PETROLOGICAL STUDIES ON CHONDRULES IN YAMATO-74 METEORITES

Makoto KIMURA, Kenzo YAGI and Kosuke ONUMA

Department of Geology and Mineralogy, Faculty of Science, Hokkaido University, Sapporo 060

Abstract: Crystallization of chondrule is investigated through the study of Yamato-74191, -74155, -74079, -74371, and -74647 meteorites. Bulk compositions of chondrules are calculated from modal analyses and mineral compositions, and are projected in the $MgO-Al_2O_3-SiO_2$ system with the compositions of glasses in chondrules, from which the process of crystallization of chondrule is suggested. According to the investigation in the peritectic system, chondrules may be regarded as products of supercooling crystallization. Variety of textures of chondrules, which are classified into porphyritic, barred, radiating, and cryptocrystalline types, is also explained by various degrees of supercooling of droplet (chondrule). Abnormal $FeO/FeO+MgO$ ratios of the olivines, pyroxenes, and glasses, and extraordinary high $K_{D}{}^{Ol-Px}_{Mg-Fe}$ values show the change of atmosphere in chondrule. It possibly resulted from a reaction in ambient gas and its diffusion into chondrule.

On the basis of mineralogy of chondrules and matrix in the Yamato-74191, a possible process of accretion of chondrules to parent body is discussed. Evidences of recrystallization of chondrules often occurring before accretion are suggested. Most of chondrules have thin rims around them, whose average composition is similar to that of the silicate portion of the L-chondrites. The rims might have been attached to chondrules after recrystallization and before accretion. Distinct shapes of chondrules mean that their accretion speeds to parent body were fairly low.

1. Introduction

Chondrites are characterized by the presence of chondrules, which have never been recognized in the terrestrial rocks, and are considered to have been originated by some extraordinary event in the primitive solar nebula. Therefore, the studies on chondrules are expected to throw light on the condition of the nebula and the formation of the planetsimals. However, the origin of chondrule is not yet evident. In this paper the results of petrological studies on chondrules in the Yamato-74 meteorites carried out by microscopic observations and EPMA analyses are discussed, with emphasis on the crystallization and accretion of chondrules.

2. Samples

Five pieces of the Yamato-74 meteorites are studied in the present paper. Yamato-74191, described by YABUKI *et al.* (1978) and YANAI *et al.* (1978), is studied in detail, because it belongs to the unequilibrated chondrite (L3). In addition, Yamato-74155 (H4), -74079 (H5), -74371 (H5), and -74647 (H5), described by KIMURA *et al.* (1978), are also studied.

3. Classification of Chondrules

Since there are various types of chondrules, they must be properly classified at first. VAN SCHMUS (1969) classified them into porphyritic, barred, radiating, glassy, and agglomeratic chondrule which is called dark-zoned one by DODD and VAN SCHMUS (1971). Although glassy one is not noticed, there are two new types of chondrules in the Yamato-74 meteorites, *i.e.*, cryptocrystalline and chromite ones in addition to the ones described above. Since the origin of dark-zoned and chromite chondrules should be considered apart from the others, they are omitted from the present discussion. Shapes and sizes of chondrules are not related to the type of chondrules.

(1) *Porphyritic chondrule*: It consists mainly of olivine, Ca-poor pyroxene, and glass. The olivines and pyroxenes are euhedral to subhedral in shape. Olivine/pyroxene ratio varies in each chondrule, and porphyritic chondrules can be classified into two sub-types by this ratio. The olivine-porphyritic chondrule does not contain pyroxene (Figs. 1–2), whereas pyroxene-porphyritic one has always pyroxene (Figs. 3–4), the amount of which varies from rare to abundant. Olivine, always present in pyroxene-porphyritic chondrule, is enclosed in pyroxene or surrounded by glass without reaction rim of pyroxene. In the olivine-rich pyroxene-porphyritic one, pyroxene is usually present in the marginal part of chondrule. Very fine-grained opaque minerals are present very often in porphyritic, barred, and radiating chondrules. Sometimes large troilite grains are included in them.

(2) *Barred chondrule*: It is characterized by parallel crystals of olivine (Fig. 5). Glass fills the interstices of these crystals.

(3) *Radiating chondrule*: It is composed of radiating laths of Ca-poor pyroxenes, usually accompanied by a small amount of Ca-rich pyroxenes (Figs. 6–7). The thickness of individual laths of pyroxene varies in a wide range. When the laths are very fine-grained, the appearance is similar to cryptocrystalline chondrule (Fig. 6), whereas those in which laths are very thick, often associated with glass, are close to the pyroxene-porphyritic chondrule (Fig. 7). The gradational textures of pyroxene-porphyritic, radiating, and cryptocrystalline chondrules suggests a series of conditions when they formed.

(4) *Cryptocrystalline chondrule*: It consists of cryptocrystalline materials

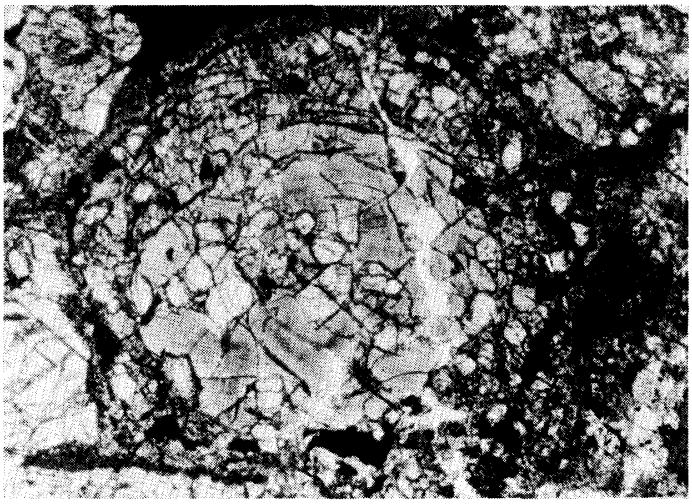

Fig. 1. Olivine-porphyritic chondrule (A28) consisting of fine-grained olivine crystals and very clear glass (degree A). Poorly recrystallized rim surrounds it. Yamato-74191. Long dimension of photograph = 0.75 mm.

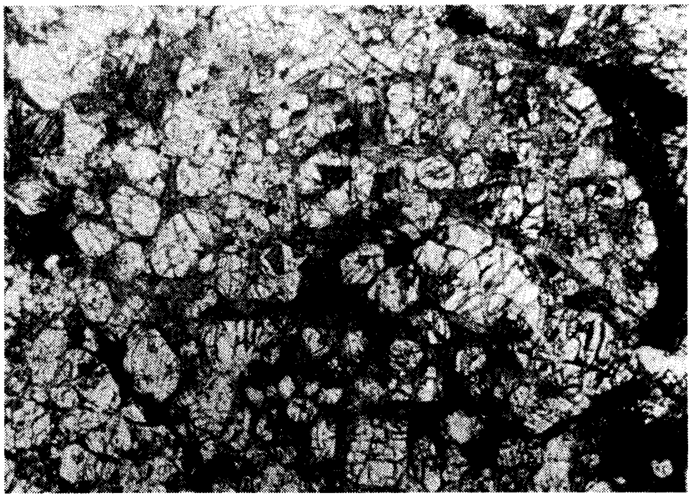

Fig. 2. Olivine-porphyritic chondrule (B85) consisting of olivine crystals and fairly devitrified glass (degree C). Yamato-74191. Long dimension of photograph = 0.75 mm.

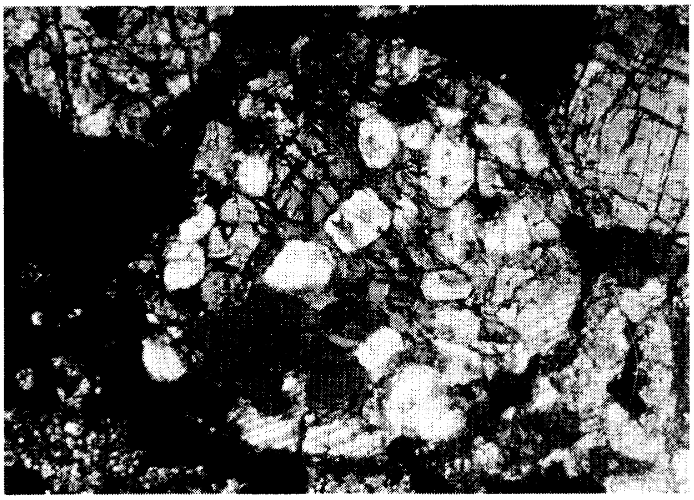

Fig. 3. Pyroxene-porphyritic chondrule (B36). Olivine grains are not surrounded by reaction rims of pyroxene, and polysynthetically twinned Ca-poor clinopyroxene grains are present in the marginal part of chondrule. Glass belongs to degree A. Thin rim surrounds this chondrule. Yamato-74191. Nicols crossed. Long dimension of photograph = 0.50 mm.

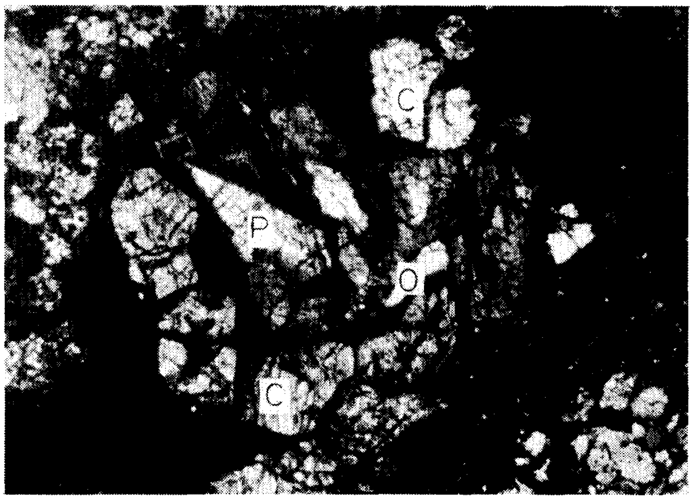

Fig. 4. Pyroxene-porphyritic chondrule (B17) consisting of Ca-poor clinopyroxene (C) including fine olivine (O), orthopyroxene (P), and glass of degree B. Yamato-74191. Nicols crossed. Long dimension of photograph = 0.60 mm.

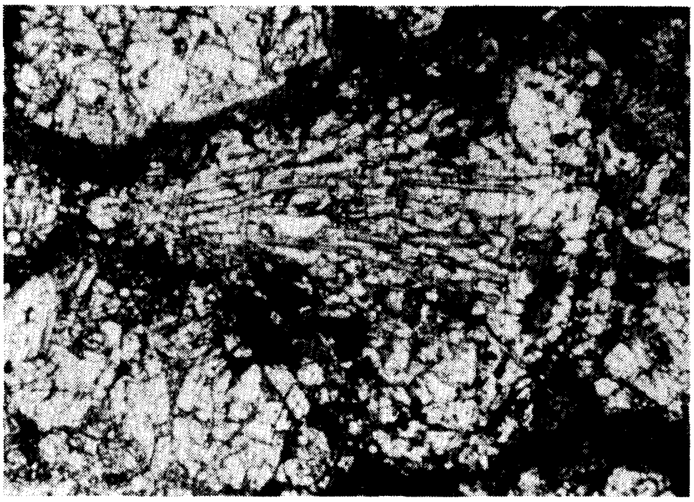

Fig. 5. Barred chondrule (B59) composed of parallel sets of olivine and glass of degree A. Yamato-74191. Long dimension of photograph = 1.3 mm.

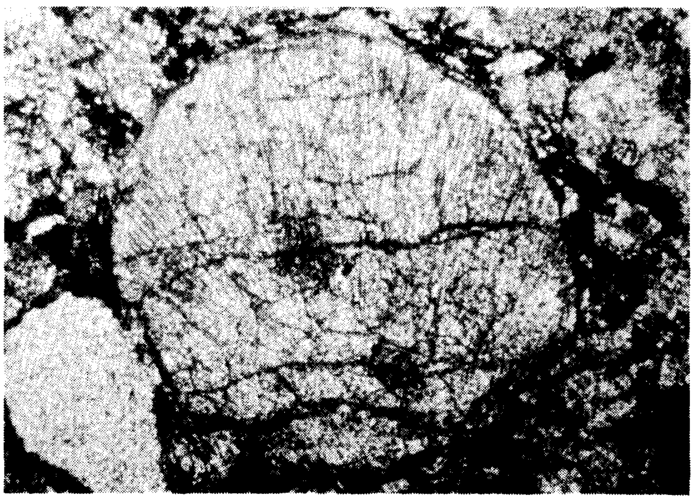

Fig. 6. Radiating chondrule (082-C12) consisting of radiating aggregate of very fine prismatic orthopyroxene crystals (in the upper) and cryptocrystalline materials (in the lower). Yamato-74082. Long dimension of photograph = 0.60 mm.

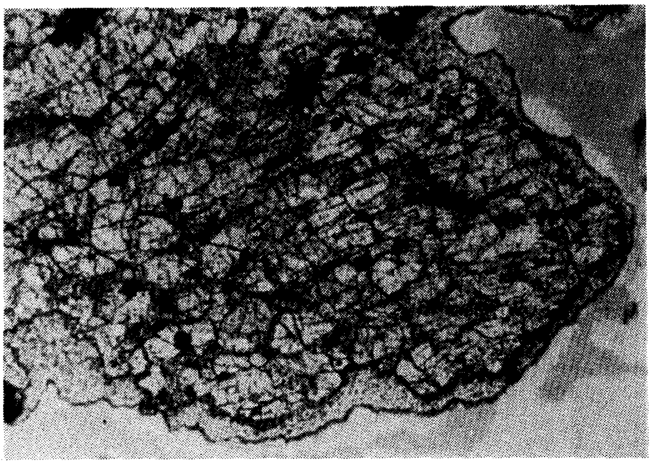

Fig. 7. Radiating chondrule (418-C4). Laths of orthopyroxene are considerably thick. Small amounts of plagioclase are noticed in the interstices of pyroxene. Yamato-74418. Long dimension of photograph = 1.7 mm.

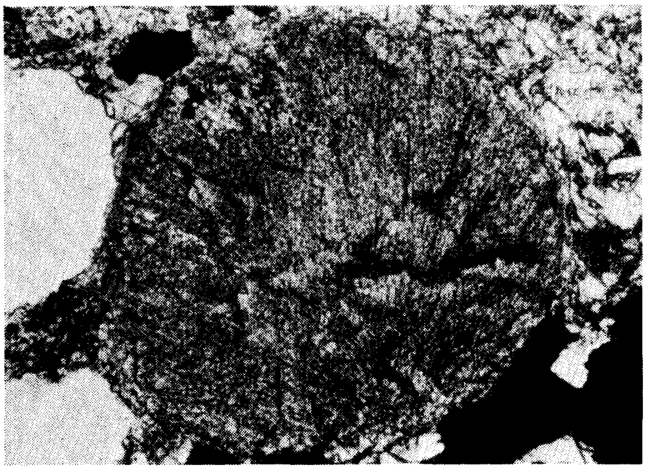

Fig. 8. Cryptocrystalline chondrule (647-C18) consisting of cryptocrystalline materials. Yamato-74647. Long dimension of photograph = 1.3 mm.

(Fig. 8). Sometimes they contain a small amount of very fine laths of pyroxene. As shown in Table 1, cryptocrystalline materials of this chondrule have compositions similar to the Ca-poor pyroxene. This chondrule is not the devitrified product of glassy chondrule, because glassy one is rich in Na–Al–Si but deficient in Fe–Mg–Ca (VAN SCHMUS, 1969).

4. Crystallization of Chondrule

4.1. Estimated bulk composition of chondrule

Bulk composition of chondrule is necessary for the study of crystallization of chondrule, but this has been poorly known. The authors calculated these in five YAMATO-74 meteorites from modal compositions of the constituent minerals, whose chemical compositions are determined by EPMA. By the same method DODD (1978) calculated the bulk compositions of chondrules in the Manych chondrite (L3). Modal compositions of chondrules are determined by the areas of the constituent minerals on photographs.

Table 1. Estimated bulk composition of chondrule (Yamato-74191) (wt.%).

Type	Olivine-porphyritic				Pyroxene-porphyritic					Barred	Radiating	Cryptocrystalline		
Chondrule	A28	B85	B38	B27	B36	B37	A6	A27	B17	B59	B15	A42	B19	B26
SiO_2	46.1	50.3	42.1	41.7	45.4	48.4	49.4	50.7	58.7	43.0	57.0	57.2	53.3	58.6
TiO_2	0.5	0.1	0.0	0.0	0.0	0.1	0.2	0.1	0.1	0.2	0.1	0.1	0.1	0.0
Al_2O_3	11.4	4.0	1.6	2.9	3.2	1.3	3.5	4.2	4.7	3.6	3.3	1.6	1.6	5.0
Cr_2O_3	0.3	0.4	0.0	0.2	0.2	0.2	0.4	0.3	0.5	0.2	0.8	0.5	0.5	1.0
FeO	12.7	11.9	20.6	19.8	16.2	8.1	11.3	11.4	6.1	7.1	7.6	15.5	16.8	10.0
MnO	0.1	0.3	0.4	0.4	0.2	0.1	0.3	0.3	0.3	0.2	0.1	0.4	0.7	0.3
MgO	24.3	27.2	33.6	34.3	33.5	40.5	32.5	31.4	24.7	43.9	27.0	21.5	22.4	22.2
CaO	0.2	3.5	1.3	0.5	0.2	1.1	1.5	1.5	2.6	1.9	2.2	2.2	2.0	1.8
Na_2O	3.0	1.8	0.2	0.8	1.1	0.2	1.2	0.6	2.0	0.6	0.9	1.0	1.1	2.3
K_2O	0.1	0.6	0.0	0.1	0.1	0.0	0.0	0.0	0.6	0.0	0.0	0.1	0.0	0.1
Total	98.7	100.1	99.8	100.7	100.1	100.0	100.3	100.5	100.3	100.7	99.0	100.1	98.5	101.3

Table 2. Estimated bulk composition of chondrule (Yamato-74155, -74079, -74371 and -74647) (wt.%).

Type	Olivine-porphyritic			Pyroxene-porphyritic			Barred	Radiating
Meteorite (Yamato-)	74079	74155	74155	74155	74647	74155	74371	74155
Chondrule	C17	C14	C12	C11	C14	C25	C20	C16
SiO_2	43.7	44.9	41.2	49.6	56.4	56.1	45.5	56.2
TiO_2	0.1	0.1	0.5	0.2	0.1	0.1	0.1	0.0
Al_2O_3	1.2	3.5	5.7	3.5	4.4	2.5	1.8	0.2
Cr_2O_3	0.2	0.2	1.2	0.8	0.1	1.0	0.1	0.6
FeO	12.8	11.9	14.5	11.4	9.1	9.7	13.6	10.9
MnO	0.3	0.3	0.3	0.4	0.3	0.4	0.3	0.4
MgO	34.5	32.1	32.4	31.0	24.5	27.8	34.7	29.8
CaO	5.9	4.4	2.1	2.1	2.3	0.5	3.5	0.4
Na_2O	0.6	1.4	0.5	1.2	0.8	0.6	0.7	0.0
K_2O	0.1	0.1	0.0	0.1	0.3	0.1	0.1	0.0
Total	99.4	98.9	98.4	100.3	98.2	98.6	100.3	98.4

Whether zoning and heterogenity of minerals are present or not is a significant problem in such a calculation. According to REID and FREDRIKSSON (1967) and IKEDA *et al.* (1978), olivine and pyroxene in the unequilibrated chondrite show compositional zoning. The results of line profiles by EPMA for chondrules whose bulk compositions are calculated show that in the marginal parts (only about 5 microns in width) of olivine and pyroxene, the iron content increases about 5 mole %. The average olivines and pyroxenes in chondrules studied here are used in calculation. After all such a calculation is justified in this case.

Bulk composition of chondrule is shown in Tables 1–2. In the calculation the data of totals lying within 98–102% and 95–105% are accepted for olivine and pyroxene, and for glass and cryptocrystalline materials, respectively.

From Tables 1–2, the following features are noticed:

(1) Abundance of elements except SiO_2 is not related to the types of chondrules. Olivine-rich chondrules are poor in SiO_2.

(2) Process of the crystallization of chondrule can be discussed with the aid of phase relations in the $MgO–Al_2O_3–SiO_2$ system.

4.2. *Investigation in the $MgO–Al_2O_3–SiO_2$ system*

When the bulk compositions of chondrules in five Yamato-74 meteorites are projected in this system (Fig. 9), the following evidences are noticed:

(1) Various types of chondrules are plotted within a narrow area.

(2) Olivine-porphyritic, some pyroxene-porphyritic, and barred chondrules

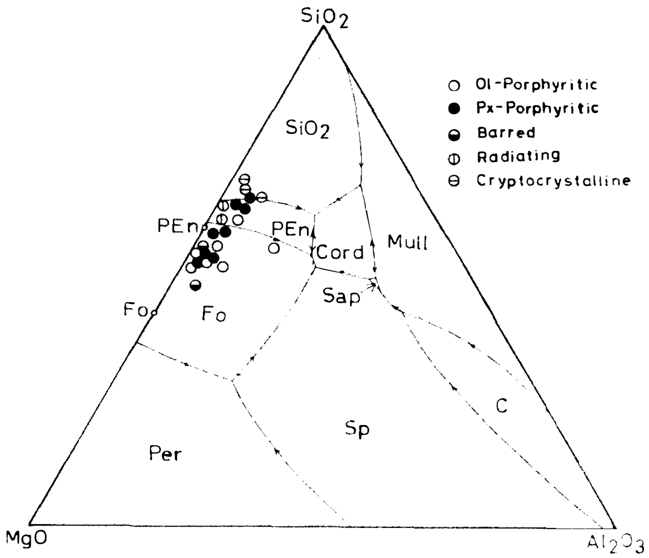

Fig. 9. Bulk compositions of chondrules in Yamato-74191, -74155, -74079, -74371, and -74647. MgO–Al_2O_3–SiO_2 system is the modified version by MUAN *and* OSBORN *(1965).*

are projected in the forsterite field, whereas pyroxene-porphyritic, radiating, and cryptocrystalline ones in protoenstatite field. Cryptocrystalline ones lie this field if they are projected in the system including a small amount of CaO because of their high CaO content.

(3) One olivine-porphyritic and some pyroxene-porphyritic ones lie in the enstatite field. Since chondrules are considered to have been formed in a non-gravitational field, gravity fractionation could not have occurred. Therefore, the presence of olivine in these chondrules must be explained without changing their bulk compositions.

Since some glasses of chondrules in Yamato-74191 are rich in MgO, Al_2O_3, and SiO_2, they can be plotted in the same system. As shown in Figs. 10–11, it is evident that the composition of glass was never attained under the equilibrated condition from its original bulk composition. Although it may be considered that chondrule is a product of mechanical mixture of olivine, pyroxene, and the pre-existing materials of glass, this hypothesis is not supported by many facts such as given below.

(1) Most of glasses are rich in SiO_2 (quartz-normative) (Table 3). Such materials are not expected to condense from the nebula (GROSSMAN, 1972).

(2) It seems that various textures of chondrules cannot be produced by mechanical mixing of the constituent minerals.

(3) Compositions of glasses are rich in elements which cannot be concentrated into olivine and pyroxene (Table 3). Glass appears to be a residual liquid.

Consequently this model should be abandoned.

Table 3. Chemical composition of glass in Yamato-74191 (wt.%).

	1	2	3	4	5	6
SiO_2	55.02	64.35	66.99	51.71	61.12	61.28
TiO_2	1.04	0.28	0.07	0.67	0.39	0.33
Al_2O_3	24.65	9.23	21.31	17.70	13.36	15.50
Cr_2O_3	0.66	0.85	0.56	1.33	0.93	0.31
FeO	4.16	3.53	1.76	3.68	2.58	4.71
MnO	0.03	0.21	0.03	0.25	0.47	0.24
MgO	6.63	7.68	0.76	10.02	7.09	5.07
CaO	0.29	7.86	0.65	7.15	7.43	4.16
Na_2O	6.52	3.97	7.40	6.54	5.93	5.75
K_2O	0.16	1.27	0.65	0.20	1.63	1.58
Total	99.16	99.23	100.20	99.24	100.93	98.92
Devitrification	A	C	A	B	B	B

4.3. *Crystallization of supercooling liquid model*

Chondrule should crystallize through some unusual process, which may be deduced from the investigation of porphyritic chondrule as mentioned below.

(1) *Olivine-porphyritic chondrule* (Fig. 10): The precursor of chondrule was probably melted completely due to some high temperature events, because barred

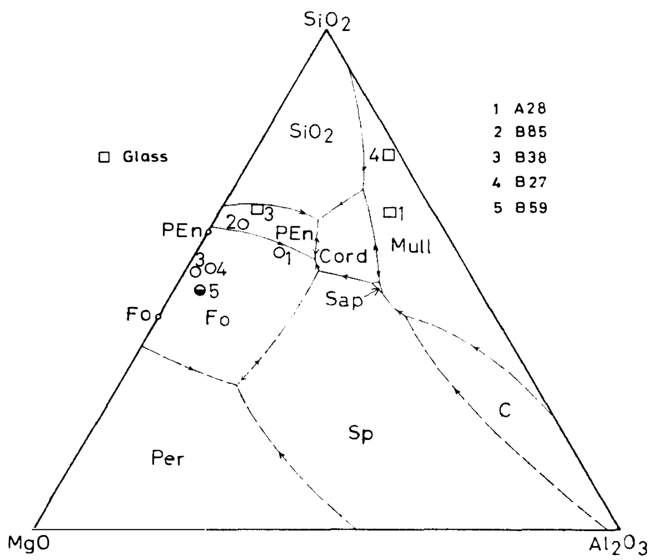

Fig. 10. Bulk compositions of olivine-porphyritic and barred chondrules in Yamato-74191. Symbols conform to Fig. 9. Compositions of glasses in chondrules are also plotted.

and porphyritic chondrules were derived from similar liquids in composition as shown in Fig. 10. After that, droplet falls on the liquidus surface of forsterite. As the droplet cools, pyroxene should begin to crystallize along the reaction line between forsterite and protoenstatite in the case of the equilibrated crystallization. But there are neither pyroxene grain, nor reaction rim of pyroxene around olivine, and the composition of glass is far beyond the reaction line. These features can be explained only by a metastable extension of the liquidus of forsterite. The composition of liquid moves on this surface without crystallization of pyroxene, beyond the reaction line. B85-chondrule, which does not contain pyroxene though its bulk composition lies in the enstatite field, may have fallen on the metastable extension of the forsterite liquidus from the beginning.

(2) *Pyroxene-porphyritic chondrule* (Fig. 11): Crystallization of olivine-rich pyroxene-porphyritic chondrule is consistent with that of olivine-porphyritic one in the early stage, but it contains pyroxene. In order to investigate the crystallization of pyroxene, composition of pyroxene+glass, which probably shows the residual liquid after crystallization of olivine, is projected on this system. Such compositions of A6- and A27-chondrules lie on the reaction line. But olivines have not reaction rims and the compositions of glasses do not lie on the reaction line. Hence liquids probably removed along the liquidus of pyroxene at such points, and only a pyroxene crystallized on the metastable extension of liquidus. Liquids of B36- and B37-chondrules moved along the metastable extension of liquidus of olivine and they removed on that of pyroxene at the points of pyroxene+glass.

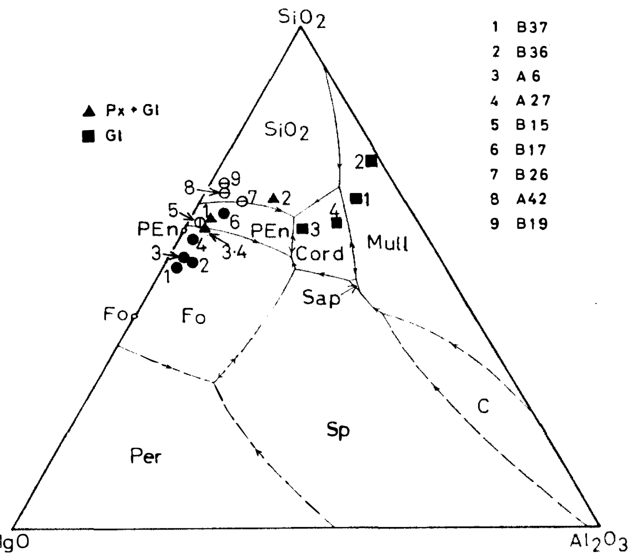

Fig. 11. Bulk compositions of pyroxene-porphyritic, radiating, and cryptocrystalline chondrules in Yamato-74191. Symbols conform to Fig. 9. Compositions of glasses and pyroxene+glass in porphyritic chondrules are also plotted.

For some pyroxene-porphyritic chondrules, which lie in the enstatite field and have pyroxene including small olivine, soon after the droplet fell on the metastable extension of olivine liquidus, it was translated into the pyroxene liquidus, and pyroxene probably crystallized surrounding olivine without reaction.

(3) *Supercooling in the peritectic system*: The above-mentioned speculation would hold, if there were no reaction between olivine and liquid assuming the metastable extension of liquidus. There is a possibility of interpreting this in the peritectic system. In Fig. 12, if the droplet A, projected on the forsterite field, is supercooled and begins to crystallize at temperature T_1 (point a), this is oversaturated with forsterite and enstatite, up to b and c, respectively. As forsterite crystallizes, the composition of liquid reaches point b, and the droplet is oversaturated with enstatite only. Then enstatite crystallizes without reaction of forsterite. Composition of liquid is beyond the reaction line, while temperature remains constant. Such droplets from olivine-rich pyroxene-porphyritic chondrules. If droplet is quenched before crystallization of pyroxene begins, olivine-porphyritic one is formed.

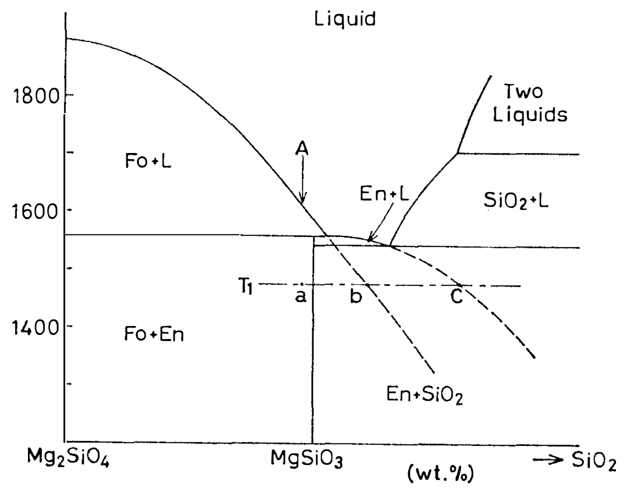

Fig. 12. A possible mechanism of supercooling crystallization in the peritectic system. The diagram is a portion of that by MUAN and OSBORN (1965).

It is concluded from the above arguments that the unusual crystallization of chondrule may have resulted from the supercooling condition, and it is probable that the rate of cooling of chondrule was fairly high because of attainment of such a condition.

4.4. *Variety of texture of chondrule*

Our supercooling model can explain the variety of texture of chondrule. Indeed BLANDER and ABDEL-GAWAD (1969) insisted that variety of texture was caused by various degrees of supercoolings of droplets. NELSON *et al.* (1972) and

BLANDER *et al.* (1976) ascertained this phenomenon by the experiments. According to BLANDER *et al.*, with increasing degree of supercooling, the change in morphology of forsterite is in the order from a bar+dendrite association through dendrite+fiber, to fiber+submicroscopic ones.

According to BLANDER *et al.*'s result, as porphyritic chondrule contains euhedral olivines and pyroxenes, the degree of supercooling of droplet was low. Barred and radiating ones were solidified from moderately supercooled droplets, based on the forms of olivines and pyroxenes. Cryptocrystalline ones were formed under the highest degree of supercooling of liquid. Especially the gradational textures of pyroxene-porphyritic, radiating, and cryptocrystalline chondrules, and the consistence of their bulk compositions with one another support this hypothesis.

4.5. *Investigation from FeO/FeO+MgO ratio*

The following facts are noticed concerning this ratio:

(1) The ratio varies in each chondrule in Yamato-74191 (Table 4).

(2) The ratios of olivine, pyroxene, and glass in pyroxene-porphyritic chondrule are different. That of pyroxene is the lowest, and that of glass is the highest of these (Table 4).

(3) The distribution coefficient of Fe and Mg between olivine and pyroxene is extraordinarily high in most of porphyritic chondrules (Table 5). This represents the unequilibrated crystallization of olivine and pyroxene, because LARIMER (1968) showed $K_D=1.1-1.2$ under the equilibrated condition.

(4) The FeO content of pyroxenes is low in porphyritic chondrules, and variable in radiating ones, as shown by DODD (1971, 1974). Cryptocrystalline ones are rich in FeO (Fig. 13).

Table 4. FeO/FeO+MgO ratio (Yamato-74191).

Chondrule	Type	Olivine	Pyroxene	Glass	Bulk	Rim
A28	Ol-P	0.34	—	0.39	0.34	n.d.
B85	Ol-P	0.30	—	0.31	0.30	0.43
B27	Ol-P	0.36	—	0.49	0.37	n.d.
B36	Px-P	0.36	0.05	0.70	0.33	0.39
A6	Px-P	0.36	0.09	0.27	0.26	0.44
A27	Px-P	0.36	0.15	0.50	0.27	0.43
B17	Px-P	0.34	0.19	0.27	0.20	0.39
B59	B	0.13	—	0.41	0.14	n.d.
B15	R	—	0.22	—	0.22	n.d.
B19	C	—	0.43	—	0.43	0.36

Type of Chondrule

Ol-P: Olivine-porphyritic, Px-P: Pyroxene-porphyritic, B: Barred, R: Radiating, C: Cryptocrystalline.

Table 5. Distribution coefficient of Mg and Fe between olivine and pyroxene in pyroxene-porphyritic chondrule (Yamato-74191).

$K_D = N_{Fa}N_{En}/N_{Fo}N_{Fs}$

Chondrule	K_D
B36	10.21
B37	1.49
A6	5.25
A27	3.14
B17	2.17

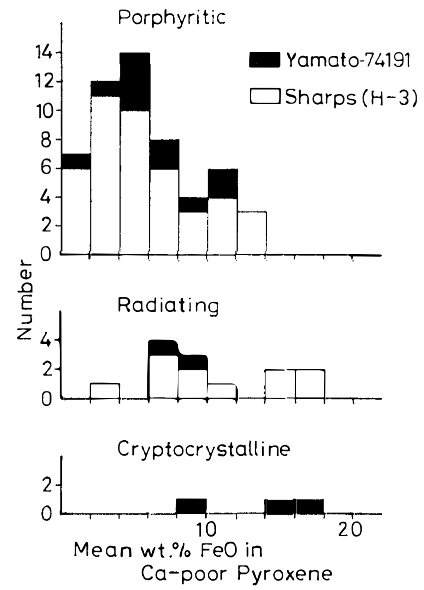

Fig. 13. Mean wt.% FeO in Ca-poor pyroxene against the number of pyroxene in porphyritic, radiating, and cryptocrystalline chondrules. The data of the Sharps meteorite described by DODD (1971) are also plotted.

LARIMER (1967, 1968) and GROSSMAN (1972) considered that fayalite and ferrosilite molecules were formed by the secondary reaction between metallic iron and nearly pure forsterite and enstatite condensed at high temperature. When the nebula cooled, the following reaction occurred:

$$CO + 3H_2 \rightleftharpoons CH_4 + H_2O. \tag{a}$$

This reaction determined the gas species in the nebula. The right handed side is stable at lower temperature. Corresponding to such an oxidized condition, fayalite and ferrosilite may be formed by the following reactions:

$$2MgSiO_3 + 2Fe + 2H_2O \rightleftharpoons Mg_2SiO_4 + Fe_2SiO_4 + 2H_2 \tag{b}$$

$$MgSiO_3 + Fe_2SiO_4 \rightleftharpoons Mg_2SiO_4 + FeSiO_3. \quad \text{(c)}$$

Regularities of the ratios of olivine, pyroxene, and glass observed in porphyritic chondrule indicate that when olivine formed, the atmosphere in chondrule was oxidized, whereas it was reduced when pyroxene formed. On the basis of LARIMER and GROSSMAN's calculation, the following crystallization path may be estimated.

(1) The precursor of chondrule was melted due to some high temperature event when the nebula cooled below 680°K (LARIMER and ANDERS, 1970) or 470–450°K (ONUMA *et al.*, 1972). At such a low temperature the precursor of chondrule was rich in FeO, as mentioned before.

(2) As soon as it was melted, olivine crystallized, and simultaneously the gas around the droplet should have been heated. According to the reaction (a), the atmosphere changed into reduced stage. If the diffusion of gas into droplet is very rapid, olivine must crystallize under the reduced condition and be poor in FeO. However, as olivine is always FeO-rich, the rate of crystallization of olivine was larger than that of the diffusion of gas, and olivine crystallized with a high FeO content which was originally present in chondrule.

(3) Later, as gas diffused enough into chondrule, pyroxene poor in FeO crystallized under the reduced condition. Since olivine did not react with liquid, FeO remained in olivine, and excess FeO was concentrated into the residual liquid (glass). Very fine opaque minerals, often noticed in chondrule, may have resulted under such a reduced condition.

(4) Cryptocrystalline chondrule was formed under the high degree of supercooling condition, which means low temperature of the ambient gas and the oxidized atmosphere in chondrule. Really it is rich in FeO and rarely contains opaque minerals. The atmosphere when radiating ones formed was variable, corresponding to different degrees of the supercooling, because the FeO content in them varies also.

5. Accretion of Chondrule

5.1. Recrystallization of chondrule prior to accretion

Although Yamato-74191 is an unequilibrated chondrite and was hardly recrystallized in parent body, some chondrules in it are recrystallized to various degrees. The evidences are as follows:

(1) Glasses in some chondrules were recrystallized completely into plagioclase (An_{74}) and clinopyroxene (Fig. 14), as in the case of type 5–6 chondrites.

(2) Degree of devitrification of glass is variable in each chondrule (Table 3). If glass is very clear and not devitrified, it belongs to degree A. Glass of degree B is slightly devitrified and shows faint birefringence. Glass of degree C is fairly recrys-

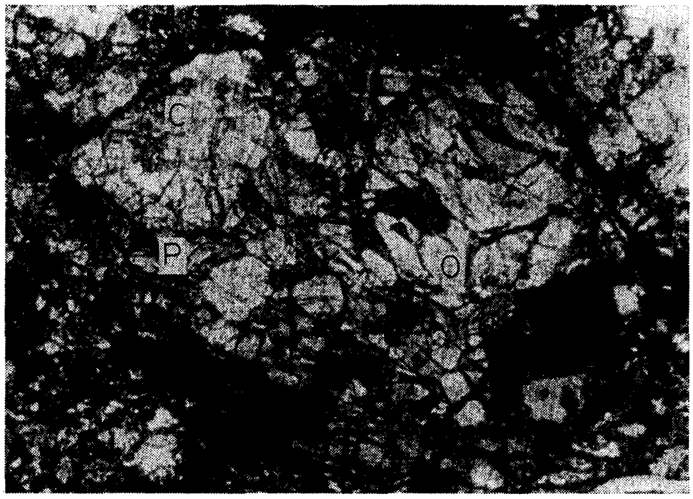

Fig. 14. Recrystallized porphyritic chondrule (B74) consisting of olivine (O), clinopyroxene (C), and plagioclase (P). Yamato-74191. Nicols crossed. Long dimension of photograph=0.75 mm.

Table 6. CaO in olivine and devitrification of glass (Yamato-74191).

Chondrule	CaO in olivine (wt.%)	Devitrification of glass
A13	0.18	A
A28	0.10	A
B36	0.12	A
B27	0.06	B
B38	0.06	B
A6	0.02	B
B85	0.02	C

tallized into cryptocrystalline materials. Although devitrification depends on the composition of glass rather than on temperature, the degree of devitrification is too variable.

(3) The CaO content in olivine is a clue to its thermal history. DODD (1969, 1973) showed that olivine in type 3 chondrite is usually rich in CaO because of quenching from high temperature, and poor for type 4 because of recrystallization at low temperature. DODD (1968) and YANG (1974) found variable CaO contents of olivines in type 3 chondrites, and concluded that some chondrules were recrystallized prior to accretion. The CaO contents of olivines in chondrules are various in Yamato-74191, but the relationships between the CaO contents and devitrification of glass are clear (Table 6). Olivine with glass of degree A and a higher CaO content than those with glasses of degree B and C.

As glass of degree B is most common in Yamato-74191, this may have been slightly recrystallized in the parent body. But the above-mentioned features could

Table 7. Chemical composition of rim and matrix (Yamato-74191) (wt.%).

	Chondrule	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	Total
Rim	B36	45.98	0.19	6.76	0.60	16.34	0.24	25.85	0.47	0.73	0.61	97.78
	B85	39.11	0.20	3.60	1.07	22.73	0.24	30.14	0.29	0.66	0.29	98.32
	A6	39.11	0.40	2.00	0.71	24.25	0.23	31.41	0.47	0.34	0.27	99.19
	A27	36.60	0.28	2.35	0.88	24.50	0.36	31.99	0.47	0.05	0.20	97.69
	B17	39.80	0.14	3.11	1.15	20.22	0.35	31.88	0.26	0.48	0.38	97.77
	B19	41.47	0.14	5.73	0.90	16.33	0.24	29.26	0.93	0.54	0.36	95.91
	B35	48.14	0.13	6.50	1.07	13.61	0.14	27.85	0.57	1.80	0.30	100.10
	Average	41.46	0.21	4.29	0.91	19.71	0.26	29.77	0.49	0.66	0.34	98.10
Matrix	(MB-1)	45.31	0.26	4.00	1.12	16.26	0.22	28.56	1.42	0.52	0.37	98.04
L-chondrite*		46.00	0.13	3.04	0.50	17.44	0.31	28.60	2.28	1.21	0.21	99.72

* Average composition of silicate portions in L-chondrite after UREY and CRAIG (1953).

not be attained by such a weak recrystallization. Especially the evidence (1) supports the intense recrystallization. Therefore, it is concluded that some chondrules were recrystallized prior to accumulation to the parent body. They should probably have passed through the high temperature region when they were floating in the nebula, though this mechanism is not yet evident.

5.2. Formation of rim around chondrule

Most of chondrules in Yamato-74191 have thin rims around them (Figs. 1–5). Rims are brown in color and consist of glassy or cryptocrystalline materials, with a small amount of very fine silicate grains, often fine troilite, and rarely metallic iron. Width of rim is uniformly 10–30 microns. Since the boundary between the rims of two chondrules is often noticed, it is evident that the rim was attached to chondrule before accretion, consistent with ASHWORTH (1977). Such materials often gathered among chondrules, attaining large sizes. REID and FREDRIKSSON 1967) found such a rim in the unequilibrated chondrite. According to VAN SCHMUS (1969), the chemical and mineralogical compositions of such materials have been poorly known, but the composition is probably close to that of the bulk composition of chondrite. Microprobe data of rims (Table 7) show that they are variable in wide range, but their average composition is similar to the average composition of silicate portions in L-chondrites of UREY and CRAIG (1953), though CaO and Na_2O contents are depleted. It is probable that the bulk composition of Yamato-74191 is poor in CaO and Na_2O.

The composition of rim is not related to the type of chondrule. When the FeO/FeO+MgO ratio of rims is compared with that of chondrules (Table 4), the former is almost constant, whereas the latter varies in a wide range. The ratio of recrystallized B85-chondrule is different from that of rim. Such recrystallized chondrules are often surrounded by clear glassy rims. All these facts suggest that the rim may have been attached after recrystallization of chondrule int he nebula.

5.3. Process of accretion

Now, the process of accretion of chondrule is estimated as follows (Fig. 15):

(1) The pre-existing solids were melted and molten chondrule was formed.

(2) After solidification, some chondrules were recrystallized in some high temperature region of the nebula.

(3) Rims were attached to chondrules, though the mechanism is not yet evident.

(4) Chondrules and other constituents (matrix) accumulated one after another to the parent body. Since most of chondrules in Yamato-74191 are not broken, the speed of their accretion was fairly low.

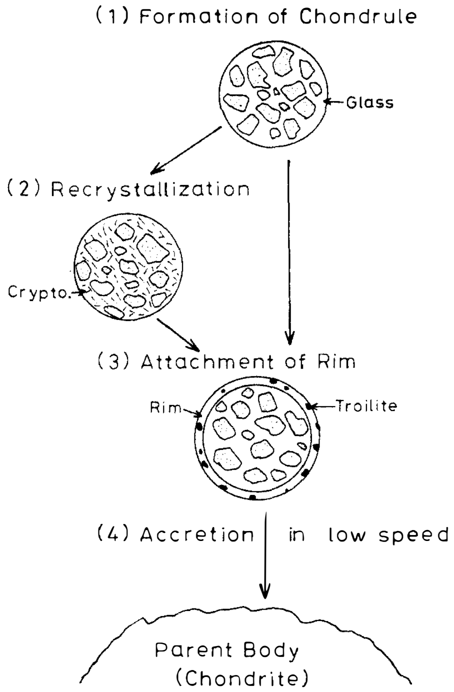

Fig. 15. Schematic illustration of various stages from formation of chondrule to accretion.

6. Summary

(1) Chondrule consists of the unequilibrated mineral assemblage, which did not result from a mechanical mixture of constituent minerals, but from the unusual crystallization, *i.e.*, it crystallized from a supercooled liquid and the change of atmosphere in chondrule was caused by a reaction in ambient gas.

(2) Variety of texture of chondrule resulted from variety of degree of supercooling of droplet.

(3) After some chondrules recrystallized, rims were attached to chondrules. Finally chondrules and matrix materials accumulated to the parent body at a fairly low speed.

Acknowledgments

The meteorites samples studied here were provided through the courtesy of Prof. T. NAGATA and Dr. K. YANAI of the National Institute of Polar Research. We are also indebted to Dr. M. KOMATSU of Niigata University for his assistance in EPMA analyses, and Messrs. K. MORIBAYASHI and T. KUWAJIMA of Hokkaido University for preparing thin sections. To all these persons, we wish to express our hearty thanks.

References

ASHWORTH, J. R. (1977): Matrix textures in unequilibrated ordinary chondrites. Earth Planet. Sci. Lett., **35**, 25–34.

BLANDER, M. and ABDEL-GAWAD, M. (1969): The origin of meteorites and the constrained equilibrium condensation theory. Geochim. Cosmochim. Acta, **33**, 701–716.

BLANDER, M., PLANNER, H. N., KEIL, K., NELSON, L. S. and RICHARDSON, N. L. (1976): The origin of chondrules: experimental investigation of metastable liquids in the system Mg_2SiO_4–SiO_2. Geochim. Cosmochim. Acta, **40**, 889–896.

DODD, R. T. (1968): Recrystallized chondrules in the Sharps (H-3) chondrite. Geochim. Cosmochim. Acta, **32**, 1111–1120.

DODD, R. T. (1969): Metamorphism of the ordinary chondrites: A review. Geochim. Cosmochim. Acta, **33**, 161–203.

DODD, R. T. (1971): The petrology of chondrules in the Sharps meteorite. Contrib. Mineral. Petrol., **31**, 201–227.

DODD, R. T. (1973): Minor elements abundances in olivines of the Sharps (H-3) chondrite. Contrib. Mineral. Petrol., **42**, 159–167.

DODD, R. T. (1974): The petrology of chondrules in the Hallingeberg meteorite. Contrib. Mineral. Petrol., **47**, 97–112.

DODD, R. T. (1978): The composition and origin of large microporphyritic chondrules in the Manych (L-3) chondrite. Earth Planet. Sci. Lett., **39**, 52–66.

DODD, R. T. and VAN SCHMUS, W. R. (1971): Dark-zoned chondrules. Chem. Erde, **30**, 59–69.

GROSSMAN, L. (1972): Condensation in the primitive solar nebula. Geochim. Cosmochim. Acta, **36**, 597–619.

IKEDA, Y., SHIMAZAKI, H. and TAKEDA, H. (1978): Yamato inseki 74191 no gansekigaku-teki kenkyû (Petrological study on Yamato-74191). Dai-3-kai Nankyoku Inseki Sinpojiumu kôen yôshu (Abstr. 3rd Symp. on Antarctic Meteorites). Tokyo, Natl Inst. Polar Res., 15–18.

KIMURA, M., YAGI, K. and OBA, Y. (1978): Petrological studies of Yamato-74 meteorites (2). Mem. Natl Inst. Polar Res., Spec. Issue, **8**, 156–169.

LARIMER, J. W. (1967): Chemical fractionations in meteorites-I. Condensation of the elements. Geochim. Cosmochim. Acta, **31**, 1215–1238.

LARIMER, J. W. (1968): Experimental studies on the system Fe–MgO–SiO_2–O_2 and their bearing on the petrology of chondritic meteorites. Geochim. Cosmochim. Acta, **32**, 1187–1207.

LARIMER, J. W. and ANDERS, E. (1970): Chemical fractionations in meteorites-III. Major element fractionations in chondrites. Geochim. Cosmochim. Acta, **34**, 367–387.

MUAN, A. and OSBORN, E. F. (1965): Phase Equilibria among Oxides in Steelmaking. Massachusetts, Addision-Wesley, 236p.

NELSON, L. S., BLANDER, M., SKAGGS, S. R. and KEIL, K. (1972): Use of a CO_2 laser to prepare chondrule-like spherules from supercooled molten oxide and silicate droplets. Earth Planet. Sci. Lett., **14**, 338–344.

ONUMA, N., CLAYTON, R. N. and MAYEDA, T. K. (1972): Oxygen isotope cosmothermometer. Geochim. Cosmochim. Acta, **36**, 169–188.

REID, A. M. and FREDRIKSSON, K. (1967): Chondrules and chondrites. Research in Geochemistry-II, ed. by P. H. ABELSON. New York, Wiley, 170–203.

UREY, H. C. and CRAIG, H. (1953): The composition of the stone meteorites and the origin of the meteorites. Geochim. Cosmochim. Acta, **4**, 36–82.

VAN SCHMUS, W. R. (1969): The mineralogy and petrology of chondritic meteorites. Earth Sci. Rev., **5**, 145–184.

YABUKI, H., YAGI, K. and ONUMA, K. (1978): Petrological studies of Yamato-74 meteorites (1). Mem. Natl Inst. Polar Res., Spec. Issue, **8**, 142–155.

YANAI, K., MIYAMOTO, M. and TAKEDA, H. (1978): A classification for the Yamato-74 chondrites based on the chemical compositions of their olivines and pyroxenes. Mem. Natl Inst. Polar Res., Spec. Issue, **8**, 110–120.

YANG, H. Y. (1974): Petrographic and microprobe studies of chondrules in the Allende, Fellix, and Lancé meteorites. Proc. Geol. Soc. China, **17**, 31–41.

(Received October 16, 1978)