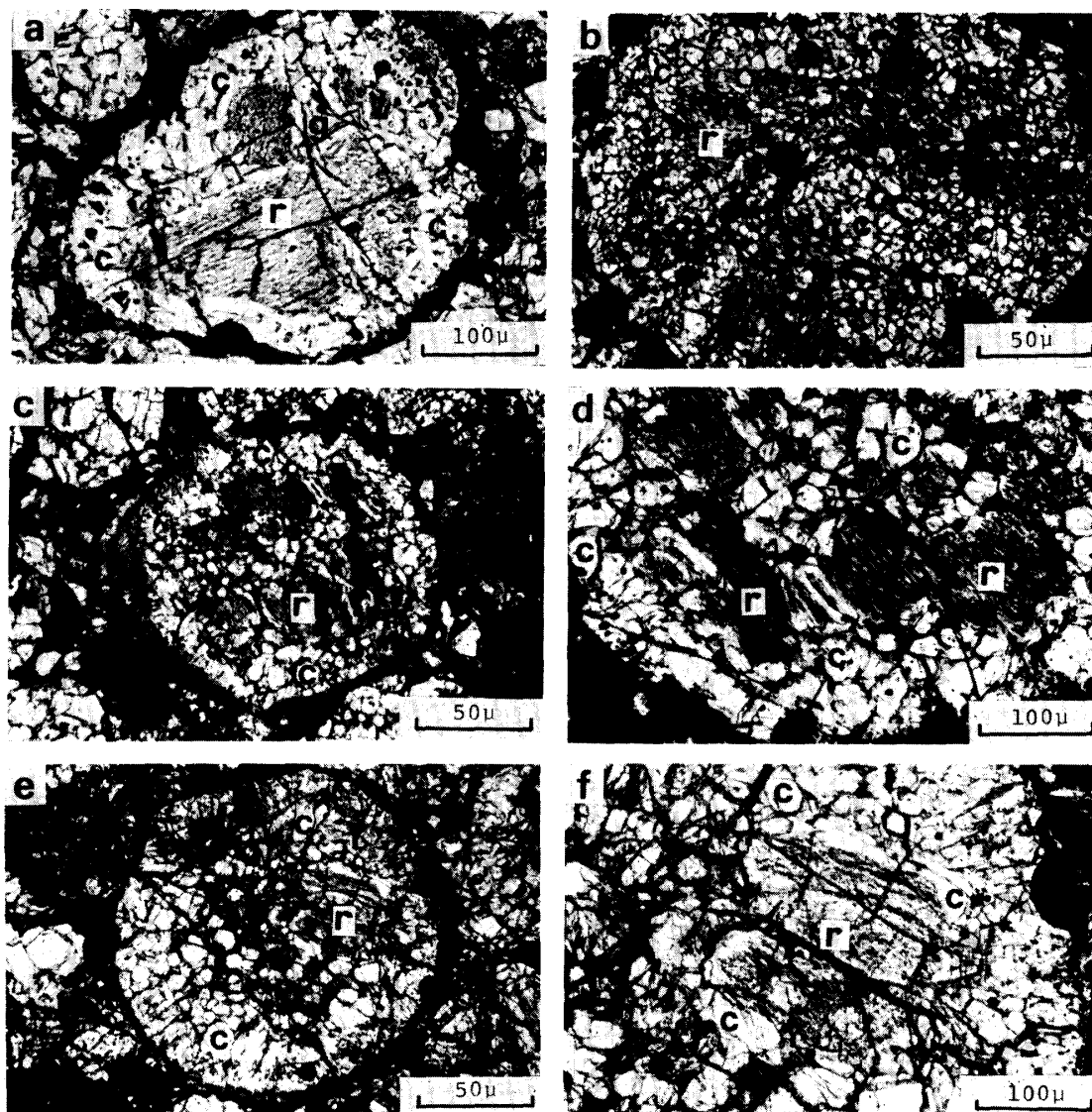


Fig. 5. Photomicrographs of the chondrules with relic olivine. (a) Chondrule 2-1, (b) Chondrule 2-3, (c) Chondrule 2-2, (d) View of enclosed relic olivine in chondrule 2-2, (e) Chondrule 2-4, (f) View of enclosed relic olivine with clear overgrowth in chondrule 2-4. *r*: relic olivine, *c*: crystallized olivine, *g*: glass.

in MgO than the former, shows “normal” zoning with a MgO-rich core and a FeO-rich rim (Figs. 6b, c), and has an irregular pattern (Figs. 6b, c).

The CaO content of the two olivines is remarkably different (Fig. 7); the euhedral clear olivine contains more CaO than the anhedral dirty olivine, and its content varies from chondrules to chondrules and grain to grain. On the other hand, the anhedral olivine has less and uniform CaO content.

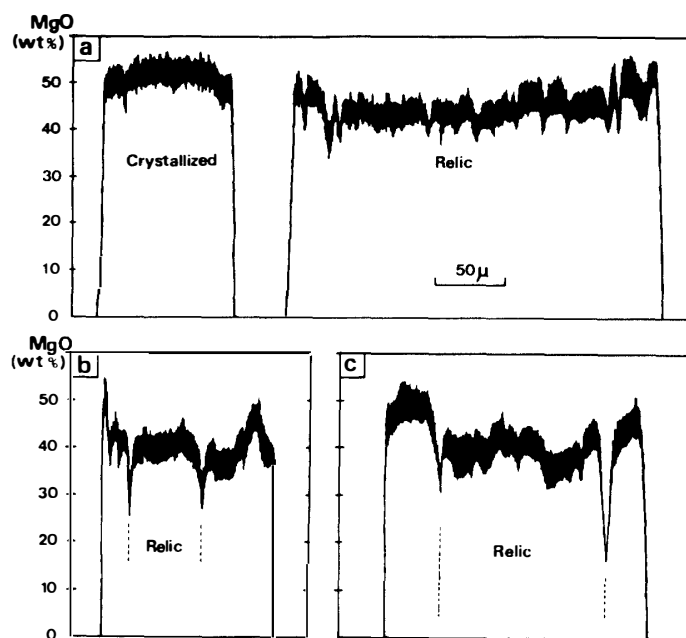


Fig. 6. (a) Scanning profiles of MgO in relic (right) and crystallized (left) olivines in chondrule 2-4, (Figs. 5e, f).
 (b) That in chondrule 2-2 (Figs. 5c, d).
 (c) That in chondrule 2-3 (Fig. 5b).

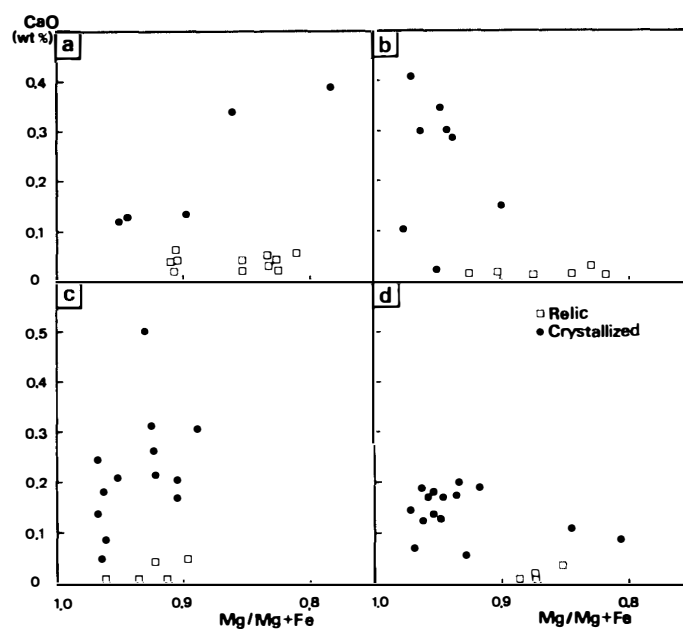


Fig. 7. CaO content of relic (open square) and crystallized (closed circle) olivines in relation to Mg/Mg+Fe ratio.

5. Discussion

5.1. *Factors which determine the texture of chondrules*

It is apparent from Fig. 1 that the texture of chondrules is mainly related to their chemical composition, especially SiO_2 content. That is, porphyritic chondrules and highly crystalline ones show wide variations in SiO_2 content, whereas radial and glassy chondrules generally have high SiO_2 contents. NAGAHARA (1979) has already mentioned that the textural variations of chondrules in the "ordinary" chondrites are primarily controlled by the chemical composition. The results of this study support the previous discussion.

In the system MgO-FeO-SiO_2 , the liquidus temperature for chondritic compositions decreases with increasing SiO_2 and FeO contents. If the chondrules were heated up to the same temperature and cooled with the same cooling conditions, the liquids with higher SiO_2 contents may become glass more easily than those with higher MgO contents, because the structure of the former liquid would be more different from that of crystal (olivine) than the latter liquid and olivine may fail to crystallize more easily. Consequently, glassy chondrules could be formed with the same heating and cooling processes as the SiO_2 -poor chondrules of porphyritic, crystalline and barred textures.

As already pointed out, radial and glassy chondrules have nearly equal compositions. The factor which causes the difference is considered to be cooling process. For the same chemical composition, the liquid cooled more rapidly and/or more super-cooled would easily form glass.

Porphyritic, highly crystalline and barred chondrules show similar compositional variations, except for the most barred chondrules with high Al_2O_3 and CaO contents. Whether the porphyritic "polyhedral" (DONALDSON, 1976) or granular crystal, or the barred elongated crystal is formed would be governed by nucleation and crystal growth mechanism. The porphyritic texture would be formed by lower degree of supercooling and/or in the existence of nucleus, and the barred texture would be formed by higher degree of supercooling and/or in the absence of nucleus (DONALDSON, 1976). If the liquid is formed below the liquidus temperatures, porphyritic texture would be easily formed because of the existence of nucleus, whereas if liquid is heated above the liquidus temperatures, barred texture would be formed. The high Al_2O_3 and CaO contents in some barred olivine chondrules may lower the liquidus temperatures. Consequently some barred chondrules may be formed in the same heating and cooling conditions as the porphyritic chondrules, and the difference would be caused by the Al_2O_3 and CaO contents. Those do not have high Al_2O_3 and CaO contents may be formed in the different physical conditions.

The abundance of crystals is apparently due to the slow cooling of the liquid, and the highly crystalline chondrules should have been kept near the solidus temperature for a long time compared with those with a smaller amount of crystal.

In conclusion, the texture of chondrules is governed mainly by the chemical com-

position and partly by heating and cooling conditions such as maximum temperature, cooling rate, degree of supercooling, or duration of heating at subliquidus temperature.

5.2. *Significance of two olivines in a chondrule*

As mentioned previously, two types of olivine are present in a single chondrule. The coexistence of olivine with "normal" zoning and "reverse" zoning (Fig. 6) and the remarkable difference in the CaO content of the two olivines (Fig. 7) can not be formed by a single crystallization sequence.

The euhedral olivine having "normal" zoning and high CaO content would have crystallized from a liquid. On the other hand, the anhedral olivine having "reverse" zoning, dirty appearance with many dusty inclusions and low CaO content is considered to be a relic mineral which was not wholly melted at the time of chondrule formation. Especially, many dusty inclusions are thought to be formed by any events such as shock of collision or impact, or thermal release of heating. In this paper, the former is called "crystallized olivine" and the latter "relic olivine". The "reverse" zoning in the relic olivine may be formed by diffusion between the relic and crystallized olivines during crystallization of the melt or weak heating at the later stage.

The occurrence of the relic mineral is the direct evidence of precursory minerals for the chondrule formation, and the possibility of secondary origin of chondrule is strongly suggested.

Existence of the precursory minerals further suggests that the temperature of chondrule formation was not excessively high and/or the duration of heating was considerably short. Because, if the materials were heated up to temperatures higher than their liquidus temperatures and kept at such temperatures for a long time, they should be wholly melted. The liquidus temperature of olivine for chondritic compositions (see Fig. 7) is 1800 to 1700°C. The maximum temperature of such chondrule formation would be in this range and the duration of heating would be short, which support the hypothesis of instantaneous heating of the precursory minerals for the chondrule formation.

5.3. *Origin of chondrules*

Origin of the chondrules is one of the major problems of the meteorite studies. Despite many works, it has not been clear even whether they are the products of primitive condensates (*i.e.* BLANDER and KATZ, 1967; WOOD and MCSWEEN, 1976; HERNDON and SUESS, 1977) or remelted products of the precursory materials (*i.e.* FREDRIKSSON, 1965; WASSON, 1972; KIEFFER, 1975; DODD, 1978), and much less is known about the mechanism of their formation. However, the recent many chemical, petrological and mineralogical studies lead to the conclusion that the chondrules were the secondary products from pre-existing materials (IKEDA, 1980; GOODING *et al.*, 1980; KLEIN *et al.*, 1980).

Petrological observations presented here strongly suggest that at least some

chondrules were formed by an instant heating near (above or below) the liquidus temperatures of the pre-existing materials and followed by crystallization. The maximum temperature and the duration of heating estimated here from the petrological observations are quite consistent with our recent experimental results on the cooling rate of barred texture (TSUCHIYAMA *et al.*, 1980), Na-vaporization of chondritic liquids (TSUCHIYAMA *et al.*, 1981) and their subliquidus crystallization (NAGAHARA and TSUCHIYAMA, in preparation). Mechanism of the formation of chondrules is still in question because of the scarcity of the information on the condition of their formation. Further petrological and experimental studies would be needed to clarify it.

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