PETROLOGICAL STUDIES OF YAMATO-74 METEORITES (2)

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Abstract: Six Yamato meteorites collected in 1974 in Antarctica are petrographically investigated. All of them are ordinary chondrites, recrystallized and shocked to various extent. From the texture and the chemical composition of olivine and orthopyroxene, Yamato-74079, -74155, -74190, -74371, -74418 and -74647 meteorites are classified respectively as H5, H4, L6, H5, H6 and H5 of VAN SCHUMUS and WOOD (1967). Difference in recrystallization of the matrices and the mineralogy is noticed between meteorites belonging to different petrologic types.

1. Introduction

In 1974, the 15th Japanese Antarctic Research Expedition (JARE-15) collected a suprisingly large number of meteorites, 663 pieces, near the Yamato Mountains in Antarctica (YANAI, 1976). They are called the Yamato-74 meteorites. In this paper, six of them, Yamato-74079, -74155, -74190, -74371, -74418 and -74647, are petrologically described. All the specimens are ordinary chondrites. Their modal composition was determined by a point counter (Table 1). The chemical composition of olivine, orthopyroxene and plagioclase was estimated by optical properties and expressed in molar percentage. For olivine, d_{130} spacing of X-ray powder pattern was also used to estimate the composition (SHINNO and HAYASHI, 1976). According to the chemical composition of olivine, Yamato-74079, -74155, -74371, -74418 and -74647 belong to H group and Yamato-74190 to L group (KEIL and FREDRIKSSON, 1964).

2. Petrography and Mineralogy

2.1. *Yamato-74155*

This meteorite is composed mainly of olivine, orthopyroxene and opaque minerals, with small amounts of Ca-poor clinopyroxene, Ca-rich clinopyroxene, cryptocrystalline materials, apatite and glass (Table 1).

The meteorite has abundant chondrules (Fig. 1), in the matrix consisting mainly of opaque minerals, fragments of chondrules and dark cryptocrystalline materials including fine olivine and pyroxene grains (Fig. 2). Cryptocrystalline materials are also present in chondrules. Glass is rarely noticed in some chondrules. Furthermore, Ca-poor clinopyroxene is often found. From these features it is evident that this meteorite has not been so highly recrystallized, and its

Table 1. Modal composition of Yamato meteorites (vol. %).

	Yamato-74155	Yamato-74079	Yamato-74371	Yamato-74647	Yamato-74418	Yamato-74190
Classification	H4	H5	H5	H5	H6	L6
Matrix						
Orthopyroxene	9.7	11.6	15.0	13.0	13.4	18.5
Ca-poor clinopyroxene	1.3	0.2	0.5	0.2	trace	—
Ca-rich clinopyroxene	0.2	0.4	0.5	0.3	0.7	0.7
Pigeonite	—	—	—	—	trace	trace
Olivine	52.7	62.3	59.3	60.6	63.1	67.9
Plagioclase	—	trace	trace	0.2	0.6	1.8
Cryptocrystalline materials	8.0	2.3	0.8	1.4	0.3	—
Spinel	—	trace	—	—	—	trace
Apatite	trace	—	trace	—	—	0.1
Opaque minerals	27.6	22.6	23.7	24.2	19.7	10.9
Others*	0.5	0.6	0.2	0.1	2.2	0.1
Total	100.0	100.0	100.0	100.0	100.0	100.0
Chondrule						
Orthopyroxene	23.2	37.3	23.4	47.6	39.8	63.4
Ca-poor clinopyroxene	9.2	1.4	1.8	1.3	—	—
Ca-rich clinopyroxene	2.7	1.9	2.6	1.1	8.2	12.4
Pigeonite	—	—	—	—	—	trace
Olivine	55.2	53.0	65.6	43.3	42.9	19.7
Plagioclase	—	trace	trace	0.7	5.1	2.8
Cryptocrystalline materials	6.3	5.5	4.0	2.7	1.0	—
Glass	trace	—	—	—	—	—
Opaque minerals	2.5	0.7	2.6	3.0	2.0	1.7
Others*	0.9	0.2	—	0.3	1.0	—
Total	100.0	100.0	100.0	100.0	100.0	100.0
Matrix	80.7	85.5	88.0	86.2	95.7	94.9
Chondrule	19.3	14.5	12.0	13.8	4.3	5.1
Total	100.0	100.0	100.0	100.0	100.0	100.0

* Brown-colored terrestrial weathering products.

petrologic type is estimated as 4.

Most of the chondrules, ranging from 0.3 to 1.0 mm in size, have distinct boundaries against the matrix, and are round, ovoid, ellipsoidal or irregular in shape. The chondrules can be classified into porphyritic, barred and radiating types of VAN SCHMUS (1969), of which porphyritic one is most abundant.

Table 2. Physical constants and molar composition of olivine, orthopyroxene and plagioclase in Yamato meteorites.

	Yamato-74155	Yamato-74079	Yamato-74371	Yamato-74647	Yamato-74418	Yamato-74190
Olvine						
d_{130}	2.7767	2.7754	2.7793	2.7774	2.7780	2.7818
$2V$(X)	89°	90°	88°	88°	88°	86°
Refractive indices						
α_D	1.667	1.661	1.667	1.665	1.672	1.678
γ_D	1.714	1.703	1.715	1.712	1.712	1.729
Unit cell parameters	(Å)					
a	4.746±0.014	4.763±0.006	4.771±0.002	4.773±0.005	4.773±0.002	4.784±0.006
b	10.275±0.012	10.254±0.005	10.243±0.002	10.242±0.006	10.256±0.002	10.267±0.004
c	6.021±0.006	6.015±0.003	5.998±0.002	5.995±0.006	6.008±0.001	5.984±0.011
Molar composition	$Fo_{83}Fa_{17}$	$Fo_{85}Fa_{15}$	$Fo_{80}Fa_{20}$	$Fo_{82}Fa_{18}$	$Fo_{81}Fa_{19}$	$Fo_{77}Fs_{23}$
Orthopyroxene						
$2V$(X)	81°	79°	81°	82°	79°	74°
Molar composition	$En_{32}Fs_{18}$	$En_{81}Fs_{19}$	$En_{82}Fs_{18}$	$En_{82}Fs_{18}$	$En_{81}Fs_{19}$	$En_{77}Fs_{23}$
Plagioclase						
$2V$(X)					57°	60°
Refractive indices						
α_D						1.536
γ_D						1.547
Molar composition					$An_{18}Ab_{82}$	$An_{20}Ab_{80}$

Most of the silicate minerals show wavy extinction and kink bands are also observed in some olivine grains, indicating shock effects.

Olivine (Fo_{83}) is most abundant in both the matrix and chondrules. They usually form euhedral or subhedral crystals, up to 0.8 mm. Sometimes small olivine grains are included in pyroxene.

Orthopyroxene, Ca-rich clinopyroxene and Ca-poor clinopyroxene are present, of which orthopyroxene (En_{82}) is most abundant, exhibiting euhedral to subhedral forms, up to 0.8 mm. Ca-poor clinopyroxene occurs as euhedral or subhedral, polysynthetically twinned crystals, up to 0.3 mm. The extinction angle ($Z \wedge c$) is about 25°. Some of them, as well as orthopyroxene, make up the radiating type chondrule (Fig. 3). Ca-rich clinopyroxene occurs as a reaction rim around orthopyroxene and Ca-poor clinopyroxene. They show higher birefringence than other pyroxenes. The extinction angle is about 40°.

Apatite is rarely present as anhedral grains, up to 0.2 mm, filling the interstices among other silicate minerals.

Dark brownish glass rarely present in chondrules is mostly devitrified.

Cryptocrystalline materials consist of aggregates of very fine grained, unidentified minerals (Fig. 4), owing to weak recrystallization of the glass in chondrules and dark matrix which are observed in petrologic type 3 chondrites.

Four kinds of opaque minerals, kamacite, taenite, troilite and chromite, are identified. They usually occur as anhedral crystals, interstitial among silicate minerals in the matrix. In the chondrules the amount of opaque minerals is small. Kamacite is most common, and sometimes occurs in intimate contact with taenite, or includes fine grains of opaque minerals. Under the crossed nicols in the reflected light, it is found that the troilite grain consists of differently oriented crystals. Chromite is also present in a small amount.

2.2. *Yamato-74079*

This meteorite is composed mainly of olivine, orthopyroxene and opaque minerals with small amounts of Ca-rich clinopyroxene, Ca-poor clinopyroxene, plagioclase, cryptocrystalline materials and spinel (Table 1).

The meteorite is a polimict breccia (WAHL, 1952), consisting of two parts, *i.e.*, normal chondritic part and brecciated part. In the latter (Fig. 5), angular fragments of silicate minerals are surrounded by the black, glassy matrix which has apparently resulted from localized fusion (VAN SCHMUS, 1969).

Various types of chondrules, 0.25 to 1.5 mm in size, are present but their shapes are less distinct than those in Yamato-74155. Glass is absent and plagioclase and Ca-poor clinopyroxene are rarely found. The matrix is more recrystallized than that of Yamato-74155. Accordingly, the petrologic type of this meteorite is 5.

Olivine (Fo_{85}) forms euhedral to anhedral crystals, up to 0.5 mm, and often shows wavy extinction. Some olivine crystals in the brecciated part have strong wavy extinction as well as kink bands (Fig. 6).

Orthopyroxene (En_{81}) occurs usually in a subhedral form, up to 0.5 mm.

Ca-rich clinopyroxene occurs as exsolution lamellae parallel to the (100) plane of the host orthopyroxene or as a reaction rim around orthopyroxene and Ca-poor clinopyroxene. Extinction angles of Ca-poor and Ca-rich clinopyroxenes are about 43° and 20°, respectively.

Very fine grains of spinel, up to 0.02 mm, are rarely included in olivine. They are isotropic, red to reddish brown in color.

Fine fibrous crystals of probably clinopyroxene are also found in the cryptocrystalline materials (Fig. 7).

Opaque phases consist of kamacite, taenite, troilite and chromite. They usually occur as anhedral grains, filling the interstices among other grains. In comparison with Yamato-74155, the amount of chromite is rather large.

2.3. *Yamato-74371*

This meteorite is composed mainly of olivine, orthopyroxene and opaque minerals, with small amounts of plagioclase, Ca-rich clinopyroxene, Ca-poor clinopyroxene, cryptocrystalline materials and apatite (Table 1).

Various types of chondrules, with comparatively distinguishable outlines, ranging from 0.3 to 1.2 mm in diameter, are distributed in the well-recrystallized matrix (Fig. 8). The petrologic feature of this meteorite is similar to that of Yamato-74079, and belongs to petrologic type 5.

Olivine (Fo_{80}) is usually euhedral or anhedral, up to 0.7 mm, and often shows wavy extinction. Rarely it is surrounded by a reaction rim of orthopyroxene.

Orthopyroxene (En_{82}) usually occurs as subhedral crystals, up to 1.0 mm, often surrounded by a reaction rim of Ca-rich clinopyroxene. Its extinction angle is about 40°. Rarely Ca-poor clinopyroxene, with the extinction angle of about 23°, is noticed, which is also surrounded by Ca-rich clinopyroxene as a reaction rim.

Only rarely plagioclase forms small untwinned crystals, less than 0.02 mm, filling the interstices among other silicate minerals.

Apatite and cryptocrystalline materials are also present, with characteristics similar to those in the above-mentioned meteorites.

Opaque minerals comprise kamacite, taenite, troilite and chromite.

2.4. *Yamato-74647*

This meteorite consists mainly of olivine, orthopyroxene and opaque minerals, with small amounts of plagioclase, Ca-rich clinopyroxene, Ca-poor clinopyroxene and cryptocrystalline materials (Table 1).

Chondrules, 0.5 to 1.5 mm in size, are hardly distinguished from well-recrystallized matrix (Fig. 9), and the texture is similar to those of the Yamato-74079 and -74371. Its petrologic type is 5.

Olivine (Fo_{82}) is subhedral in shape, ranging up to 1.0 mm, and shows wavy extinction. Sometimes it is surrounded by a thin reaction rim of clinopyroxene.

Orthopyroxene (En_{82}) forms subhedral and anhedral crystals, up to 1.0 mm. Ca-poor clinopyroxene is rarely present. Ca-rich clinopyroxene is also noticed

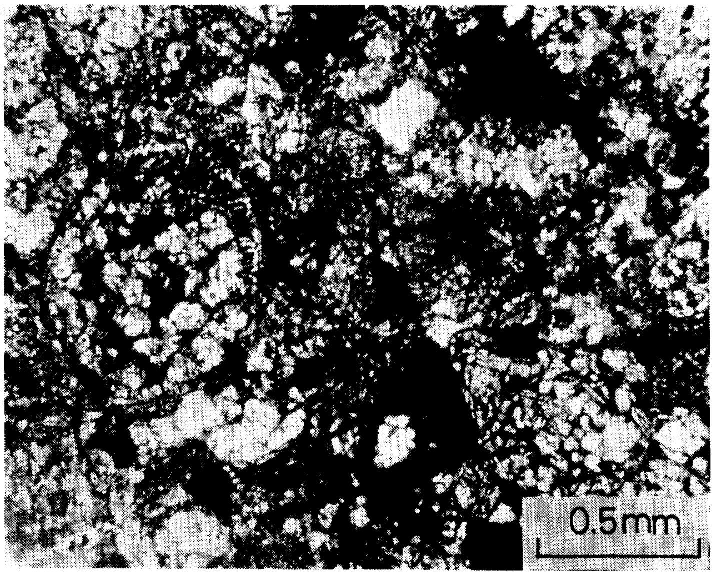

Fig. 1. Porphyritic and radial chondrules with distinct outlines are distributed in the poorly recrystallized matrix. Yamato-74155.

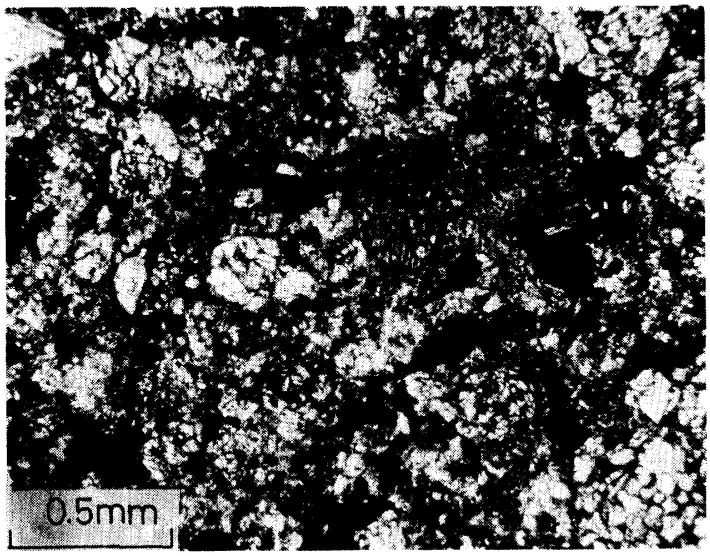

Fig. 2. Fine-grained matrix composed of fragments of silicate minerals, cryptocrystalline materials and opaque minerals. Yamato-74155.

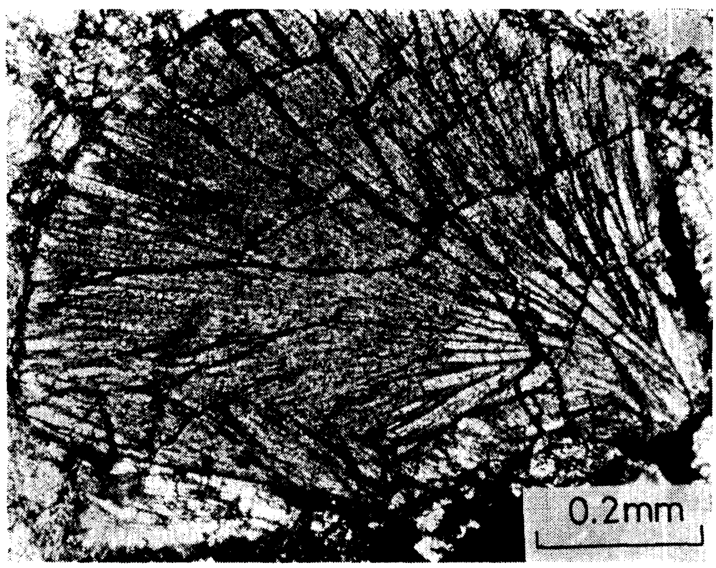

Fig. 3. An ellipsoidal radiating type chondrule consisting of Ca-poor clinopyroxene crystals. Yamato-74155.

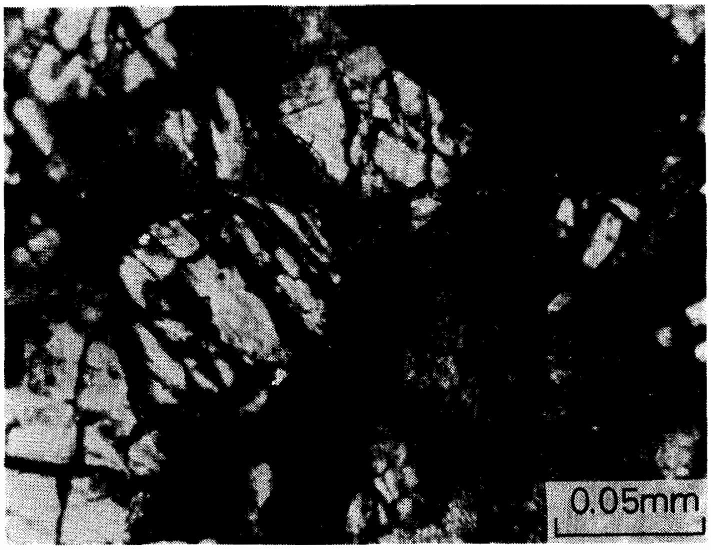

Fig. 4. Olivine and surrounding cryptocrystalline materials filled with unidentified minerals. Yamato-74155.

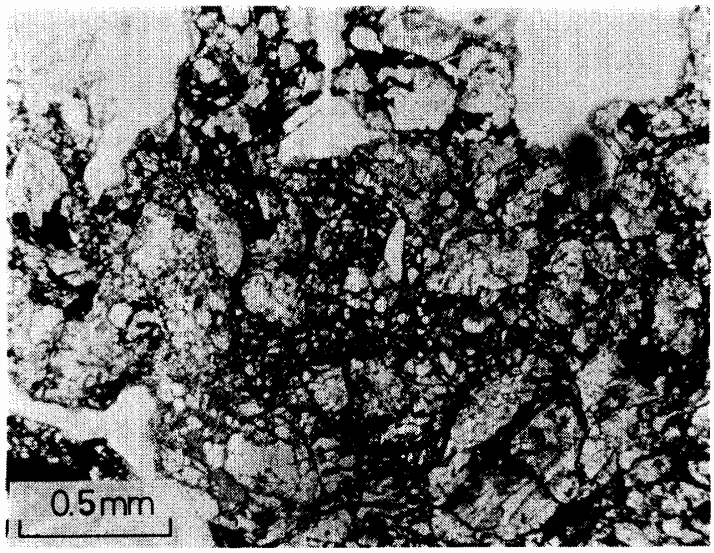

Fig. 5. Brecciated part consisting of fragments of minerals and locally fused, dark, glassy materials. Yamato-74079.

Fig. 6. Distinct kink bands in a broken olivine chondrule in the lower right corner of the brecciated part as shown in Fig. 5. Yamato-74079. Nicols crossed.

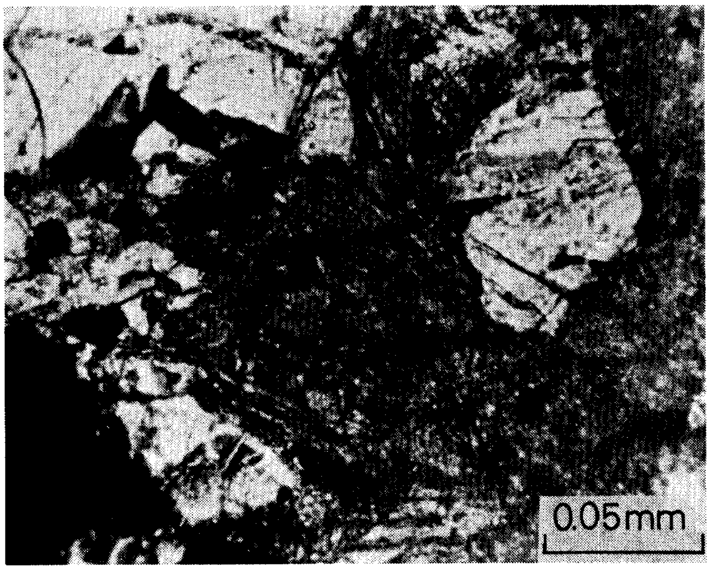

Fig. 7. Fibrous crystals of probably clinopyroxene in the cryptocrystalline materials surrounding olivine crystals. Yamato-74079.

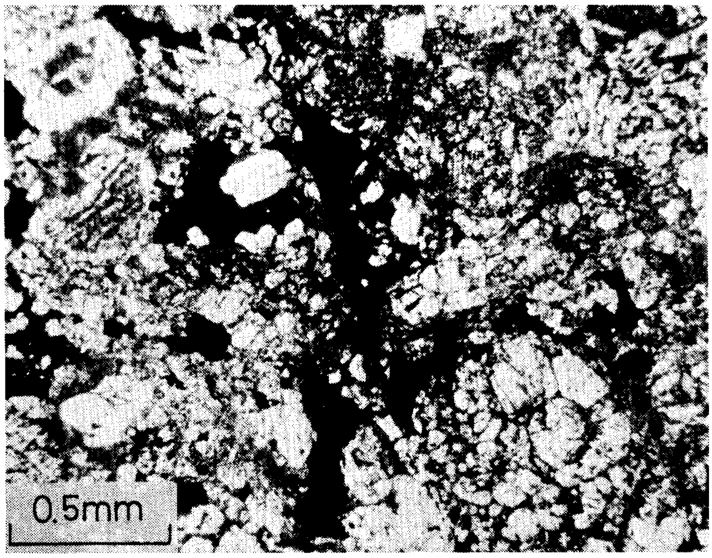

Fig. 8. Barred and porphyritic chondrules in the well-recrystallized matrix. Yamato-74371.

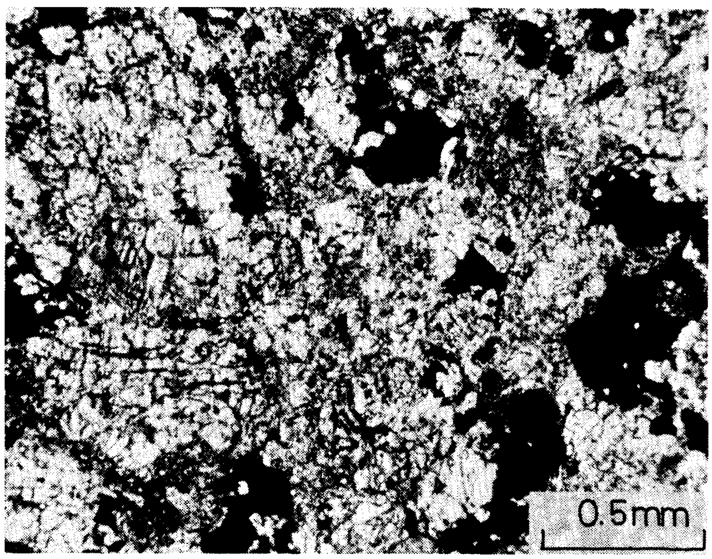

Fig. 9. Poorly distinguished two chondrules in the highly recrystallized matrix (in the left part). Yamato-74647.

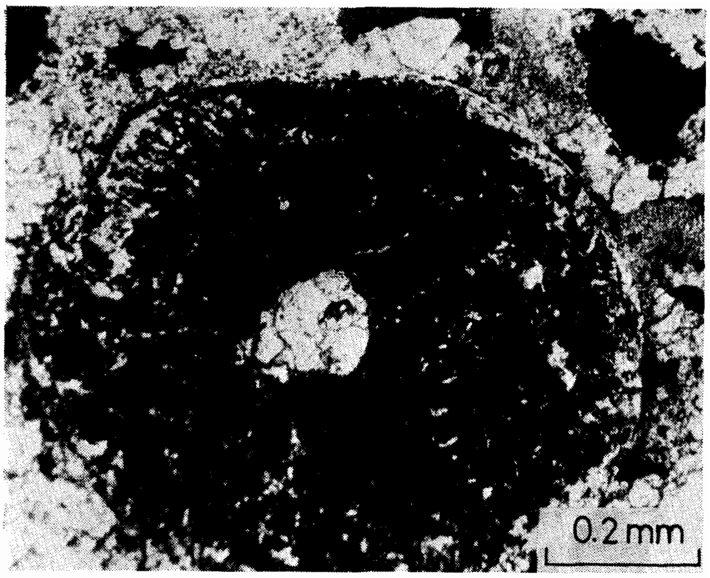

Fig. 10. A rounded chondrule consisting mostly of fine crystals of chromite, enclosing a crystal of orthopyroxene in the center. Yamato-74647.

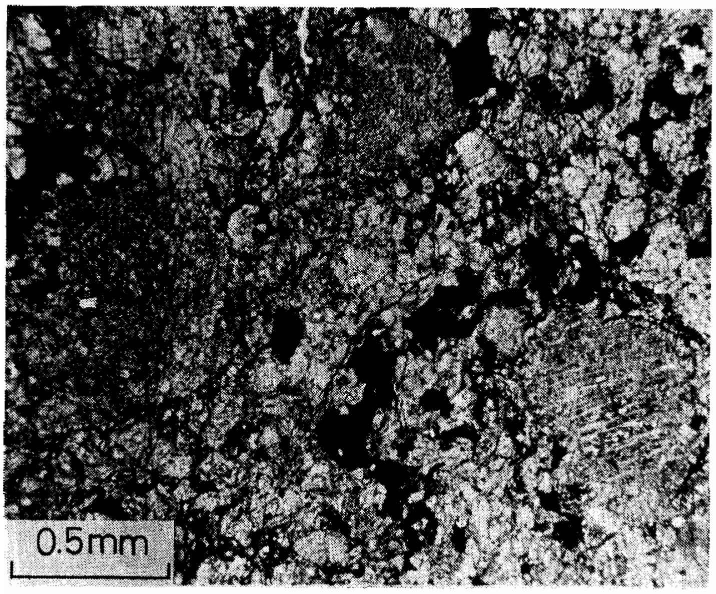

Fig. 11. Irregular-shaped chondrules in the highly recrystallized matrix. In the lower right corner, a barred-type chondrule, consisting of olivine and maskelynitized plagioclase, is noticed. Yamato-74418.

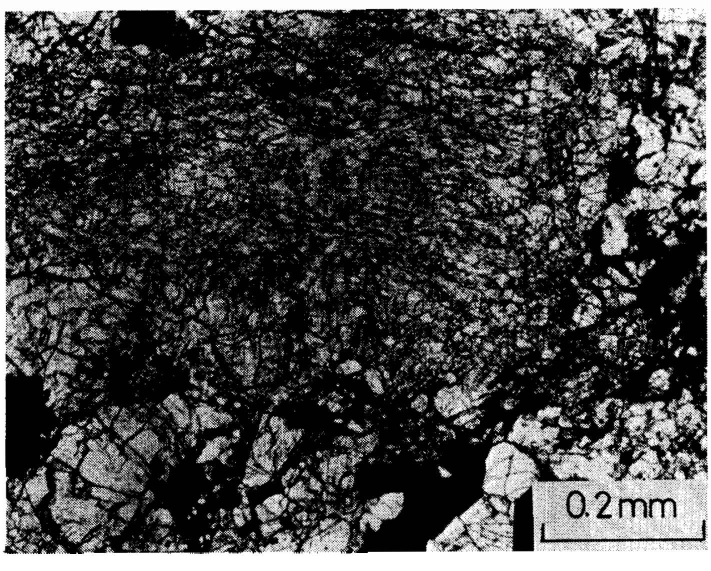

Fig. 12. Mosaic aggregate of differently oriented, rounded or elongated olivine crystals. Yamato-74418.

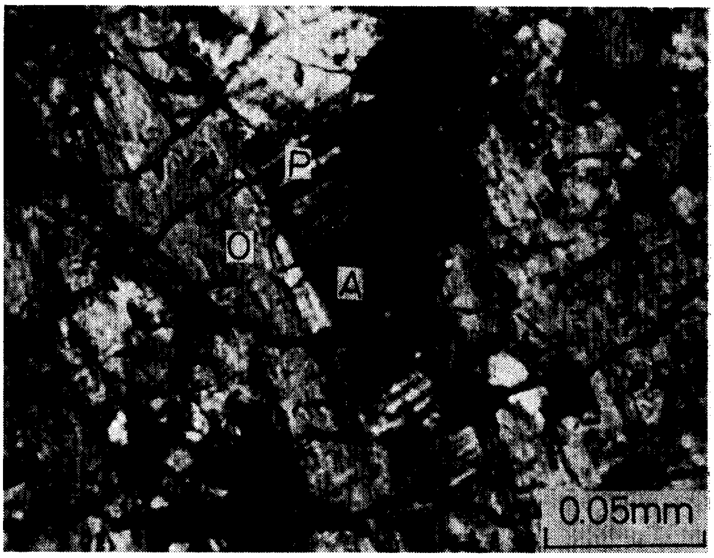

Fig. 13. Clinopyroxene (augite) lamellae (dark grey, A) enclosed in orthopyroxene (grey, O). The former (A) has numerous exsolution lamellae of clinopyroxene (pigeonite) (white, P), parallel to (001) plane. Yamato-74418. Nicols crossed.

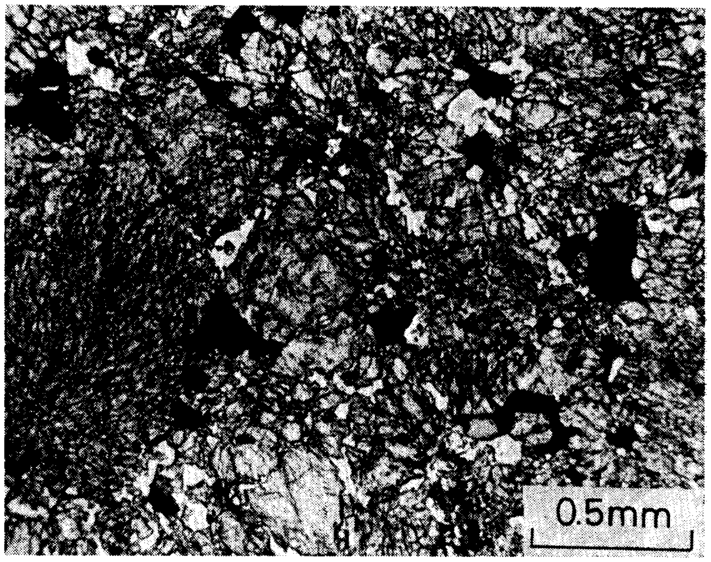

Fig. 14. An irregular-shaped chondrule consisting of radiating orthopyroxene crystals (left) enclosed in the highly recrystallized, coarse-grained matrix. Yamato-74190.

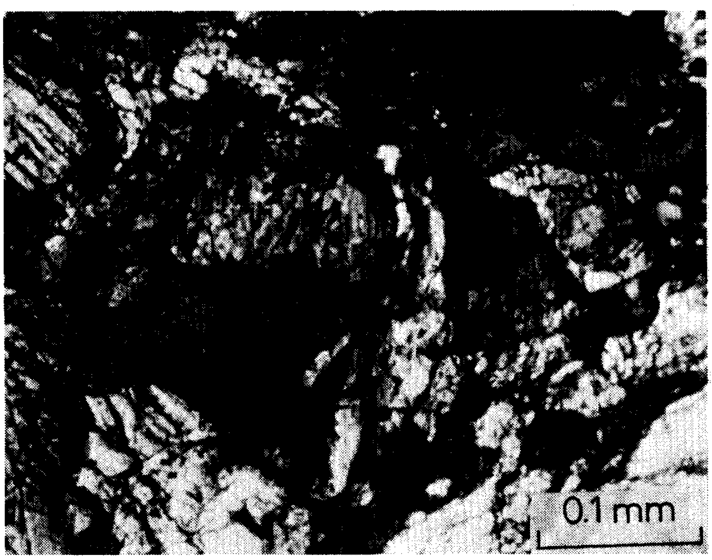

Fig. 15. Wavy extinction and kink bands in a large olivine crystal in the matrix. Yamato-74190. Nicols crossed.

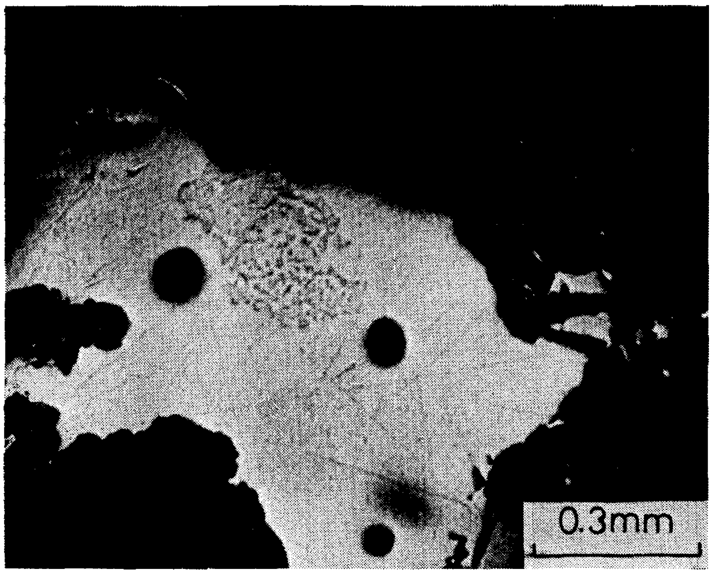

Fig. 16. Myrmekitic intergrowth of taenite (grey) in homogeneous kamacite (light grey). Yamato-74190. Reflected light.

as a reaction rim or exsolution lamellae in orthopyroxene.

Plagioclase occurs rarely as anhedral grains, less than 0.1 mm in size.

The opaque phases consist of kamacite, taenite, troilite and chromite. There is one chondrule which is composed mostly of the aggregate of very fine crystals of chromite (Fig. 10).

2.5. *Yamato-74418*

This meteorite comprises olivine, orthopyroxene and opaque minerals, with accessary plagioclase, Ca-rich clinopyroxene, Ca-poor clinopyroxene and cryptocrystalline materials (Table 1).

Though Ca-poor clinopyroxene and cryptocrystalline materials are rarely noticed, the matrix of this meteorite is highly recrystallized and the amount of chondrules is very small (Fig. 11). These features indicate that this meteorite belongs to petrologic type 6.

Most silicate minerals show distinct wavy extinction and plagioclase crystals are often maskelynitized. Veining consisting of fused, dark-colored materials, occurs in this meteorite (VAN SCHMUS, 1969). Moreover, constituent minerals sometimes consist of mosaic aggregates of differently oriented crystals (Fig. 12). These features resulted from the intensive shock event during cosmic collision (CARTER *et al.*, 1968).

Some silicate minerals are brownish in color, and opaque minerals are sometimes oxidized into reddish brown products due to terrestrial weathering.

Chondrules, 0.4 to 1.5 mm in size, are irregular in shape and similar to the matrix. Porphyritic type chondrules are less abundant compared with the abovementioned meteorites.

Olivine (Fo_{81}) occurs as subhedral or anhedral grains, up to 0.6 mm, and shows distinct wavy extinction and fractured feature.

Orthopyroxene (En_{81}) occurs as subhedral or anhedral crystals, up to 0.6 mm, and is sometimes accompanied by Ca-rich clinopyroxene as a reaction rim or exsolution lamellae. The extinction angle of Ca-rich clinopyroxene is about 39°. Rarely Ca-rich clinopyroxene lamellae, enclosed in a large orthopyroxene crystal, have further exsolution lamellae of other clinopyroxene (Fig. 13). Host and lamellae clinopyroxenes have the (011) plane and *b*-axis in common to each other. The former is probably augite, and the latter pigeonite. Only one Ca-poor clinopyroxene is found, which has a reaction rim of Ca-rich clinopyroxene, with the extinction angle of about 21°.

Plagioclase (An_{18}) forms anhedral crystals, filling the interstices among olivine and pyroxene grains. This is a high-temperature plagioclase.

The opaque minerals comprise kamacite, taenite, troilite and chromite. They often show complicated intergrowths with one another. Especially taenite and kamacite sometimes form myrmekitic intergrowth.

2.6. *Yamato-74190*

This meteorite is composed mainly of olivine, orthopyroxene and opaque minerals, with small amounts of plagioclase, Ca-rich clinopyroxene, apatite and spinel (Table 1).

The meteorite is well-recrystallized like Yamato-74418, and most of chondrules, irregular in shape, are no longer distinguishable from the granular matrix (Fig. 14). They are radiating or barred types, while porphyritic one is absent.

Most of the silicate minerals show wavy extinction and kink bands (Fig. 15), and plagioclase is sometimes completely or partially maskelynitized.

Olivine (Fo_{75}) occurs usually as subhedral grains, up to 2 mm.

Orthopyroxene (En_{77}) occurs usually as subhedral grains, up to 1.7 mm, sometimes accompanied by Ca-rich clinopyroxene reaction rims or exsolution lamellae. The extinction angle is about 37°. Rarely Ca-rich clinopyroxene surrounding orthopyroxene as a reaction rim has exsolution lamellae of clinopyroxene, probably pigeonite.

Plagioclase (An_{20}) is often present as anhedral grains, up to 0.2 mm, rarely twinned on albite law. This is a high-temperature type.

Apatite is often present as anhedral grains, up to 0.4 mm, filling the interstices among other grains in the matrix.

Very fine grains of spinel, 0.001 to 0.002 mm in size, are rarely included in olivine.

Four kinds of opaque minerals, kamacite, taenite, troilite and chromite, are observed. Aggregates of very fine chromite crystals are often included in silicate minerals. Myrmekitic intergrowths of kamacite and taenite are found (Fig. 16).

3. Discussion

From the petrography and the composition of olivine, the Yamato-74155, -74079, -74371, -74647, -74418 and -74190 meteorites are respectively H4, H5, H5, H5, H6 and L6. Clear differences in texture and modal compositions (Table 1) are noticed among meteorites of different petrologic types.

The matrix of Yamato-74155 (H4) is least recrystallized, consisting of opaque minerals, fragments of silicate grains and cryptocrystalline materials, and is rich in various types of chondrules which are clearly distinguished from the matrix. Most of them still retain their original shape. The amount of Ca-poor clinopyroxene is fairly large. A fairly high content of cryptocrystalline materials is noticed and rare glass is also present, but plagioclase is absent. All these features indicate a low grade of recrystallization.

On the contrary, the matrices of Yamato-74079, -74371 and -74647 (all H5) are recrystallized to a considerable extent. Although various types of chondrules are noticed, their amount is not so large, and some chondrules are similar to the matrix in both texture and mineralogy. Ca-poor clinopyroxene and cryptocrystalline materials are rarely noticed. Plagioclase, though very small in size, is often found.

Yamato-74418 (H6) has features similar to the H5 chondrites, *i.e.*, the presence of Ca-poor clinopyroxene and cryptocrystalline materials, though they are much smaller in amount. This meteorite has also features similar to Yamato-74190 (L6) as mentioned below. Both are characterized by the high grade recrystallization of matrices, and the very small amount of chondrules and their irregular shape. The difference between chondrules and matrix is not distinct. Porphyritic type chondrules are rare, whereas plagioclase is often found, sometimes attaining to a large size. Some orthopyroxenes have exsolution lamellae of Ca-rich clinopyroxene. All these features indicate an advanced stage of recrystallization.

Modes of exsolution in pyroxenes in general deserve special mention. Exsolution of Ca-rich clinopyroxene lamellae parallel to (100) in the orthopyroxene is noticed in both H5 and H6 chondrites, whereas the exsolution of pigeonite lamellae parallel to (011) in the Ca-rich clinopyroxene (augite) is confined to H6 and L6 chondrites.

In the present case it is noticed that the content of chromite increases with increasing petrologic type, as described by DODD *et al.* (1967).

Regardless of the chemical groups and petrologic types, the evidences of shock effects such as wavy extinction, kink band and fractured texture are noticed in the silicate minerals of all of these meteorites. Especially, Yamato-74418 was intensively shocked, which is indicated by mosaic feature of the silicate minerals (CARTER *et al.*, 1968).

Acknowledgments

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References

CARTER, N. L., RALEIGH, C. B. and DECARLI, P. S. (1968): Deformation of olivine in stony meteorites. J. Geophys. Res., **73**, 5439–5461.

DODD, R. T., VAN SCHMUS, W. R. and KOFFMAN, D. M. (1967): A survey of the unequilibrated ordinary chondrites. Geochim. Cosmochim. Acta, **31**, 921–951.

KEIL, K. and FREDRIKSSON, K. (1964): The iron, magnesium, and calcium distribution in coexisting olivine and rhombic pyroxenes of chondrites. J. Geophys. Res., **69**, 3487–3515.

SHINNO, I. and HAYASHI, M. (1976): Kanranseki no kagaku sosei to koshi-men kankaku d_{130} (Chemical composition and d_{130}-spacing of olivine). Kobutsugaku Zasshi (J. Miner. Soc. Japan), **12**, Spec. Issue, 194–205.

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

VAN SCHMUS, W. R. and WOOD, J. A. (1967): A chemical-petrologic classification for the chondrites. Geochim. Cosmochim. Acta, **31**, 747–765.

WAHL, W. (1952): The brecciated stony meteorites and meteorites containing foreign fragments. Geochim. Cosmochim. Acta, **2**, 1269–1278.

YANAI, K. (1976): 1974-nen no nankyoku-san Yamato inseki no tansa to saishû (Search and collection of Yamato meteorites, Antarctica, in October and November 1974). Nankyoku Shiryo (Antarct. Rec.), **56**, 70–81.

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