PETROLOGICAL STUDIES ON YAMATO-74354, -74190, -74362, -74646 AND -74115 CHONDRITES

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Abstract: Petrological description has been done on five different Yamato -74354 (L6), -74362 (L6), -74190 (L6), -74646 (LL6) and -74115 (H5) chondrites. Detailed microprobe analyses of the constituent minerals and chondrules indicate that these chondrites consist of homogeneous silicate minerals and remarkably heterogeneous Fe-Ni metals. They show various degrees of recrystallization but the equilibrium temperature of olivine, pyroxenes and chromite is about 900°C and is quite similar among these five chondrites. The degree of recrystallization, therefore, would depend not only on the equilibrium temperature but also largely on the duration of recrystallization. It is also suggested that the bulk chemical composition of chondrules has been hardly affected by thermal metamorphism.

1. Introduction

Ordinary chondrites have been considered to be thermally metamorphosed and recrystallized. Silicate minerals within them have a considerably homogeneous composition, but Ni-Fe metal grains show a remarkable compositional zoning. So, they are not wholly equilibrated. In this paper, the author uses the term "ordinary chondrite" according to VAN SCHMUS and WOOD (1967). For understanding the parental body of chondrites, the conditions of metamorphism and their thermal history, especially the relations between the chemical group and the petrologic type, are important. The classification by VAN SCHMUS and WOOD (1967) which is widely accepted, is based upon the assumptions that the textural variations correspond to the mineralogical variations and there is no difference in texture and mineralogy among the different chemical groups of chondrites. However there seem to exist many difficulties in classifying the chondrites; for example, the petrologic type can not be defined uniquely by their criteria. In this paper, therefore, the petrologic type is defined so as to minimize the contradictions.

Yamato-74354 (L6), -74190 (L6), -74362 (L6), -74646 (LL6) and -74115 (H5) were examined for their texture, chemical compositions and characters of the constituent minerals. All of them are composed of olivine, orthopyroxene, Ca-rich clinopyroxene, chromite, Ni-Fe metal, troilite, plagioclase and rarely apatite.

In the following descriptions, the results of the studies on major silicate minerals and chromite are presented.

2. Yamato-74354 (L6) Chondrite

2.1. Texture

This chondrite is weakly recrystallized; the outline of chondrules is easily defined and the internal texture of each chondrule is well preserved. The chondrules show barred-olivine, porphyritic, granular or radial-pyroxene texture (Photo 1). The matrix minerals are mostly olivine, and orthopyroxene is less abundant. Composite grains consisting of olivine and orthopyroxene intergrowth are rarely

Table 1. Representative chemical compositions of major minerals in Yamato-74354 chondrite.

	OL	OPX	CPX	PL	CHR
SiO_2	38.020	55.056	52.695	65.968	—
Al_2O_3	0.034	0.188	0.485	21.028	6.278
TiO_2	0.028	0.000	0.544	—	3.038
FeO	22.384	14.044	5.023	—	30.483
MnO	0.494	0.000	0.274	—	1.074
MgO	38.853	29.582	16.691	—	2.932
CaO	0.050	0.616	21.733	1.955	—
Na_2O	0.007	0.000	0.548	9.831	—
K_2O	—	—	—	1.200	—
Cr_2O_3	0.000	0.131	0.782	—	52.921
Total	99.869	99.617	98.774	99.983	96.699
Si	0.9923	1.9768	1.9623	2.9077	—
Al	0.0011	0.0385	0.0213	1.0923	0.2706
Ti	0.0005	0.0000	0.0152	—	0.0837
Fe	0.4886	0.4217	0.1564	—	0.9340
Mn	0.0109	0.0000	0.0086	—	0.0325
Mg	1.5117	1.5835	0.9266	—	0.1602
Ca	0.0014	0.0237	0.8671	0.0923	—
Na	0.0004	0.0000	0.0396	0.8402	—
K	—	—	—	0.0675	—
Cr	0.0000	0.0037	0.0230	—	1.5329
Total	3.0068	4.0173	4.0201	5.0000	3.0143
	Fo 75.57	En 78.05	En 47.52	An 9.23	Fe^{3+} 0.9558
	Fa 24.43	Fs 20.78	Fs 8.02	Ab 84.02	Y_{Cr} 0.7967
		Wo 1.17	Wo 44.46	Or 6.75	X_{Fe} 0.8357

observed. In the barred-olivine chondrule, there exists exceptionally clear plagioclase between olivine bars (Photo 2). The outline of chondrules becomes obscure (Photo 3). Sometimes metal grains surround the chondrules and moreover, small metal grains, mostly kamacite, are dispersed within the chondrules and irregular large grains occur over the chondrules and matrix.

2.2. *Mineralogy*

Olivine, pyroxenes, plagioclase, chromite and Ni-Fe metal were analyzed with the microprobe. Results are shown in Figs. 1–4 and representative chemical compositions of them are listed in Table 1.

2.2.1. Olivine

Olivine occurs as relatively large and euhedral to subhedral grains. The chemical composition of olivine is uniform within and among different grains. No compositional zoning is found. The composition of olivine ranges from $Fa_{23.8}$ to $Fa_{25.2}$ with the mean value of $Fa_{24.5}$ (Fig. 1). This value is the average of L-type chondrite given by KEIL and FREDRIKSSON (1964).

2.2.2. Pyroxenes

Orthopyroxene occurs mostly as small subhedral grains and large euhedral grains rarely exist. It also has a considerably uniform composition, ranging from $En_{78.9}Fs_{20.0}Wo_{1.1}$ to $En_{76.9}Fs_{21.6}Wo_{1.5}$ with the mean value of $En_{77.9}Fs_{20.7}Wo_{1.4}$ (Figs. 1 and 2). On the other hand, Ca-rich clinopyroxene is slightly heterogeneous and its composition ranges from $En_{47.5}Fs_{7.2}Wo_{45.6}$ to $En_{46.9}Fs_{8.7}Wo_{44.4}$ with the mean

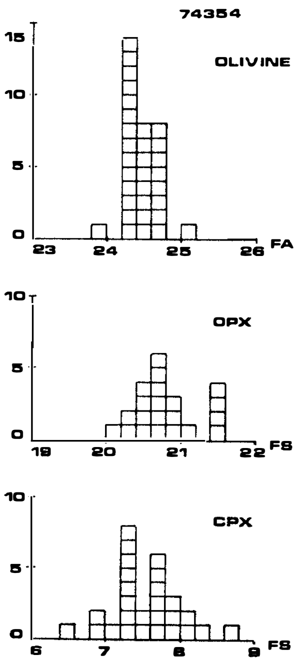

Fig. 1. Iron content of olivine, orthopyroxene and Ca-rich clinopyroxene in Yamato-74354 chondrite. One square denotes one point of measurement. The analyses are made on grains in both chondrules and matrix and on both core and rim of single grain.

value of $En_{47.2}Fs_{7.8}Wo_{45.0}$. Clinopyroxene is small in size and its composition varies with grains.

2.2.3. Plagioclase

As mentioned above, clear plagioclase exists within barred-olivine chondrules. Other plagioclase occurs mostly as interstitial very fine grains. The composition

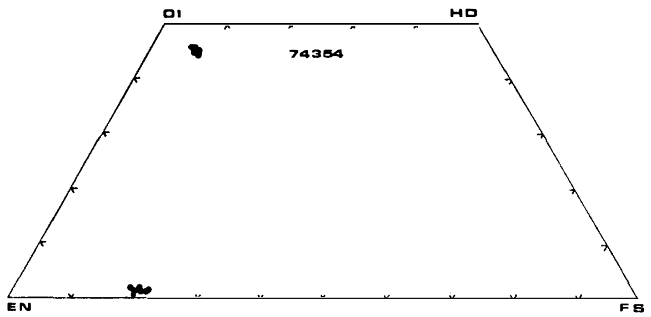

Fig. 2. Compositions of ortho- and clinopyroxene in Yamato-74354 chondrite.

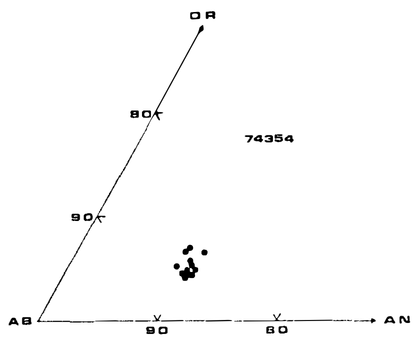

Fig. 3. Composition of plagioclase in Yamato-74354 chondrite. The analyses are made on matrix and chondrules.

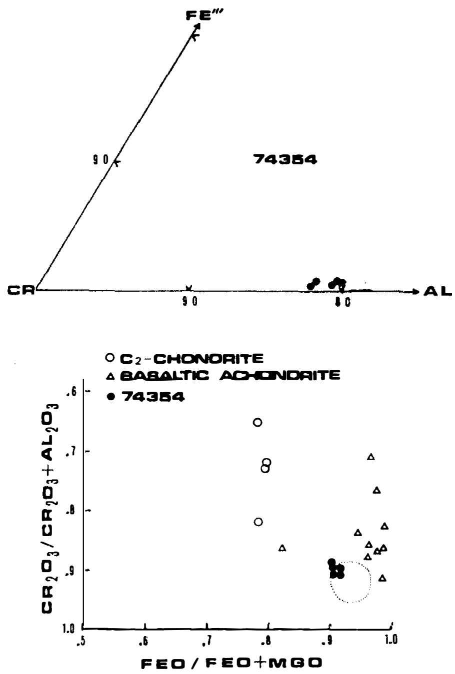

Fig. 4. Composition of chromite in Yamato-74354 chondrite. In the lower figure, the area enclosed by a dotted line is the average composition of chromite in ordinary chondrites. The data of C2 chondrite and achondrite are after BUNCH *et al. (1967).*

of plagioclase varies slightly among different grains. It ranges from $An_{10.7}Ab_{85.5}Or_{3.8}$ to $An_{9.2}Ab_{83.7}Or_{7.1}$ with the mean composition of $An_{10.2}Ab_{84.1}Or_{5.7}$ (oligoclase) (Fig. 3).

2.2.4. Chromite

Chromite occurs as anhedral grains and is often associated with metal grains. Chromite is nearly homogeneous and has a very low content of Fe^{3+}; the $Fe^{2+}/Fe^{2+}+Mg$ ratio is about 0.9 and the Cr/Cr+Al ratio is 0.9 (Fig. 4). BUNCH *et al.* (1967) showed that the chromite in ordinary chondrites has a very narrow compositional range.

2.3. *Equilibrium temperature*

Since BOYD (1973) showed a geotherm using the solvus of Ca-rich and Ca-poor pyroxenes, and the solubility of alumina in orthopyroxene, many workers have investigated the "geothermometer". For example, WOOD and BANNO (1973) basically used the miscibility gap determined by DAVIS and BOYD (1966) and treated the solubility of enstatite in diopside coexisting with orthopyroxene by an ideal solution model. Then WELLS (1977) reexamined the semiempirical equation using simple mixing models and improved the two-pyroxene thermometer. OBATA *et al.* (1974) treated the partitioning of Fe and Mg between olivine and Ca-rich clinopyroxene using simple mixture and ideal solution models. POWELL and POWELL (1974) also proposed an olivine-clinopyroxene geothermometer using Fe-Mg exchange reactions. Then MORI (1978) restudied the system CaO-MgO-Al_2O_3-SiO_2 and proposed three empirical equations for olivine, pyroxenes and spinel. EVANS and FROST (1975) proposed an olivine-spinel thermometer on the

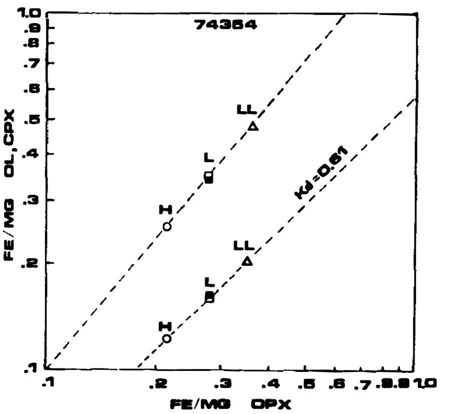

Fig. 5. The Fe/Mg ratios of coexisting olivine and orthopyroxene, and coexisting clinopyroxene and orthopyroxene in Yamato -74354 chondrite. Filled square denotes Yamato-74354 and open symbols average compositions of ordinary chondrites after VAN SCHMUS and WOOD (1967).

basis of Fe-Mg partition.

These geothermometers are thought to contain a considerable amount of error, perhaps more than $\pm 50°C$.

In Yamato-74354 chondrite, olivine, pyroxenes and chromite are nearly homogeneous (Fig. 5) so that the equilibrium temperature can be estimated using the above-mentioned geothermometers. Estimated temperature by the two-pyroxene thermometer and the olivine-clinopyroxene thermometer is between about 900°C and 1000°C and about 700°C by the olivine-chromite thermometer. Considering the uncertainties of the thermometers and the difference of diffusion rate in the silicate minerals and oxide, olivine and pyroxenes have been equilibrated at about 950°C and olivine and chromite at about 700°C.

BUNCH and OLSEN (1974) discussed that the partition coefficient of Fe and Mg between coexisting orthopyroxene and Ca-rich clinopyroxene is different among the chemical groups of ordinary chondrites and that the equilibrium temperature is different among different groups. However, considering the error of the thermometer, their conclusion can not be accepted.

3. Yamato-74190 (L6) Chondrite

3.1. Texture

This chondrite is coarse-grained and shows a texture of strong recrystallization (Photo 4). Matrix is well recrystallized and consists of relatively coarse-grained anhedral to subhedral silicate minerals. Chondrules are hardly defined, although relics of chondrules such as barred-olivine chondrules are rarely observed (Photo 5). Many of silicate grains are anhedral olivine. Orthopyroxene is less abundant. Clinopyroxene occurs as a minor and interstitial mineral. In spite of the highly recrystallized texture, no clear plagioclase is found, because plagioclase in this chondrite is changed into maskelynite. Most of metal grains are taenite. Kamacite is rare. Chromite is often associated with metal grains and is mostly irregular in shape.

3.2. Mineralogy

Olivine, pyroxenes, plagioclase, chromite and Ni-Fe metal were analyzed with the microprobe. Results are shown in Figs. 6–11 and representative chemical compositions of these minerals are listed in Table 2.

3.2.1. Olivine

Olivine in this chondrite is almost homogeneous and shows no compositional zoning. As is shown in Fig. 6, its composition ranges from $Fa_{23.9}$ to $Fa_{25.8}$ with the mean composition of $Fa_{24.6}$ which is close to the average composition of olivine in L-type chondrites. Not only Fe/Fe+Mg ratio, but also other major elements are nearly constant between and within grains.

Table 2. Representative chemical compositions of major minerals in Yamato-74190 chondrite. CHR1 represents chromite in the matrix and CHR2 represents that within the chondrule-like glassy part.

	OL	OPX	CPX	PL	CHR1	CHR2
SiO_2	37.141	55.675	53.427	64.294	—	—
Al_2O_3	0.018	0.189	0.541	21.465	5.814	17.328
TiO_2	0.034	0.192	0.472	—	2.780	1.407
FeO	22.725	13.903	4.975	—	30.743	27.450
MnO	0.468	0.529	0.248	—	1.001	0.729
MgO	39.175	28.636	16.280	—	2.234	4.906
CaO	0.023	0.656	22.293	2.706	—	—
Na_2O	0.007	0.028	0.607	9.748	—	—
K_2O	—	—	—	0.468	—	—
Cr_2O_3	0.000	0.050	0.846	—	53.821	45.593
Total	99.591	99.858	99.689	98.681	96.394	97.413
Si	0.9761	1.9940	1.9710	2.8705	—	—
Al	0.0005	0.0080	0.0235	1.1295	0.2534	0.6940
Ti	0.0007	0.0052	0.0131	—	0.0773	0.0360
Fe	0.4995	0.4164	0.1535	—	0.9507	0.7801
Mn	0.0104	0.0161	0.0077	—	0.0314	0.0210
Mg	1.5349	1.5290	0.8953	—	0.1231	0.2486
Ca	0.0007	0.0252	0.8812	0.1295	—	—
Na	0.0004	0.0020	0.0434	0.8453	—	—
K	—	—	—	0.0267	—	—
Cr	0.0000	0.0014	0.0247	—	1.5734	1.2250
Total	3.2031	3.9971	4.0135	5.0015	3.0093	3.0046
	Fo 75.45	En 77.59	En 46.39	An 12.95	Fe^{3+} 0.1042	0.0481
	Fa 24.55	Fs 21.13	Fs 7.95	Ab 84.39	Y_{Cr} 0.8148	0.6227
		Wo 1.28	Wo 45.66	Or 2.67	X_{Fe} 0.8730	0.7465

3.2.2. Pyroxenes

Orthopyroxene also shows a narrow range of composition. As is shown in Figs. 6 and 7, the composition ranges from $En_{78.1}Fs_{20.7}Wo_{1.2}$ to $En_{75.8}Fs_{22.3}Wo_{1.9}$ with the mean composition of $En_{77.8}Fs_{20.7}Wo_{1.5}$. Clinopyroxene occurs as minor grains. They are homogeneous, the composition ranging from $En_{46.0}Fs_{8.9}Wo_{45.1}$ to $En_{47.5}Fs_{6.7}Wo_{46.8}$ with the mean composition of $En_{46.5}Fs_{7.5}Wo_{46.0}$. Their Al_2O_3 and TiO_2 contents are relatively low. BUNCH and OLSEN (1974) already pointed out that clinopyroxene in the unequilibrated chondrite contains larger amount of Al, Ti and Cr than that in the ordinary chondrites. This fact may correspond to the occurrence of chromite in the ordinary chondrites.

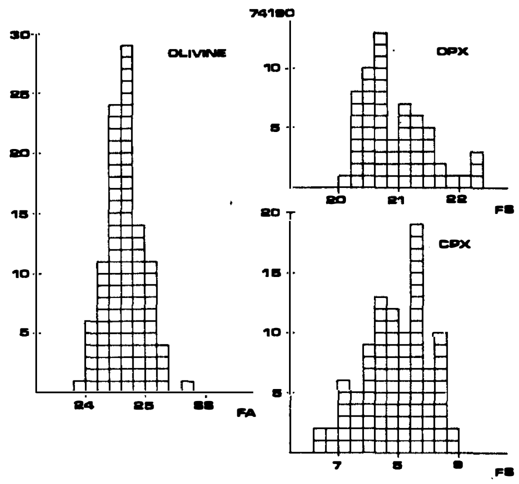

Fig. 6. Iron contents of olivine, orthopyroxene and Ca-rich clinopyroxene in Yamato-74190 chondrite. Symbols are the same as those in Fig. 1.

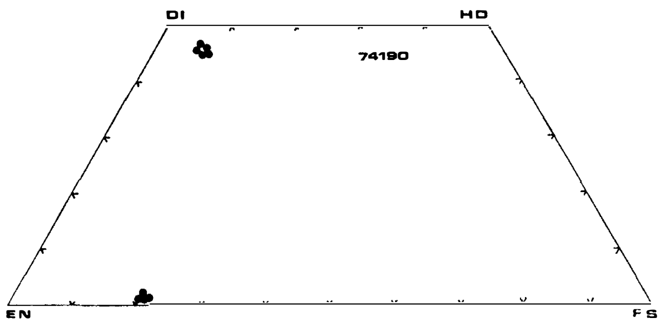

Fig. 7. Compositions of ortho- and clinopyroxene in Yamato-74190 chondrite.

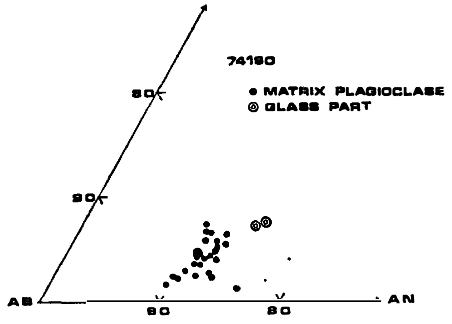

Fig. 8. Composition of plagioclase in Yamato-74190 chondrite. Filled circle denotes maskelynitized plagioclase in the matrix and double circle large maskelynite, which is round shaped resembling chondrule, and was analyzed by a defocused beam (about 10 μ) of EPMA.

3.2.3. Plagioclase

As mentioned above, plagioclase has been changed into maskelynite and no clear plagioclase is observed. The maskelynite has oligoclase composition (Fig. 8). Exceptionally, large maskelynite exists in this chondrite (Photo 6). It has a round shape, 0.5 mm in diameter, and seems to be a chondrule. It is very heterogeneous; the Na and K contents are high in the outer portion, whereas, the Ca, Al, Si and Ti contents high in the central portion. The chemical composition obtained by a defocused electron beam of EPMA is close to that of plagioclase ($An_{15}Ab_{78}Or_7$). Moreover, euhedral chromian spinel crystals which are slightly more aluminous than those in the matrix, exist within it and their composition resembles those in C2 chondrites given by BUNCH *et al.* (1967) (Figs. 9 and 10). It is questionable whether it had been a chondrule before maskelynitized or not: however, its composition is considerably similar to that

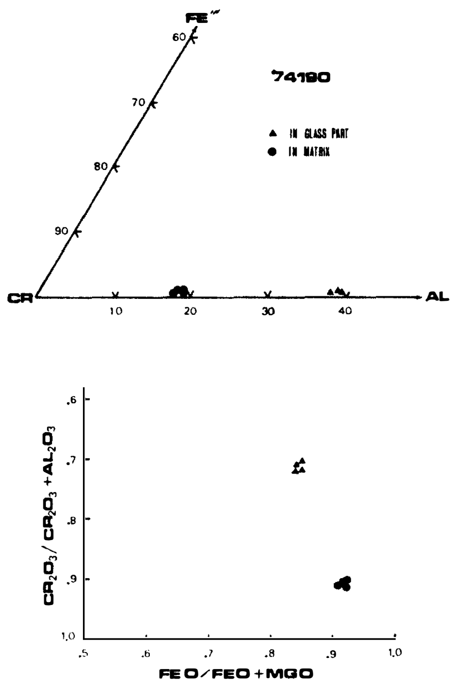

Fig. 9. Composition of chromite in Yamato-74190 chondrite. Filled circle denotes chromite in the matrix which has an anhedral shape and often coexists with metal grains. Filled triangle denotes euhedral chromian spinel within the glassy part.

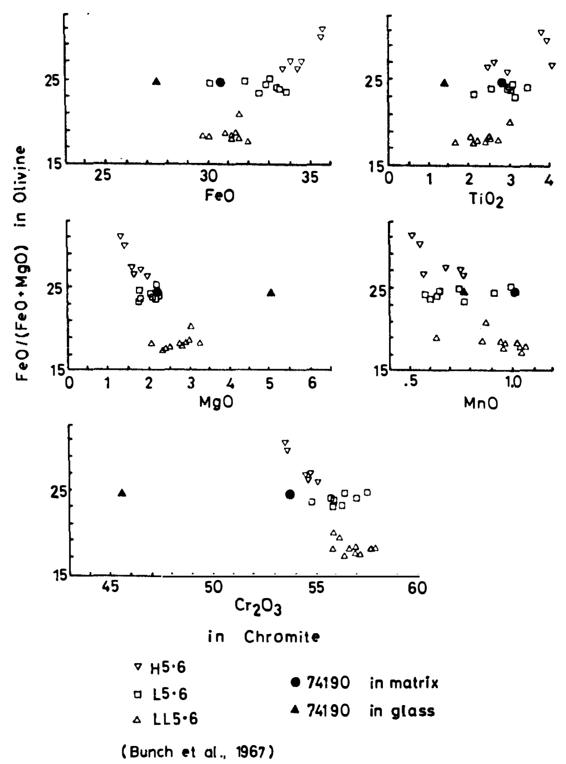

Fig. 10. Composition of chromite coexisting with olivine of ordinary chondrites after BUNCH et al. (1967). Filled circle and filled triangle are average composition of chromite in the matrix and the glassy part respectively in Yamato-74190 chondrite.

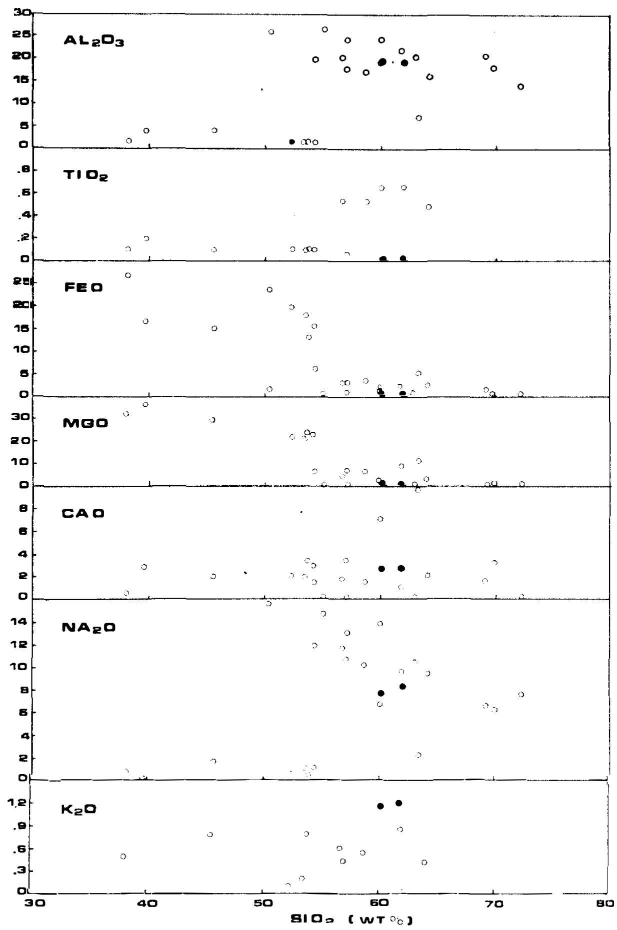

Fig. 11. Chemical compositions of glasses in unequilibrated chondrites (open circle) and chondrule-like glassy part of Yamato-74190 chondrite (filled circle). Glassy part is considerably heterogeneous, and two areas separated by chromite and secondary metal were analyzed separately. They are recalculated to 100 %. Data sources are from DUBE *et al. (1977),* FODOR *and* KEIL *(1967),* GRAHAM *et al. (1976) and* VAN SCHMUS *(1969).*

of glass contained within the unequilibrated chondrite (Fig. 11).

3.2.4. Chromite

Chromite of this chondrite shows a very uniform composition, which is within the average compositional area drawn by BUNCH *et al.* (1967). As mentioned above, chromite contained in chondrule-like glass has a distinct composition, being lower in FeO/FeO+MgO and $Cr_2O_3/Cr_2O_3+Al_2O_3$ ratios than that in the matrix. Chromite in the matrix contains 2.4 to 3.0 wt.% TiO_2 and about 1 wt.% MnO, whereas that in the glass contains 1.4 to 2.0 wt.% TiO_2 and 0.7 to 0.8 wt.% MnO. Chromite within the glass might have crystallized from melt and that in the matrix might have recrystallized (Figs. 9 and 10).

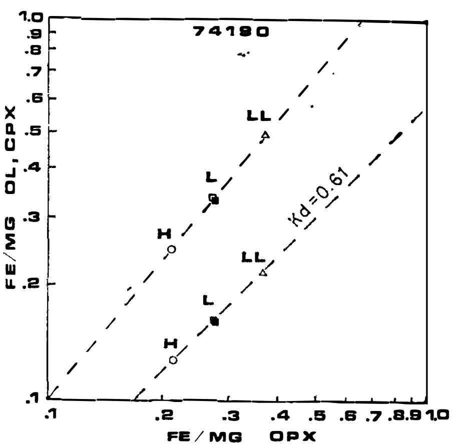

Fig. 12. The Fe/Mg ratios of olivine and orthopyroxene and of clinopyroxene and orthopyroxene in Yamato-74190 chondrite. Symbols are the same as those in Fig. 5.

3.3. Equilibrium temperature

The Fe/Mg relationships between coexisting olivine and orthopyroxene, and between coexisting orthopyroxene and clinopyroxene are shown in Fig. 12. These values are close to the average values of L-type chondrites. Estimated temperature is between 880°C and 1000°C by the two-pyroxene thermometer and the olivine-clinopyroxene thermometer. So, olivine and pyroxenes have been equilibrated at about 940°C and olivine and chromite at about 750°C. This chondrite shows a strongly recrystallized texture; nevertheless, the estimated equilibrium temperature is nearly the same as the above-described Yamato-74354 chondrite.

4. Yamato-74362 (L6) Chondrite

4.1. Texture

This chondrite shows a mildly recrystallized texture (Photo 7). Silicate minerals are fine-grained and recrystallization of the matrix is weak but chondrules are hardly defined. Relict of barred-olivine chondrule structure is rarely observed (Photo 8). Most of the silicate minerals are olivine with less abundant orthopyroxene. Clinopyroxene is much less abundant and occurs as small, interstitial anhedral grains. Plagioclase is not observed under the microscope and is barely found by the microprobe. It usually occurs as an irregular and interstitial mineral. Metal grains are both kamacite and taenite, but taenite is much more abundant than kamacite. Kamacite of this chondrite is relatively large. As in the previous noted samples, chromite is associated with metal grains, especially with taenite.

4.2. Mineralogy

Olivine, pyroxenes, plagioclase, chromite and Ni-Fe metal were analyzed with the microprobe. Results are shown in Figs. 13–16 and representative chemical compositions of these minerals are listed in Table 3.

Table 3. Representative chemical compositions of major minerals in Yamato-74362 chondrite.

	OL	OPX	CPX	PL	CHR
SiO_2	38.203	55.447	54.212	64.006	—
Al_2O_3	0.040	0.155	0.591	21.184	6.284
TiO_2	0.000	0.139	0.407	—	2.555
FeO	22.830	13.895	4.670	1.410	31.940
MnO	0.439	0.459	0.197	—	0.870
MgO	38.291	28.957	16.059	—	2.068
CaO	0.024	0.809	22.591	2.542	—
Na_2O	0.000	0.000	0.498	9.486	—
K_2O	—	—	—	0.884	—
Cr_2O_3	0.000	0.090	0.643	—	55.471
Total	99.827	99.951	99.869	99.513	99.187
Si	0.9984	1.9858	1.9889	2.8586	—
Al	0.0012	0.0065	0.0256	1.1151	0.5325
Ti	0.0000	0.0038	0.0112	—	0.1381
Fe	0.4990	0.4162	0.1433	0.0527	1.9205
Mn	0.0097	0.0139	0.0061	—	0.0530
Mg	1.4919	1.5461	0.8783	—	0.2217
Ca	0.0007	0.0310	0.8880	0.1217	—
Na	0.0000	0.0000	0.0354	0.8214	—
K	—	—	—	0.0504	—
Cr	0.0000	0.0025	0.0187	—	3.1533
Total	3.0009	4.0058	3.9955	5.0197	6.0191
	Fo 74.94	En 77.56	En 45.99	An 12.25	Fe^{3+}0.1316
	Fa 25.06	Fs 20.88	Fs 7.50	Ab 82.68	Y_{Cr} 0.8260
		Wo 1.56	Wo 46.50	Or 5.07	X_{Fe} 0.8897

4.2.1. Olivine

Olivine in this chondrite is euhedral to subhedral and is nearly homogeneous and each grain does not show a compositional zoning. However, a small compositional variation is observed between grains as is shown in Fig. 13. The composition ranges from $Fa_{24.0}$ to $Fa_{26.8}$ with the mean composition of $Fa_{25.1}$. The histogram shows a relatively broad peak.

4.2.2. Pyroxenes

Orthopyroxene has a small range of compositional variation. As is shown in Figs. 13 and 14, the composition ranges from $En_{79.0}Fs_{20.1}Wo_{0.9}$ to $En_{75.5}Fs_{22.2}Wo_{2.3}$ with the mean composition of $En_{77.4}Fs_{21.0}Wo_{1.6}$. The peak is relatively broad. Most

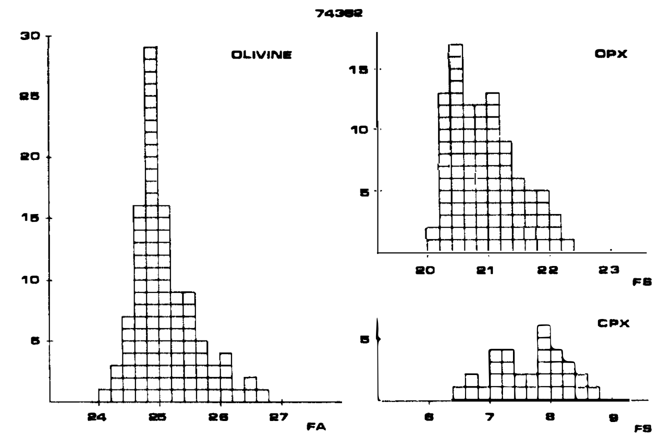

Fig. 13. Iron contents of olivine, orthopyroxene and clinopyroxene in Yamato-74362 chondrite. Symbols are the same as those in Fig. 1.

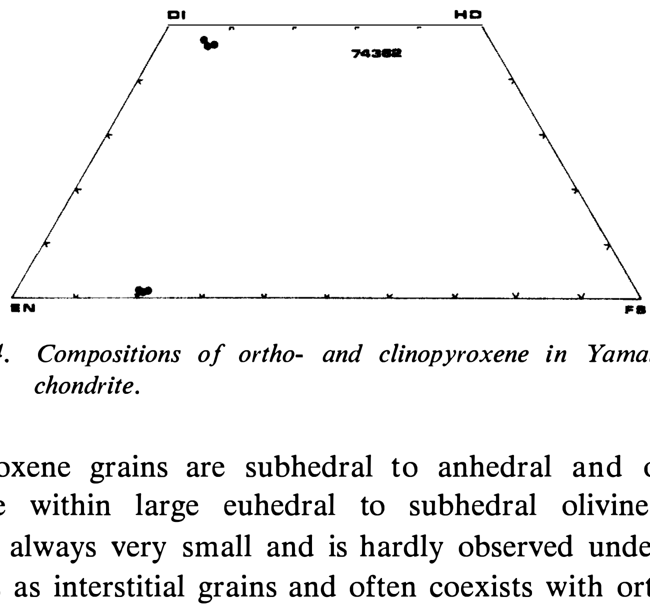

Fig. 14. Compositions of ortho- and clinopyroxene in Yamato-74362 chondrite.

of the orthopyroxene grains are subhedral to anhedral and occasionally show poikilitic texture within large euhedral to subhedral olivine grains. Ca-rich clinopyroxene is always very small and is hardly observed under the microscope. It usually occurs as interstitial grains and often coexists with orthopyroxene. The Fe/Fe+Mg ratio is relatively wide compared with those of olivine and orthopyroxene. The composition ranges from $En_{46.3}Fs_{8.7}Wo_{45.0}$ to $En_{47.0}Fs_{6.5}Wo_{46.5}$ with the mean composition of $En_{46.6}Fs_{7.7}Wo_{45.7}$.

4.2.3. Plagioclase

Plagioclase of this chondrite is small and interstitial, similar to that in the above-described Yamato-74354 chondrite, and hardly be observed under the microscope. It shows a narrow compositional variation. As is shown in Fig. 15, the composition ranges from $An_{9.8}Ab_{86.2}Or_{4.0}$ to $An_{10.9}Ab_{80.3}Or_{8.8}$ with the mean composition of $An_{10.0}Ab_{83.6}Or_{6.4}$. This compositional range is smaller than that in Yamato-74190 chondrite. It is curious that Yamato-74190 chondrite, which has

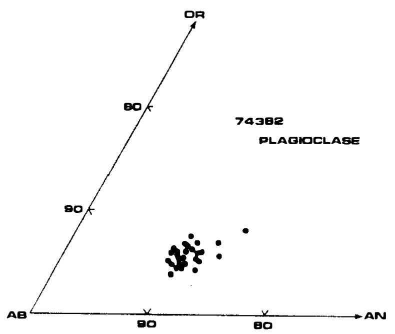

Fig. 15. *Composition of plagioclase in Yamato-74362 chondrite.*

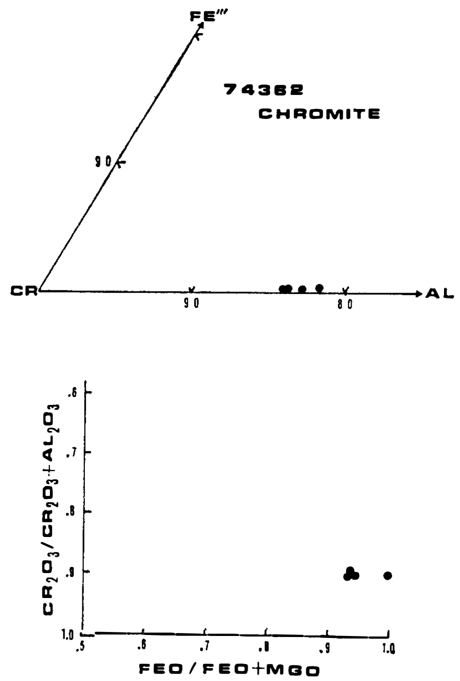

Fig. 16. *Composition of chromite in Yamato-74362 chondrite.*

a highly recrystallized texture, shows a large variation of plagioclase composition than that in Yamato-74362 chondrite which has a weakly recrystallized texture. Plagioclase contains small amount of TiO_2 and FeO.

4.2.4. Chromite

Chromite in this chondrite occurs as minor grains and usually coexists with metal grains. As shown in Fig. 16, the FeO/FeO+MgO ratio ranges from 0.92 to 1.00, which is especially high, compared with those in the above-described chondrites and the average composition of chromite in the ordinary chondrites. The chromite contains 2.5 to 3.0 wt.% TiO_2 and 0.6 to 0.9 wt.% MnO.

4.3. Equilibrium temperature

The Fe/Mg relationships between coexisting olivine and orthopyroxene, and coexisting clinopyroxene and orthopyroxene are shown in Fig. 17. These values are close to the average values for L-type chondrite. Estimated temperature is between 850°C and 1000°C by the two-pyroxene thermometer and the olivine-clinopyroxene thermometer, and 750°C by the olivine-spinel thermometer. So, olivine and pyroxenes have been equilibrated at about 930°C and olivine and chromite at about 750°C. These values are also nearly the same as the above-described two chondrites. Although these three samples have recorded nearly equal equilibrium temperature, they show various degrees of recrystallization, so

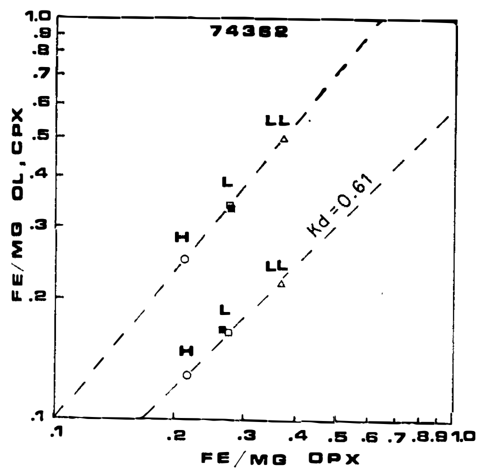

Fig. 17. The Fe/Mg ratios of coexisting olivine and orthopyroxene and of clinopyroxene and orthopyroxene in Yamato-74362 chondrite. Symbols are the same as those in Fig. 5.

the degree of recrystallization depends mainly upon the duration of thermal metamorphism.

5. Yamato-74646 (LL6) Chondrite

5.1. *Texture*

Yamato-74646 chondrite belongs to LL-type chondrite and has a "dark-light" texture, which is often observed in this type of chondrites. Both dark and light parts contain olivine, orthopyroxene, clinopyroxene, chromite, Ni-Fe metal and troilite, and show a relict texture of chondrules. The matrix of the dark part is composed of very fine aggregate of minerals, and discrimination of each crystal is difficult. In the dark part, silicate minerals are dispersed in the black matrix (Photo 9), whereas the light part is mainly composed of small silicate minerals (Photo 10). Most of silicate minerals are olivine with a small amount of pyroxenes. Both parts contain chondrules (Photos 11 and 12). Under the microscope, boundary of the two parts is ambiguous and gradual (Photo 13), suggesting that the "dark-light" structure is secondary and that the two parts are primarily one phase. The "dark-light" structure has been considered to be formed by shock of impact (FREDRIKSSON and KEIL, 1963). FREDRIKSSON and KEIL (1963) considered that they originally had a homogeneous texture because chemical and petrologic characters are identical.

5.2. *Mineralogy*

Olivine, pyroxenes, plagioclase, chromite and Ni-Fe metal were analyzed with

Table 4. Representative chemical compositions of major minerals in Yamato-74646 chondrite.

	OL	OPX	CPX	CHR
SiO_2	37.770	54.965	54.099	—
Al_2O_3	0.037	0.220	0.580	5.770
TiO_2	0.006	0.230	0.394	3.493
FeO	25.766	16.101	5.951	31.232
MnO	0.428	0.540	0.171	0.873
MgO	35.147	28.085	15.652	2.339
CaO	0.349	0.645	21.890	—
Na_2O	0.018	0.031	0.487	—
K_2O	—	—	—	—
Cr_2O_3	0.000	0.067	0.627	54.849
Total	99.521	100.884	99.852	98.556
Si	1.0051	1.9718	1.9921	—
Al	0.0012	0.0093	0.0252	0.2454
Ti	0.0001	0.0062	0.0109	0.0948
Fe	0.5734	0.4830	0.1833	0.9425
Mn	0.0097	0.0164	0.0053	0.0267
Mg	1.3943	1.5020	0.8592	0.1258
Ca	0.0100	0.0248	0.8636	—
Na	0.0009	0.0022	0.0348	—
K	—	—	—	—
Cr	0.0000	0.0019	0.0183	1.5649
Total	2.9947	4.0175	3.9927	3.0000
	Fo 70.86	En 74.73	En 45.08	Fe^{3+} 0.2849
	Fa 29.14	Fs 24.03	Fs 9.62	Y_{Cr} 0.7469
		Wo 1.23	Wo 45.31	X_{Fe} 0.8394

the microprobe. Results are shown in Figs. 18–22 and representative chemical compositions of these minerals are listed in Table 4.

5.2.1. Olivine

Olivine in this chondrite is subhedral to anhedral in the light part and is subhedral to euhedral in the dark part. The former olivine is usually larger in size than the latter. Olivine is considerably homogeneous in both parts. The compositional range is $Fa_{27.8}$ to $Fa_{29.6}$ with the mean composition of $Fa_{28.6}$ (Fig. 18). It is slightly more magnesian than the average composition of olivine in LL-type chondrites.

5.2.2. Pyroxenes

Orthopyroxene occurs as small grains, and in the light part it often coexists

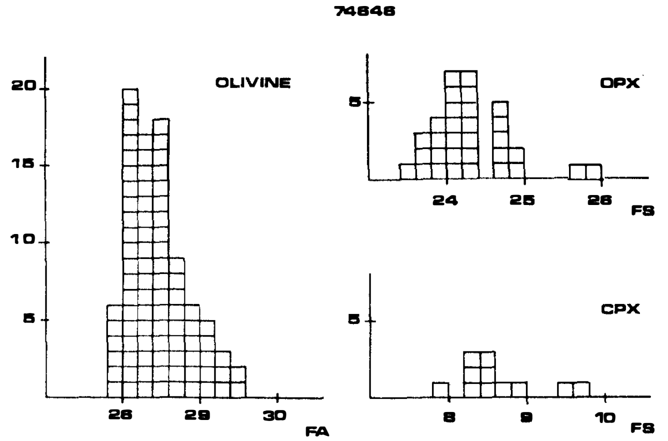

Fig. 18. Iron contents of olivine, orthopyroxene and clinopyroxene in Yamato-74646 chondrite. Symbols are the same as those in Fig. 1.

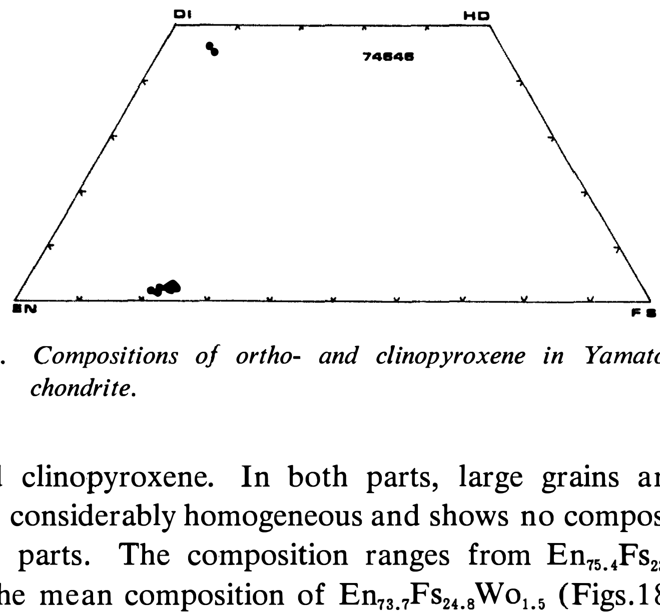

Fig. 19. Compositions of ortho- and clinopyroxene in Yamato-74646 chondrite.

with olivine and clinopyroxene. In both parts, large grains are not observed. Orthopyroxene is considerably homogeneous and shows no compositional difference between the two parts. The composition ranges from $En_{75.4}Fs_{23.5}Wo_{1.1}$ to $En_{71.6}Fs_{25.9}Wo_{2.5}$ with the mean composition of $En_{73.7}Fs_{24.8}Wo_{1.5}$ (Figs.18 and 19). It is close to the average composition of LL-type chondrites.

Ca-rich clinopyroxene is very scarce and occurs as minor grains, intergrown with orthopyroxene in both parts. Its chemical composition is relatively uniform, ranging from $En_{45.8}Fs_{7.9}Wo_{46.3}$ to $En_{45.0}Fs_{9.7}Wo_{45.3}$ with the mean composition of $En_{45.5}Fs_{8.6}Wo_{45.9}$.

5.2.3. Plagioclase

Most of plagioclase crystals are anhedral and less than 10 μ in diameter in both parts. In the light part, it is particularly small and much less in amount. As shown in Fig. 20, plagioclase in this chondrite shows very wide compositional

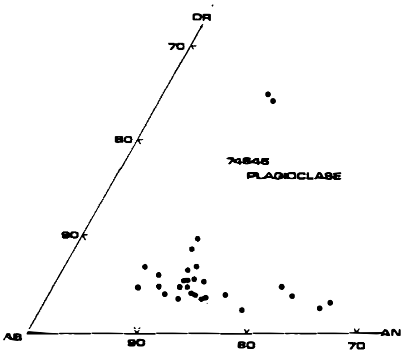

Fig. 20. Composition of plagioclase in Yamato-74646 chondrite. Plagioclase occurs in both dark and light part. Existence of K-rich feldspar is remarkable.

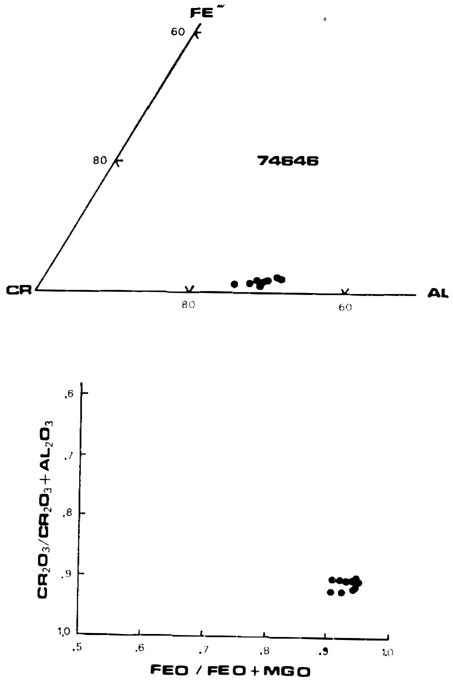

Fig. 21. Composition of chromite in Yamato-74646 chondrite. Considerably Al-rich compositions and a wide range of variation are characteristic.

variation; the compositional range is from $An_{8.0}Ab_{83.9}Or_{8.1}$ to $An_{26.8}Ab_{70.3}Or_{2.7}$ with the mean composition of $An_{14.2}Ab_{79.0}Or_{6.8}$. Such compositional variation is observed between different grains and not within a single grain. Moreover, exceptionally high-K feldspar exists in the dark part, which is $An_{7.6}Ab_{67.4}Or_{25.0}$ and coexists with sodic plagioclase. Such a high-K feldspar is rare in ordinary chondrites.

5.2.4. Chromite

Chromite in this chondrite occurs as minor grains and often coexists with metal grains similar to the samples described above. Chromite is more abundant in the dark part than in the light part. It shows a slight heterogeneity in composition among different grains. But the compositional variation is all within the compositional area of ordinary chondrite and this fact applies to both parts. The Cr/Cr+Al ratio is slightly lower than that of chromite in the other chondrites described above (Fig. 21).

5.3. Equilibrium temperature

The Fe/Mg relations between the coexisting olivine and orthopyroxene, and between coexisting clinopyroxene and orthopyroxene are shown in Fig. 22. The

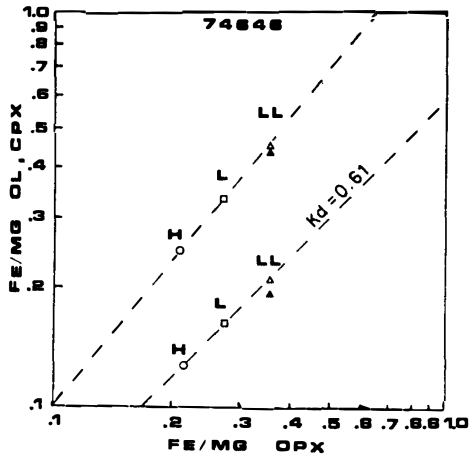

Fig. 22. The Fe/Mg ratios of coexisting olivine and orthopyroxene and of clinopyroxene and orthopyroxene in Yamato-74646 chondrite. Symbols are the same as those in Fig. 5. Both olivine and clinopyroxene are relatively Mg-rich compared with the average values.

Fe/Mg ratios of olivine and clinopyroxene are slightly lower than the average values of LL-type chondrite. The composition of olivine, pyroxenes and chromite are nearly uniform, so the equilibrium temperature was estimated similar to the above estimation. The results are; between 900°C and 1000°C by the two-pyroxene thermometer and the olivine-clinopyroxene thermometer and 750°C by the olivine-spinel thermometer. So, olivine and pyroxenes have been equilibrated at about 950°C and olivine and chromite at about 750°C. These values are the same as the above-mentioned three L-type chondrites.

6. Yamato-74115 (H5) Chondrite

6.1. Texture

Yamato-74115 chondrite belongs to H-type chondrite and shows considerably weak recrystallization. Chondrules are easily defined and they have sharp outlines. Internal textures of chondrules, such as barred-olivine, porphyritic-olivine (Photo 14), granular-olivine, skeletal-olivine (Photo 15) and excentroradial pyroxene textures are well preserved. Rarely, chondrules which consist of wholly devitrified glass are contained. Matrix of chondrules also consists of devitrified glass or extremely fine intergrowth of orthopyroxene and clinopyroxene with a small amount of plagioclase. In an excentroradial pyroxene chondrule, which consists mainly of orthopyroxene, Ca-rich clinopyroxene and/or minor blebs of sodic plagioclase exist between orthopyroxenes which have different crystallographic orientations. Olivine of porphyritic chondrules is often narrowly outlined by Ca-rich clinopyroxene. In the matrix, most of grains are olivine with a small amount of orthopyroxene. Ca-rich clinopyroxene does not exist excepting the case when it outlines the olivine grains. Clear plagioclase does not exist in this chondrite either within the chondrules or in the matrix, and there exists turbid and very fine aggregate of plagioclase. Metal occurs not only in the matrix, but also within the chondrules. Chromite occurs coexisting with metal.

6.2. *Mineralogy*

Olivine, pyroxenes, plagioclase, chromite and Ni-Fe metals were analyzed with the microprobe. Results are shown in Figs. 23–26 and representative chemical

Table 5. Representative chemical compositions of major minerals in Yamato-74115 chondrite.

	OL	OPX	CPX	CHR
SiO_2	39.068	54.865	56.075	—
Al_2O_3	0.013	0.161	0.980	6.836
TiO_2	0.001	0.224	0.281	2.172
FeO	17.320	10.676	3.909	30.296
MnO	0.417	0.546	0.460	1.304
MgO	43.335	30.616	17.037	3.175
CaO	0.030	1.012	19.439	—
Na_2O	0.000	0.005	1.075	—
K_2O	—	—	—	—
Cr_2O_3	0.000	0.150	0.493	55.887
Total	100.205	98.256	99.702	99.670
Si	0.9912	1.9753	2.0295	—
Al	0.0004	0.0069	0.0405	0.2857
Ti	0.0000	0.0061	0.0076	0.0579
Fe	0.3675	0.3215	0.1184	0.8984
Mn	0.0090	0.0167	0.0141	0.0392
Mg	1.6398	1.6433	0.9195	0.1678
Ca	0.0008	0.0391	0.7540	—
Na	0.0000	0.0003	0.0755	—
K	—	—	—	—
Cr	0.0000	0.0043	0.0141	1.5668
Total	3.0086	4.0132	3.9733	3.0158
	Fo 81.90	En 82.01	En 51.31	Fe^{3+} 0.0975
	Fa 18.10	Fs 16.04	Fs 6.61	Y_{Cr} 0.8035
		Wo 1.95	Wo 42.08	X_{Fe} 0.8268

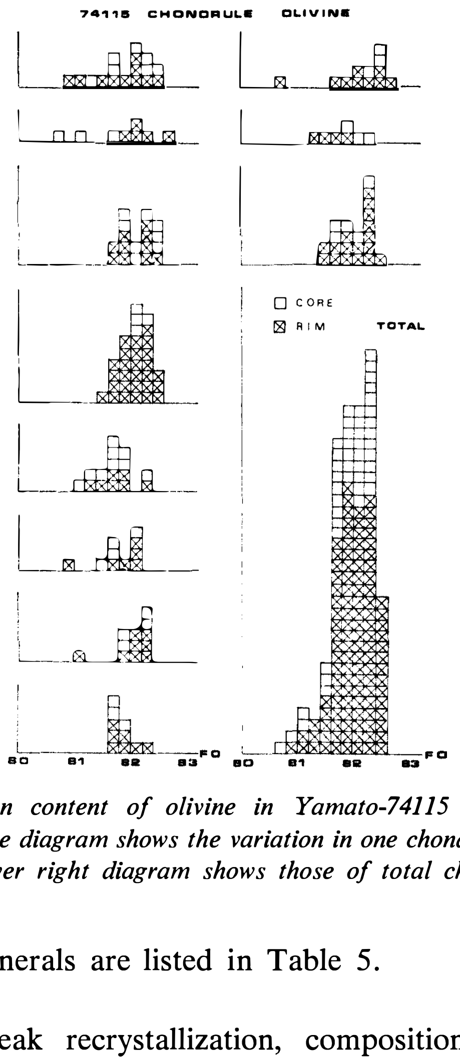

Fig. 23. Iron content of olivine in Yamato-74115 chondrite. One diagram shows the variation in one chondrule. The lower right diagram shows those of total chondrules.

compositions of these minerals are listed in Table 5.

6.2.1. Olivine

In spite of such weak recrystallization, composition of olivine is highly homogeneous between and within grains. As is shown in Fig. 23, olivine in each chondrule has a considerably uniform composition, and as a whole, this chondrite shows a very narrow compositional variation. It ranges from $Fa_{17.4}$ to $Fa_{19.4}$ with the mean composition of $Fa_{18.0}$. Olivine in the matrix has almost the same compositional variation. It is surprising that homogenization of olivine did not cause textural recrystallization. The lacking of interstitial fluid phase during recrystallization may preserve the texture without changing the outline of chondrules and crystals.

6.2.2. Pyroxenes

Similarly, pyroxenes have a considerably uniform composition. Both orthopyroxene and Ca-rich clinopyroxene have a quite narrow range of compositional variations within grains and between each grain and chondrule. Orthopyroxene ranges from $En_{82.5}Fs_{16.5}Wo_{1.0}$ to $En_{82.2}Fs_{16.2}Wo_{1.6}$ with the mean composition of

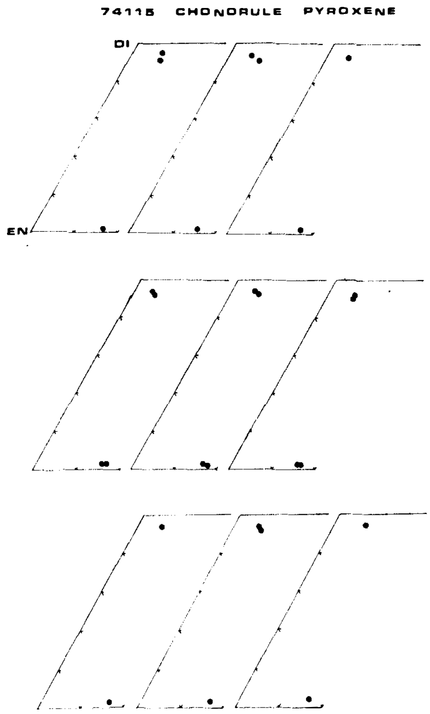

Fig. 24. Compositions of ortho- and clinopyroxene in Yamato-74115 chondrite. One quadrilateral shows the composition for one chondrule.

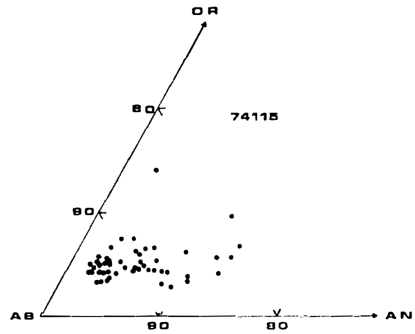

Fig. 25. Composition of plagioclase in Yamato-74115 chondrite. Relatively Na-rich composition and wide range of variation are characteristic.

$En_{82.3}Fs_{16.3}Wo_{1.4}$. Clinopyroxene ranges from $En_{49.0}Fs_{5.0}Wo_{46.0}$ to $En_{47.0}Fs_{5.0}Wo_{48.0}$ with the mean composition of $En_{48.9}Fs_{5.1}Wo_{46.0}$ (Fig. 24). Compared with the average composition of H-type chondrite, clinopyroxene in Yamato-74115 chondrite is slightly rich in Fe.

6.2.3. Plagioclase

Differing from olivine and pyroxenes, plagioclase shows a considerably wide range of compositional variation. As mentioned above, plagioclase occurs as fine aggregate or minor blebs, so this variation represents the heterogeneity of different grains. As shown in Fig. 25, it ranges from $An_{2.1}Ab_{93.7}Or_{4.2}$ to $An_{14.2}Ab_{78.5}Or_{7.3}$. Compared with the other samples described above, this is rich in Na.

6.2.4. Chromite

Chromite in this chondrite shows a small variation of composition. The Cr/Cr+Al ratio ranges from 0.68 to 0.77 and this is relatively aluminous (Fig. 26). This value is within the average value of ordinary chondrite.

6.3. Chemical composition of chondrules

As mentioned above, Yamato-74115 chondrite contains clearly defined chon-

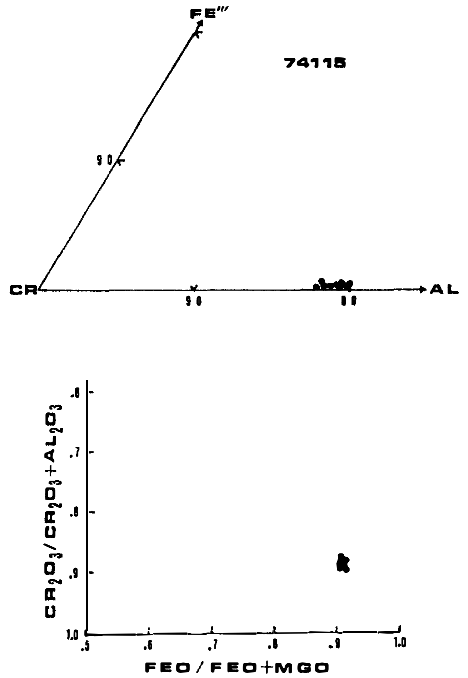

Fig. 26. Composition of chromite in Yamato-74115 chondrite.

drules. The chemical composition of chondrules has been determined with the electron microprobe, for Manych (L3) chondrite by DODD (1978), for Richardton (H5) by EVENSEN *et al.* (1979) and for Yamato-74191 (L3) chondrite by IKEDA and TAKEDA (1979). IKEDA and TAKEDA (1979) have discussed the relations between the texture and the chemical composition of chondrules, and concluded that the chemical composition of chondrules are represented by the mixture of olivine, orthopyroxene, clinopyroxene and plagioclase and that chondrules are characterized by different combination of these minerals.

For understanding the effect of metamorphism, the relations between the chemical composition and the texture of chondrules have been determined. Results are shown in Fig. 27. The SiO_2 content varies with the type of the chondrules. The average SiO_2 content increases in the following order; granular-olivine chondrule (42–48 wt.%), porphyritic-olivine chondrule (41–55 wt.%), barred-olivine chondrule (47–51 wt.%), excentroradial-pyroxene chondrule (48–53 wt.%) and devitrified glassy chondrule (53–57 wt.%). As the SiO_2 content increases, the FeO and MgO contents decrease remarkably and the TiO_2 content increases slightly. However, the contents of Al_2O_3, MnO, CaO, Na_2O, K_2O and Cr_2O_3 are almost constant. Barred-olivine chondrules which are made up of barred olivine and glassy matrix having an Na-rich plagioclase composition, show abnormal compositions; they are exceptionally poor in MgO and rich in Na_2O, K_2O and Al_2O_3.

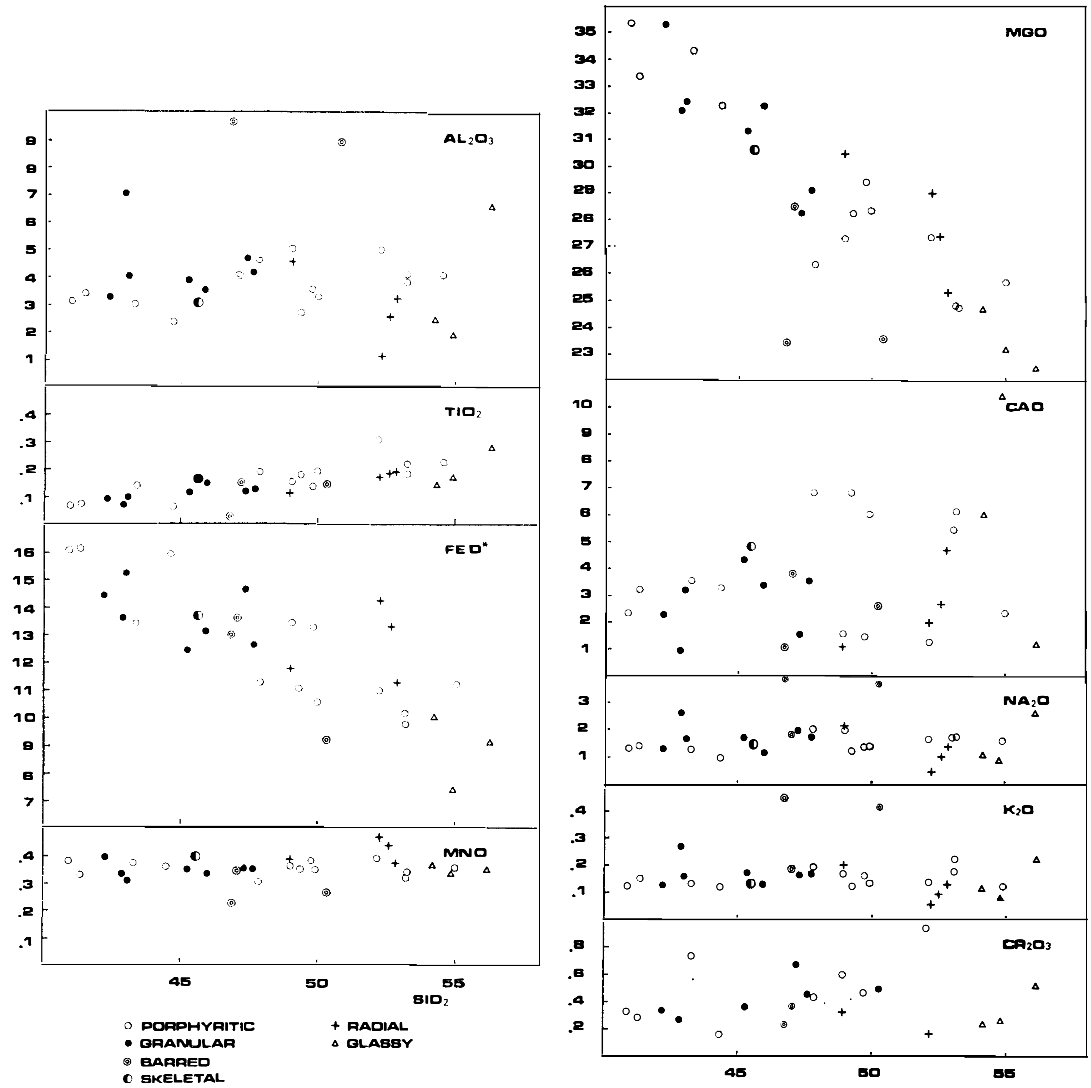

Fig. 27. Compositional variations of chondrules of Yamato-74115 chondrite. Chondrules are classified by texture. Open circle; porphyritic-olivine chondrule, solid circle; granular-olivine chondrule, double circle; barred-olivine chondrule, half circle; skeletal-olivine chondrule. Cross; radial-pyroxene chondrule, open triangle; devitrified chondrule. All the oxides are shown as wt. % when recalculated to 100%.

This is probably due to a high content of plagioclase component. Chondrules, excepting the barred-olivine chondrule, show a considerably linear trend as shown in Fig. 27. The decrease of MgO and FeO and the constancy of other elements indicate that these chemical trends are controlled by olivine and/or orthopyroxene and partially clinopyroxene and Na-rich plagioclase. As shown in Figs. 28 and 29, the ratios of FeO/FeO+MgO, Mg/Si, Fe/Si and Ca/Si do not depend on the texture of chondrules. These values are quite similar to those of

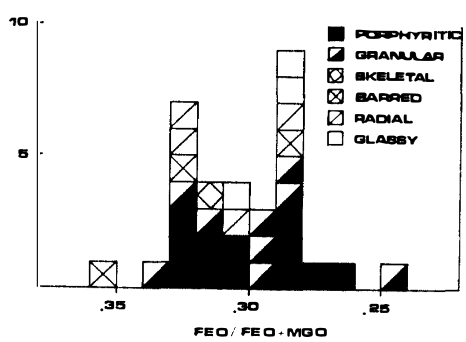

Fig. 28. The FeO/FeO+MgO ratios of chondrules of Yamato-74115 chondrite. One square shows the ratio of one chondrule.

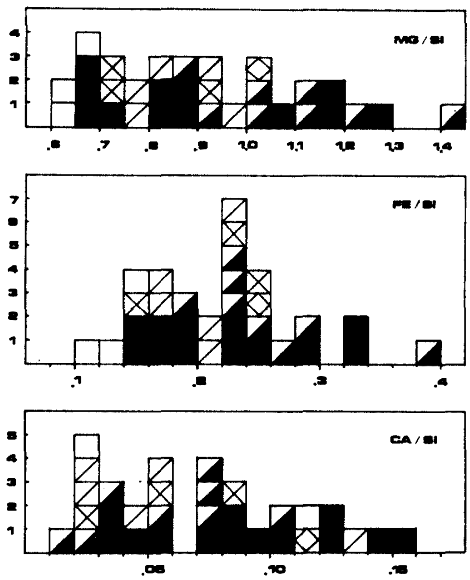

Fig. 29. The Mg/Si, Fe/Si and Ca/Si ratios of chondrules of Yamato-74115 chondrite. Symbols are the same as those in Fig. 28.

Richardton (H5) chondrite described by EVENSEN *et al.* (1979).

6.5. *Equilibrium temperature*

The Fe/Mg ratios of coexisting pairs of olivine and orthopyroxene, and coexisting clinopyroxene and orthopyroxene are shown in Fig. 30. The Fe/Mg ratio of olivine is smaller than that of the average value of H-type chondrite, whereas the Fe/Mg ratio of clinopyroxene is slightly larger than that of the average H-type chondrite. Olivine, pyroxenes and chromite are nearly homogeneous in this chondrite, so the equilibrium temperature can be estimated. Temperature is

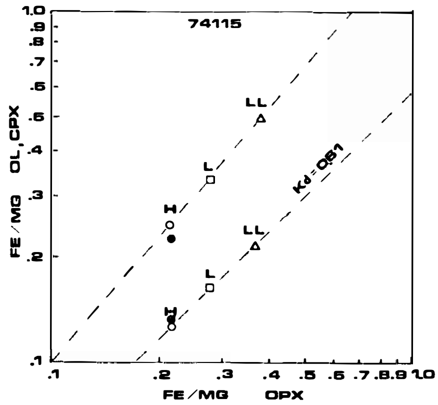

Fig. 30. The Fe/Mg ratios of olivine and orthopyroxene and of clinopyroxene and orthopyroxene in Yamato-74115 chondrite. Symbols are the same as those in Fig. 5.

between 800°C and 850°C by the two-pyroxene thermometer and the olivine-clinopyroxene thermometer, and 700°C by the olivine-spinel thermometer. So olivine and pyroxenes have been equilibrated at about 830°C and olivine and chromite at about 700°C. These temperatures are slightly lower than those estimated for the above-described samples. Considering the fact that this chondrite shows a very weakly recrystallized texture, the degree of recrystallization depends partly on the metamorphic temperature. The occurrence of clinopyroxene of this chondrite is different from that of other above-mentioned samples; that is, clinopyroxene in this chondrite occurs as narrow rim of olivine, whereas those in other chondrites occur as interstitial and minor anhedral grains. The estimated equilibrium temperature, therefore, may not necessarily represent the same event of the planetary history.

7. Conclusion

Detailed petrographic studies have been done on five ordinary chondrites. In spite of the wide variation in texture and especially the degree of recrystallization, olivine, pyroxenes and chromite of all the samples show very narrow compositional variations and their compositions are close to the average composition of the respective chemical groups of chondrites. Equilibrium temperatures estimated by the same thermometer are, therefore, nearly the same for type-6 chondrites. This fact indicates that the degree of recrystallization depends not only upon the temperature but also upon the duration of thermal metamorphism. It is suggested that the classification of ordinary chondrites should be based on whether the silicate minerals excepting plagioclase are nearly homogeneous or not.

Plagioclase shows a relatively large compositional variation, which seems to depend on the degree of recrystallization.

Chemical composition of chondrules in weakly recrystallized chondrite seems to have been preserved after homogenization of major silicate minerals.

Acknowledgments

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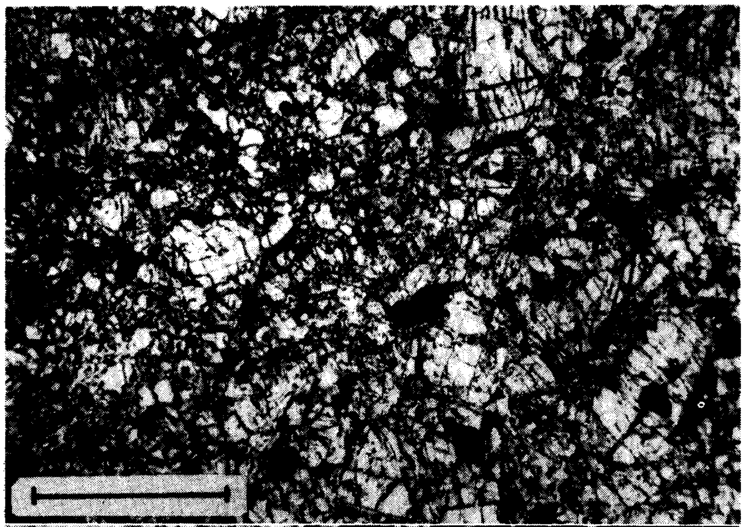

Photo 1. Texture of Yamato-74354 chondrite. Major minerals are olivine and the matrix is weakly recrystallized. Transmitted light.

Photo 2. Relict of barred-olivine chondrule in Yamato-74354 chondrite. Interstices of olivine bars are filled with clear plagioclase. Transmitted light.

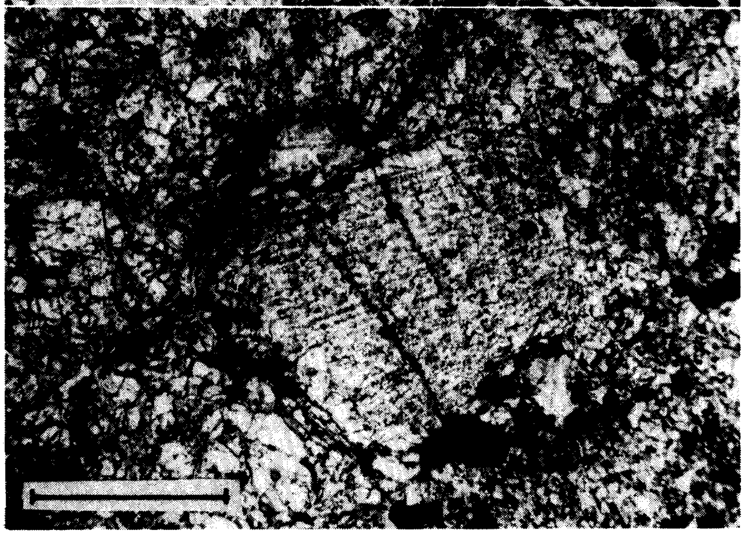

Photo 3. Fragment of radial-pyroxene chondrule in Yamato-74354 chondrite. Transmitted light.

Scale bar is 0.5 mm.

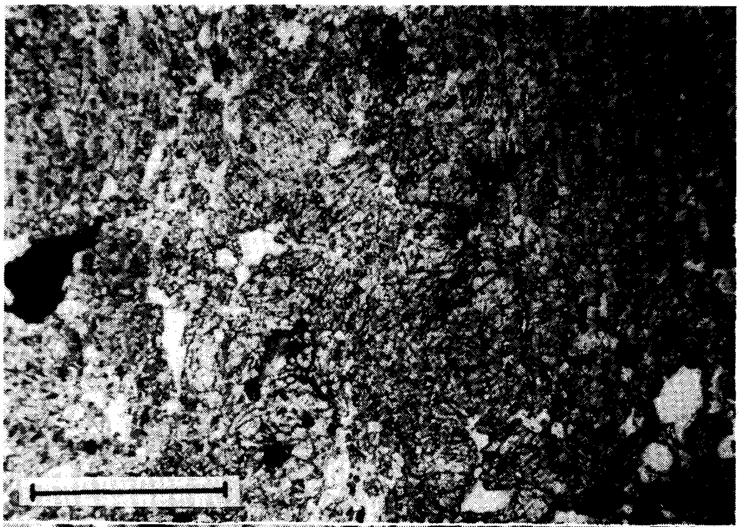

Photo 4. Texture of Yamato-74190 chondrite. Strongly recrystallized matrix is observed. Transmitted light.

Photo 5. Relict of barred-olivine chondrule in Yamato-74190 chondrite. Interstices of olivine crystals are maskelynite. Transmitted light.

Photo 6. Chondrule-like glassy part in Yamato-74190 chondrite. Glass is maskelynite and has a heterogeneous plagioclase composition. Euhedral opaque minerals within it are chromite. Opaque minerals around it are Ni-Fe metal and troilite. Transmitted light.

Scale bar is 0.5 mm.

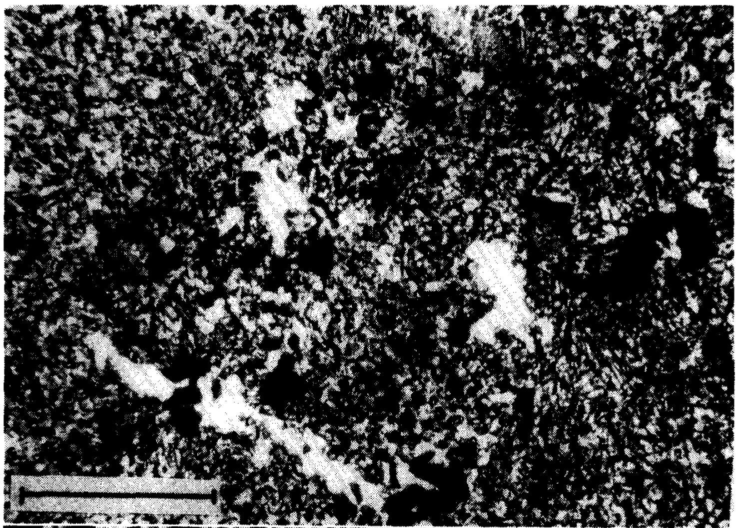

Photo 7. Texture of Yamato-74362 chondrite. Mildly recrystallized texture is observed and chondrules are hardly defined. Transmitted light.

Photo 8. Relict of barred-olivine chondrule in Yamato-74362 chondrite. Interstices of olivine bars are filled with aggregate of fine-grained plagioclase. Transmitted light.

Photo 9. Texture of Yamato-74646 chondrite. Irregular shaped fragments and minerals are dispersed in the dark part. Transmitted light.

Scale bar is 0.5 mm.

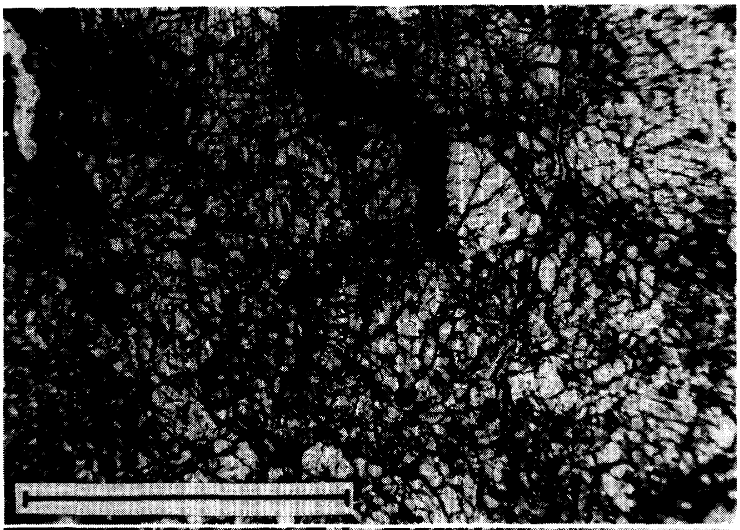

Photo 10. Texture of Yamato-74646 chondrite. Silicate minerals are mostly olivine and show a light texture. Interstices of silicate minerals are fine aggregate of plagioclase. Transmitted light.

Photo 11. Relict of skeletal-olivine chondrule in the light part in Yamato-74646 chondrite. Transmitted light.

Photo 12. Relict of radial pyroxene chondrule in the dark part in Yamato-74646 chondrite. Extremely irregular shape is characteristic. Transmitted light.

Scale bar is 0.5 mm.

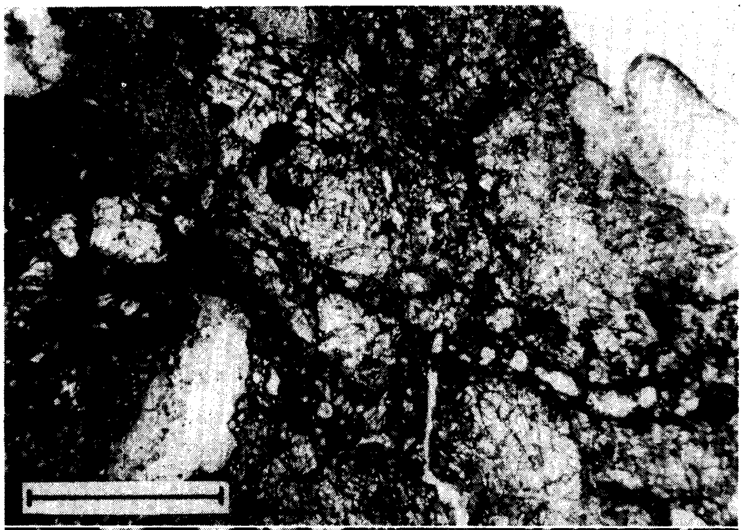

Photo 13. Irregular boundary of dark-light structure. Boundary is not clear and transitional. Transmitted light.

Photo 14. Porphyritic-olivine chondrule in Yamato-74115 chondrite. Narrow rim of clinopyroxene outlines the euhedral olivine grain. Groundmass of chondrule is fine intergrowth of ortho- and clinopyroxene. Transmitted light.

Photo 15. Skeletal-olivine chondrule in Yamato-74115 chondrite. Interstices of olivine and groundmass are composed of fine intergrowth of ortho- and clinopyroxene and/or devitrified glass with plagioclase composition. Transmitted light.

Scale bar is 0.5 mm.