SOME UNIQUE METEORITES FOUND IN ANTARCTICA AND THEIR RELATION TO ASTEROIDS

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Abstract: Mineralogical examination of the smaller sized Yamato achondrites identify two unique meteorites: Yamato-74130 is the most iron-rich ureilite with Na, Cr-rich augite instead of pigeonite; Yamato-74160 was extensively recrystallized but the composition and proportion of olivine (Fa_{30}), orthopyroxene ($Ca_4Mg_{72}Fe_{24}$), augite ($Ca_{43}Mg_{46}Fe_{11}$) and plagioclase (An_8 and An_{16}) is consistent with LL7 chondrites. ALHA77005 is a unique achondrite with olivine, possible three pyroxene assemblage and maskelynite. These meteorites provide evidence that there may be other "thermalized" asteroids than the howardite parent body. Yamato-74356 is different from eucritic polymict breccias common in the Antarctic meteorites and is only one example of common eucrite. Detailed petrologic description is given on unique achondrites, recrystallized diogenite Yamato-74013 and rapidly cooled eucrite Yamato-74450 with pyroxene phenocrysts. The bulk chemistry and the mineralogical reexamination of Yamato -75028 indicate that it is composed of the H5-type clasts and chondrule-rich H(L)3-like matrix with the H5 fragments. The fact may imply close relationship in the collisional evolution of some asteroids with these materials.

1. Introduction

Two characteristic features one may anticipate from the Antarctic meteorites are (1) Some meteorites which are otherwise difficult to recognize on earth because of their similarity to some terrestrial rocks can be found easily on bare ice; and (2) The terrestrial contamination of meteorite will be small especially for carbonaceous chondrites. The chance of finding an unusual meteorite may be proportional to the number of samples we study. Thus, the discovery of large numbers of Yamato meteorites may lead to interesting new discoveries. We report in this paper the mineralogy and chemistry of some unique meteorites which show some uncommon features, or are rare among the Yamato meteorites.

A major group of achondrites including the diogenite-howardite-eucrite family and ureilites is characterized by the presence of low-Ca pyroxenes. Occurrence of augite (with olivine in most cases) as the dominant mineral is rare in achondrites. We report on unique achondrites containing augite found in the Antarctic meteorites collected by JARE in 1974 and a joint U.S.-Japan team for meteorite search in Antarctica.

We also report the results of reexamination of some chondrites which revealed uncommon features in the course of their preliminary examination (YANAI *et al.*, 1978). Most of the preliminary examinations of these meteorites have been based on very small chips from near surface weathered materials close to the fusion crust. Further detailed investigation on much larger thin sections produced from fresher interior chips of chondritic breccias Yamato-75028 and -75258 were performed. Their bulk chemistry are given together with those of the related meteorites.

This type of study is especially required for polymict breccias and brecciated meteorites, for which homogeneity of the samples are not guaranteed. Iron staining in some brecciated chondrites poses some problems. A detailed method to avoid the iron contamination is given in the accompanying paper (MIYAMOTO *et al.*, 1979).

2. Samples and Experimental Techniques

The mineralogical description of the samples are given in the results. The numbers and their amounts (in parentheses) of samples supplied for the re-examination study and bulk chemical analyses are: Yamato-74013 (3.850 g), Y-74450 (0.866 g), Y-74642 (1.531 g), Y-75028 (1.181 g) and Y-75258 (2.545 g). An epoxy mount (potted butt) prepared from a part of the chips was sliced to produce one to three polished thin sections. Their bulk chemistries were obtained by a standard wet chemical method by H. HARAMURA of the University of Tokyo through the courtesy of Prof. I. KUSHIRO of the Geological Institute. A fused bead analyses of Yamato-75015, Y-74136 and Y-74648 were performed at the NASA-JSC.

For a new identification of pebble-sized possible unique achondrites to be included in the Antarctic meteorite catalog (YANAI, 1979), only small chips about a few mm's in diameter were supplied from the curator: Yamato-74130,1 (0.130 g), Y-74160,2 (0.056 g), Y-74356,1 (0.014 g), Allan Hills ALHA77005 (0.342 g), and ALHA77256 (0.5 g). A small epoxy mount was prepared for each of the above samples and was sliced to produce one or two polished thin sections. For relatively large samples, one thick section cemented by Stick-wax was produced and was finished (polished) to about 0.1 mm thick so that single crystals of particular compositions could be separated after microprobe analyses. A few single crystals of pyroxenes in Y-74356 and ALHA77005 and 77256 were separated for X-ray diffraction study and after they were mounted in araldite and polished, oriented single-crystals were prepared for the microprobe study.

The quantitative chemical analyses were made with a JOEL JXA-5 electron probe X-ray microanalyzer with a 40° take-off angle. The method is the same as that of NAKAMURA and KUSHIRO (1970). The pyroxene crystals were mounted approximately along the *c*-axis, and were aligned with spindle axis parallel to the c^* direction. Precession photograph of $h0l$ nets were taken using Zr-filtered Mo $K\alpha$ radiation.

3. Summary of the Yamato Collection

It is anticipated that only few people may have a systematic understanding of the overall content of the Yamato collection. Since a theme of this paper is to describe briefly all the unique Yamato meteorites in the context of the total Yamato collection, we first summarize the statistics of the Yamato meteorite collection in Appendix. The data source is *Catalog of Yamato Meteorites* compiled by K. YANAI (1979).

The data we have at present (YANAI *et al.*, 1978) is a tentative one but they indicate that the E type chondrite is rare and the equilibrated H-type chondrites are most abundant. However it should be mentioned that some meteorites given different members might be fragments of the same fall. For example 30 diogenites showing recrystallized textures may be the same fall. Iron and stony iron meteorites are rare and only one pallasite and no mesosiderite have been recognized. The first aubrite has been found in the 1978 Allan Hills collection. Breccias of eucritic compositions are common achondrites.

4. Results

4.1. Description of the unique achondrites

4.1.1. Yamato-74130 ureilite

This is a 17.9 g fragment similar to the Y-74123 ureilite (TAKEDA *et al.*, 1978c). A thin section made from a small fragment about 5 mm in diameter shows all characteristics of ureilite textures. Three large crystals of olivine and one pyroxene crystal are set in a dark carbonaceous matrix (Fig. 1) which fills

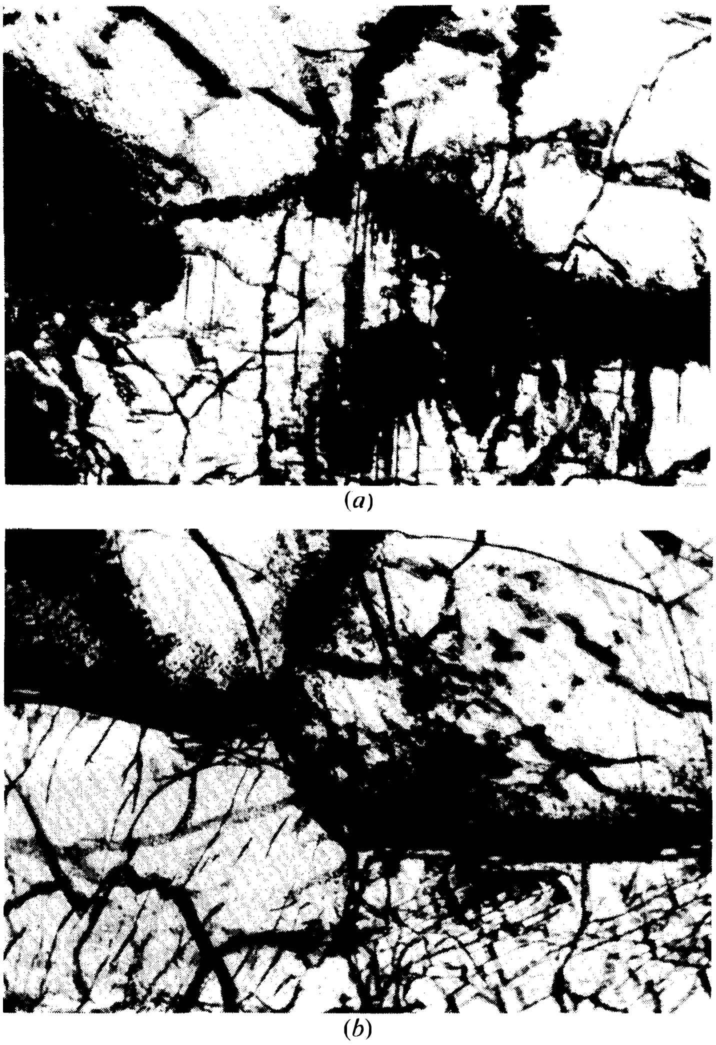


Fig. 1. Photomicrographs of (a) Yamato-74130 and (b) Allan Hills ALHA77257 ureilites. Width 0.95 mm.

the grain boundaries. Some shock features are observed in olivines. The unique features of this achondrite are the occurrence of augite $Ca_{33}Mg_{53}Fe_{13}$ (Fig. 2) instead of pigeonite, and olivine more Fe-rich (Fa_{24}) than found among the previously known ureilites (BERKLEY *et al.*, 1978). Reverse chemical zoning characteristics of ureilites has been observed at grain boundaries rich in carbonaceous material. The augite crystal is uniform in composition and is subcalcic with considerable cosmochroe pyroxene component. The amount of Na_2O reaches 0.87 wt.% (Table 1 and 2). Chemical composition of a few metal grain (wt.%) Fe 95.5, Co 0.39, Ni 3.49, P 0.15 agrees with those of ureilites.

The Antarctic ureilites provided us with the extreme ends of the chemical variation. Y-74659 is the most Mg-rich one, and Allan Hills ALHA77257 is

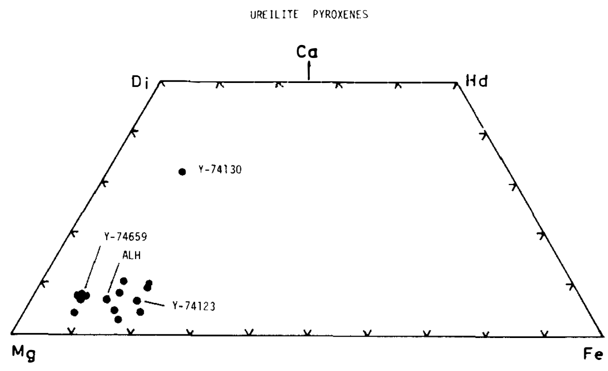


Fig. 2. Pyroxene quadrilateral of the Antarctic ureilites with other known ureilites. Yamato-74659, -74123, -74130 and ALHA77257 are shown together with data by BERKLEY *et al. (1978).*

the second most Mg-rich one (TAKEDA *et al.*, 1978c). The bulk chemistry of Y-74130 estimated from mineral compositions in the ratios of 85% olivine and 15% augite is compared with those of other Yamato ureilites in Table 3.

4.1.2. Allan Hills ALHA77005

This is a unique achondrite found by the U.S.-Japan joint party at Allan Hills, and is composed of olivine, pyroxene, maskelynite and opaques (chromite etc.). A preliminary petrographic description given by MASON (1978) reported only one kind of pyroxene. We found Opx-Pig-Aug assemblage by electron microprobe. Opx-like phases ($Ca_{2.7}Mg_{77.7}Fe_{19.6}$) are present in light-colored portion with small amounts of Mg-rich olivine (Fa_{25}). The chemical zoning is from $Ca_6Mg_{72}Fe_{22}$ to $Ca_{14}Mg_{66}Fe_{20}$ in a low-Ca pyroxene. The Opx-like phase was found to be pigeonite by the single crystal X-ray diffraction method. The presence of diffuse streaks where Opx-reflections are expected suggests inversion from Opx by the high temperature shock effect. The augite ($Ca_{36}Mg_{51}Fe_{13}$)-pigeonite ($Ca_7Mg_{51}Fe_{13}$) pair is present in dark olivine-rich portion. The three-pyroxene assemblage were modified by the shock events, but the temperature estimated by the pigeonite-geothermometer (ISHII, 1975) 1150°C may represent the equilibrated one. More detailed work on the application of pyroxene geothermometry to this meteorite appears in *Mineral. J.* by ISHII *et al.* (1979). MCSWEEN *et al.* (1979) also investigated this meteorite but they do not mention whether their pyroxene is pigeonite or orthopyroxene. They suggested that this meteorite is related to shergottite.

4.1.3. Yamato-74013 recrystallized diogenite

A unique feature of the Yamato recrystallized diogenites among known diogenites was first pointed out by REID (TAKEDA *et al.*, 1975). About thirty such diogenites have been recovered in the Yamato meteorite field (YANAI, 1979;

Table 1. Representative pyroxene compositions (wt. %) of the Yamato-74123 and -74130 ureilites and Yamato-76160.

Samples	Y-74123		Y-74130	Y-74160		
	Pig P18	Pig P14	Aug P23	Aug P29	Opx P29	Opx P31
SiO_2	53.20	54.40	52.30	53.30	53.90	54.10
Al_2O_3	0.43	0.44	2.74	0.78	0.40	0.50
TiO_2	0.05	0.05	0.20	0.33	0.18	0.19
Cr_2O_3	1.15	1.14	1.84	1.17	0.34	0.52
FeO	12.04	11.96	7.91	7.85	15.49	15.17
MnO	0.39	0.41	0.34	0.26	0.39	0.38
MgO	27.80	27.80	18.68	16.79	25.90	26.10
CaO	3.67	3.57	14.84	18.32	2.08	2.09
Na_2O	0.05	0.05	0.87	0.81	0.09	0.08
Total	98.78	99.82	99.72	99.61	98.77	99.13
			Cations (Oxygen 6)			
Si	1.941	1.958	1.920	1.973	1.979	1.977
Al (IV)	0.018	0.019	0.080	0.027	0.017	0.022
Al (VI)	0.000	0.000	0.039	0.007	0.000	0.000
Ti	0.001	0.001	0.006	0.009	0.005	0.005
Cr	0.033	0.032	0.053	0.034	0.010	0.015
Fe	0.367	0.360	0.243	0.243	0.476	0.464
Mn	0.012	0.013	0.011	0.008	0.012	0.012
Mg	1.512	1.492	1.022	0.926	1.418	1.421
Ca	0.143	0.138	0.584	0.727	0.082	0.082
Na	0.004	0.003	0.062	0.058	0.006	0.006
Total	4.031	4.016	4.020	4.012	4.005	4.004
Ca*	7.1	6.9	31.6	38.3	4.1	4.2
Mg	74.7	75.0	55.3	48.9	71.8	72.3
Fe	18.2	18.1	13.1	12.8	24.1	23.6

* Atomic percent.

TAKEDA *et al.*, 1978b). More detailed petrographic description is given in this paper.

Yamato-74013 has granoblastic texture, primarily orthopyroxene, with grain size 0.1–0.2 mm in finer-grained areas, 0.4–0.5 mm in coarser-grained areas. Finer grained portions have a haze of tiny inclusions of troilite, with yet smaller blebs of metallic iron in some troilite grains. In areas that are coarser-grained, the troilite also is coarser and the pyroxene clear.

The fine-grained areas are more abundant than the coarse-grained, and cover

Table 2. *Representative olivine and plagioclase compositions (wt. %) of the Yamato-74123 and -74130 ureilites and the Yamato-74160, -75028 and -75258 chondrites.*

	Olivine				Plagioclase	
	Y-74123 Ol 26	Y-74130 Ol 31	Y-74160 Ol 32	Y-75028 Ol 26	Y-74160 Ab 29	Y-75258 Ab 2
SiO_2	37.8	37.6	36.7	38.2	66.0	66.1
Al_2O_3	0.06	0.04	0.02	0.01	20.3	21.20
TiO_2	0.01	0.00	0.00	0.00	0.04	0.00
FeO	19.71	21.04	26.40	17.89	0.20	0.37
MnO	0.45	0.42	0.39	0.48	0.00	0.00
MgO	40.2	39.7	35.4	42.9	0.05	0.00
CaO	0.40	0.24	0.02	0.04	1.86	2.11
Na_2O	0.09	0.04	0.03	0.00	10.02	10.49
K_2O	0.00	0.00	0.00	0.00	1.10	0.76
Cr_2O_3	0.83	0.39	0.01	0.00	0.00	0.00
Total	99.55	99.47	98.99	99.52	99.57	101.03
	Cations					
	(Oxygen=4)				(Oxygen=32)	
Si	0.981	0.982	0.988	0.981	11.693	11.564
Al	0.002	0.001	0.001	0.000	4.244	4.371
Ti	0.000	0.000	0.000	0.000	0.005	0.000
Fe	0.428	0.460	0.594	0.384	0.029	0.054
Mn	0.010	0.009	0.009	0.011	0.000	0.000
Mg	1.558	1.546	1.420	1.642	0.013	0.000
Ca	0.011	0.007	0.001	0.001	0.353	0.396
Na	0.004	0.002	0.002	0.000	3.439	3.559
K	0.000	0.000	0.000	0.000	0.249	0.170
Cr	0.017	0.008	0.000	0.000	0.000	0.000
Total	3.011	3.015	3.015	3.019	20.025	20.114
Mg*	78.4	77.1	70.5	81.0	K 6.2	4.1
Fe	21.6	22.9	29.5	19.0	Na 85.1	86.3
					Ca 8.7	9.6

* Atomic percent.

areas up to 3 cm or more in diameter and seem to be surrounded by coarse-grained areas, giving the fine grained areas the appearance of clots in a network of veins. The fine-grained areas show a subtle parallel structure that transects the granularity. This structure is marked by relative abundance of opaque (troilite) grains, and short fractures. They are most prominent in areas of dense opaque

Table 3. Bulk chemistry of Yamato ureilites.

	Y-74123	Y-74659	Y-74130
SiO_2	33.21	42.91	39.8
TiO_2	0.08	0.14	0.08
Al_2O_3	0.90	1.07	0.45
Fe_2O_3	3.33	1.47	—
FeO	17.34	8.83	18.7
FeS	0.82	0.49	—
MnO	0.37	0.42	0.42
MgO	37.29	38.78	36.7
CaO	0.55	1.71	2.45
Na_2O	0.03	0.07	0.18
K_2O	<0.02	<0.02	—
H_2O (−)	0.38	0.17	—
H_2O (+)*	3.73	3.65	—
P_2O_5	0.61	0.14	—
NiO	0.18	—	—
Ni	—	0.14	—
Cr_2O_3	0.73	0.64	0.64
Total	99.57	100.65	99.42

* Including volatile compositions released up to 1100 °C. Analyses by H. HARAMURA except Y-74130, which was estimated from the mineral composition.

inclusions. The orientation of this structure is largely uniform over dimensions of the samples studied (2–3 cm). In three dimensions, the structure is relatively coarse on two faces, and fine on the orthogonal face of the sample.

Chromite occurs as isolated clots up to 5 mm diameter and in veinlets. Chromite in both occurrences contains inclusions of troilite, rare silicate (composition to be determined) and metal. The isolated chromites are rounded; they are surrounded by a 0.2–0.3 mm zone of clear, coarser pyroxene and are foci for radiating fracture patterns.

It is believed that we are dealing with a single or very small number of coarse pyroxene crystals that have been recrystallized by shock processes to a fine-grained granoblastic texture. The bulk chemistry of three such diogenites is given in Table 4.

4.1.4. Allan Hills ALHA77256 diogenite

ALHA77256 is the only monomict diogenite found in Antarctica. It is composed of orthopyroxene $Ca_{1.7}Mg_{74.3}Fe_{24.0}$ and Al-rich chromite. Many unbrecciated clasts of orthopyroxene with 120° triple point junctures have been preserved.

Table 4. *Bulk chemical compositions (wt. %) of Antarctic achondrites.*

Samples	Y-74013 Dio[b]	Y-74136 Dio[d]	Y-74648 Dio[d]	Y-75032 Dio[a]	Y-74159 Euc[a]	Y-74450 Euc[a]	Y-75015 Euc[d]	ALHA76005 Euc[c]
SiO_2	51.35	53.43	53.58	51.92	49.04	49.36	48.12	48.21
TiO_2	0.13	0.11	0.12	0.40	1.09	1.04	0.73	0.78
Al_2O_3	0.89	0.86	0.97	2.28	10.35	10.82	12.65	12.02
FeO	16.35	16.01	16.07	18.85	19.23	18.26	17.96	18.89
MnO	0.48	(0.45)	(0.45)	0.55	0.53	0.51	(0.51)	0.52
MgO	26.04	26.45	26.08	20.99	8.29	8.06	8.15	7.66
CaO	1.10	1.08	1.30	3.31	9.48	9.52	9.53	9.08
Na_2O	0.04	0.00	0.02	0.12	0.58	0.51	0.39	0.56
K_2O	0.02	0.03	0.03	0.04	0.07	0.06	0.07	0.06
H_2O (−)	0.00			0.00	0.00	0.00		0.27
H_2O (+)*	0.4			0.32	0.32	0.35		1.1
P_2O_5	0.09			0.03	0.07	0.10		0.10
Cr_2O_3	2.49	1.00	1.22	0.72	0.44	0.33	0.37	0.40
FeS	0.82			0.30	0.15	0.64		0.17
NiO	0.006			0.003	0.003	0.003		0.011
Co	0.003			0.003	0.003	0.003		0.003
Total	100.21	99.42	99.84	99.84	99.65	99.57	98.48	99.83

Dio: diogenite, Euc: eucrite.
a : standard wet chemical analyses by H. HARAMURA in TAKEDA *et al.*, 1978b.
b : standard wet chemical analyses by H. HARAMURA. This study.
c : standard wet chemical analyses by H. HARAMURA in MIYAMOTO *et al.*, 1979.
d : fused bead analyses by C. DARDANO, R. BROWN, M. B. DUKE and H. TAKEDA. This study, the value in ( ) estimated from the iron content.
* Including volatile compositions released up to 1100°C.

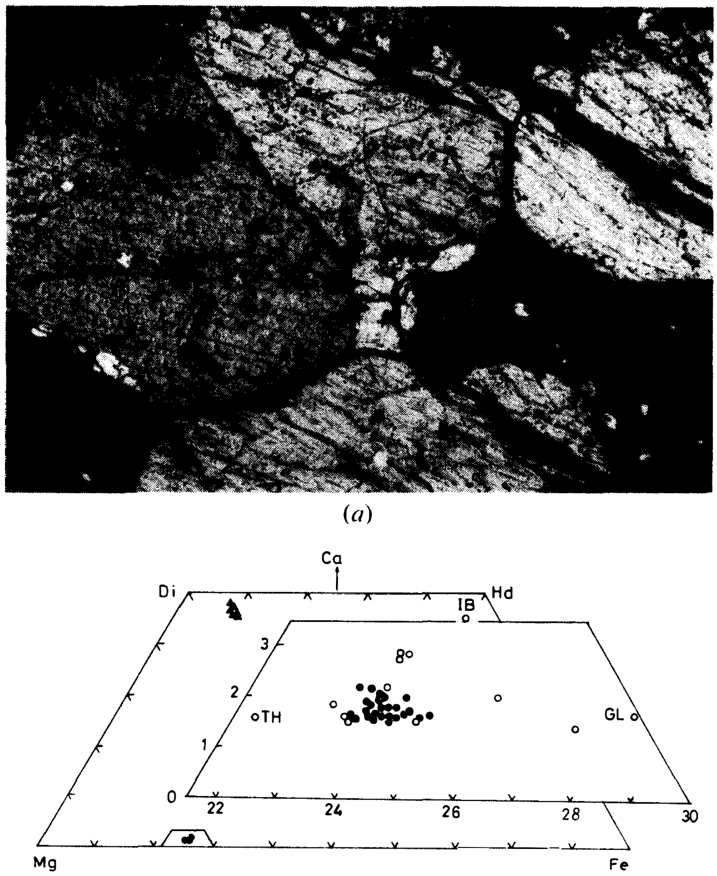
Some orthopyroxene crystals have abundant small augite inclusions (Fig. 3).

4.1.5. Yamato-75032 intermediate between diogenites and eucrites

This meteorite is unique because it is composed of both inverted low-Ca pigeonite and primary orthopyroxene (TAKEDA and MIYAMOTO, 1977; TAKEDA *et al.*, 1979). The bulk chemistry by H. HARAMURA is given in our previous paper (TAKEDA *et al.*, 1978b).

4.1.6. Yamato-74356 eucrite

This meteorite is a 10.0 g mass (2.2×2.1 cm) with almost abraded fusion crust (shiny black). The interior is pale brown to pale gray. It is a common eucrite like the Juvinas eucrite. This meteorite is unique among the Antarctic achondrites because most of the other Antarctic eucrites are polymict breccias (TAKEDA *et al.*, 1978b; MIYAMOTO *et al.*, 1978). This eucrite contains a pigeonite-augite pair with uniform compositions, but it is shocked. The grain size was



(a)

(b)

Fig. 3. Photomicrographs (a) and pyroxene quadrilateral (b) of the Allan Hills ALHA77256 diogenite. Width 0.95 mm. White inclusions are augites.

too small to do any other work. Single crystal diffraction study indicates that the pigeonite exsolves augite with (001) plane in common.

4.1.7. Yamato-74450 eucrite

This appears to be a monomict breccia, in which the basalt fragments have a characteristic texture not common in eucrites (DUKE and SILVER, 1967). The texture is apparently porphyritic, with equant clinopyroxene phenocrysts incorporated in a plagioclase-clinopyroxene intergrowth dominated by parallel laths of the minerals in some cases, and radiating pyroxenes between subparallel plagioclase laths. Mesostasis apparently has some crystallinity, as it shows weak birefringence, although it is generally filled with micron-sized inclusions. Pyroxenes are colorless to pale brown, grading to pinkish brown in some interstitial areas. Interstices are locally very rich in troilite and ilmenite. Ilmenite appears to be more abundant than in most eucrites.

Although most fragments in the thin section are of the type described, at one edge a small bit of a fragment with coarser sub-ophitic texture is present, suggesting that the range of rock textures observable in this meteorite could be extended by study of additional thin sections. Coarse grained portions in other small rock chips have been reported by TAKEDA (1979).

Examination of four other thin sections indicates that the other portions are composed of more brecciated matrix. One thin section contains pigeonite similar to Juvinas in the brecciated matrix. Exsolution lamellae of augite on (001) similar to those found in Juvinas are observed under the microscope.

4.2. *Description of the unique chondrites*

The bulk chemistries of the Yamato chondrites and the Yamato carbonaceous chondrites by H. HARAMURA (Table 5) are plotted in Fig. 4 showing differences in the overall abundance (Fe/Si) and state of oxidation of Fe in chondrite. It is to be noted that Yamato-75028 locates between the H and L groups and that Yamato-74642 is the closest to the LL group among the C2 chondrites, while Yamato-75258 is the closest to the C group among the LL chondrites. Y-75258 weighing 971 g is brecciated and shows the light-dark textures, which are the characteristics of some LL meteorites. Microprobe analyses of their olivine and pyroxene show that it is the LL6 chondrite.

4.2.1. Yamato-74160

This is a 31.4 g individual with a black fusion crust and olive yellow to pale gray interior. The meteorite is brecciated and is composed of subangular recrystallized clasts, which consist of olivine (~49%), low-Ca pyroxene (ortho-

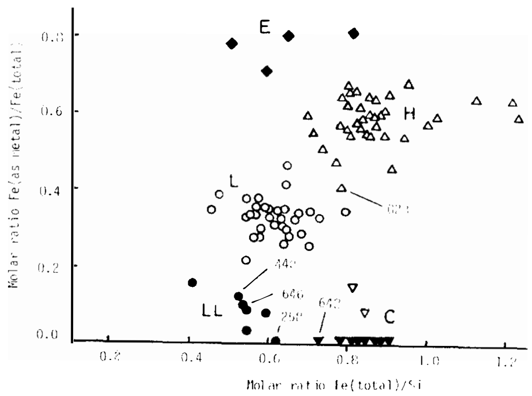


Fig. 4. Differences in the overall abundance (Fe/Si) and state of oxidation (Fe metal/total Fe) of Fe in chondrites (WOOD, 1968). 028 and 258 indicate Yamato-75028 and -75258, and 442, 646, and 642 are Yamato-74 meteorites. Other data after UREY and CRAIG (1953).

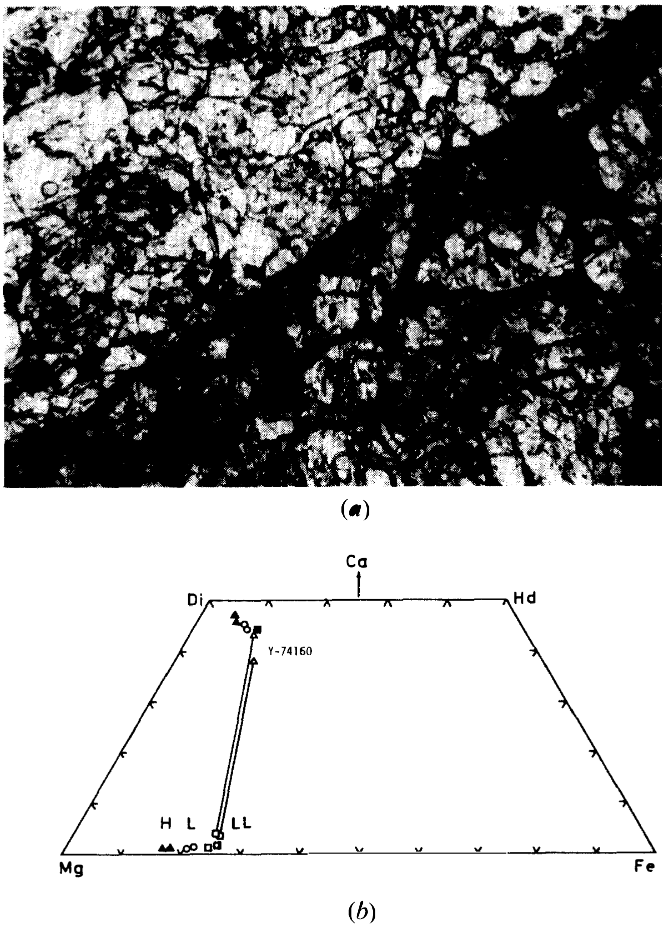


Fig. 5. Photomicrograph (a) and pyroxene quadrilateral (b) of Yamato-74160.

pyroxene) (~29%), augite (~9%), plagioclase (~8%), chromite (~3%), troilite (~2%) and Ca phosphate (~0.5%). Metal (Fe 50.0, Co 2.3, Ni 46.7 wt.%) has been detected with chromite and troilite in very small amounts. Microprobe analyses show olivine (Fa_{30}), orthopyroxene ($Ca_4Mg_{72}Fe_{24}$), augite ($Ca_{43}Mg_{46}Fe_{11}$) of uniform composition. The percent mean deviation of *Fa* content in olivine is about 1%, and *Fs* content of pyroxene is about 2.5%. The plagioclase shows a small range of compositions with dominant values at An_8 and An_{18}. The chemical compositions of a coexisting group of minerals and some representative ones are given in Tables 1 and 2. The silicate minerals in the clasts exhibiting a glanoblastic texture have rounded grain boundaries (Fig. 5). The brecciated matrix itself appears to be recrystallized and became transparent.

The bulk chemical composition of Yamato-74160 given in Table 5 together with other Yamato LL chondrites was estimated from the weight percentage of minerals obtained by the point count method given above and from the values in Tables 1 and 2. The compositions and texture are suggestive of an extensively recrystallized LL chondrite. The temperature of the last equilibration of the Opx-Aug pair (Fig. 5) estimated from the improved Wood-Banno pyroxene geothermometer (ISHII *et al.*, 1979), 1090°C is considerably higher than 970°C (ISHII *et al.*, 1979) of ordinary chondrites.

4.2.2. Yamato-75028

This chondrite is a 6.1 kg stone collected by Prof. MATSUMOTO and his party (MATSUMOTO, 1978). A preliminary examination of this chondrite lists it as H3 on the basis of their olivine and pyroxene compositions (YANAI *et al.*, 1978). Microprobe analyses showed olivine ranging in the composition from Fa_{14} to Fa_{21} with a mean of $Fa_{19.4}$. Their percent mean deviation is greater than 5%, but a prominent peak was observed within the known range of iron concentration of olivine of the H6 chondrites. By definition after VAN SCHMUS and WOOD (1967), it should be classified as H3, but no apparent chondrules were observed on the surface of the specimen, which is very weathered and iron-oxides cover the entire surface.

The bulk chemistry obtained after the preliminary examination revealed that it is intermediate between H and L group (Fig. 4). The previous study was based on a small polished grain mount. A new larger thin section 10×8.8 mm in size shows that the thin section consists of round clasts (or chondrules) of higher petrologic grade (H5–6) and the matrix with distinct spherical chondrules (Fig. 6). The H5-like materials are well mixed with the materials of a lower petrologic type. The metal and troilite are dispersed evenly in the matrix and are not abundant within the H5 clasts. A troilite fragment 1.0×1.4 mm in size was seen in the matrix.

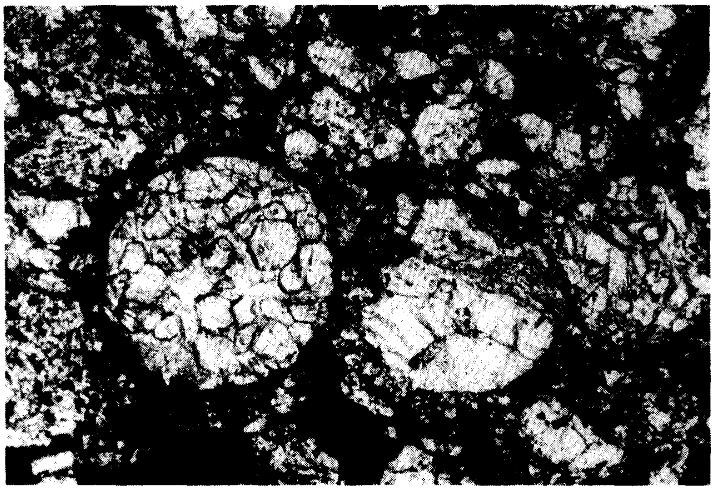


Fig. 6. Photomicrograph of the Yamato-75028 chondrites. Well defined chondrules in the H(L)3-like matrix. Width 0.95 mm.

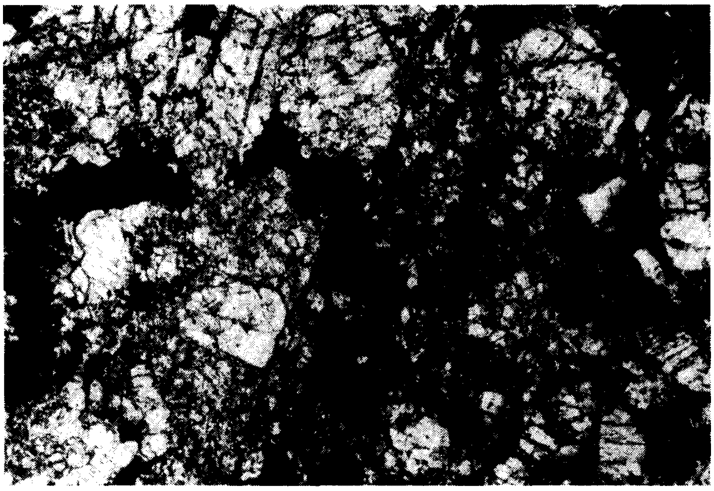


Fig. 7. Photomicrograph of the Yamato-75028 chondrite. H5-like fragment (left) with sharp boundary.

Table 5. Bulk chemical compositions of the Yamato chondrites.

Samples	Y-75028	Y-74191	Y-74442	Y-74646	Y-75258	Y-74642	Y-74662	Y-74160
SiO_2	36.62	40.09	40.47	40.26	38.74	28.53	29.18	43.9
TiO_2	0.16	0.24	0.23	0.15	0.18	0.24	0.22	0.13
Al_2O_3	2.14	2.89	3.63	3.37	2.03	3.58	2.38	2.0
Fe_2O_3						4.26		
FeO	17.43	14.68	17.89	19.02	25.38	18.28	22.53	18.6
MnO	0.30	0.35	0.35	0.37	0.36	0.25	0.22	0.34
MgO	23.92	24.89	24.95	25.11	25.05	19.24	19.29	26.5
CaO	1.72	1.79	1.98	1.72	1.79	2.03	1.70	2.2
Na_2O	0.85	0.97	0.94	0.97	0.93	0.29	0.28	0.95
K_2O	0.10	0.13	0.23	0.13	0.08	0.06	0.04	0.09
H_2O (−)	0.13	0.05	0.00	0.00	0.00	1.54	1.56	—
H_2O (+)*	0.4	1.13	0.58	0.64	0.2	11.82	13.26	—
P_2O_5	0.37	0.20	0.22	0.25	0.34	0.25	0.23	0.2
FeS	3.02	5.01	4.84	4.59	3.75	7.60	7.38	2.6
Fe	10.80	5.66	2.48	1.96				0.03
Ni	1.00	0.85	0.99	1.01		1.08		0.03
NiO	0.69				1.23		0.85	—
Co	0.034	0.032	0.015	0.031	0.024	0.036	0.059	0.003
Cr_2O_3	0.57	0.75	0.82	0.78	0.57	0.51	0.52	1.0
Total	100.25	99.71	100.62	100.36	100.65	99.59	99.70	98.57

* Including volatile compositions released up to 1100°C.

Analyses by H. HARAMURA by the courtesy of Prof. I. KUSHIRO, except Y-74160, which is cstimated from the mineral compositions.

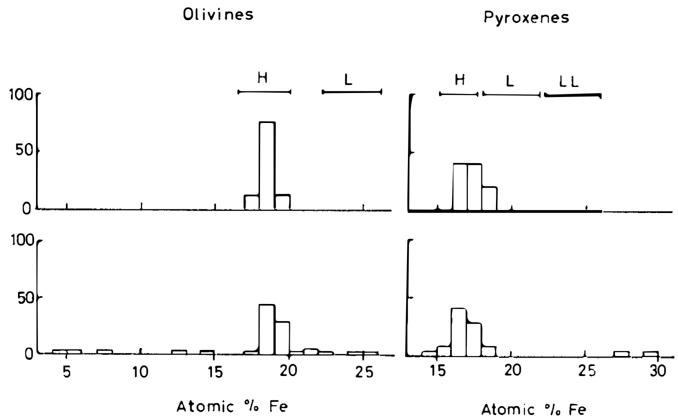


Fig. 8. Histograms of the olivine and pyroxene compositions of Yamato-75028. Top: H5-like clast, bottom: H(L)3-like matrix.

The largest clast observed within the thin section we examined is 5.5×2.9 mm in size. The clast has very sharp boundary (Fig. 7). It consists of olivine and orthopyroxene of uniform composition (Fig. 8) comparable to the H chondrites. No chondrules were observed in the clast and the matrix within the clast appears to be less abundant and does not show a polygonal texture of recrystallized plagioclases.

Within the matrix, various types of chondrules have been observed. One very ideally spherical chondrule 0.31 mm in diameter (Fig. 6) has a porphiritic texture with several olivine crystals in a glass. Their core compositions are more Mg-rich than that in the clast and are zoned towards the margin. Another ellipsoidal chondrule 1.0×0.70 mm in size is composed of three large single crystals of olivine joining at the center with 120° triple point juncture. The compositions of the three olivines are almost identical and similar to those in the clast.

5. Discussion

5.1. Discussion of meteorite classification

The Yamato achondrites appear to contribute significantly to our understanding of the meteorite groups. Because perhaps only one in a thousand (*e.g.* ALHA77005) is unique, it appears that the previous meteorite collections broadly define the meteorites population quite accurately. However, the fact that some meteorites apparently fill holes between meteorite classes may require reconsideration of some classification schemes.

The Yamato recrystallized diogenites first reported by TAKEDA *et al.* (1975) are now known for thirty meteorites. They may be the same fall. Yamato-75032 is an intermediate member between diogenite and cumulate eucrite. The meteorite will be classified as a diogenite, if the presence of considerable amount of plagioclase is criterion of eucrite; and will be a eucrite if the occurrence of inverted pigeonite is the characteristic of the cumulate eucrite. The Yamato-74450 is the most quickly cooled eucrite, and contains pyroxene phenocrysts and apparently richer in pyroxene than the peritectic proportion (olivine-pyroxene-plagioclase). It may be the first direct example of crystal separation in the eucrite basalts. With only one exception, Yamato-74356, all the Antarctic eucrites are howardites of eucritic compositions or eucritic polymict breccias. The significance of these Yamato achondrites has been discussed in connection with their pyroxene crystallization and thermal history of their primitive layered crust of the howardite parent body (TAKEDA *et al.*, 1976, 1979; TAKEDA, 1979).

The new finding of the augite-bearing ureilite, Yamato-74130, poses some problems both on the classification and the origin of the ureilites. It could be included in the diopside-olivine achondrites because of the occurrence of the high-Ca clinopyroxene. However, the amounts of CaO and MgO are significantly lower and that of augite is smaller for Yamato-74130 than the nakhlite. The textures and bulk chemistry (Table 3) are much closer to ureilites than to nakhlites. The Fe concentration of olivine in Yamato-74130 is one of the highest in ureilites. The high concentrations of Na_2O, Cr_2O_3 and Al_2O_3 in pyroxene indicate absence of crystallization of plagioclase and chromite in Yamato-74130. These elements may also be concentrated in augite rather than pigeonite.

An evidence of high temperature annealing was observed in Yamato-74160. This meteorite was classified as a unique achondrite in the preliminary examination and has resemblance to chassignite. The amounts of olivine ($\sim$50%) and ortho-pyroxene ($\sim$30%) and the estimated bulk chemistry are in favor of an extensively recrystallized LL chondrite (LL7). The brecciated texture of Yamato-74160 is also common features of the LL group (KEIL and FREDRIKSSON, 1964; MASON and WIIK, 1964).

The sodium-rich plagioclase present as a discrete elongated grain about 0.15 mm in the longest dimension. There are two dominant compositions at around $An_{8.0}$ and $An_{16.8}$, with percent mean deviation of 4.8 and 1.7, respectively. The existing phase diagram of plagioclase does not predict that the binary loop of the peristerite intergrowth extends up to such high temperature as estimated from the Opx-Aug geothermometer. The sodium-rich component has composition near pure albite. The higher An content 8.0 may indicate higher temperature composition. The clustering of the two component compositions of Yamato-74160 is so good that one may suspect that they are the coexisting pair.

5.2. *Discussion of meteorite origin*

It has been considered difficult to crystallize augite and olivine from a residue of the crystal differentiation for some terrestrial mantle rocks. It may also be difficult to produce very similar cumulate textures of ureilites for various degree of crystal fractionation from the common melt. An alternate model, which involves a sedimentation of vapor grown crystals of olivine and pyroxene towards the center of a disc within the early solar nebula, coarted by later products of carbon dusts around the grain, and compaction of these mixtures by the subsequent accretion (TAKEDA, 1978), may be as plausible or unreal as a cumulate model from the melt (BERKLEY *et al.*, 1978). Although the crystallization sequence of origin of ureilites may be worthwhile examining.

Retention of the planetary-type gas and the stronger shock effect at the grain boundaries than in the interior of grains are compatible with the above model. However, it is not well understood whether this gas is still retained during the long period of annealing as evident from the ureilite textures. The rapid cooling from the high temperature annealing period (TAKEDA and YANAI, 1978) as postulated from the crystallography of the Yamato-74659, is also compatible with the uniform composition of augite with no exsolution of low-Ca pyroxene.

Evidence for mixing among asteroids has been pointed out by WILKENING (1977), from her observation on meteorites in meteorites. Foreign inclusions called xenoliths or clasts have been found thus far within host meteorites representing eight meteorite classes (WILKENING, 1977; ANDERS, 1978). Of the 27 xenoliths carbonaceous chondrites predominate accounting for 20 out of 27 xenoliths. Ordinary chondrites and their relatives are the second most abundant class, with five representatives. St. Mesmin chondrite is the only case where an H xenolith was found in the LL hosts (DODD, 1974).

These previous examples are small xenoliths or clasts in homogeneous host meteorites, and their bulk chemistries are not affected significantly. The bulk chemistry of Yamato-75028 is intermediate between those of the H and L groups (Fig. 4) but is similar to that of H3 chondrite, Tieshetz. Because half fragments of H5 were seen in the chondrule-rich matrix within a thin section examined, the host may be the L material, but one can not exclude a possibility that the host is the H, or LL material. The textures are not indicative of the brecciated LL matrix. The round fragments (chondrules) in the matrix have the H5 composition. One chondrule is composed entirely of three olivine crystals within the compositional range of H6.

A plausible interpretation of Yamato-75028 is a low metallic and sulfide iron H3 chondrite with the abundant H5-type components. The equilibrated components could be either "equilibrated chondrules" or brecciated fragments of an H5 body. If a chondrite parent body has a type 6 core and type 3 crust and type 4 and 5 intermediate layers between them (ANDERS, 1978), one might expect brecciated regolith chondrites of mixtures of various petrologic types such as Yamato-75028, by analogy of the howardite parent body (TAKEDA, 1979). It is not well established whether the size of the chondrite parent body may be so small as to retain thick regolith or there may be an individual parent body for different petrologic types. At present, one might invoke a soft collision of small H5 and L(H)3 parent body. It is also possible to grow the H5-like olivine in a chondrule for a certain growth condition. More extensive studies of large portion of Yamato-75028 may support one of the above models.

5.3. *Conclusion*

In conclusion, an implication of the new unique meteorites found in Antarctica with respect to the origin and evolution of asteroids proposed by some investigators (GAFFEY and McCORD, 1977; MATSON *et al.*, 1976) is the following: (1) several unique meteorites found in about one thousand collections suggest a possibility that some unidentified objects in the asteroid surface materials may be found in the Antarctic meteorites; (2) there may be "thermalized" asteroids which are composed of olivine and pyroxene other than the howardite parent body; (3) co-existence of the H5 and L3 chondrites or the H5 and H3 ones will give some constraints on the distribution and collisional evolution of the asteroids.

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APPENDIX: CLASSIFIED LIST OF THE YAMATO METEORITES

Irons (2 finds)

Octahedrite (reheated, 1 find)
Y-75031 60.2 g

Ataxite (Ni-poor, 1 find)
Y-75105 19.5 g

Stony Irons (1 find)

Pallasite (1 find)
Y-74044 51.8 g

Stones (987 finds)

Chondrites (96 finds+842 unclassified)

Enstatite chondrite (1 find)
Y-691 715 g

H chondrites (unclassified, 5 finds)

Y-697	25 g	Y-74089	43.1 g	Y-74156	714.7 g	Y-74364	757.8 g
Y-74375	92.7 g						

H6 chondrites (9 finds)

Y-694	62 g	Y-74094	867.2 g	Y-74192	420.3 g	Y-74374	205.2 g
Y-74418	567.2 g	Y-74459	1719.7 g	Y-74471	85.7 g	Y-74640	1065.9 g
Y-75096	91.8 g						

H6–5 chondrites (7 finds)

Y-74014	2369.9 g	Y-74038	208.9 g	Y-74115	1045.1 g	Y-74163	134.2 g
Y-74371	5067.9 g	Y-74462	205.0 g	Y-75259	70.0 g		

H5 chondrites (8 finds)

Y-696	41 g	Y-698	10 g			Y-74001	246.1 g
Y-74079	620.8 g	Y-74609	257.2 g	Y-74647	2323.8 g	Y-75012	69.9 g
Y-75269	87.2 g						

H5–4 chondrites (4 finds)

Y-74054	134.9 g	Y-74082	179.8 g	Y-74193	1818.5 g	Y-74497	301.2 g

H4 chondrites (8 finds)

Y-7301	650 g	Y-74155	3073.4 g	Y-74376	120.0 g	Y-74491	134.5 g
Y-74495	220.2 g	Y-74498	124.0 g	Y-74507	116.1 g	Y-75100	85.0 g

H3(?) chondrites (2 finds)
Y-74492 112.1 g Y-75028* 6100.0 g (with equil. clasts)

L chondrites (unclassified, 14 finds)

Y-74048	67.1 g	Y-74049	13.0 g	Y-74050	18.9 g	Y-74051	20.9 g

Y-74052	58.0 g	Y-74053	88.2 g	Y-74055	13.0 g	Y-74061	9.2 g
Y-74062	10.3 g	Y-74063	35.2 g	Y-74064	2.0 g	Y-74070	58.7 g
Y-74605	580.8 g						

L6 chondrites (16 finds)

Y-699	10 g	Y-7304	500 g	Y-7305	900 g	Y-74035	115.7 g
Y-74067	4.0 g	Y-74080	536.9 g	Y-74164	284.8 g	Y-74354	2721.1 g
Y-74362	4175.0 g	Y-74445	2293.2 g	Y-74650	163.2 g	Y-74663	213.9 g
Y-75017	87.2 g	Y-75071	6.9 g	Y-75102	11000 g	Y-75288	93.9 g

L6–5 chondrites (5 finds)

Y-74007	162.3 g	Y-74036	201.4 g	Y-74118	845.1 g	Y-74190	3235.7 g
Y-74455	114.1 g						

L5 chondrites (2 finds)

Y-74454	578.8 g	Y-75289	50.9 g

L5–4 chondrites (1 find)

Y-74457 120.8 g

L4 chondrites (6 finds)

Y-74165	203.4 g	Y-74367	165.6 g	Y-74603	188.7 g	Y-75097	2570.2 g
Y-75108	590.8 g	Y-75110	706.9 g				

L3 chondrites (3 finds)

Y-74065	12.1 g	Y-74066	12.4 g	Y-74191	1091.6 g

LL chondrites (unclassified, 1 find)

Y-75294(?) 14.1 g

LL6 chondrites (2 finds)

Y-74646	554.7 g	Y-75258	971.0 g

LL4 chondrite (1 find)

Y-74442 173.3 g

Unique (LL7?) (1 find)

Y-74160* 31.4 g

Carbonaceous Chondrites (7 finds)

CC (unclassified, 3 finds)

Y-74641	4.5 g	Y-75003	1.5 g	Y-75293	8.1 g

CC4 (1 find)

Y-693 150 g

CC2 (3 finds)

Y-74642	10.6 g	Y-74662	150.9 g	Y-75260	4.0 g

Achondrites (42 finds, 29 paired)

Ureilites (3 finds)

Y-74123	69.9 g	Y-74130*	17.9 g	Y-74659	18.9 g

Diogenites (30 finds, 29 paired)

Y-692	138 g	Y-74005	3.8 g	Y-74010	298.5 g	Y-74011	206.0 g
Y-74013*	2059.5 g	Y-74031	6.1 g	Y-74037	591.9 g	Y-74096	16.1 g
Y-74097	2193.9 g	Y-74109	43.5 g	Y-74125	107.0 g	Y-74126	14.5 g
Y-74136	725.0 g	Y-74150	33.4 g	Y-74151	49.1 g	Y-74162	3.9 g
Y-74344	1.4 g	Y-74347	7.8 g	Y-74368	4.1 g	Y-74448	17.7 g
Y-74546	7.3 g	Y-74606	2.9 g	Y-74648	185.5 g	Y-75001	4.1 g
Y-75004	37.0 g	Y-75007	2.6 g	Y-75014	3.0 g	Y-75032**	189.1 g
Y-75285	3.1 g	Y-75299	9.1 g				

Eucrites (1 find)

Y-74356	10.0 g

Eucrites (polymict, 7 finds)

Y-74159	98.2 g	Y-74450*	235.6 g	Y-75011	121.5 g	Y-75015	166.6 g
Y-75295	8.8 g	Y-75296	8.6 g	Y-75307	7.9 g		

Howardites (polymict, 1 find)

Y-7308	480g

* Unique meteorites described in this paper. After Catalog of Yamato Meteorites (YANAI, 1979).

** Unrecrystallized diogenite.