MINERALOGICAL AND PETROGRAPHICAL STUDIES OF THE YAMATO METEORITES, YAMATO-7301(j), -7305(k), -7308(l) AND -7303(m) FROM ANTARCTICA

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Abstract: **In 1973, the 14th Japanese Antarctic Research Expedition party collected twelve meteoritic stones in the bare ice field near the Yamato Mountains, Antarctica. Four of the stones were named Yamato-7301, -7305, -7308 and -7303. Yamato-7301, -7305 and -7303 are ordinary chondrites and are classified respectively as H4, L5 and L5 chondrites, while Yamato-7308 is a howardite. Yamato-7301, -7305 and -7303 are composed chiefly of olivine (Fo_{75-80}) and orthopyroxene (En_{75-83}), with subordinate amounts of clinopyroxene, plagioclase and phosphate minerals. Opaque minerals, nickel-iron, troilite and chromite, are more abundant in Yamato-7301 than in Yamato-7305 and -7303. Yamato-7308 is composed mainly of pyroxene and plagioclase (anorthite), with olivine, silica minerals, opaque minerals and glassy material in minor amounts. The composition of orthopyroxene is variable ranging from En_{80} to En_{37}, and also clinopyroxene varies considerably in composition. The result suggests that Yamato-7308 originated from the fractional crystallization of the parent magma of the achondrite.**

1. Introduction

In 1969, the 10th Japanese Antarctic Research Expedition (JARE-10) found nine meteoritic stones near the Yamato Mountains in Antarctica (YOSHIDA *et al.*, 1971). Afterwards, these stones were confirmed to be meteorites belonging to different types, *i.e.*, an enstatite chondrite, a hypersthene achondrite, a C3 chondrite and ordinary chondrites (SHIMA *et al.*, 1973). Therefore, the JARE-14 resurveyed the same area in the hope of finding more meteorites, and succeeded in collecting twelve meteoritic stones in the bare ice field in December 1973 (SHIRAISHI *et al.*, 1976). Four of the stones were named Yamato-7301, -7305, -7308 and -7303. Of these, Yamato-7301, -7305 and -7303 are chondrites weighing 650, 900 and 500 grams, respectively. Yamato-7308 is an achondrite, 480 grams in weight. This paper presents the mineralogical and petrographical studies of the meteorites. The details of petrological aspects will be soon published elsewhere (YAGI *et al.*, 1978).

2. Structure and Mineralogy

2.1. Yamato-7301

Yamato-7301 meteorite is an ordinary chondrite, consisting of silicate minerals, olivine, pyroxene and plagioclase, and opaque minerals, nickel-iron, troilite and chromite. Subordinate amount of apatite is present. Owing to weathering, most part of nickel-iron and sulfide minerals in this meteorite are oxidized into reddish brown weathering products. Chondrules consisting mainly of olivine and orthopyroxene are generally spherical in shape (Fig. 1), and show various internal structures, *i.e.*, radiating, microporphyritic and so on. The interstices among olivine and pyroxene crystals are filled with dark-colored, microcrystalline materials and occasionally fine laths of pyroxene crystal, but glassy material is not found. Chondrules can be clearly recognized in the matrix, but the chondrule-matrix boundary is not very distinct.

Olivine: The composition is $Fo_{79\text{-}80}$ by the probe analysis (Table 1) and $Fo_{77\text{-}82}$ by the optics ($2V = -85°$ to $-88°$). Olivine crystals both in chondrules and in the matrix are generally corroded along their margin. A thin reaction rim of orthopyroxene is commonly present around olivine crystals in chondrules. A few grains of olivine show a zonal structure, which is due to the dispersive occurrence of very fine-grained and transparent particles.

Table 1. Electron microprobe analyses of olivines (wt. %).

	A	B	C	D	E	F	G
SiO_2	39.06	39.08	38.57	39.32	37.69	38.23	36.33
TiO_2	0.01	0.00	0.02	0.00	0.05	0.02	0.00
Al_2O_3	0.02	0.03	0.02	0.02	0.01	0.01	0.00
FeO	18.42	18.99	21.68	22.10	22.78	23.15	33.19
MnO	0.40	0.41	0.43	0.44	0.42	0.38	0.66
MgO	41.80	41.72	38.39	37.87	38.14	37.58	29.21
CaO	0.02	0.07	0.03	0.03	0.02	0.02	0.07
Na_2O	0.01	0.01	0.00	0.01	0.01	0.00	0.00
Cr_2O_3	0.04	0.15	—	—	0.01	0.01	—
NiO	0.02	0.00	—	—	0.03	0.00	—
Total	99.80	100.46	99.14	99.79	99.16	99.40	99.46
Fo	79.8	79.3	75.5	75.0	74.5	74.0	60.5
Fa	20.2	20.7	24.5	25.0	25.5	26.0	39.5

A and B: Olivines from Yamato-7301
C and D: Olivines from Yamato-7305
E and F: Olivines from Yamato-7303
G: Olivine from Yamato-7308

Table 2. Electron microprobe analyses of orthopyroxenes (wt. %).

	A	B	C	D	E	F	G	H	I	J	K	L	M
SiO_2	56.57	55.95	56.35	56.07	56.47	56.15	55.94	55.18	54.09	52.71	52.17	51.50	49.44
TiO_2	0.18	0.13	—	0.23	0.23	0.14	0.04	0.10	0.25	0.24	0.44	0.18	0.46
Al_2O_3	0.19	—	—	0.15	0.13	0.14	0.49	0.53	0.50	0.40	0.44	0.24	0.31
FeO	11.43	11.59	13.60	13.68	13.82	14.26	14.02	15.26	20.12	23.42	26.39	29.62	35.45
MnO	0.53	0.40	0.35	0.46	0.47	0.45	0.51	0.49	0.59	0.74	0.90	0.88	1.03
MgO	29.95	30.32	29.23	28.47	27.97	28.30	27.08	27.30	23.31	20.39	17.90	15.63	11.73
CaO	0.87	0.83	0.61	0.61	0.80	0.62	0.84	0.78	1.11	1.45	1.49	1.32	1.40
Na_2O	0.02	—	—	0.00	0.02	0.00	0.02	0.00	0.02	0.03	0.02	0.02	0.00
Cr_2O_3	0.21	—	0.13	—	0.11	0.08	0.35	0.38	0.36	—	0.22	0.11	0.09
NiO	0.01	—	—	—	0.09	0.05	0.00	0.00	0.00	—	0.02	0.01	0.00
Total	99.96	99.23	100.27	99.67	100.11	100.19	99.30	100.02	100.35	99.38	99.99	99.50	99.91
Wo	1.6	1.6	1.2	1.2	1.5	1.0	1.7	1.6	2.1	3.0	3.2	2.5	3.1
En	80.6	80.5	78.0	77.3	76.4	76.7	76.4	75.1	65.3	58.2	53.2	46.6	36.2
Fs	17.8	17.9	20.8	21.5	22.1	22.3	21.9	23.3	32.6	38.8	43.6	50.9	60.7

A and B: Bronzites from Yamato-7301
C and D: Bronzites from Yamato-7305
E and F: Bronzites from Yamato-7303
G–M: Orthopyroxenes from Yamato-7308

Table 3. Electron microprobe analyses of clinopyroxenes (wt. %).

	A	B	C	D	E	F	G	H	I	J
SiO_2	55.04	55.09	53.95	54.43	52.49	52.12	51.08	52.25	48.46	52.15
TiO_2	0.34	0.35	0.47	0.48	0.73	0.65	0.89	0.32	0.72	0.29
Al_2O_3	1.14	0.39	0.43	0.47	0.73	0.95	1.08	0.36	1.66	0.45
FeO	4.70	6.37	4.76	5.59	9.91	12.04	17.54	25.77	26.12	28.81
MnO	0.32	0.30	0.28	0.21	0.45	0.50	0.54	1.33	0.87	0.79
MgO	16.88	20.09	16.22	15.56	14.72	12.94	9.93	18.78	8.46	14.41
CaO	19.25	16.66	22.06	21.60	20.54	20.45	19.22	1.92	12.84	3.81
Na_2O	0.78	0.39	0.56	0.52	0.15	0.16	0.10	0.00	0.05	0.03
Cr_2O_3	0.66	0.70	0.82	0.89	—	0.38	0.37	—	—	—
NiO	0.00	0.02	0.04	0.12	—	0.01	0.00	—	—	—
Total	99.11	100.36	99.59	99.87	99.72	100.20	100.75	100.73	99.18	100.74
Wo	41.5	33.5	45.4	45.3	42.0	42.6	41.1	4.0	28.2	8.1
En	50.3	56.2	46.4	45.3	41.5	37.8	29.8	53.0	25.7	42.7
Fs	8.2	10.3	8.2	9.4	16.5	19.6	29.1	43.0	46.1	49.2

A and B: Augites from Yamato-7301
C and D: Augites from Yamato-7303
E–G: Augites from Yamato-7308
H: Clinohypersthene from Yamato-7308
I: Subcalcic ferroaugite from Yamato-7308
J: Pigeonite from Yamato-7308

Pyroxene: The composition of orthopyroxene is $\mathrm{En}_{80\text{-}81}$ by the probe (Table 2) and $\mathrm{En}_{77\text{-}81}$ by the optics ($2V = -75°$ to $-80°$). Several orthopyroxene crystals have a reaction rim of augite, the optic axial angle and the extinction angle of which are $2V = +53°$ and $c \wedge Z = 47° - 48°$, respectively. The microprobe analysis of augite is $\mathrm{Wo}_{42\text{-}34}$ $\mathrm{En}_{50\text{-}56}$ $\mathrm{Fs}_{8\text{-}10}$ (Table 3).

Plagioclase: Plagioclase is generally minute and anhedral, and occurs interstitially among other silicate and opaque grains. The composition is $\mathrm{An}_{18\text{-}30}$ ($2V = -60°$ to $-74°$) by the optics. Plagioclase in this meteorite exhibits a high-temperature polymorph. Albite-twinning is occasionally observed.

Apatite: Apatite is present in a minor amount as subhedral or anhedral grains in the matrix. The optic axial angle is very small and biaxially negative.

Opaque minerals: The opaque phase of this meteorite is composed of kamacite, taenite, troilite and chromite. The reddish brown oxidation products of weathering are present around nickel-iron and troilite grains.

2.2. *Yamato-7305*

Yamato-7305 meteorite is also an ordinary chondrite. The mineral composition is olivine, pyroxene, plagioclase, apatite and opaque minerals. In the plane polarized light, chondrules are recognizable in the matrix, but the chondrule-matrix boundary is poorly defined (Fig. 2). In the thin section of this meteorite,

Table 4. Electron microprobe analyses of plagioclases and maskelynites (wt. %).

	A	B	C	D	E	F	G
SiO_2	66.32	66.88	45.18	44.98	45.78	45.34	45.63
TiO_2	0.07	0.00	0.04	0.05	0.03	0.00	0.00
Al_2O_3	21.04	22.02	35.22	35.22	33.60	34.36	34.49
FeO	0.28	0.92	0.11	0.07	0.17	0.32	0.01
MnO	0.01	0.00	0.01	0.03	0.03	0.01	0.03
MgO	0.03	0.71	0.02	0.03	0.03	0.02	0.02
CaO	2.17	2.09	19.42	18.70	18.10	19.05	18.83
Na_2O	8.66	6.35	0.73	0.73	1.24	0.91	0.91
K_2O	1.08	1.59	0.03	0.05	0.08	0.07	0.08
Cr_2O_3	—	—	0.00	—	—	0.02	0.00
NiO	—	—	0.00	—	—	0.00	0.00
BaO	—	—	0.00	—	—	0.00	0.00
Total	99.66	100.56	100.77	99.86	99.06	100.09	99.99
Or	6.7	12.2	0.2	0.3	0.5	0.4	0.5
Ab	82.0	74.3	6.2	6.4	11.0	8.3	8.3
An	11.3	13.5	93.6	93.3	88.5	91.3	91.2

A: Oligoclase from Yamato-7305
B: Oligoclase from Yamato-7303
C–E: Anorthites from Yamato-7308
F and G: Maskelynites from Yamato-7308

fused veins are present penetrating the matrix. The veins are dark brown in color, and are composed of vitrified silicate material and spherular microparticles of troilite and nickel-iron (Fig. 3).

Olivine: Olivine is usually anhedral in the matrix, and euhedral or subhedral in several chondrules. Olivine crystals in chondrules are occasionally corroded and surrounded with a thin rim of orthopyroxene. The composition is $Fo_{75\text{-}76}$ by the probe (Table 1) and Fo_{75-78} ($2V = -85°$ to $-86°$) by the optics.

Pyroxene: Orthopyroxene, En_{77-78} by the microprobe analysis (Table 2), is subhedral or anhedral in shape, and several grains are surrounded by the rim of augite. Stillwater-type exsolution lamellas of clinopyroxene are found in a few augite grains.

Plagioclase: Plagioclase in high-temperature form occurs as an interstitial material among olivine, pyroxene and opaque grains in both the matrix and the chondrules. The composition is An_{11} by the probe (Table 4) and $An_{14\text{-}18}$ ($2V = -55°$ to $-59°$) by the optics. Albite-twinning is observed in several grains.

Opaque minerals: Kamacite, taenite, troilite and chromite are present in this meteorite.

2.3. *Yamato-7308*

Yamato-7308 meteorite is classified as a pyroxene-plagioclase achondrite. It contains significant amounts of Ca-rich plagioclase and Ca-poor ortho- and clinopyroxenes and subordinate amounts of silica minerals, olivine and opaque minerals. The matrix is characterized by the brecciated structure consisting of large, angular grains of pyroxene and plagioclase embedded in the fine-grained matrix of the same mineral grains (Fig. 4). As various kinds of lithic fragments are present in the matrix, Yamato-7308 is assigned to a howardite, or a polymict breccia.

2.3.1. Diogenite fragment

This fragment consists mainly of equigranular crystals of orthopyroxene (bronzite), with a subordinate amount of minute, opaque grains (Fig. 5).

2.3.2. Eucrite fragment

The fragment contains lath-shaped plagioclase crystals enclosed by brown-colored pigeonite grains, showing a typical ophitic texture (Fig. 6). Plagioclase laths exhibit Carlsbad-twinning, and exsolution lamellas of augite are distinct in parallel to the (100) plane of the host pigeonite.

2.3.3. Adcumulus fragment

Fig. 7 shows a fragment consisting of nearly equigranular aggregate of plagioclase and pigeonite crystals. Every grain of pigeonite has well-developed exsolution lamellas of augite. Small grains of silica minerals, probably quartz and tridymite, are occasionally found.

2.3.4. Nodular orthopyroxene aggregates

These fragments are composed mainly of orthopyroxene aggregates, but the structure is not diogenitic. One fragment consists of complicated aggregate of fine-grained orthopyroxene with minor amounts of opaque grains, clinopyroxene and plagioclase (Fig. 8). The other has a core consisting of equigranular aggregates of orthopyroxene, which are surrounded by aggregates of fine needles of orthopyroxene crystals (Fig. 9).

2.3.5. Glass and devitrified glass fragments

A pale yellow and transparent glassy fragment contains euhedral, long rectangular crystals of orthopyroxene (Fig. 10). Orthopyroxene grains are generally rimmed with augite, whereas the devitrified glass fragment, brown and

Table 5. Electron microprobe analyses of quartz and glass spherules from Yamato-7308 (wt. %).

	A	B	C	D	E
SiO^2	98.03	98.74	53.23	52.42	50.97
TiO_2	0.24	0.21	0.25	0.30	0.20
Al_2O_3	0.26	0.40	5.78	6.04	4.93
FeO	0.58	0.16	15.63	16.00	16.79
MnO	0.06	0.00	0.55	0.53	0.56
MgO	0.39	0.00	18.89	18.98	20.72
CaO	0.86	0.04	4.86	4.54	3.90
Na_2O	0.00	0.11	0.06	0.11	0.08
K_2O	0.01	0.03	0.16	0.16	0.20
Cr_2O_2	0.03	—	0.87	0.80	1.08
NiO	0.02	—	0.00	0.00	0.04
BaO	0.00	—	0.00	0.00	0.00
Total	100.48	99.69	100.28	99.88	99.48

	m		CIPW norm	
	Q	2.46	1.02	—
	Or	1.11	1.11	1.11
	Ab	0.52	1.05	0.52
	An	15.02	15.30	12.52
Di	Wo	3.83	3.02	2.90
	En	2.31	1.81	1.71
	Fs	1.32	1.06	1.06
Hy	En	44.77	45.47	45.77
	Fs	27.30	28.09	27.04
Ol	Fo	—	—	2.88
	Fa	—	—	1.94
	Cm	1.34	1.12	1.57
	Il	0.46	0.61	0.46

A and B: Quartz
C–E: Glass spherules

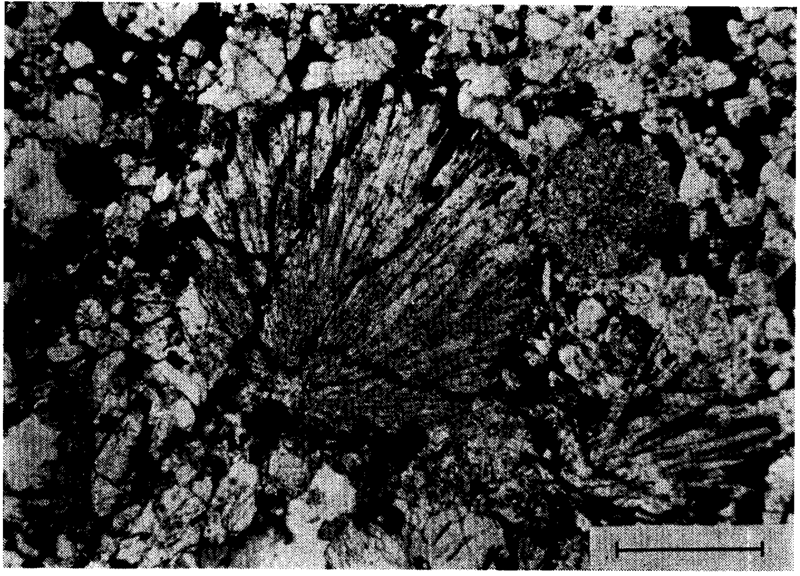

Fig. 1. Thin section of Yamato-7301. Matrix is rich in opaque minerals, and a radiating chondrule is composed of ortho-pyroxene crystals. The bar is 0.5 mm in length.

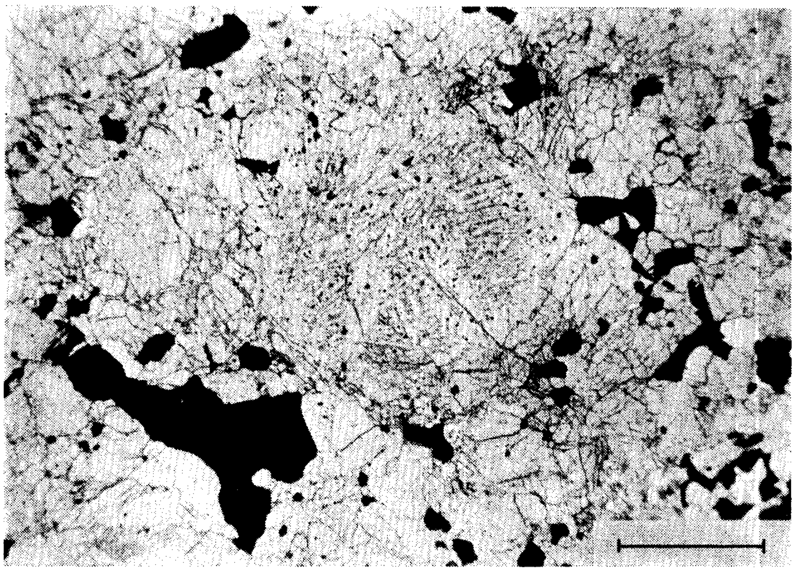

Fig. 2. Thin section of Yamato-7305. The chondrule in the center of the photograph is composed of olivine, and it is poorly defined in the matrix. The bar is 0.5 mm in length.

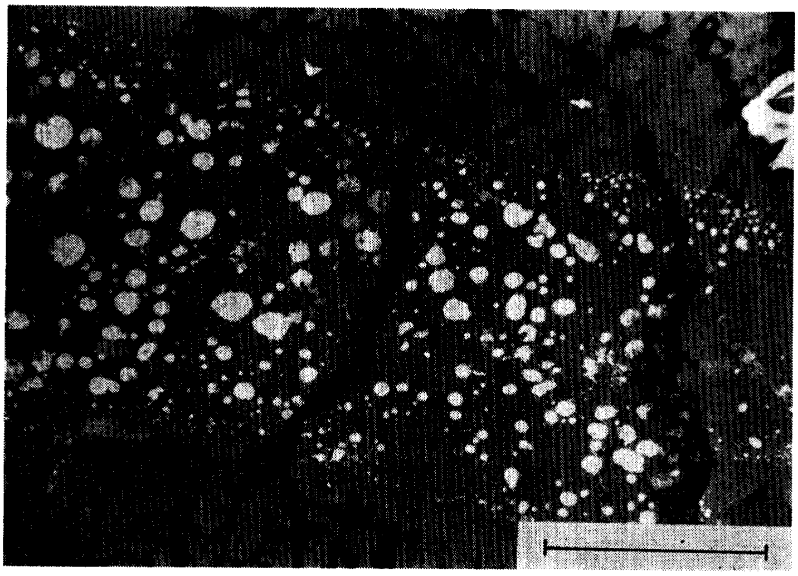

Fig. 3. Fused particles composed of troilite and nickel-iron occurring in the fused veins in the matrix of Yamato-7305. Reflected light. The bar is 0.1 mm in length.

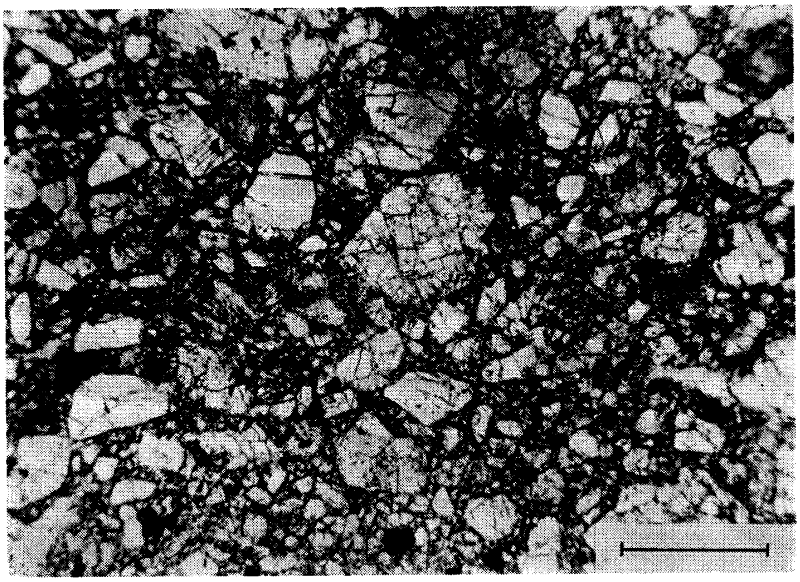

Fig. 4. Brecciated structure consisting of angular pyroxene and plagioclase grains in the matrix of Yamato-7308. The bar is 0.5 mm in length.

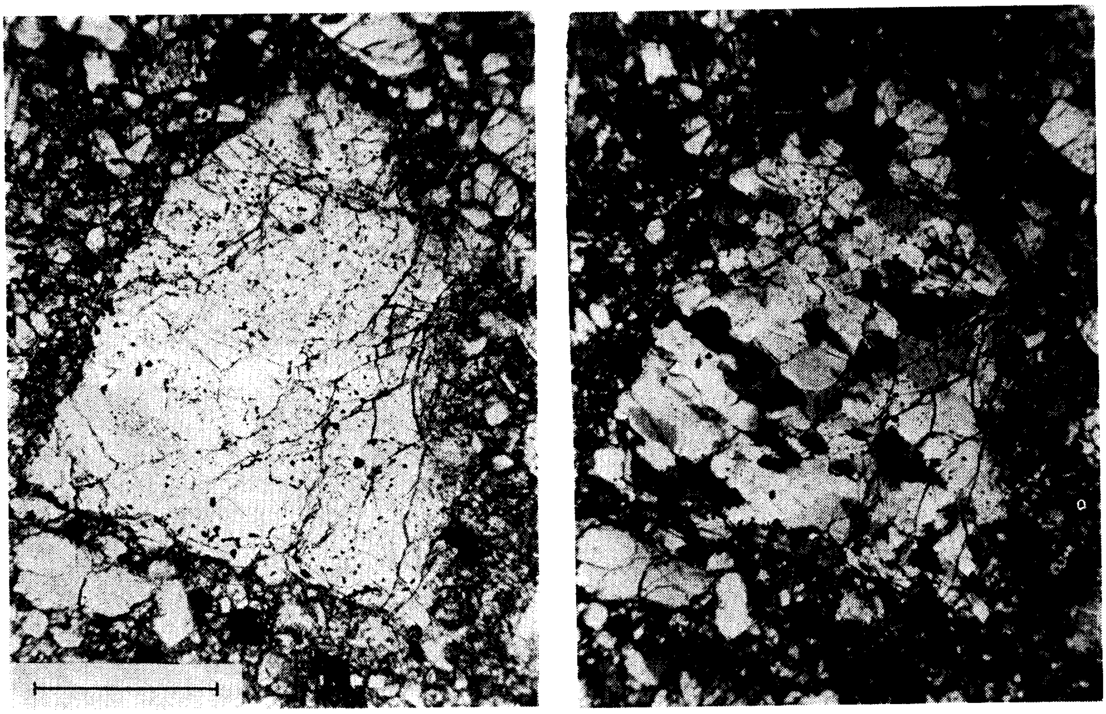

Fig. 5. A diogenite fragment composed of equigranular orthopyroxene grains in Yamato-7308. The bar is 0.5 mm in length. Left: Open nicols; Right: Cross nicols.

Fig. 6. An ophitic-textured fragment composed of pigeonite and plagioclase in Yamato-7308. The bar is 0.1 mm in length.

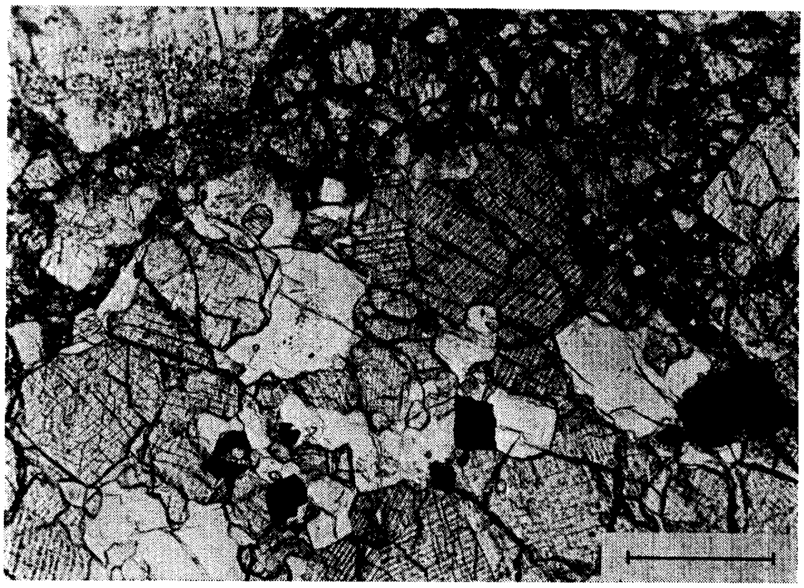

Fig. 7. An adcumulate fragment composed of pigeonite and plagioclase in Yamato-7308. Exsolution lamellas of augite are distinct in pigeonite grains. The bar is 0.2 mm in length.

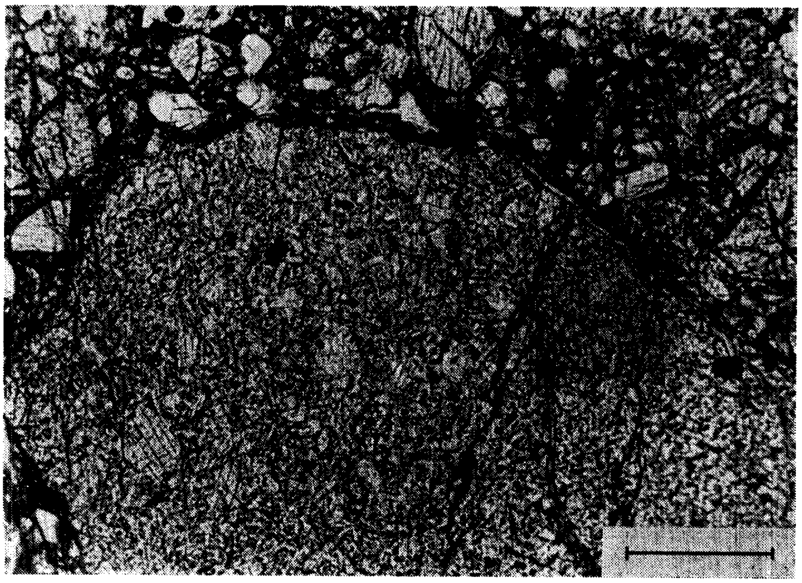

Fig. 8. A nodular fragment composed largely of fine-grained orthopyroxene aggregate in Yamato-7308. The bar is 0.2 mm in length.

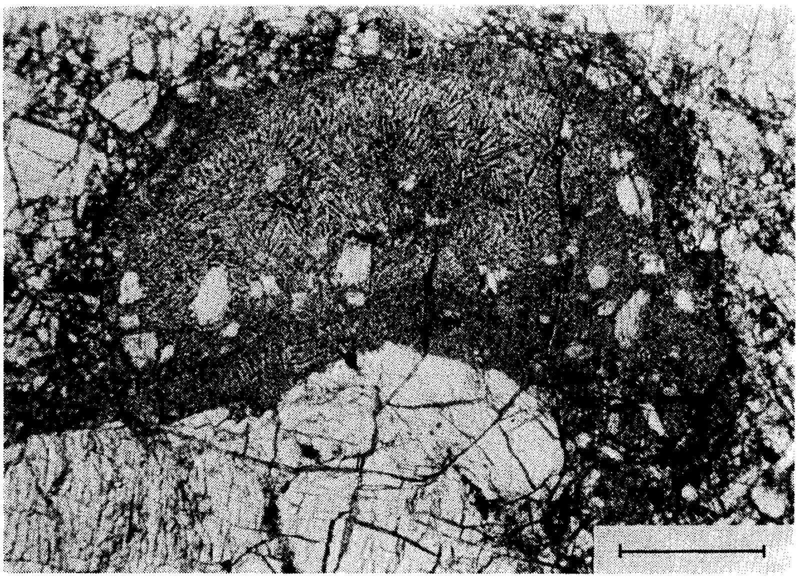

Fig. 9. A fragment composed of fine needles of orthopyroxene surrounding the coarse-grained orthopyroxene aggregate. Yamato-7308. The bar is 0.2 mm in length.

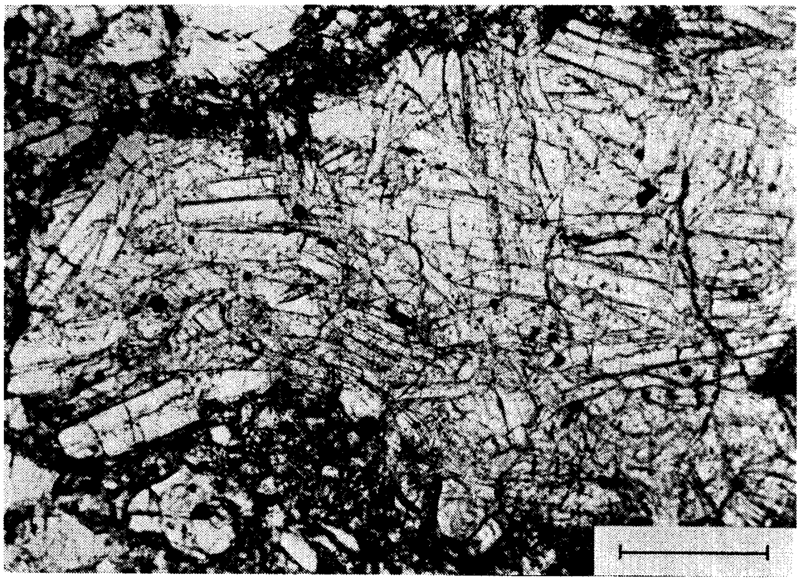

Fig. 10. A yellow-colored glass fragment including euhedral orthopyroxene crystals in Yamato-7308. The bar is 0.2 mm in length.

Fig. 11. A black-colored cryptocrystalline material in Yamato-7308. Silicate grains are pyroxene and plagioclase. The bar is 0.1 mm in length.

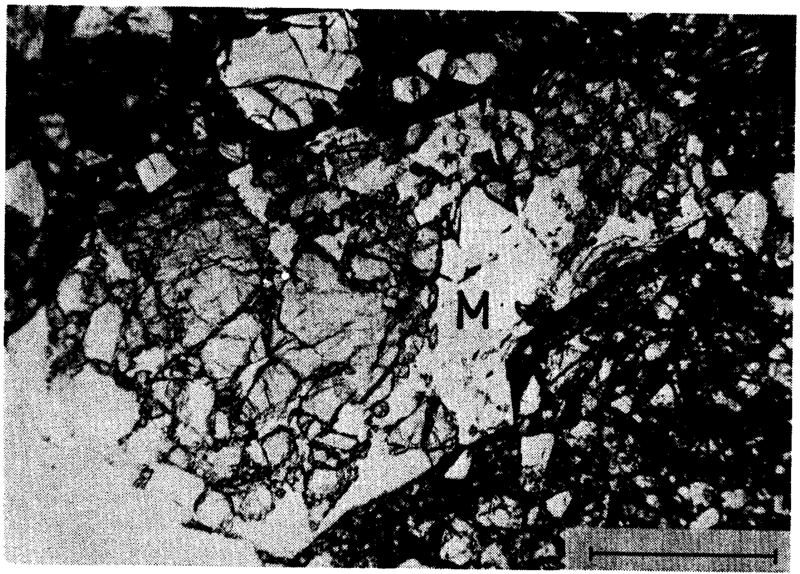

Fig. 12. Maskelynite (M) in the eucritic fragment of Yamato-7308. The bar is 0.5 mm in length.

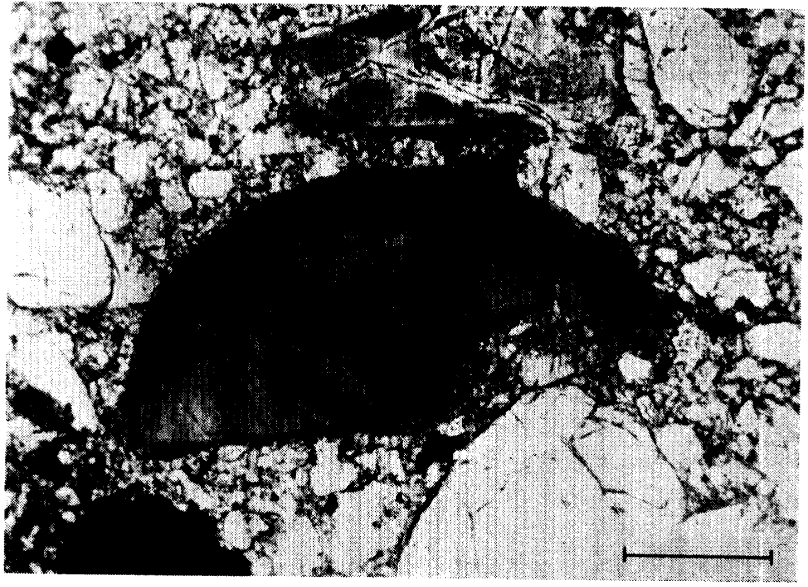

Fig. 13. A brown-colored spherule fragment composed of radial growth of fine acicular crystals in Yamato-7308. Minute metallic spherules are included. The bar is 0.2 mm in length.

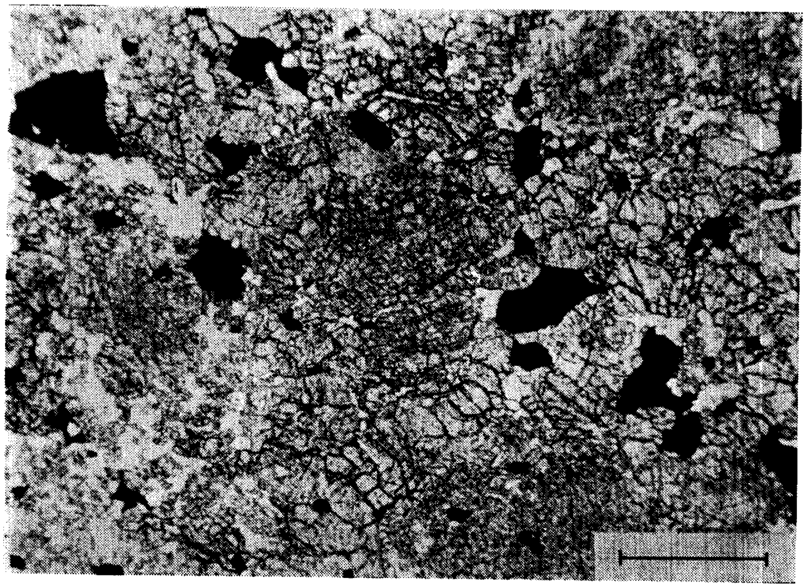

Fig. 14. Thin section of Yamato-7303. An olivine chondrule in the center of the photograph is deformed and is poorly defined in the matrix. The bar is 0.5 mm in length.

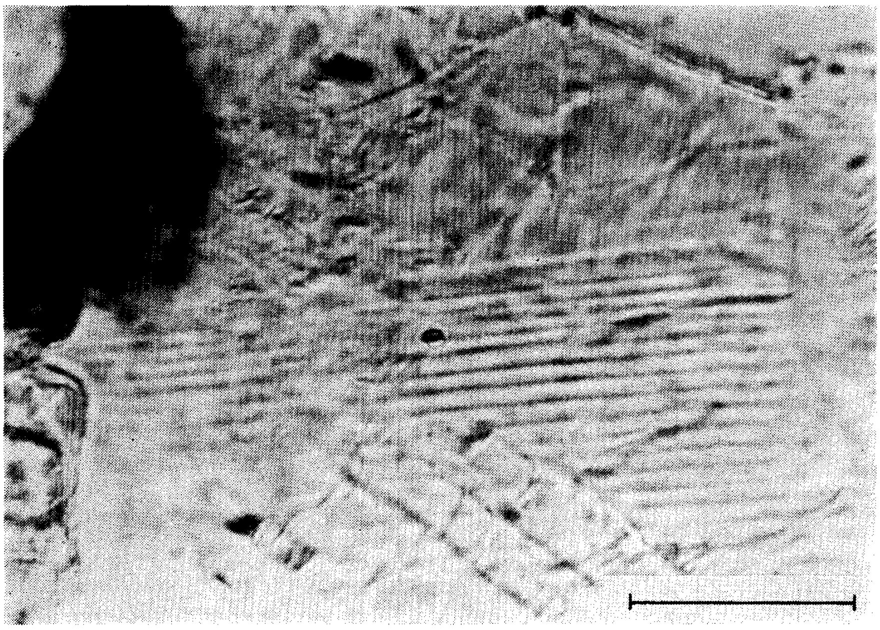

Fig. 15. A plagioclase grain showing shock-induced lamellar structure in Yamato-7303. The bar is 0.02 mm in length.

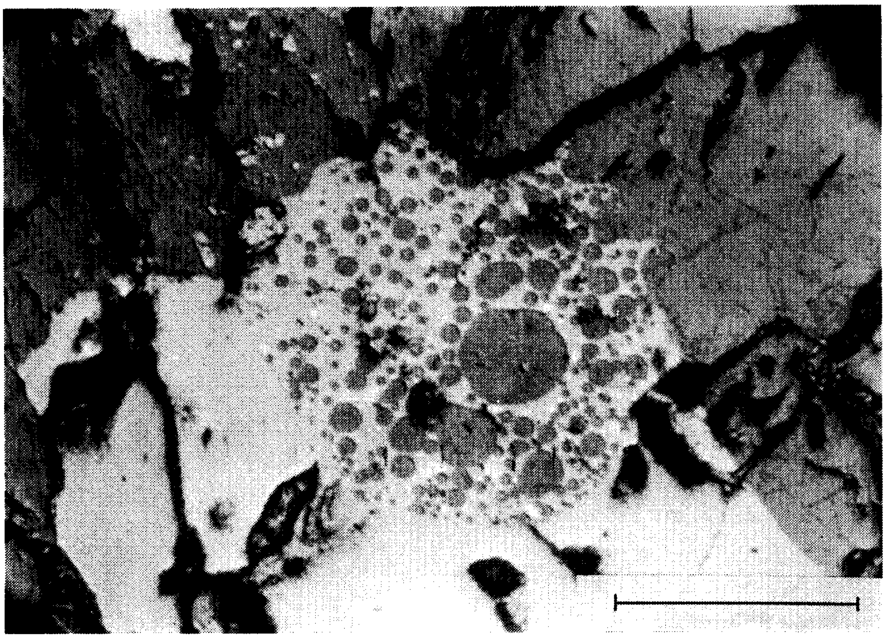

Fig. 16. A troilite grain including fused silicate droplets in the margin. Yamato-7303. Reflected light. The bar is 0.1 mm in length.

dark brown in color, includes orthopyroxene and plagioclase crystals.

2.3.6. Cryptocrystalline material

The cryptocrystalline material, black in color and isotropic, including pyroxene and plagioclase crystals is rarely found in this meteorite (Fig. 11).

2.3.7. Maskelynite-bearing fragment

The fragment consists of maskelynite and brown-colored clinopyroxene (Fig. 12). Pyroxene crystals exhibit a strong wavy extinction and complicated lamellar structure, probably due to shock effect. Fine lamellar is occasionally observed in the partially maskelynitized plagioclase.

2.3.8. Spherules and spherule fragments

Spherular microparticles and their fragments are pale brown or dark brown in color, and contain tiny metallic inclusions, spherical in shape (Fig. 13). The particles are glassy or cryptocrystalline, and the cryptocrystalline particles are composed of radially-arranged aciculae exhibitting parallel extinction. The chemical composition and CIPW norm of glassy spherules are shown in Table 5.

Olivine: Olivine is very rare in Yamato-7308 meteorite, and the composition is Fo_{61} by the microprobe analysis (Table 1).

Pyroxene: The composition of orthopyroxene ranges widely from En_{76} to En_{36} in the microprobe data (Table 2) and from En_{81} to En_{58} ($2V=-82°$ to $-55°$) by the optics. Main clinopyroxene species is pigeonite ($Wo_8\,En_{43}\,Fs_{49}$), and other clinopyroxenes are augite, clinohypersthene and subcalcic ferroaugite (Table 3). Inverted pigeonite is present.

Plagioclase: Plagioclase in Yamato-7308 is Ca-rich, and is mostly assigned to anorthite. The composition is $An_{89\text{-}94}$ by the probe (Table 4) and $An_{79\text{-}95}$ ($2V=-88°$ to $-80°$) by the optics. Carlsbad- and albite-twins are very common. Maskelynite, analogous to plagioclase in composition, is An_{91} by the probe (Table 4).

Silica minerals: Both tridymite and quartz are recognized in Yamato-7308. The optic axial angle of tridymite is about $+54°$, and every grain is twinned. Chemical composition of quartz is presented in Table 5.

Opaque minerals: Nickel-iron, troilite, chromite and ilmenite are present in subordinate amounts. Ilmenite occurs commonly with chromite.

2.4. *Yamato-7303*

Yamato-7303 meteorite is an ordinary chondrite, consisting of olivine, pyroxene, plagioclase and opaque minerals and containing accessory amounts of apatite and whitlockite. Chondrules are generally deformed, and the chondrule-matrix boundary is poorly defined in the plane polarized light (Fig. 14). Mineral grains are mostly anhedral and irregular in shape except euhedral and subhedral olivine and pyroxene grains in a few microporphyritic chondrules. In chondrules, the interstitially filling material among olivine and orthopyroxene phenocrysts is recrystallized into fine-grained and transparent aggregate of pyroxene and plagioclase. Every silicate grain shows a strong undulatory extinction. In addition, plagioclase shows a finely lamellar structure or partial maskelynitization.

Olivine: The composition is $Fo_{74\text{-}75}$ by the probe (Table 1) and $Fo_{71\text{-}83}$ ($2V=-83°$ to $-89°$) by the optics. The wavy extinction is distinct in every grain, and kink bands are present in a few grains.

Pyroxene: The composition of orthopyroxene is $En_{76\text{-}77}$ by the probe analysis (Table 2) and $En_{75\text{-}77}$ ($2V=-72°$ to $-74°$) by the optics. Augite is present as a reaction rim around the host orthopyroxene, and its optical property is $c\wedge Z=43°-45°$. The chemical composition determined by the probe is Wo_{45} $En_{45\text{-}46}$ $Fs_{8\text{-}9}$ (Table 3). Stillwater-type exsolution lamellas are observed in a few augite grains.

Plagioclase: The composition is An_{14} by the probe (Table 4) and $An_{12\text{-}18}$ ($2V=-53°$ to $-60°$) by the optics. The optical data indicate that plagioclase is a high-temperature type. Plagioclase occurs as minute grains, anhedral and irregular in shape, filling the interstices among olivine, pyroxene and opaque minerals. Plagioclase in this meteorite often has a characteristic lamellar structure

Table 6. Modal composition of Yamato-7301, -7305, -7308 and -7303 (vol. %).

	Yamato-7301	Yamato-7305	Yamato-7308	Yamato-7303
Matrix	87.7	85.6	100.0	85.7
Chondrule	12.3	14.4	—	14.3
Total	100.0	100.0	100.0	100.0
Matrix				
Olivine	51.7	50.2	0.4	53.3
Orthopyroxene	19.0	30.7	69.6	21.6
Clinopyroxene	3.2	2.1	12.8	1.3
Plagioclase	3.7	7.5	13.1	6.6
Silica mineral	—	—	0.1	—
Glass and devitrified glass	—	—	0.7	—
Opaque phase	11.4	9.5	2.3	17.2
Others	11.0*	—	1.0**	—
Total	100.0	100.0	100.0	100.0
Chondrule				
Olivine	56.3	39.7	—	46.2
Orthopyroxene	30.5	47.0	—	37.6
Clinopyroxene	6.6	6.1	—	4.3
Plagioclase	4.2	4.0	—	6.5
Opaque phase	2.4	3.2	—	5.4
Total	100.0	100.0	—	100.0

* Reddish brown oxidized products of metallic and sulfide phases

** Dark-colored undetermined material

due to shock effect (Fig. 15), and is frequently changed locally to maskelynite.

Opaque minerals: Kamacite, taenite, troilite and chromite are present. They are generally present in the irregularly-shaped grains, but short veins of nickel-iron and troilite are also observed in the local part of the meteorite. Fig. 16 shows a locally fused part of troilite, which contains numerous rounded silicate droplets.

Phosphate minerals: Apatite is present, filling the interstices between olivine and pyroxene grains in the matrix. The optical property is biaxial, negative, with a very small optic axial angle. Whitlockite is frequently present as rims along the margin of apatite crystals.

Table 7. Chemical composition of Yamato-7301, -7305, -7308 and -7303 (wt. %).

	Yamato-7301	Yamato-7305	Yamato-7308		Yamato-7303
			A	B	
Silicate phase					
SiO_2	35.98	39.15	51.06	55.2	39.38
MgO	23.30	24.52	22.02	26.3	24.60
FeO	18.92	13.10	16.00	12.5	13.02
Al_2O_3	1.88	2.08	3.64	0.6	2.16
CaO	1.66	1.83	3.50	1.2	1.79
Na_2O	1.01	1.05	0.16	trace	1.00
K_2O	0.12	0.13	0.06	trace	0.13
Cr_2O_3	0.60	0.31	0.68	1.3	0.41
MnO	0.35	0.38	0.57	0.5	0.38
TiO_2	0.10	0.11	0.22	0.1	0.10
P_2O_5	0.25	0.27	0.01	trace	0.27
$H_2O(+)$	1.24	—	—	—	—
CO_2	0.35	—	—	—	—
NiO	0.88	—	—	—	—
CoO	0.05	—	—	—	—
Metal phase					
Fe	7.21	7.64	0.39	0.5	7.50
Ni	0.77	0.96	115ppm	trace	0.83
Co	0.05	0.06	70ppm	trace	0.06
Cu	95ppm	100ppm	125ppm	—	110ppm
Zn	—	—	15ppm	—	—
Sulfide phase					
FeS	5.05	7.57	0.75	1.4	8.44
NiS	0.29	0.06	—	—	0.03
(Total Fe)	(25.13)	(22.64)	(13.31)	(11.1)	(22.98)
Total	100.06	99.22	99.09	99.6	100.10

A: Bulk chemical composition of Yamato-7308
B: Chemical composition of diogenite fragment in Yamato-7308

3. Mineral Composition and Bulk Chemical Composition

Table 6 shows the modal composition of Yamato-7301, -7305, -7308 and -7303 meteorites. In Yamato-7301, -7305 and -7303, olivine and orthopyroxene are main mineral components. On the other hand, in the case of Yamato-7308, orthopyroxene is most abundant, and plagioclase and clinopyroxene rank next. Bulk chemical compositions of the meteorites determined by the X-ray fluorescence analysis and ordinary wet-chemical methods are shown in Table 7. $H_2O(+)$ and CO_2 in Yamato-7301 meteorite are ascribed to the presence of weathering products. Therefore, NiO, CoO and a significant amount of FeO in the silicate phase are assumed to have depleted by the weathering of metallic and sulfide phases.

Table 8. Atomic ratios of metallic Fe/total Fe, Fe/Si and Mg/Si of Yamato-7301, -7305 and -7303.

	Metallic Fe/Total Fe	Fe/Si	Mg/Si
Yamato-7301	0.29	0.70	0.94
Yamato-7305	0.34	0.58	0.93
Yamato-7303	0.33	0.58	0.93

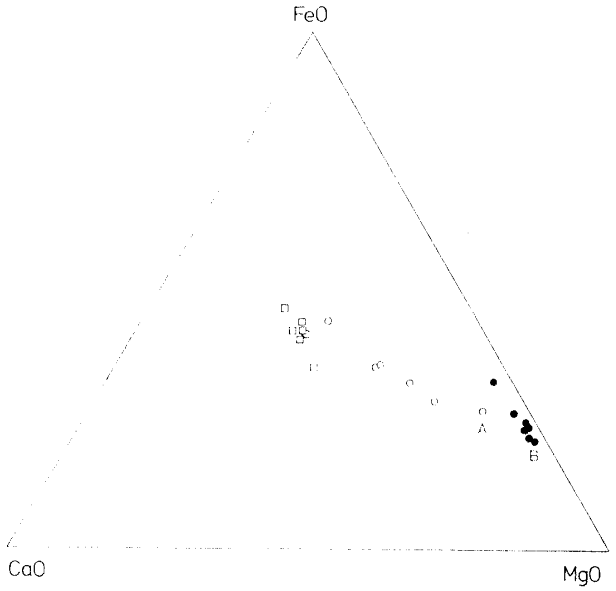

Fig. 17. CaO-FeO-MgO diagram of eucrites, howardites and diogenites.
Squares: Eucrites; Open circles: Howardites; Closed circles: Diogenites.
A: Yamato-7308
B: Diogenite fragment in Yamato-7308

4. Discussion

The structural and mineralogical features of Yamato-7301, -7305 and -7303 are chondritic. On the basis of the bulk chemical composition, atomic ratios of metallic Fe/total Fe, Fe/Si and Mg/Si were calculated (Table 8). Referring to VAN SCHMUS and WOOD's (1967) criteria, it is assigned that Yamato-7301 is a high-iron chondrite, and that both Yamato-7305 and Yamato-7303 are low-iron chondrites. Lower values of metallic Fe/total Fe and Fe/Si of Yamato-7301 in comparison with high-iron chondrites in general are ascribed to the oxidation and depletion of a part of iron in metallic and sulfide phases by the weathering after the fall on the earth. According to the mineral compositions and textures, Yamato-7301, -7305 and -7303 are classified as H4, L5 and L5 chondrites, respectively. Yamato-7308 is a polymict brecciated achondrite composed of various types of mineral grains and lithic fragments. Fig. 17 shows a CaO-FeO-MgO diagram of howardites, eucrites and diogenites based on their bulk chemical compositions (PRIOR, 1918; UREY and CRAIG, 1953; MASON, 1963; MASON and WIIK, 1966; DUKE and SILVER, 1967; MASON, 1967; MCCARTHY *et al.*, 1972; WÄNKE *et al.*, 1974). It is noted from the diagram that Yamato-7308 is most magnesian among the howardites ever reported. Orthopyroxenes, dominant mineral constituents of Yamato-7308, show a wide compositional variation ranging from En_{80} to En_{37}. The regular compositional trend ranging from En-rich pyroxenes to En-poor ones in Fig. 18 indicates that pyroxenes in Yamato-7308 were produced by the fractional crystallization which is common to the genesis

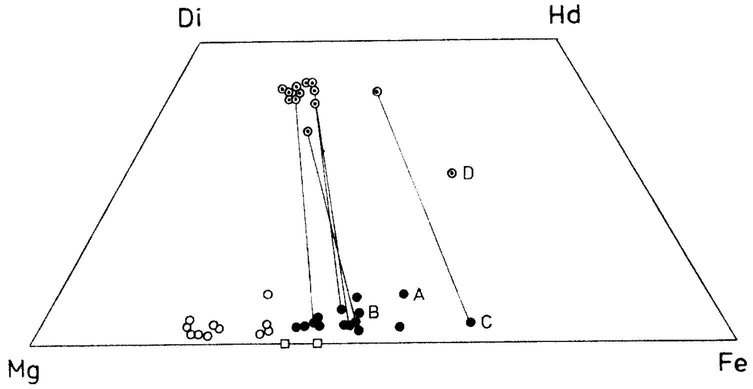

Fig. 18. Pyroxene composition of Yamato-7308.
Open circles: Orthopyroxenes from diogenite fragments.
Closed circles: Orthopyroxenes and pigeonites from eucritic fragments.
Double circles: Clinopyroxenes, mostly exsolved from orthopyroxenes, and some independent augites.
A: Pigeonite
B: Clinohypersthene
C: Ferrohypersthene
D: Subcalcic ferroaugite

of terrestrial igneous rocks. The occurrence of diogenite-like fragments consisting of bronzite and eucritic fragments consisting of pigeonite and Ca-rich plagioclase is significant for the petrogenesis of Yamato-7308. The presence of ophitic-textured eucrite similar to basaltic rock (Fig. 6) distinctly indicates that it was produced by the magmatic activity on the Yamato-7308 parent body. The crystallization of Mg-rich pyroxene fraction free from plagioclase would take place from the parent magma in the early stage, forming the residual liquid concentrated more in Ca, Al and Fe. Producing gradually Fs-increased pyroxenes by subsequent reactions between Mg-rich pyroxenes and the liquid, the crystallization in the later stage would produce the eucritic fraction. Adcumulate fragment in Fig. 7 composed of pigeonite, anorthite and accessory silica minerals, which is compared to cumulate eucrites, Moore County (HESS and HENDERSON, 1949), Serra de Mage (DUKE and SILVER, 1967) and Moama (LOVERING, 1975), would have slowly crystallized from eucritic liquid in the magma chamber under the equilibrium condition. The temperature of pyroxene formation in Yamato-7308 is estimated at about 1,000°C, according to the pigeonite eutectoid reaction line proposed by ISHII (1975).

The origin of various crystalline lithic fragments in howardites can be explained by magmatic process accompanied by fractional crystallization. Another significant feature of Yamato-7308 is the brecciated structure, which is commonly observed in most howardites (WAHL, 1952; MASON, 1962; DUKE and SILVER, 1967). The most probable source of brecciation is impact phenomena on the surface of the parent body. Repeated impact events would bring about the brecciation of rocks and crystals, and promote mixing of rock and crystal fragments. Glassy materials and maskelynite were produced probably by shock effect following the impact. The chemical composition of glassy spherules in Yamato-7308 is nearly corresponding to the bulk chemical composition of the meteorite, except the lower content of Na_2O and the higher contents of Al_2O_3 and K_2O in spherules. The decrease of Na_2O is ascribed to the volatilization of Na, and the increase of Al_2O_3 and K_2O may be due to inhomogeneity of the source material on the parent body. In comparison with glassy materials of other howardites, Bununu and Malvern (NOONAN, 1974; DESNOYERS and JEROME, 1977), Yamato-7308 spherules are rich in MgO, similar to the bulk chemical composition. In the maskelynite-bearing eucritic fragments, brown-colored clinopyroxene grains present a distinctly strong wavy extinction and a complex lamellar structure. However, eucritic fragments with an ophitic texture, in which plagioclase is not maskelynitized at all and brown-colored clinopyroxene shows only a slight wavy extinction, are also present in the same thin section of Yamato-7308. This fact is different from Yamato-7303, in which shock-induced lamellar structure and partial maskelynitization are prevalently observed in every plagioclase grain. It is suggested that impact events would have been locally strong on the Yamato-7308 parent body and might have been caused by not very large projectiles. It seems inadequate to regard howardites as a simple mechanical mixture of two end-materials, diogenitic fractions and eucritic ones (MCCARTHY *et al.*, 1972). This model cannot explain the observed regular, continuous compositional trend of pyroxenes in Yamato-7308. Howardites might have been produced by the low pressure fractional crystallization of magnesian pyroxenes and rare olivine from the magma on the achondrite parent body, followed by the formation of eucritic liquids, and by the subsequent brecciation and mixing caused by impact events. This view is also supported by a parent body model of achondrites of TAKEDA *et al.* (1976) who regarded the pyroxenes of all these achondrites as a product of a single step differentiation of a thin crust formed on a parent body of achondrites early in the solar system's history.

Recently STOLPER (1977), in his experimental petrologic study on eucrites of various types, proposed a quite opposing hypothesis for the genesis of eucrites, howardites and diogenites. According to him, eucrites may represent melts in early stages of basaltic achondrite parent body by partial melting, and further melting in these source regions, after exhaustion of plagioclase, may have produced Mg-rich liquids, from which Mg-rich pyroxenes and rare olivine in howardite and diogenites crystallized out. According to this hypothesis, eucrites should be much older than diogenites. In Yamato-7308, eucritic fragments show various grades of shock metamorphism. In some adcumulate, coarse-grained eucrite fragments, calcic plagioclase crystals are partially or completely maskelynitized, and clinopyroxenes show strong shock effects, whereas the ophitic-textured eucrite fragments are free from such shock metamorphism. The diogenite fragments, except rare cases, are also free from such metamorphism. From these complicated relations, it is difficult to determine the sequence of formation of these lithic fragments. STOLPER's hypothesis seems not supported by the observation in Yamato-7308. There is little evidence indicating the presence of lithic fragments consisting of olivine in most howardites and also in Yamato-7308. However, finding of the dunnite fragment composed of Mg-rich olivine in the Washougal howardite by JEROME and MICHEL-LEVY (1972) is interesting, because it may suggest that the fractionation of Mg-rich olivine from the parent magma could have taken place prior to the fractional crystallization of Mg-rich pyroxene, and that the parent liquid would have been more magnesian, different from the composition of the primary liquid proposed by STOLPER (1977).

5. Conclusion

In the present mineralogical and petrographical work, Yamato-7301, -7305 and -7303 were classified as H4, L5 and L5 chondrites, respectively. Whereas, Yamato-7308 is a howardite, a polymict breccia originated from the fractional crystallization of the parent magma on the parent body and from the subsequent brecciation and mixing of rocks and crystals by impact events. Shock-induced features are distinctly observed in both Yamato-7308 and Yamato-7303 by the presence of maskelynite and glassy materials in the former and by the shock-produced lamellar structure and maskelynitization of plagioclase in the latter. However, the situation is different between Yamato-7308 and Yamato-7303. In the case of Yamato-7308, it is supposed that shock effect was caused by impacts of not very large projectiles.

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