A CLASSIFICATION FOR THE YAMATO-74 CHONDRITES BASED ON THE CHEMICAL COMPOSITIONS OF THEIR OLIVINES AND PYROXENES

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Abstract: Electron microprobe studies have been made of olivines and pyroxenes in thirty three Yamato chondrites collected in Antarctica in 1974, together with two chondrites collected in 1975 and two Mt. Baldr chondrites. The small fragments used for the analyses were so chipped from the meteorites that contamination to the original materials is minimal. On the basis of histograms of iron contents of olivines and orthopyroxenes, the following chondrites have been identified: 4 unequilibrated chondrites; 8 H type, 2 L type and 1 LL type moderately equilibrated ones; and 12 H type, 9 L type and 1 LL type equilibrated chondrite. Absence of the E type chondrite and predominance of the H type ones are notable features but may not be significant at this stage of identification.

1. Introduction

As a part of a preliminary examination of the Yamato meteorites collected in 1974, microprobe analyses of olivines and pyroxenes in the chondrites have been carried out. A primary purpose of this study is to help to make a catalogue of the Yamato meteorites, which will be used as a guidebook in processing, allocation and distribution of the meteorites for investigators in various fields in a manner designed to produce the best possible research results. Many of these meteorites will have been preserved at low temperatures under exceptionally clean circumstances. We therefore had to selected a method of investigation that would allow least contamination, even at the expense of some uncertainties of the classification.

For this purpose, very small amounts of sample have been chipped from near the surface. In addition, in order to process large numbers of samples, the method of sample preparation and microprobe analyses had to be carried out in an efficient manner. The CaO, MgO, and FeO contents of olivines and pyroxenes in three to five polished grain mounts or polished small sections have been analyzed at one time to obtain histograms of iron contents in two minerals such as given by DODD *et al.* (1967). Because of the limitation of this method, we admit that a chemical-petrologic classification (VAN SCHMUS and WOOD, 1967) of the Yamato meteorites given in this paper is a tentative one.

Statistics on the classification of the Yamato chondrites may be used to deduce the distribution of chondrite falls among different chemical and petrologic types. However, the number of meteorites thus far identified may be still too small to draw any definite conclusions on this subject.

2. Experimental Techniques

The samples used for this study were selected on the basis of one or more of the following criteria:

1. Chondrites weighing more than 100 g.
2. Samples with small broken fragments.
3. Samples brought to curator's attention by special features such as well recrystallized texture or brecciated texture.

0.01–1 g fragments were chipped from the original meteorite samples. Many of these samples were covered by crusts of iron oxides or hydroxides, and even in the interior of many samples some oxidized portions were found. For those meteorites for which only small fragments were supplied polished grain mounts have been prepared for the microprobe analysis. Several fragments were mounted in araldite resin about 5 mm in diameter and a few mm thick on a cover glass; the final samples used were in the form of 5 mm square polished sections mounted on glass. A fragment larger than about 5 mm in diameter was mounted in epoxy, and a slice of 0.2 to 0.5 mm thick was cut and cemented by araldite. The polished sections were prepared for microprobe analyses by coating with carbon.

The quantitative chemical analyses of olivines, orthopyroxene and augites were made with a JEOL JXA-5 electron probe X-ray microanalyzer with a 40° take off angle. The method was the same as that described by NAKAMURA and KUSHIRO (1970). The CaO, MgO and FeO contents (weight percentage) were all analyzed at one time. The SiO_2 contents were calculated from the CaO, MgO and FeO contents so that all these cations are combined to produce stoichiometric olivine or pyroxene formulas. The sodium, aluminum and calcium contents have been checked to identify large plagioclase grains in the chondrites of petrologic type 6.

Measurements for each meteorite section or grain mount were made on about 10 to 80 points on different chondrules, grains or crystals of olivine and pyroxene. Random selections of points have been tried in order to obtain about 50 orthopyroxene measurements and a comparable number of olivine measurements in each sample. However, some polished grain mounts contained only a small number of mineral grains, and some sections contained very large chondrules.

The homogeneity of the compositions for equilibrated chondrites was checked by monitoring the intensities of the three elements on the scan chart, and only a few representative values were recorded. In this case the actual number of the examined grains is larger than the number of analyzed points.

Grains with total weight percents ($CaO+MgO+FeO+SiO_2$) outside the range between 95 to 102% were interpreted as glass or another mineral phase or inaccurate analyses, and were rejected. Any point whose Ca, Mg, Fe, and Si contents were inappropriate to either olivine or pyroxene was then discarded. Thus, the total number of measurements was generally smaller than 50.

After the data were screened for spurious measurements, the weight percents of the metal oxides in the olivine or pyroxene at each sample point were used to calculate atomic % calcium, magnesium, and iron in the olivine or pyroxene. Mean concentrations of these three elements were calculated for the olivines and pyroxenes in each sample, and the "percent mean deviation" proposed by DODD *et al.* (1967), but for the atomic % of iron rather than weight percent iron, were determined for the olivines and pyroxenes of various ordinary chondrites.

Although the parameter "percent mean deviation" has been used as an index of olivine or pyroxene heterogeneity by the above authors (DODD *et al.*, 1967), it was found that for the method of measurements we employed in this reconnaissance study a histogram of percent of measurements against atomic % iron is a good measure of the spread of the frequency distribution. The smaller number of analyzed points is due to the small number of grains available for the analyses in one case and is due to selected analyses of the homogeneous samples in other cases. First, actual number of measurements were plotted for 1% intervals of atomic percent iron. Then, percent of measurements were computed by normalizing total number of measurements to 100%.

3. Results

Histograms of iron contents, in atomic percent, of olivines and orthopyroxenes for thirty three Yamato-74 chondrites, two Yamato-75 chondrites, and two Mt. Baldr chondrites are given in Figs. 1 to 5. The histograms are arranged in three major groups, according to their petrologic types. Except for unequilibrated ordinary chondrites (Figs. 1–2), they are further classified according to their chemical types. In these figures, the ranges of atomic percent of iron for the known H6, L6, and LL6 type chondrites are given on top of each figure.

The numbers in the figures are the sample numbers of the Yamato meteorites, respectively. Yamato- should be added to each number when it is quoted, since some numbers are quite similar to those of the Apollo 17 Station 4 samples. The histograms are arranged in the order of increasing sample numbers. If the histograms were arranged according to their iron content distribution independently of whether it is olivine or orthopyroxene, the same sample number would appear in different figures. For example, Yamato-74495 is listed in Fig. 2a for olivine, but would be in Fig. 1b for orthopyroxene. This discrepancy implies

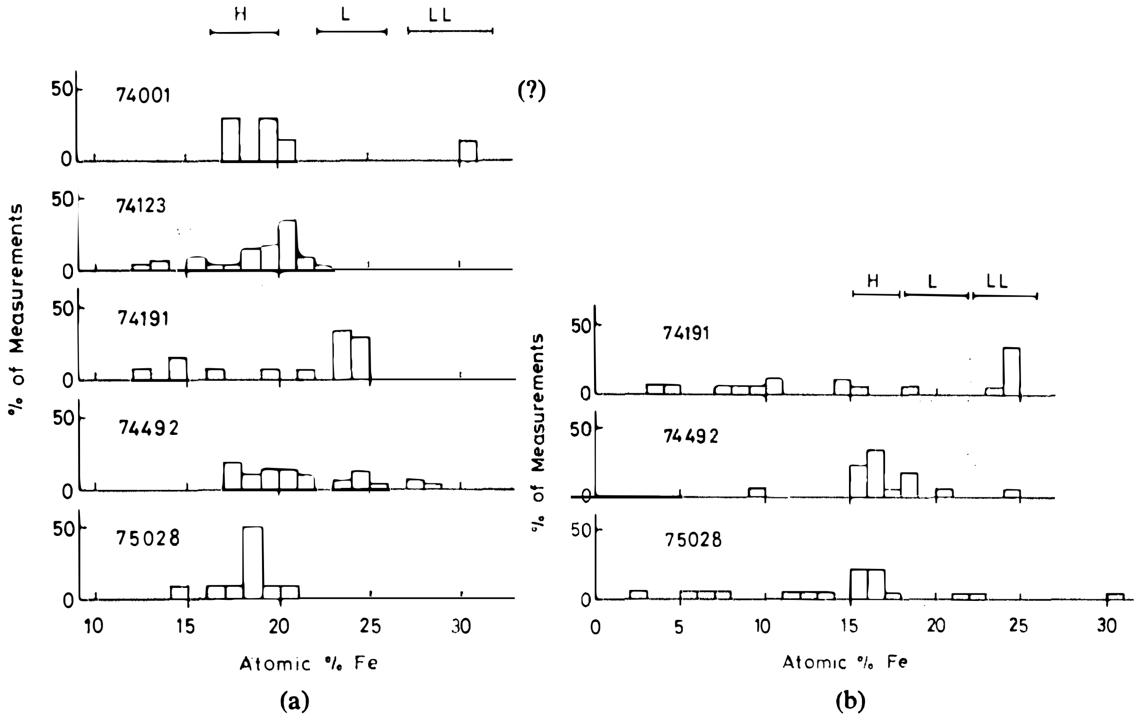

Fig. 1. Iron contents of (a) olivines and (b) orthopyroxenes in unequilibrated chondrites. The numbers are names of the Yamato meteorite samples. 74001 is more equilibrated since the high Fe peak may be due to Fe-rich inclusions.

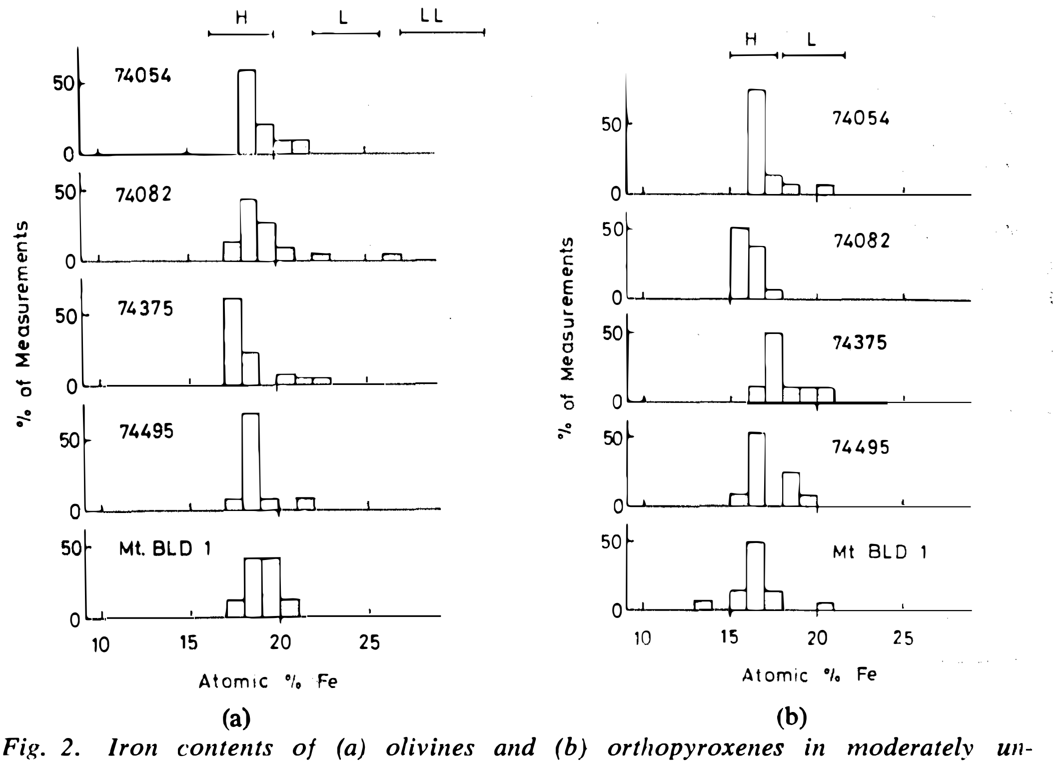

Fig. 2. Iron contents of (a) olivines and (b) orthopyroxenes in moderately unequilibrated H group ordinary chondrites.

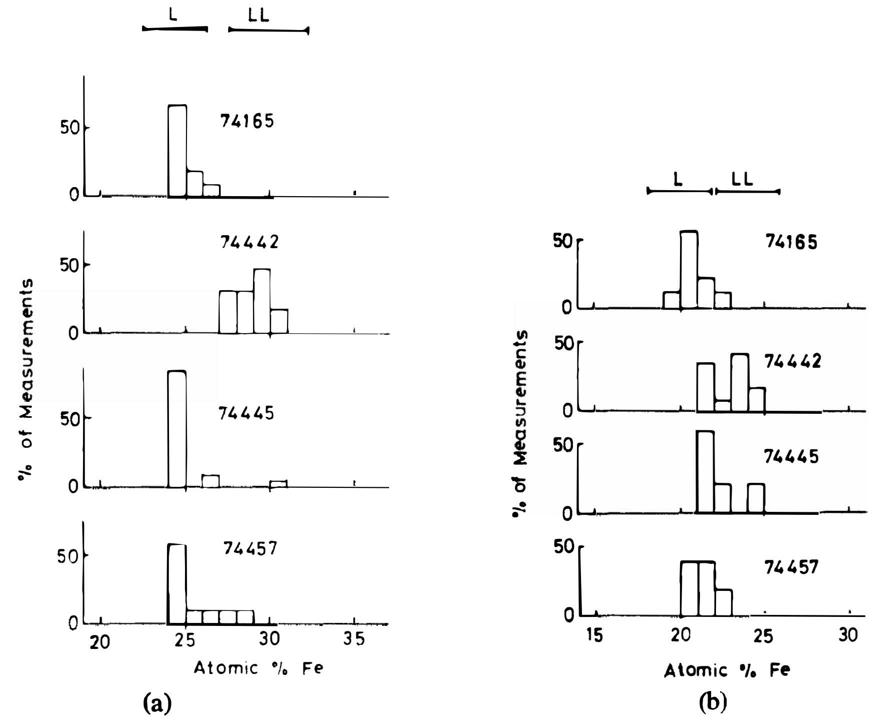

Fig. 3. Iron contents of (a) olivines and (b) orthopyroxenes in moderately unequilibrated L and LL group ordinary chondrites.

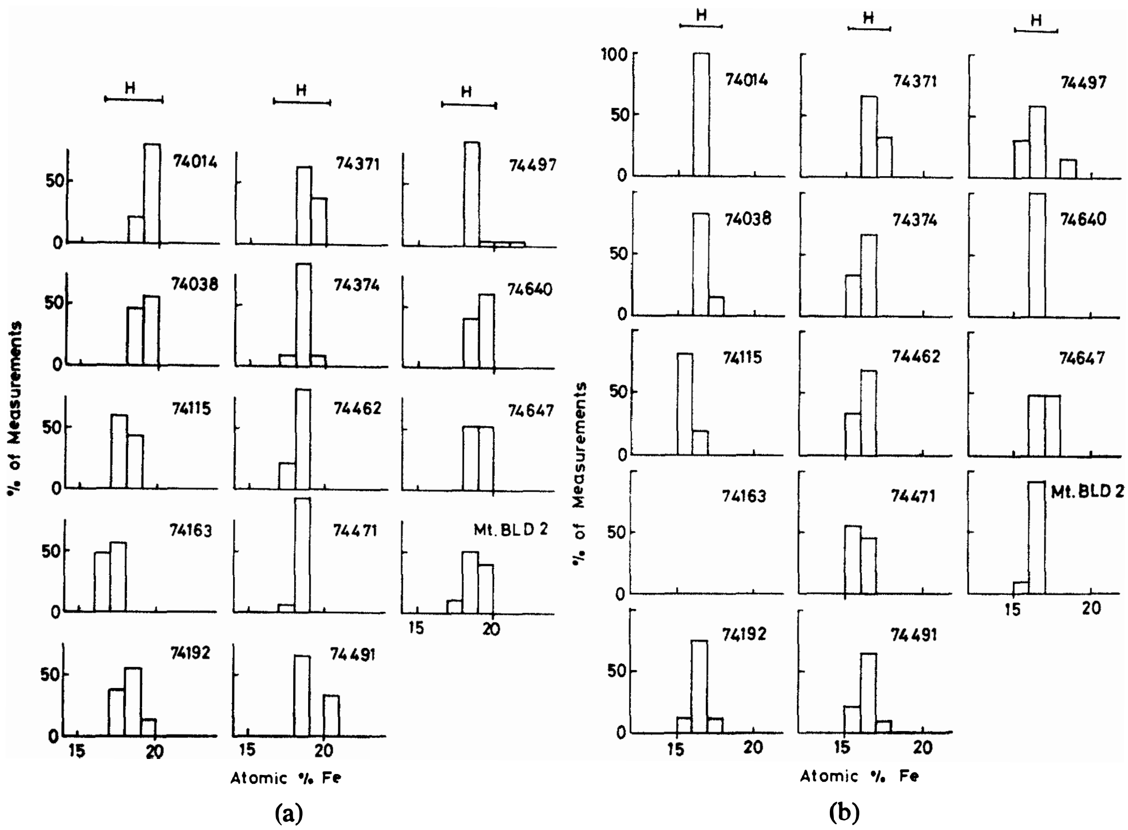

Fig. 4. Iron contents of (a) olivines and (b) orthopyroxenes in equilibrated H group ordinary chondrites.

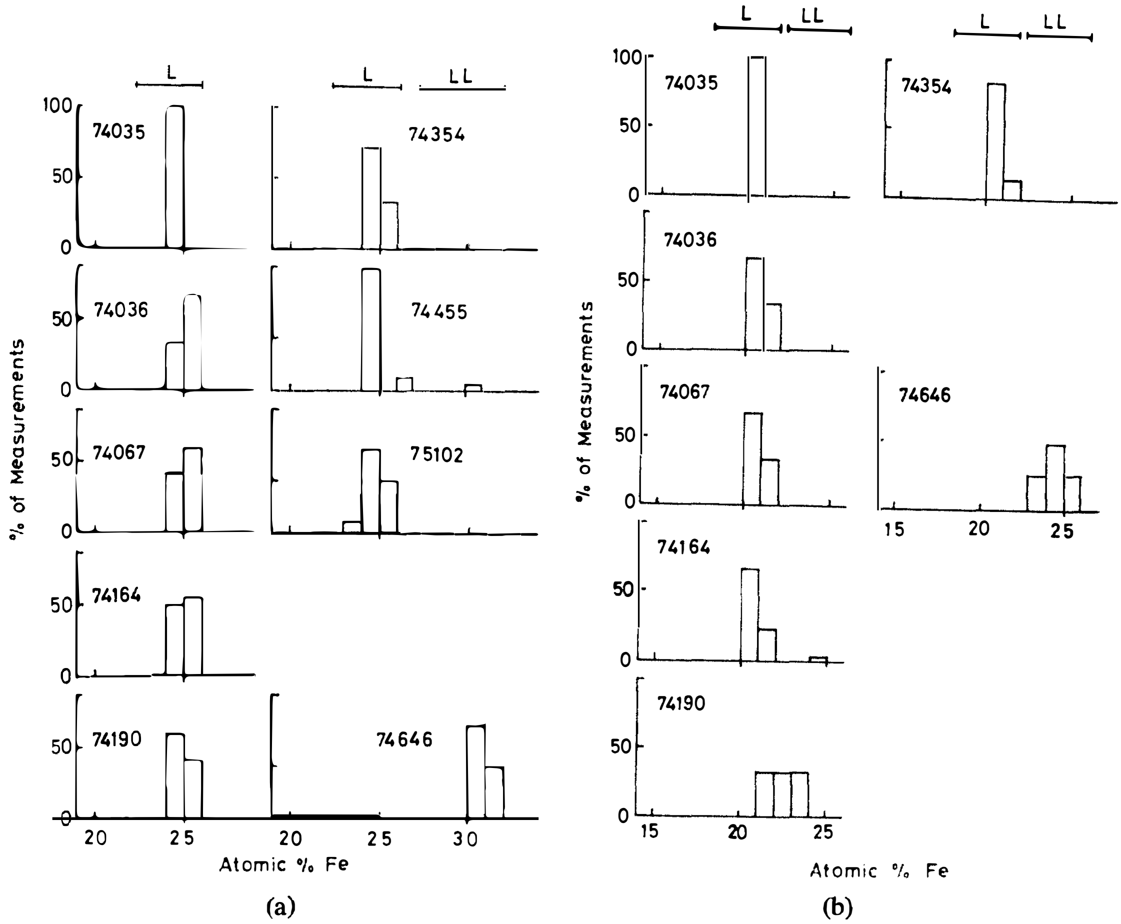

Fig. 5. Iron contents of (a) olivines and (b) orthopyroxenes in equilibrated L and LL group ordinary chondrites.

ambiguity in the final classification of this meteorite. In such cases the classification is mainly based on their olivine values. Yamato-74497 is given in Fig. 4a, but two measurements on different probe samples gave somewhat different results. Some numbers that appear in the olivine, but are missing or are left blank in the orthopyroxene figure, indicate that orthopyroxene composition could not be measured within the probe samples prepared for those numbers.

The chondrites grouped as unequilibrated chondrites are given in Figs. 1a and 1b. The iron contents of their olivines and pyroxenes are irregularly distributed from 2 atomic % to as much as 30%. The distributions lack distinct modes and are quite similar for members of all three chemical groups. Therefore, their chemical groups had to be based on their amounts of the metallic Fe–Ni by visual estimation. In some samples (*e.g.* Yamato-74001), the amounts of the samples were too small to draw confident conclusions. The petrologic type of this group corresponds to 3 or 3–4.

Histograms for those meteorites which are grouped as moderately unequilibrated ordinary chondrites (Figs. 2 and 3) show distinct modes in the olivine and pyroxene distributions. Their peaks occur at iron concentrations appropriate to the equilibrated H, L, and LL group chondrites (DODD *et al.*, 1967; VAN SCHMUS, 1969; BUNCH and OLSEN, 1974). The entire range of the iron concentrations, however, falls outside the known range of the equilibrated chondrites. The petrologic type of the moderately unequilibrated chondrites corresponds to that of type 4–5 or 4–3.

Table 1. Distribution of the analyzed meteorites among the chemical-petrologic types.

Unequilibrated chondrites (Type 3 or 3–4)		
H(?): 3*		74123, 74492, 75028.
L: 1		74191.
Moderately unequilibrated ordinary chondrites (Type 4–3 or 4–5)		
H: 8	H4–5:	74001, 74054, 74375, 74491, 74647, (Mt. Baldr No. 1).
	H4:	74082, 74495.
L: 2	L4–5:	74165, 74457.
LL: 1		74442.
Equilibrated ordinary chondrites (Type 6–5 or 5–6)		
H: 12	H6–5:	74014, 74192, 74374, 74462, 74471, 74640, (Mt. Baldr No. 2).
	H5–6:	74038, 74115, 74163, 74371, 74497.
L: 9	L6–5:	74035, 74067, 74164, 74354, 74445, 74455, 75102.
	L5–6:	74036, 74190.
LL: 1	LL6–5:	74646.

* Total number for each chemical group.

Table 2a. Mean compositions of olivines and percent mean deviations of their iron concentrations in the analyzed chondrites of petrologic type 3 and 4.

Sample No.	Mean composition			No.	Mean dev.	% mean dev.	Remarks
	Ca	Mg	Fe				
Yamato-74123	0.2	81.3	18.5	25	2.2	12	H3
74191	0.2	81.0	18.8	25	1.6	8.4	L3
74492	0.2	77.8	22.0	25	3.7	17	H(?)3
75028	0.1	80.5	19.4	14	2.6	13	H3–4
74001	0.0	77.3	22.7	8	5.5	24(?)	H4(?)
74054	0.0	81.0	19.0	26	0.49	2.6	H4–5
74082	0.1	80.6	19.3	25	0.99	5.1	H4
74375	0.0	81.7	18.3	26	0.83	4.6	H4
74491	0.0	81.4	18.6	13	0.47	2.6	H4
74495	0.0	81.3	18.7	12	0.53	2.9	H4
74497	0.0	81.3	18.7	16	0.55	2.9	H5–4
74647	0.1	81.1	19.0	9	0.74	3.9	H4–5
Mt. Baldr No. 1	0.0	81.0	18.9	10	0.52	2.8	H5–4
Yamato-74165	0.0	74.8	25.2	21	0.90	3.6	L4
74442	0.0	71.0	29.0	16	0.71	2.4	LL4
74445	0.0	75.1	24.9	22	0.77	3.1	L6(?)
74457	0.0	74.7	25.3	9	0.93	3.7	L4–5

No.: Number of measurements.

Table 2b. Mean compositions of olivines and percent mean deviations of their iron concentrations in the analyzed chondrites of petrologic type 5 and 6.

Sample No.	Mean composition			No.	Mean dev.	% mean dev.	Remarks
	Ca	Mg	Fe				
Yamato-74014	0.0	80.9	19.1	5	0.16	0.83	H6
74038	0.1	81.1	18.9	38	0.25	1.3	H5–6
74115	0.0	82.2	17.8	30	0.24	1.3	H5–6
74163	0.0	82.3	17.7	16	0.28	1.6	H5–6
74192	0.0	81.7	18.2	17	0.34	1.8	H6
74371	0.0	81.4	18.6	13	0.23	1.2	H5–6
74374	0.0	81.5	18.4	12	0.27	1.5	H6
74462	0.0	81.7	18.3	15	0.21	1.1	H6–5
74471	0.0	81.7	18.3	20	0.20	1.1	H6
74640	0.1	80.9	19.0	3	0.10	0.52	H6
Mt. Baldr No. 2	0.0	81.2	18.7	10	0.37	1.98	H6–5
Yamato-74035	0.0	75.5	24.5	10	0.23	0.94	L6
74036	0.0	74.8	25.2	23	0.36	1.4	L5–6
74067	0.0	74.9	25.1	17	0.39	1.6	L6
74164	0.0	74.8	25.1	20	0.26	1.04	L6
74190	0.0	75.3	24.7	5	0.36	1.5	L5–6
74354	0.0	75.2	24.8	32	0.26	1·2	L6
74455	0.0	75.0	25.0	17	0.28	1.2	L6–5
75102	0.0	75.3	24.6	14	0.36	1.5	L6–5
74646	0.0	69.4	30.6	3	0.33	1.09	LL6–5

No.: Number of measurements.

All analyzed chondrites whose iron concentrations fall within the range of the known equilibrated chondrites are given in Figs. 4 and 5. The petrologic types of these meteorites are that of 6 or 5. Those meteorites which contain sodium-rich plagioclase large enough to be analyzed by the electron microprobe techniques were assigned to petrologic type 6–5 and others 5–6. Very few meteorites contain either olivines or pyroxenes having iron contents outside the above range. The Yamato-74163 olivines are slightly more iron-poor than the common equilibrated ones, but their individual values (16.7 to 17.6 atomic % Fe) are very close to the lower limit of the known range.

The numbers of newly identified Yamato-74 chondrites together with two Yamato-75 and two Mt. Baldr chondrites for each chemical-petrologic group are summarized in Table 1. The mean compositions and the percent mean deviations (%M.D.) of iron concentrations in their olivines are given in Tables 2a and 2b. Those chondrites with %M.D. greater than 6 are assigned to petrologic type 3 and are grouped as unequilibrated chondrites in Table 1. Those with %M.D. of 2 to 5 are classified as moderately unequilibrated ordinary chondrites (petrologic type 4), and those with %M.D. of less than 2 as equilibrated chondrites

(Type 5 to 6).

The meteorite classification based on the histograms of the iron concentrations of olivines is consistent with that by %M.D. except in a few cases. Yamato-74491, -74497 and -74647 were listed as equilibrated ordinary chondrites in Figs. 4a and 4b, but %M.D. computed with more data (Table 2) were greater than 2. They are listed as H4–5 in Table 1. Both the histogram and %M.D. of Yamato-74445 indicate that this chondrite is L4, but its texture is that of petrologic type 6. Fine iron-rich inclusions were found in the Yamato-74445 olivines.

4. Discussion

As was stated in the introduction, this study has been carried out as a part of our preliminary examination of the Yamato meteorites. It was required that the identification of the meteorite type should be done quickly and the method consume the least amounts of the samples, while not introducing any contamination into the original samples. As a consequence, we have to admit that the chemical-petrologic types thus deduced are useful for curatorial work but may still have some ambiguities. Further detailed studies are required on the bulk chemistry and the texture of those meteorites that can be classified into two alternate types by the data available at present.

One difficulty in classifying the chondrites by their olivine and pyroxene compositions is that the chemical groups of the type 3 chondrites are indistinguishable. In addition, many samples used are small fragments of the oxidized crusts. When the total number of chondrules or mineral fragments that can be analyzed is small, we cannot obtain an unbiased statistical distribution of their iron concentrations. The presence of iron oxides or hydroxides makes it difficult to observe their texture and tends to give higher iron contents when the electron beam irradiates the oxidized portion. Sometimes even the interiors of the meteorites are heavily oxidized. Severe oxidation by weathering is one of the characteristics of the Yamato meteorites.

By investigating Table 2b, we can state that many equilibrated chondrites have %M.D. less than 2.0. The histogram of Yamato-74163 shows that some olivines have their iron contents outside the known range of the H type chondrite, although it is equilibrated. This chondrite is slightly more reduced than the regular H type chondrites. Although %M.D. = 5.0 has been used as a minimum value for the petrologic type 3 chondrites, it may not be the best criterion to classify truly unequilibrated chondrites. Many chondrites that have %M.D. greater than 5 show a prominent peak within the known range of iron concentration of olivine and orthopyroxene of the equilibrated chondrites. Such a frequency distribution pattern of iron concentration is essentially identical to that of the type 4 chondrite. Yamato-74123 and -75028 are such examples. These chondrites may better be classified as type 4.

From the experience to classify chondrites on the basis of a histogram of iron concentrations of olivines obtained by the microprobe technique, we examined various criteria to differentiate chondrites among the six petrologic types. If we could propose a modified version of the classification, the following conditions would be simple criteria to the petrologic type:

(1) Type 3 should have no prominent peak in the histogram within the known range of iron concentration of olivine.

(2) Type 4 should have such peak but the range of iron concentrations extends outside the known range of the equilibrated chondrite.

(3) Type 5 and 6 should have iron concentrations of olivine all within the known range of the equilibrated chondrites.

(4) Type 6 should have large enough plagioclase to be analyzed by electron microprobe in addition to condition (3).

In light of the recent studies on breccias in the lunar samples and on impact phenomena on the planetary surfaces, it is not surprising that polymict breccia of the different chondrites have been found to be common. Some meteorites such as Yamato-74442 show a brecciated texture. Strict classification according to the chemical-petrologic types, thus may not be meaningful.

Since the Yamato meteorites have been considered to be the best known random sampling of falls of meteorites on our earth, distribution of the classified Yamato meteorites among chemical and petrologic grids will be of paramount importance. The data we have at present indicate that the E type chondrite is rare and the equilibrated H type chondrites are most abundant. However it should be kept in mind in interpreting our results that some meteorites given different numbers might be fragments of one and the same fall. The total number of samples studied is still to small to exclude a case where some meteorites with a similar appearance had been selected preferentially for our analyses. At least samples weighing more than 50 g should be identified before drawing any definite conclusion of this subject of our special interest.

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