



Yamato 792947, 793408 and 82038: The most primitive H chondrites, with abundant refractory inclusions

M. KIMURA^{1*}, H. HIYAGON², H. PALME³, B. SPETTEL⁴, D. WOLF³, R. N. CLAYTON⁵, T. K. MAYEDA⁵,
T. SATO¹, A. SUZUKI⁶ AND H. KOJIMA⁷

¹Faculty of Science, Ibaraki University, Mito 310-8512, Japan

²Department of Earth and Planetary Science, University of Tokyo, Tokyo 113-0033, Japan

³Universität zu Köln, Institut für Mineralogie und Geochemie, 50674 Köln, Germany

⁴Max-Planck-Institut für Chemie, 55020 Mainz, Germany

⁵Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637, USA

⁶Faculty of Science, Tohoku University, Sendai 980-8578, Japan

⁷National Institute of Polar Research, Tokyo 173-8515, Japan

*Correspondence author's e-mail address: kimura@mito.ipc.ibaraki.ac.jp

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Abstract—In this paper we report petrological and chemical data of the unusual chondritic meteorites Yamato (Y)-792947, Y-93408 and Y-82038. The three meteorites are very similar in texture and chemical composition, suggesting that they are pieces of a single fall. The whole-rock oxygen isotopes and the chemical compositions are indicative of H chondrites. In addition, the mineralogy, and the abundances of chondrule types, opaque minerals and matrices suggest that these meteorites are H3 chondrites. They were hardly affected by thermal and shock metamorphism. The degree of weathering is very low. We conclude that these are the most primitive H chondrites, H3.2–3.4 (S1), known to date. On the other hand, these chondrites contain extraordinarily high amounts of refractory inclusions, intermediate between those of ordinary and carbonaceous chondrites. The distribution of the inclusions may have been highly heterogeneous in the primitive solar nebula. The mineralogy, chemistry and oxygen isotopic compositions of inclusions studied here are similar to those in CO and E chondrites.

INTRODUCTION

The main groups of chondritic meteorites are carbonaceous (hereafter C), ordinary (O) and enstatite (E) chondrites. The ordinary chondrites are subdivided into H, L and LL groups based on total amount of metallic iron and the FeO contents of ferromagnesian minerals. A major difference between ordinary and carbonaceous chondrites is the low abundance of refractory inclusions in O chondrites compared to C chondrites (Grossman *et al.*, 1988).

Ungrouped or unusual "O-chondritic" meteorites are rare, compared with the large number of ungrouped C chondrites (e.g., Meibom and Clarke, 1999). Only a few unusual "O-chondritic" meteorites have been reported (Wasson *et al.*, 1993; Bischoff *et al.*, 1997). Yanai and Kojima (1995) also pointed out that Yamato (Y)-793408, temporarily classified as L3, is anomalous because of the small chondrule size. Nobuyoshi *et al.* (1997) suggested that this chondrite has a higher total Fe/Si ratio than normal L chondrites, and the chondrule size distribution resembles that in CO chondrites. Y-792947 (H3) and Y-82038 (H3) chondrites are similar in texture and chondrule size to Y-793408. Kimura *et al.* (1999) noticed that wet chemical data of these chondrites (Yanai and Kojima, 1995), have

higher Al, Mg and Ca concentrations than those of O chondrites.

Here we report on the petrography, bulk chemistry and oxygen isotopic compositions of these chondrites. We conclude that these chondrites are the most primitive H3 chondrites to date, and contain the highest amount of refractory inclusions in O chondrites. The preliminary results were reported by Kimura *et al.* (2000).

SAMPLES AND EXPERIMENTAL METHODS

The original weights of Y-792947, Y-793408 and Y-82038 were 233.4, 1140 and 199.9 g, respectively. We investigated three polished thin sections of Y-793408 (89-5, 91-3 and 91-4) (1.5 cm² in total area), a section of Y-792947 (61-1) (0.7 cm²), and a section of Y-82038 (61-3) (0.5 cm²). Oxygen isotopic compositions of refractory inclusions were measured on another section of Y-792947 (H-3).

Backscattered electron images and mineral analyses were obtained using a JEOL 733 electron probe microanalyzer. In order to identify refractory inclusions, whole areas of thin sections were mapped by x-ray lines of Al, Si, Ca and Ti. For silicate and oxide analyses, the beam currents were usually 10 nA,

and 30 nA for metals and sulfides. The silicate and oxide analyses were corrected using the Bence–Albee method. The conventional ZAF correction method was applied for analyses of metals and sulfides. The x-ray overlaps of K_{β} on K_{α} lines of some successive elements were corrected with a deconvolution program. In addition, we determined bulk compositions of inclusions and chondrules with the defocused beam method. The data were recalculated by the correction method of Ikeda (1980).

Raman spectra of a Ti-oxide phase were measured by JASCO NRS-2000 spectrometer with a nitrogen-cooled charge-coupled device (CCD) detector. A microscope was used to focus the excitation laser beam (514.5 nm lines of a Princeton Instruments Inc. Ar⁺ laser) to a 2 μ m spot. The laser power was 40 mW.

About 1 g of Y-793408,96 and Y-82038,69 was homogenized and aliquots were taken for instrumental neutron activation analysis (INAA) and x-ray fluorescence (XRF). Sample Y-792947,68 was not homogenized, only crushed, and coarse pieces were taken for analysis. Two ~100 mg samples of each meteorite were irradiated in the TRIGA reactor of the Institut für Kernchemie at the Universität Mainz at a neutron flux of $7 \times 10^{11} \text{ n} \times \text{cm}^{-2} \times \text{s}^{-1}$ for 6 h. Samples were repeatedly counted on large Ge and Ge(Li) detectors with increasing durations. Peak deconvolution of spectra was done utilizing procedures by Kruse (1979). Appropriate standards of pure elements were irradiated. Two 120 mg splits were analyzed by XRF, following the procedures by Wolf and Palme (2001).

The analysis method for determining the oxygen isotopes of bulk meteorites was the same as described by Clayton *et al.* (1991). The oxygen isotopic compositions of inclusions were measured using a CAMECA ims-6f ion microprobe after the method by Hiyagon and Hashimoto (1999).

PETROGRAPHY

Overall Texture

The three chondrites have very similar textures typical of unequilibrated ordinary chondrites (UOCs), consisting mainly of chondrules, isolated minerals and matrix (Fig. 1a). Table 1 summarizes the petrographic features of the samples. Chondrules and isolated silicate minerals occupy 70–77 vol% of these chondrites. The modal fractions of the matrices and opaque minerals (Fe–Ni metal > troilite) are 12–17% and 8–13%, respectively. We found 43 refractory inclusions and their fragments in the sections studied.

There is no textural evidence for shock metamorphism in these meteorites. They are assigned to shock stage S1 using the criteria of Stöffler *et al.* (1991). These meteorites are moderately weathered, with the degrees of B of Ikeda and Kojima (1991) or W2 of Wlotzka (1993), which seem to be consistent with high bulk contents of Fe₂O₃ (2.85, 4.59 and 4.60 wt% for Y-792947, Y-793408 and Y-82038) and H₂O (+)

TABLE 1. Summary of petrography of Y-792947, Y-793408 and Y-82038.

Meteorite	Y-792947	Y-793408	Y-82038
Section no.	61-1	89-5, 91-3, 91-4	61-3
Total area (cm ²)	0.70	1.48	0.49
Modal compositions (vol%)			
Chondrules and silicate			
isolated minerals	77	70	76
Matrix	15	17	12
Opaque minerals	8	13	12
Number of inclusions	9	27	7
Weathering degree*	B/W2	B/W2	B/W2
Shock stage	S1	S1	S1

*Weathering degrees by Ikeda and Kojima (1991); Wlotzka (1993).

(3.00, 3.70 and 2.80%), respectively (Yanai and Kojima, 1995). Weathering also affected the oxygen isotopic compositions, requiring an HCl wash to remove low $\delta^{18}\text{O}$ Antarctic weathering products.

Inclusions

The refractory inclusions are small in apparent size, ranging from 17 to 306 μ m (80 μ m in average). The size distribution of the inclusions overlaps with those of UOCs (100–250 μ m after Bischoff and Keil, 1983) and CO chondrite (20–400 μ m in Y-81020 after Kimura *et al.*, 2001). The inclusions do not always show fragmental texture. Many inclusions are surrounded by rims consisting mostly of high-Ca pyroxene (Fig. 1b).

Most of the inclusions are dominated by spinel (Fig. 1b). Some inclusions contain abundant olivine (Fig. 1c). Other minerals present in the inclusions are high-Ca pyroxene, nepheline, sodalite, hibonite, ilmenite, perovskite, rutile and whitlockite. Nepheline and sodalite are predominantly encountered in the cores and margins of most of the inclusions (Fig. 1b,d,e). Seven inclusions contain hibonite, surrounded by spinels (Fig. 1e). Ilmenite, <10 μ m in size, is often enclosed in spinel (Fig. 1b,d,e), but perovskite, <3 μ m in size (Fig. 1d), and rutile, ~2 μ m, are rarely found in spinels from inclusions. Whitlockite occurs in the peripheral parts of a single inclusion.

Chondrules and Matrices

Sharply delineated chondrules are the most abundant component in Y-792947 and the other meteorites. Their apparent sizes range from 0.05 to 0.8 mm (0.32 mm on average). The abundances of porphyritic, barred and non-porphyritic (radial and cryptocrystalline) chondrules are 80, 4 and 16%, respectively.

Chondrules usually contain a glassy groundmass often in direct contact with matrix. Among 81 chondrules observed in detail, 15 contain nepheline often with sodalite. These phases

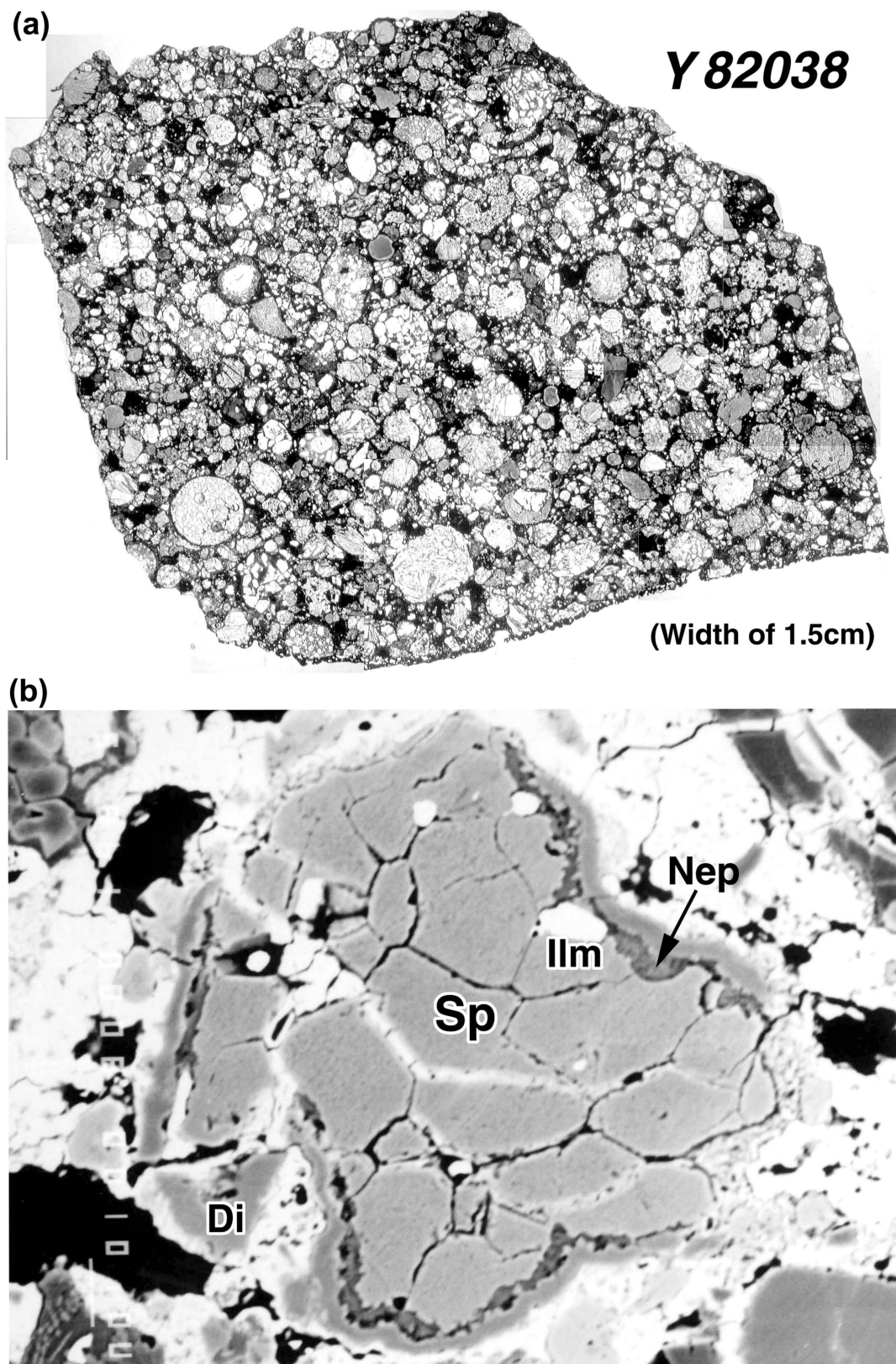


FIG. 1. (a) Photomicrograph (transmitted light) of a section of Y-82038 (61-3). The textures of Y-792947, Y-793408 and Y-82038 are very similar, and are typical of UOCs, consisting of sharply delineated chondrules, isolated minerals and matrix. (b) Backscatter electron (BSE) image of a refractory inclusion in Y-793408, mainly consisting of spinel (Sp) with ilmenite (Ilm), surrounded by nepheline (Nep) and diopside (Di) rim. Width 130 μm. *Figure 1 is continued on the next page.*

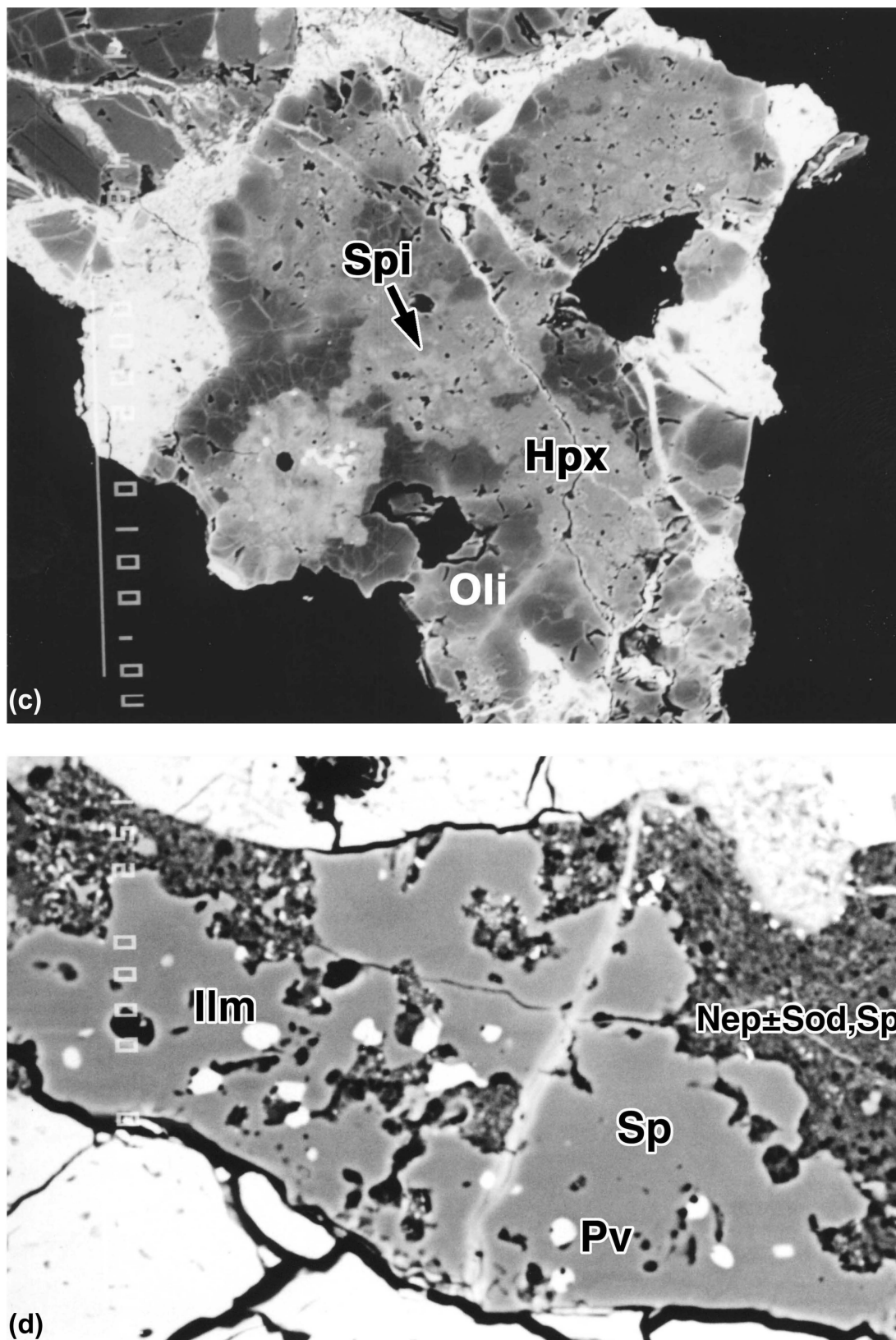


FIG. 1. *Continued.* (c) BSE image of an olivine-rich (Oli) inclusion in Y-793408. Spinel and high-Ca pyroxene (fassaïtic to diopsidic) (Hpx) are encountered in the center of this inclusion. Width 230 μm . (d) BSE image of a spinel-rich inclusion. This inclusion is characterized by a high abundance of nepheline mixed with sodalite (Sod) and fine-grained spinel. It shows a perovskite (Pv) grain enclosed in spinel. Width 90 μm . *Figure 1 is continued on the next page.*

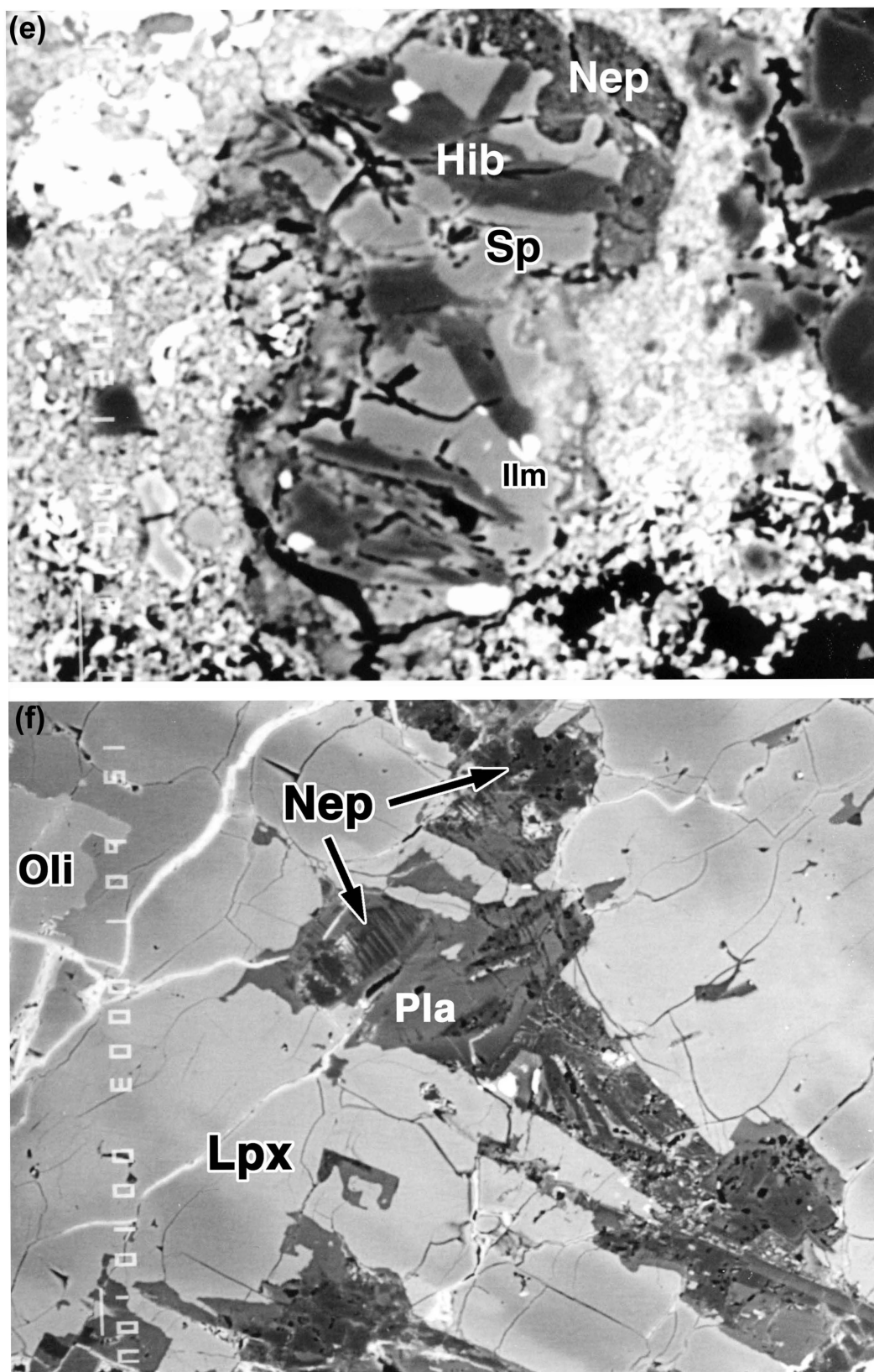


FIG. 1. *Continued.* (e) BSE image of a hibonite-bearing (Hib) inclusion. Width 90 μm . (f) Photomicrograph of a chondrule, mainly consisting of low-Ca pyroxene (Lpx) with olivine. Nephelines often occur as lamellae, in groundmass of anorthitic plagioclase (Pla). Width 190 μm .

replace plagioclase, and nepheline often occurs as lamellae in plagioclase (Fig. 1f). This paragenesis is also reported in CV chondrites (MacPherson *et al.*, 1993; Kimura and Ikeda, 1997a), and UOCs (Kimura and Ikeda, 1997b). Chondrules often contain spinel and ilmenite.

Matrices in Y-792947 and the related meteorites are very fine grained, and contain a large number of submicron-sized opaque grains.

MINERALOGY

Olivine

Table 2 shows selected analytical data of silicate and oxide phases. Olivine is commonly encountered in chondrules and some inclusions, but also occurs as isolated mineral grains. In spite of the various occurrences, olivines show similar broad compositional ranges (Fig. 2), $Fa_{0.3-48}$ in Y-792947, $Fa_{0.5-41}$ in Y-793408 and $Fa_{0.3-45.3}$ in Y-82038. The grand average composition in these chondrites is Fa_{16} with a PMD of 75. In

olivine-rich inclusions, peripheral olivines are usually more enriched in FeO than those in the central parts (*e.g.*, Fa_{24} vs. Fa_1).

Figure 3 shows the concentrations of Cr_2O_3 and CaO in olivines. The contents of these minor elements are indistinguishable for chondrules and inclusions. The CaO contents decrease with increasing FeO contents. The distributions of these elements overlap with those in UOCs.

Pyroxene

Low-Ca pyroxenes, mainly clinoenstatites, and minor high-Ca pyroxenes occur in chondrules and as isolated minerals. These pyroxenes show wide compositional ranges (Fig. 4). A single chondrule containing FeO-rich low-Ca pyroxenes (Fs_{40-53}), was found, whereas all other chondrules have pyroxene with less than Fs_{40} .

In inclusions, high-Ca pyroxenes contain 0–14.5 wt% TiO_2 and 0.05–26.2% Al_2O_3 , which decrease toward the rims of the inclusions. Hedenbergite ($Fs_{36-43}Wo_{47-48}$) is encountered in the rim of a spinel-rich inclusion.

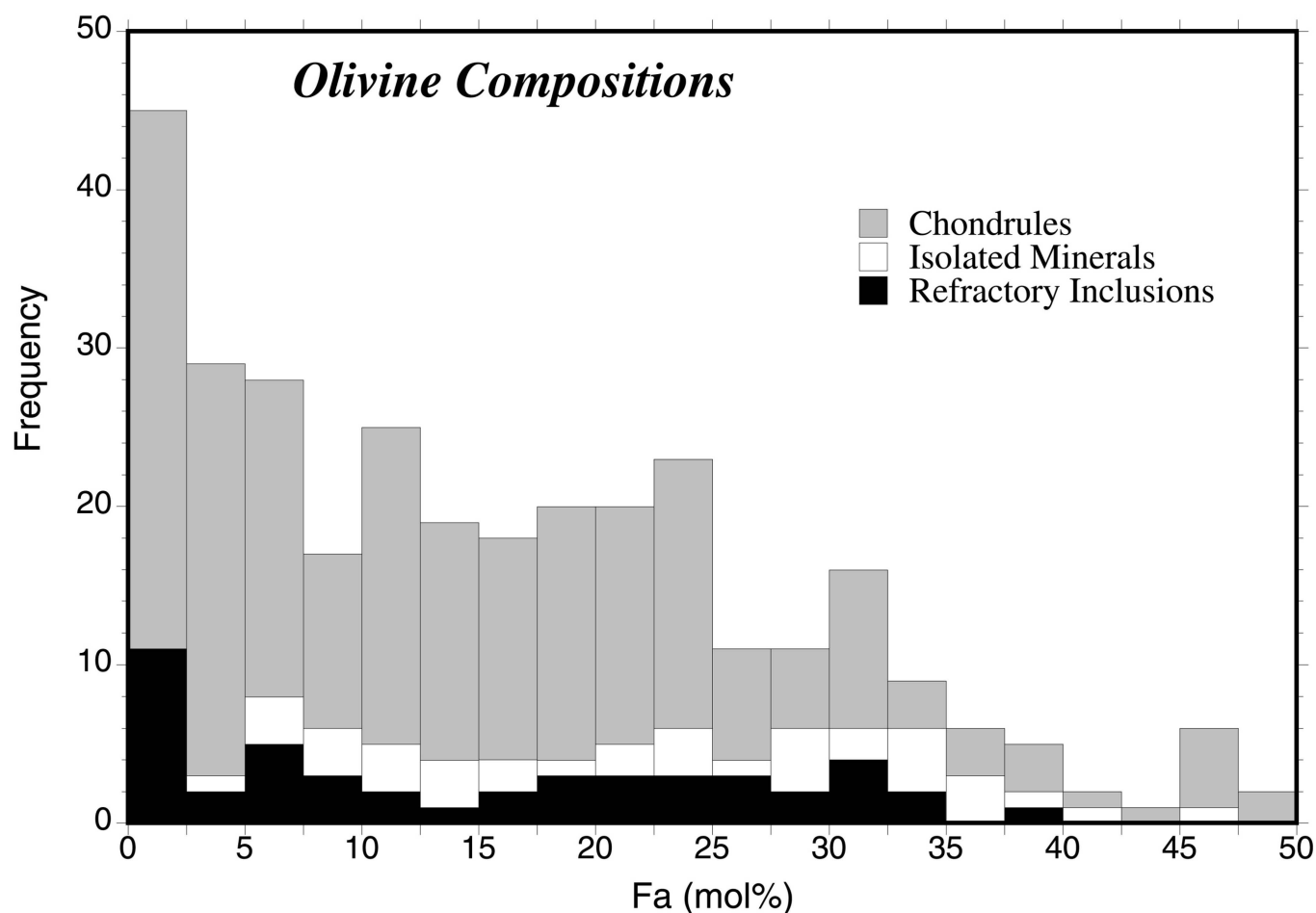


FIG. 2. Histogram of fayalite contents of olivines in Y-792947, Y-793408 and Y-82038. Olivines show wide compositional variation, independent of their occurrence.

TABLE 2. Selected analyses of silicate and oxide phases in Y-792947, Y-793408 and Y-82038.

Meteorite	Phase	Component	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	V ₂ O ₃	FeO	NiO	MnO	MgO	CaO	ZnO	Na ₂ O	K ₂ O	Total
Y-792947	Olivine	Chondrule	35.8	b.d.	0.18	b.d.	n.a.	35.9	0.11	0.51	27.0	0.05	n.a.	0.07	b.d.	99.6
Y-82038	Olivine	Chondrule	43.2	b.d.	0.04	b.d.	n.a.	0.64	b.d.	b.d.	55.8	0.43	n.a.	b.d.	b.d.	100.1
Y-82038	Olivine	Inclusion	39.1	b.d.	b.d.	b.d.	n.a.	19.7	0.13	0.39	39.7	0.10	n.a.	b.d.	b.d.	99.0
Y-793408	Low-Ca pyroxene	Chondrule	58.7	b.d.	0.88	0.65	n.a.	0.74	b.d.	b.d.	38.1	0.55	n.a.	b.d.	b.d.	99.6
Y-793408	Low-Ca pyroxene	Chondrule	52.0	0.23	1.19	0.53	n.a.	24.6	0.10	0.64	17.5	3.20	n.a.	b.d.	b.d.	100.0
Y-793408	High-Ca pyroxene	Chondrule	50.4	0.78	5.98	2.23	n.a.	1.67	b.d.	1.20	19.9	16.9	n.a.	0.17	b.d.	99.2
Y-792947	High-Ca pyroxene	Inclusion	29.3	12.0	24.6	0.14	n.a.	2.21	b.d.	b.d.	9.55	21.7	n.a.	0.06	b.d.	99.6
Y-792947	High-Ca pyroxene	Inclusion	53.7	0.20	1.75	0.18	n.a.	0.45	b.d.	b.d.	18.0	25.2	n.a.	0.18	b.d.	99.7
Y-792947	High-Ca pyroxene	Inclusion	49.5	b.d.	0.04	0.31	n.a.	25.6	0.10	0.34	2.88	22.0	n.a.	0.05	b.d.	100.8
Y-792947	Feldspar	Chondrule	65.3	b.d.	19.9	b.d.	n.a.	0.42	b.d.	b.d.	0.37	1.79	n.a.	10.4	0.42	98.6
Y-793408	Feldspar	Chondrule	46.7	b.d.	33.1	0.14	n.a.	0.40	0.22	b.d.	0.27	16.8	n.a.	2.26	0.07	99.9
Y-793408	Glass	Chondrule	70.6	0.73	12.6	b.d.	n.a.	2.17	0.13	b.d.	3.68	2.06	n.a.	5.01	2.84	99.8
Y-793408	Nepheline	Chondrule	45.9	b.d.	33.1	0.12	n.a.	0.23	b.d.	b.d.	b.d.	0.27	n.a.	20.8	0.14	100.5
Y-793408	Nepheline	Inclusion	42.5	0.09	34.7	b.d.	n.a.	0.48	b.d.	b.d.	b.d.	0.06	n.a.	20.7	0.04	98.6
Y-82038	Spinel	Chondrule	0.06	0.15	60.6	7.31	0.11	13.9	b.d.	b.d.	17.1	b.d.	0.18	b.d.	n.a.	99.4
Y-82038	Spinel	Chondrule	0.52	0.23	b.d.	63.2	0.58	32.6	b.d.	0.67	0.99	0.06	b.d.	b.d.	n.a.	98.9
Y-792947	Spinel	Inclusion	0.04	0.08	57.8	9.87	b.d.	9.59	0.11	0.13	18.8	b.d.	3.07	b.d.	n.a.	99.4
Y-82038	Spinel	Inclusion	b.d.	0.22	68.1	b.d.	0.24	9.34	0.12	b.d.	21.9	b.d.	b.d.	b.d.	n.a.	99.9
Y-82038	Spinel	Inclusion	b.d.	b.d.	64.4	0.19	0.12	17.6	b.d.	0.17	15.4	b.d.	2.35	b.d.	n.a.	100.2
Y-82038	Hibonite	Inclusion	0.19	4.18	84.6	b.d.	0.23	0.61	b.d.	b.d.	2.20	8.33	b.d.	b.d.	n.a.	100.3
Y-792947	Ilmenite	Chondrule	b.d.	52.8	b.d.	b.d.	n.a.	43.1	b.d.	0.86	2.11	b.d.	n.a.	b.d.	0.09	98.9
Y-82038	Ilmenite	Inclusion	b.d.	51.5	b.d.	b.d.	b.d.	45.4	0.14	0.43	2.04	b.d.	b.d.	b.d.	n.a.	99.5

b.d. = below detection limits (3σ), 0.03 for SiO₂, Al₂O₃, MgO and CaO; 0.04 for TiO₂, Na₂O and K₂O; 0.08 for V₂O₃, NiO and MnO; 0.10 for Cr₂O₃; and 0.17 for ZnO.

n.a. = not analyzed.

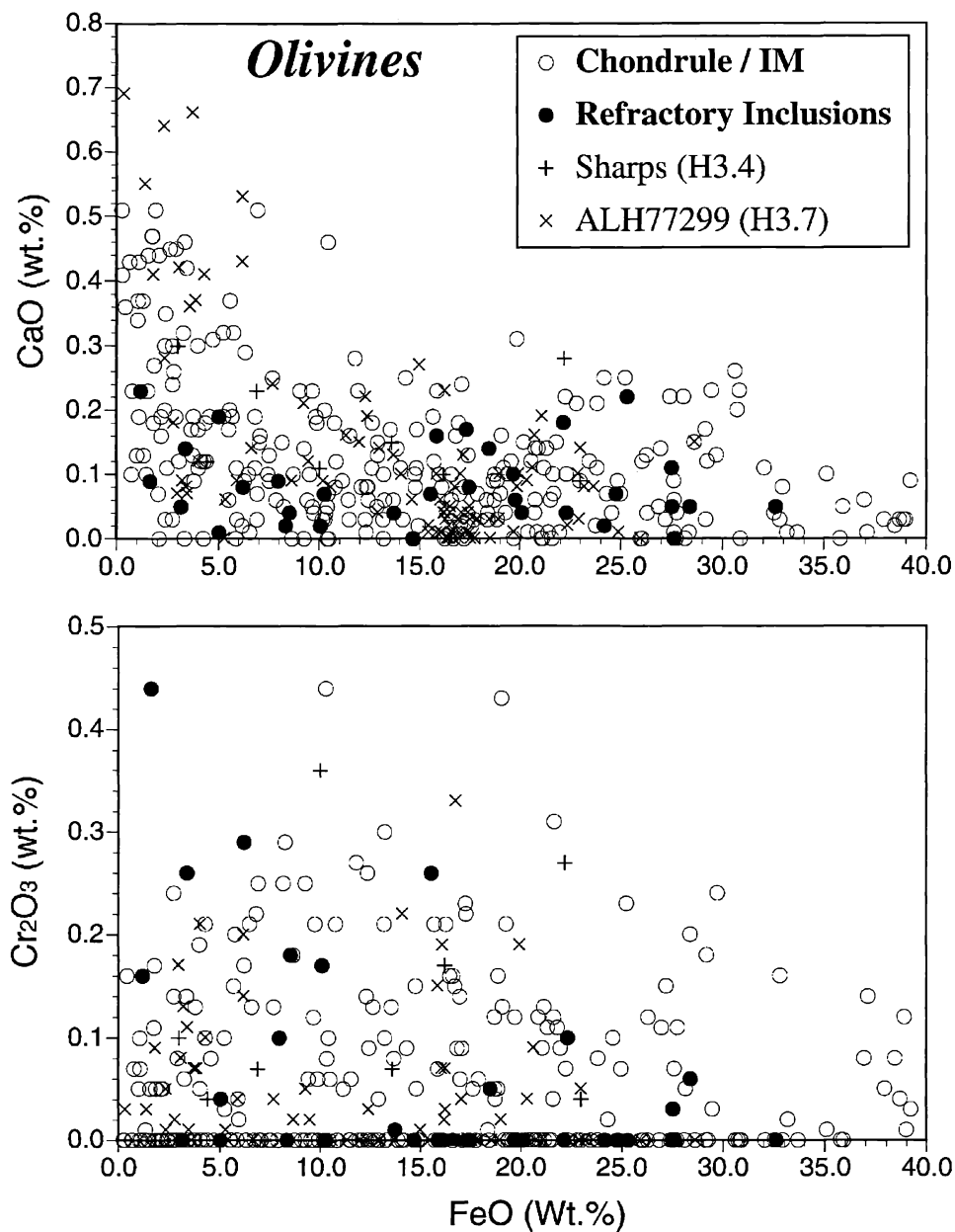


FIG. 3. Plot of CaO and Cr₂O₃ vs. FeO for olivines in chondrules, isolated minerals (IM) and refractory inclusions in Y-792947, Y-793408 and Y-82038. The distributions of these minor elements are consistent with those in the other type 3 chondrites. Sharps H3.4 after Rubin and Pernicka (1989); ALH 77299 H3.7 after Kimura (unpubl. data).

Plagioclase and Glass

Plagioclases (An_{0.4-83}) rarely occur in groundmasses of chondrules. Anorthitic plagioclases are often replaced by nepheline and sodalite, as mentioned before. Clean to devitrified glasses are abundantly encountered in the groundmass, and are enriched in normative plagioclase components. Some glasses are enriched in K₂O (up to 8.2%).

Nepheline and Sodalite

These feldspathoids are usually found together in intimate contact, which makes it difficult to obtain precise compositional data, in particular for sodalites. Nephelines, both in inclusions and chondrules, are almost pure (<0.5 wt% CaO and <0.1 K₂O).

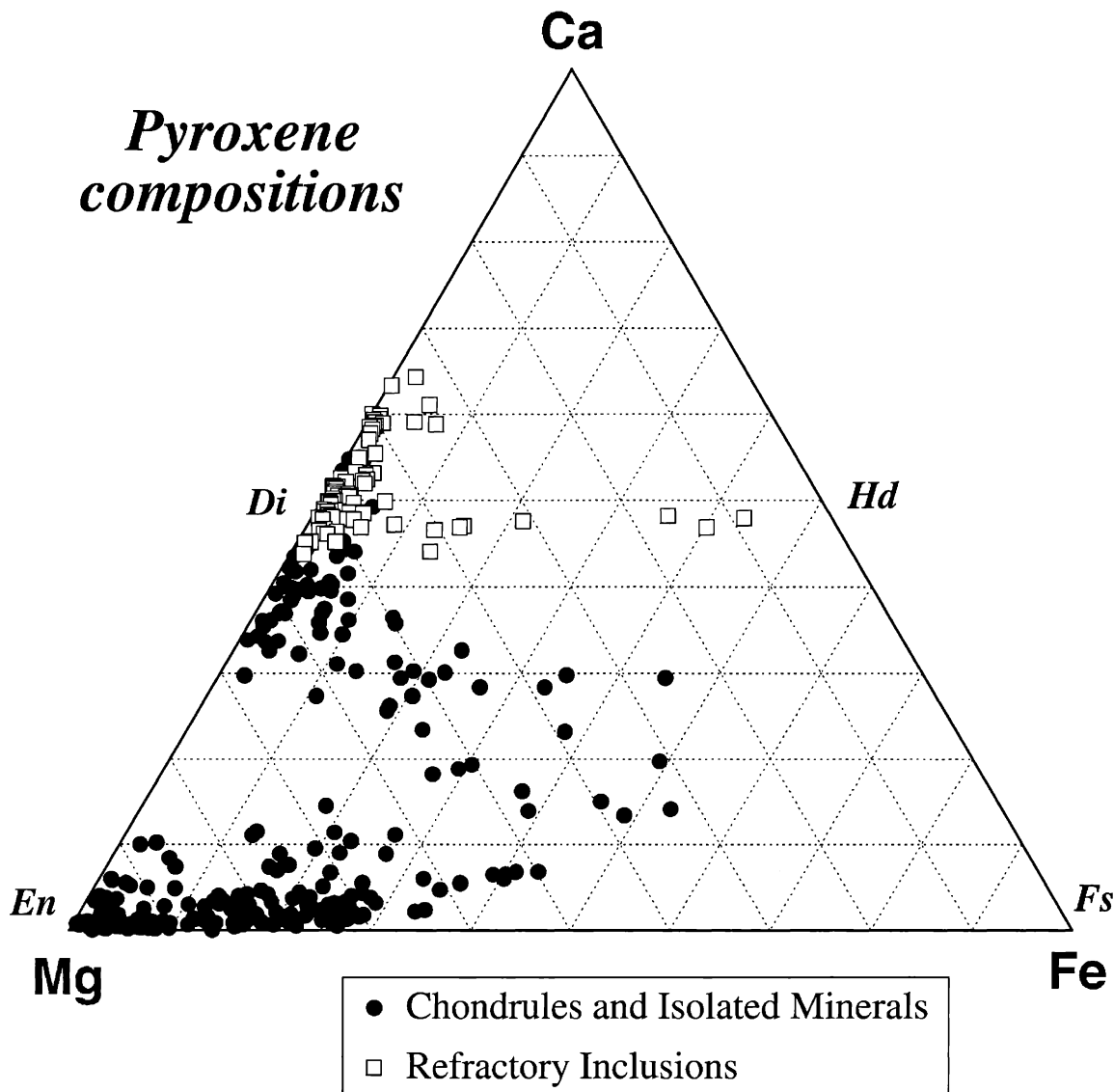


FIG. 4. Plot of atomic Ca–Mg–Fe ratio of pyroxenes in Y-792947, Y-793408 and Y-82038. Pyroxenes in chondrules and isolated minerals show wide compositional variation. Refractory inclusions contain magnesian high-Ca pyroxenes (diopside to fassaite) and hedenbergites.

Spinel Group Minerals

Spinel group minerals in inclusions contain 0–1.5 wt% TiO₂, 0–46.4 Cr₂O₃, 0–0.6 V₂O₃, 8.2–28.7 FeO and 0.0–3.1 ZnO. Atomic Mg/Mg + Fe and Al/Al + Cr ratios range from 0.13 to 0.83 and 0.33 to 1.00, respectively (Fig. 5). A characteristic feature of the spinels is their high concentrations of FeO and Cr₂O₃. Both elements are correlated with each other and they often increase from cores to rims of inclusions (e.g., 0.8 to 46.4 wt%, and 13.5 to 28.7 wt%, respectively). The high Cr₂O₃ contents found in some spinels exceed the Cr₂O₃ level in spinels of inclusions from other chondrites. The ZnO contents are in general very high (average 1.2 wt%), especially in FeO-rich spinels.

Spinel group minerals are often encountered in chondrules and as isolated minerals. They also show wide compositional variation, 0–5.1 wt% TiO₂, 0.0–66.1 Al₂O₃, 0.3–65.4 Cr₂O₃, 0–0.8 V₂O₃, 10.1–35.1 FeO, 0.6–26.0 MgO and 0.0–1.7 ZnO. In some cases almost pure chromite was found in these chondrites (Fig. 5).

Other Oxide Minerals

Hibonites contain 1.3–7.4 wt% TiO₂ and 0.8–3.7% MgO. Ilmenites contain 0–1.1 wt% MnO and 1.0–2.1% MgO in both in inclusions and in chondrules.

An inclusion in Y-792947 contains a Ti-oxide enclosed by spinel. This phase was identified as rutile using laser micro

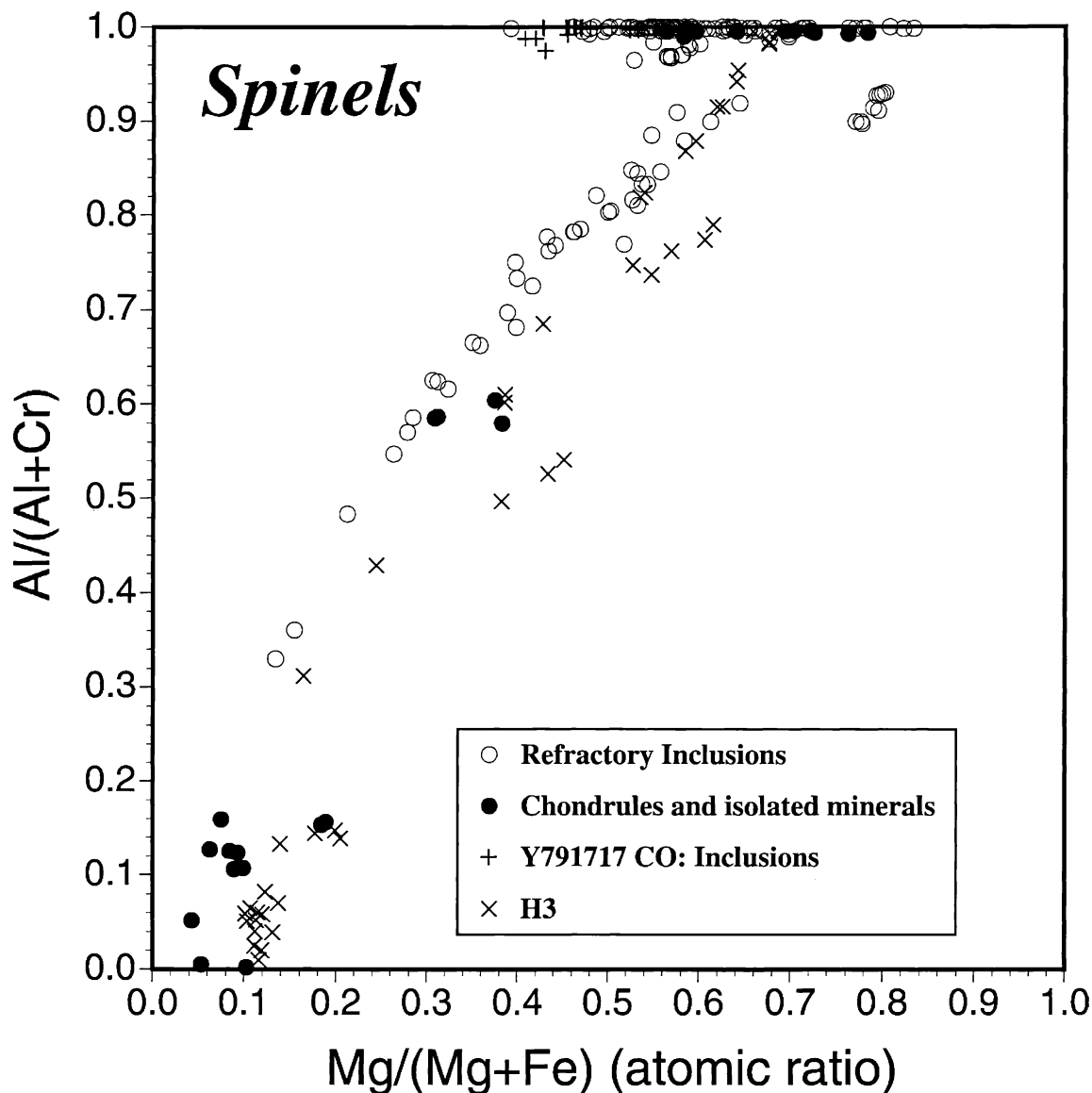


FIG. 5. Plot of atomic $\text{Mg}/(\text{Mg} + \text{Fe})$ vs. $\text{Al}/(\text{Al} + \text{Cr})$ ratios of spinels in Y-792947, Y-793408 and Y-82038, compared with those in Y-791717 (CO3) (Lin *et al.*, 1998) and other H3 chondrites (Kimura, 2000; unpubl. data). Spinel in refractory inclusions vary widely in compositions from Al and Mg-rich to Fe and Cr-rich. On the other hand, nearly pure chromites are often encountered in chondrules and as isolated minerals.

Raman spectroscopy (peaks of 611, 445 and 230 cm^{-1}). Rutile is a very rare phase in inclusions.

Fe-Ni Metal and Troilite

Fe-Ni metals and troilites are encountered in chondrules and in matrix as isolated minerals, abundantly in association with each other. Kamacites and taenites contain 0.30–0.66 and 0.01–0.19 wt% Co, and 4.54–7.02 and 25.4–54.75 Ni, respectively. Both metals contain <0.1% Si, <0.05 P and <0.3 Cr. Troilites have Ni and Cu contents below detection limits (0.03 wt%).

Bulk Compositions of Refractory Inclusions, Chondrules and Matrix

Table 3 shows the chemical compositions of refractory inclusions and chondrules in Y-792947 and the two related meteorites. Refractory inclusions are enriched in Al, Fe and Na, and depleted in Ca, consistent with abundant FeO-rich spinels and feldspathoids, and minor Ca phases. From Fig. 6 it is apparent that inclusions have a wide compositional range, overlapping with the compositions of inclusions in CO chondrites and UOCs (Fig. 6).

From the bulk chemical data, chondrules are classified into sodic plagioclase (SP), intermediate plagioclase (IP) and calcic

TABLE 3. Bulk compositions of refractory inclusions and matrices in Y-792947, Y-793408 and Y-82038.

Meteorite	Unit	No.	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	NiO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	SO ₃	Cl	Total
Y-792947	Inclusion	B1	10.3	2.3	48.0	0.2	17.1	0.3	0.2	10.2	2.7	3.2	0.3	b.d.	b.d.	0.6	95.4
Y-793408	Inclusion	895-A1	36.8	1.5	15.9	0.3	5.6	0.3	b.d.	23.5	13.1	0.1	b.d.	b.d.	b.d.	b.d.	97.0
Y-793408	Inclusion	895-E1	9.8	4.5	48.9	0.2	16.8	1.0	b.d.	6.7	3.6	2.2	0.2	0.5	b.d.	0.4	94.9
Y-793408	Inclusion	895-F2	19.6	2.2	40.6	0.2	9.0	b.d.	b.d.	16.5	8.8	0.1	b.d.	b.d.	b.d.	b.d.	96.8
Y-793408	Inclusion	895-G1	31.8	0.6	25.8	0.8	7.7	b.d.	b.d.	19.9	11.9	b.d.	b.d.	b.d.	b.d.	b.d.	98.6
Y-793408	Inclusion	913-A1	23.8	0.3	37.4	0.2	11.6	1.3	b.d.	5.8	2.0	8.5	2.3	b.d.	0.4	0.9	94.5
Y-793408	Inclusion	913-B1	15.5	5.9	38.0	0.2	17.0	1.0	0.2	9.6	6.2	1.4	0.6	b.d.	b.d.	0.1	95.6
Y-793408	Inclusion	913-C1	19.7	1.6	40.8	0.4	11.3	0.7	b.d.	13.2	9.4	0.7	0.3	b.d.	b.d.	b.d.	98.1
Y-793408	Inclusion	913-E1	27.7	0.8	38.0	b.d.	8.2	0.3	b.d.	3.6	0.2	14.5	2.4	b.d.	0.3	2.4	98.5
Y-793408	Inclusion	913-H1	35.6	1.1	17.0	b.d.	13.8	1.2	b.d.	11.4	13.1	1.5	0.3	b.d.	b.d.	0.2	95.2
Y-793408	Inclusion	914-A1	3.0	1.1	57.5	0.2	17.9	b.d.	0.2	12.3	0.3	1.2	0.2	b.d.	b.d.	0.3	94.2
Y-793408	Inclusion	914-A1	8.8	1.9	49.0	0.3	19.0	0.6	b.d.	10.9	1.5	2.0	0.3	b.d.	0.3	0.4	94.8
Y-793408	Inclusion	914-B1	18.5	0.8	33.8	0.4	19.9	1.0	0.2	10.9	8.1	0.4	0.1	b.d.	0.3	0.2	94.7
Y-793408	Inclusion	914-J1	33.1	0.2	21.3	0.3	15.6	1.3	b.d.	6.4	4.6	10.8	0.1	b.d.	0.5	0.6	94.7
Y-793408	Inclusion	914-K1	12.6	0.8	44.9	0.2	19.1	0.6	b.d.	7.9	0.4	5.7	0.8	b.d.	1.0	0.8	94.7
Y-82038	Inclusion	A1	0.1	3.1	62.6	0.2	20.1	b.d.	0.2	12.2	0.5	0.1	b.d.	b.d.	b.d.	b.d.	99.0
Y-82038	Inclusion	A2	8.9	5.8	47.5	b.d.	19.5	0.4	0.2	10.0	1.0	3.8	0.4	b.d.	b.d.	0.7	98.3
Y-82038	Inclusion	C1	21.1	0.1	31.4	0.4	16.9	1.1	b.d.	3.8	4.3	10.6	2.0	4.5	0.5	1.3	97.9
Y-82038	Inclusion	D1	25.1	2.2	35.5	0.3	7.2	b.d.	b.d.	16.6	12.9	0.1	0.1	b.d.	b.d.	b.d.	100.0
Y-82038	Inclusion	E1	3.4	2.1	62.7	0.2	14.1	1.4	b.d.	8.9	2.5	1.2	0.2	b.d.	b.d.	0.3	96.9
Y-82038	Inclusion	I1	37.8	0.2	4.8	0.2	12.1	0.4	0.2	39.5	3.5	0.1	0.1	b.d.	b.d.	b.d.	99.0
Y-792947	Matrix	Average	29.6	0.1	1.9	0.3	33.5	1.5	0.2	21.8	0.5	0.3	0.1	0.3	0.3	b.d.	90.4
Y-793408	Matrix	Average	22.9	0.0	2.1	0.2	45.4	2.6	0.2	11.4	0.3	0.2	0.1	0.1	1.2	0.3	86.7
Y-82038	Matrix	Average	21.1	0.0	2.3	b.d.	42.7	3.1	b.d.	10.5	0.5	0.3	0.2	0.1	0.8	b.d.	82.0

b.d. = below detection limits (3 σ); 0.07 for Na₂O, K₂O and Cl; 0.08 for P₂O₅; 0.13 for NiO and MnO; 0.14 for Cr₂O₃ and SO₃.

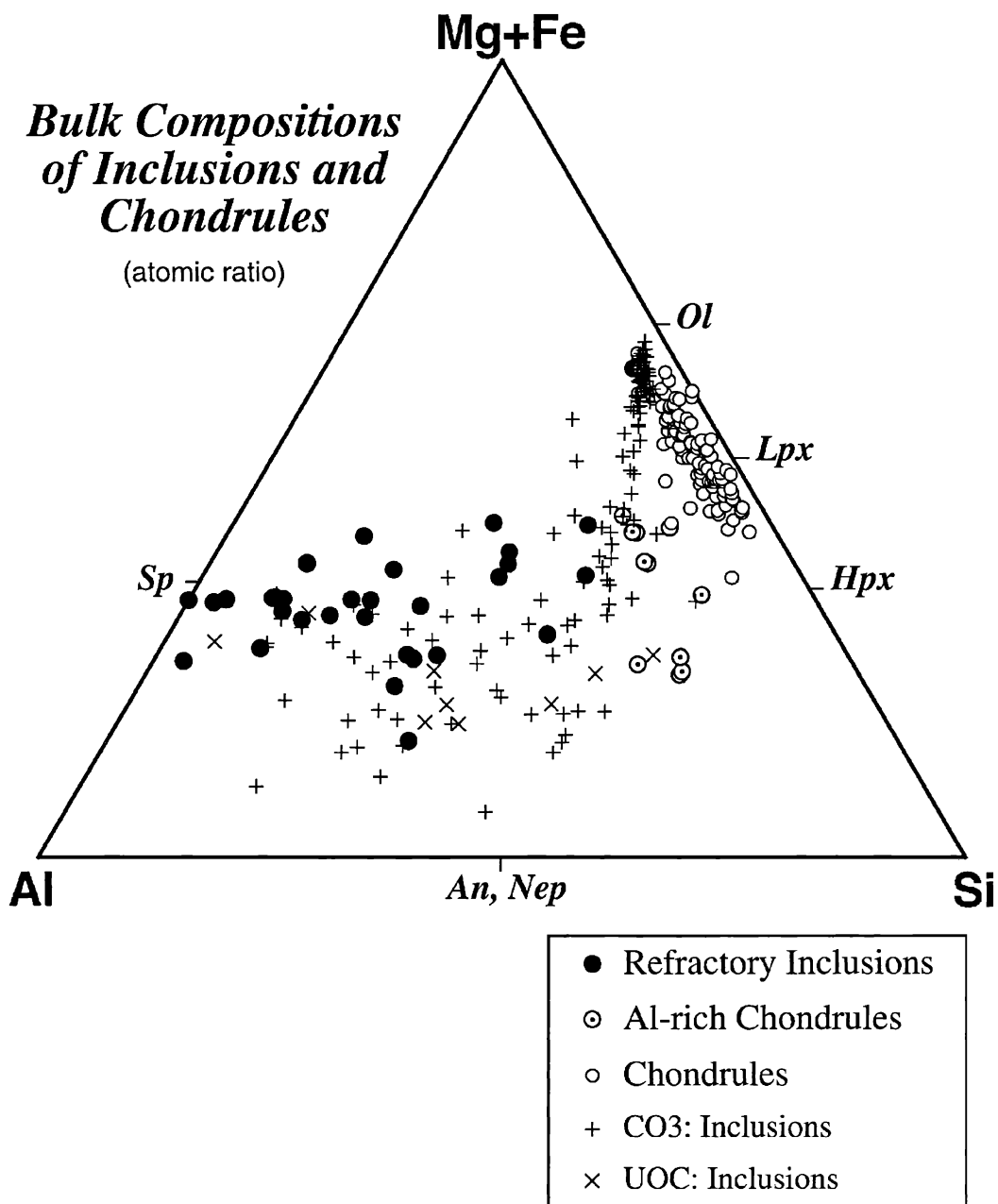


FIG. 6. Plot of atomic (Mg + Fe)–Al–Si for bulk compositions of refractory inclusions, some Al-rich chondrules and normal chondrules in Y-792947, Y-793408 and Y-82038. Compositions of the inclusions overlap with those in CO3 (Kimura *et al.*, 2001) and other O chondrites (Bischoff and Keil, 1983, 1984).

plagioclase (CP) types based on the normative plagioclase content (Ikeda, 1983). The SP type occupies ~80% and ~30% of chondrules in UOCs and C chondrites, respectively. Of 116 chondrules in Y-792947 and related meteorites 71% are classified as SP and 29% as IP, which is typical of UOCs. About 2.5% of all chondrules are Al-rich chondrules (>10% Al₂O₃). This is close to those in UOC (1.8% after Bischoff and Keil, 1984).

Matrices are highly enriched in FeO and NiO (Table 3), reflecting terrestrial weathering. In Fig. 7, the matrices plot

within the range of CO chondrites, but are different from those of UOC.

Bulk Chemical Compositions of Yamato 792947, 793408 and 82038

Table 4 gives the whole-rock chemical compositions of Y-792947, Y-793408 and Y-82038. There is almost perfect agreement in the chemical composition of these three meteorites

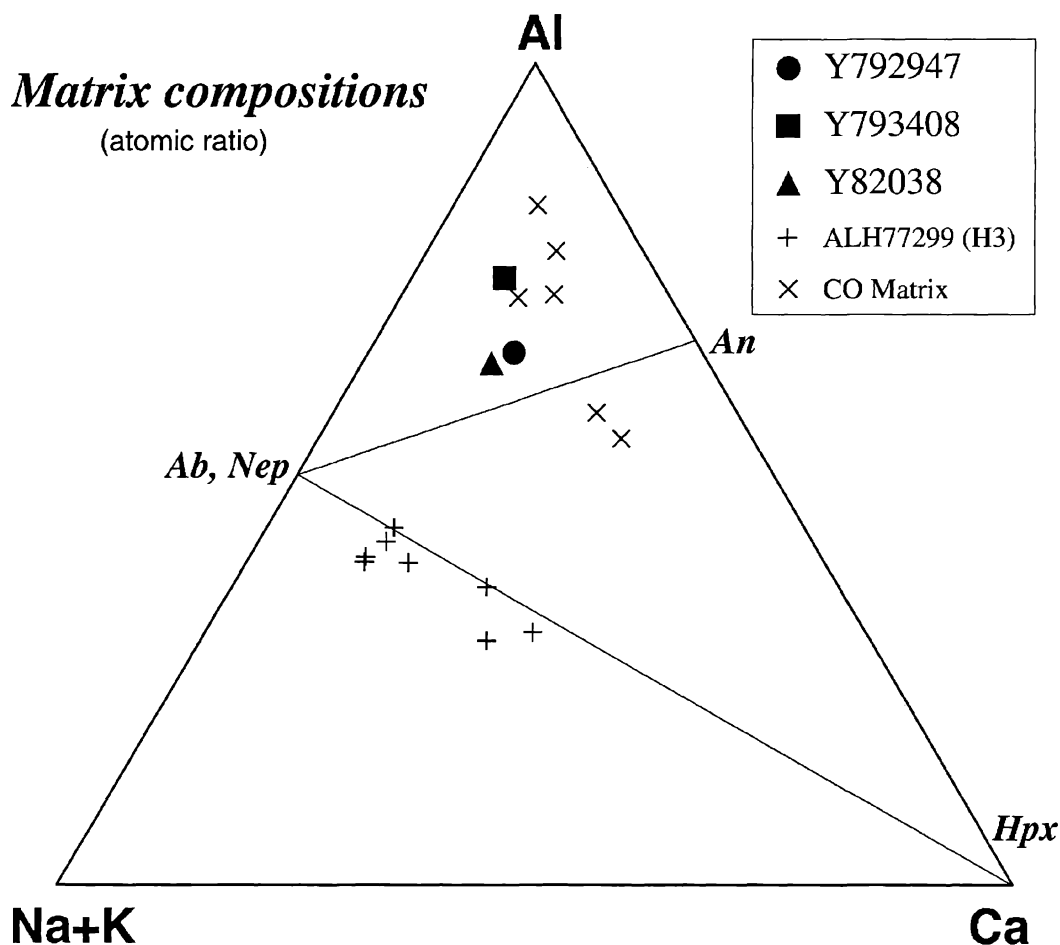


FIG. 7. Matrix compositions of the H3 chondrites studied here in atomic Al–(Na + K)–Ca plot, compared with those in ALH 77299 (H3) (Ikeda *et al.*, 1981) and CO3 chondrites (McSween and Richardson, 1977). The matrices in Y-792947, Y-793408 and Y-82038 seem to be similar to those in CO3 chondrites, and different from those in H3 chondrite.

confirming petrological observations. For evaluating the significance of the chemical composition of these meteorites it is useful to remember the three major chemical characteristics that distinguish O chondrites from other groups of chondritic meteorites, in particular carbonaceous chondrites: (a) the Mg/Si ratios of O chondrites are nearly 10% lower than the CI ratio and more than 10% below the Mg/Si ratio of CV. (b) O chondrites are lower in all refractory elements relative to CI chondrites by 25% and by 35% relative to CV chondrites as seen from the Al/Si and Ca/Si ratios. (c) O chondrites have depletion patterns of moderately volatile elements different from C chondrites, particularly Mn, Na and Zn (see Table 5 and Palme, 2000, 2001).

Y-792947, Y-793408 and Y-82038 have the same Mg/Si ratios and the same depletion in refractory elements (Al/Si and Ca/Si ratios) as H chondrites (Table 5). Y-792947, Y-793408 and Y-82038 have the same Mn/Mg ratios as H chondrites which distinguishes them from carbonaceous chondrites. Atomic Al/Mn (9.9) and Zn/Mnx100 (1.72) ratios of Y-792947, Y-793408 and Y-82038 are also within the range of O chondrites (Kallemeyn *et al.*, 1996).

One of the few differences of Y-792947, Y-793408 and Y-82038 from H chondrites are slightly lower Na/Mg ratios. The extra depletion of Na may be caused by terrestrial weathering (Gibson and Bogard, 1978; Dreibus *et al.*, 1995). Rather high Br contents of Y-792947 and others (Table 4) may be also a result of weathering.

However, the Fe/Mg ratios of Y-792947, Y-793408 and Y-82038 (Table 4) are also within the range of H chondrites, suggesting that the Fe contents of these meteorites were not affected by weathering. Figure 8 shows the siderophile (Ni) and chalcophile (Se) elemental abundances of Y-792947, Y-793408 and Y-82038, confirming the close similarity of these meteorites to H chondrites. It is evident that they did not lose any of these elements during terrestrial weathering.

Oxygen Isotopic Compositions

Table 6 gives the whole-rock oxygen isotopic compositions of acid-washed Y-792947, Y-793408 and Y-82038. The compositions are close to the mean values for H3 chondrites

TABLE 4. Bulk chemical compositions of Y-793408, Y-792947 and Y-82038.*

el	me	Y-793408,96			Y-792947,68			Y-82038,69			Grand average
		XRF and INAA (average)	A 162.7 (mg)	B 86.0 (mg)	XRF and INAA (average)	A 97.6 (mg)	B 111.3 (mg)	XRF and INAA (average)	A 166.8 (mg)	B 70.63 (mg)	
Mg (%)	X	12.82	—	—	13.21	—	—	13.06	—	—	13.03
Si	X	15.66	—	—	16.02	—	—	15.73	—	—	15.8
Al	X	1.01	—	—	1.05	—	—	1.01	—	—	1.02
Ca	X	1.11	—	—	1.18	—	—	1.17	—	—	1.15
Ca	I	1.3	1.3	1.3	1.35	1.4	1.3	1.15	1.2	1.1	1.27
Fe	X	24.44	—	—	23.6	—	—	25.19	—	—	24.41
Fe	I	23.8	24.49	23.1	23.77	24.23	23.3	24.87	24.41	25.32	24.14
Na (ppm)	I	4790	4890	4690	4580	4470	4690	4720	4770	4670	4697
P	X	1100	—	—	1090	—	—	1110	—	—	1100
K	I	680	690	670	525	500	550	720	720	720	642
Sc	I	7.12	7.39	6.85	7.54	7.87	7.21	7.19	7.19	7.18	7.28
Ti	X	560	—	—	580	—	—	630	—	—	590
V	X	56	—	—	44	—	—	57	—	—	52
Cr	I	3390	3560	3220	3300	3330	3270	3440	3430	3450	3377
Cr	X	3258	—	—	3322	—	—	3310	—	—	3297
Mn	I	2040	2040	2040	2060	2010	2110	2070	2080	2060	2057
Mn	X	2190	—	—	2260	—	—	2200	—	—	2217
Co	I	702	727	677	870	713	684	745	725	765	772
Ni	I	15400	15600	15200	15750	15800	15700	16200	15700	16700	15783
Zn	I	38	36	40	50	40	59	38.5	37	40	42
Ga	I	5.05	5	5.1	5.15	5.2	5.1	5	5	5	5.07
As	I	1.97	2	1.94	2.02	2.1	1.94	2.14	2.14	2.14	2.04
Se	I	7.63	7.85	7.4	7.95	8	7.9	7.75	7.6	7.9	7.78
Br	I	7.83	7.98	7.68	5.16	4.63	5.69	11.35	11.3	11.4	8.11
Ru	I	1.05	0.99	1.1	1.2	1.1	1.3	1.15	1.1	1.2	1.13
Sb	I	0.07	0.08	0.06	0.07	0.08	0.06	0.07	0.07	0.08	0.07
La	I	0.27	0.28	0.26	0.28	0.28	0.28	0.27	0.27	0.27	0.27
Sm	I	0.186	0.183	0.17	0.183	0.182	0.183	0.18	0.18	0.179	0.183
Eu	I	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Dy	I	0.45	0.47	0.43	0.45	0.39	0.5	0.42	0.43	0.4	0.44
Yb	I	0.2	0.2	0.2	0.19	0.2	0.18	0.18	0.18	0.18	0.19
Lu	I	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Hf	I	0.16	0.12	0.19	0.15	0.15	0.15	0.16	0.15	0.17	0.16
Re	I	0.06	0.06	0.07	0.07	0.06	0.07	0.06	0.06	0.07	0.06
Os	I	0.92	0.92	0.92	0.97	0.95	0.98	0.99	0.94	1.04	0.96
Ir	I	0.74	0.762	0.718	0.753	0.74	0.766	0.773	0.749	0.796	0.755
Pt	I	1.5	1.5	1.5	1.25	1	1.5	1.55	1.6	1.5	1.42
Au	I	0.201	0.206	0.196	0.197	0.2	0.193	0.21	0.203	0.217	0.203

Abbreviations: el = element; me = analytical method: X = x-ray fluorescence spectroscopy (XRF), I = instrumental neutron activation analysis (INAA); XRF and INAA average = XRF data and average of two aliquots A and B, analyzed by INAA; grand average = average of Y-793408, Y-792947 and Y-82038.

*1 σ standard deviation: XRF = below 3%; INAA = below 3% = Fe, Na, Sc, Cr, Mn, Co, Ir, Au; 3–5% = K, Ni, As, Sm; 5–15% = Ga, Se, Br, La, Yb, Lu, Re, Os; 15–25% = Ca, Zn, Ru, Sb, Eu, Dy, Hf, Pt.

($\delta^{17}\text{O} = +2.76$ and $\delta^{18}\text{O} = +4.05$ after Clayton *et al.*, 1991), and plot in the range of H chondrites (Fig. 9).

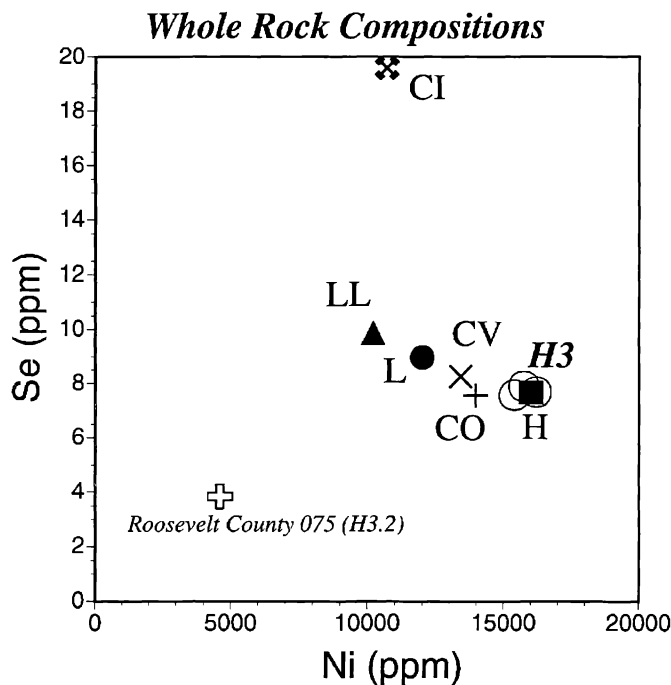
The oxygen isotopic compositions of some inclusions in Y-792947 are shown in Table 6 and Fig. 10. A fine-grained olivine inclusion (#21) plots just on the carbonaceous chondrite

anhydrous mineral (CCAM) line, despite significant enrichment of the olivine in FeO ($\sim\text{Fo}_{70}$). On the other hand, analytical points of the other inclusions, Cr-rich spinel (1.0–46.4 Cr_2O_3), Fe-rich olivine ($\sim\text{Fo}_{76}$), feldspathoids and rim diopside, plot near the terrestrial fractionation (TF) line, consistent with such

TABLE 5. Comparison of the chemical compositions of Y-793408, Y-792947 and Y-82038 with the common classes of chondrites (after Wasson and Kallemeyn, 1988).*

	Y-793408,96	Y-792947,68	Y-82038,69	CI	CV	H	L	EH
Mg/Si	0.820	0.820	0.830	0.900	0.930	0.830	0.810	0.630
Al/Si	0.064	0.066	0.064	0.081	0.110	0.067	0.066	0.049
Ca/Si	0.071	0.074	0.074	0.089	0.122	0.074	0.071	0.051
Fe/Mg	1.860	1.800	1.900	1.900	1.620	1.960	1.440	2.740
Cr/Mg	0.026	0.025	0.026	0.028	0.025	0.026	0.026	0.030
Mn/Mg	0.016	0.016	0.016	0.020	0.010	0.017	0.017	0.021
Na/Mg	0.037	0.035	0.036	0.052	0.023	0.046	0.047	0.064

*Percent weight ratios.

FIG. 8. Plot of Ni vs. Se for whole-rock compositions of Y-792947, Y-793408 and Y-82038 (H3), in comparison with those of the other H chondrites (after Wasson and Kallemeyn, 1988) and Roosevelt County 075 (H3.2) (after McCoy *et al.*, 1993). The H3 chondrites studied here are close to other H chondrites in their siderophile and chalcophile elements, whereas Roosevelt County 075 lost almost all these elements by terrestrial weathering.

phases in C chondrites (*e.g.*, Imai and Yurimoto, 2000; Hirai and Hiyagon, 2001).

DISCUSSION

Classification of Yamato 792947, 793408 and 82038

Y-792947, Y-793408 and Y-82038 are indistinguishable, in petrography, mineralogy, bulk chemistry and oxygen isotopic compositions. There is therefore little doubt that these meteorites are paired with each other.

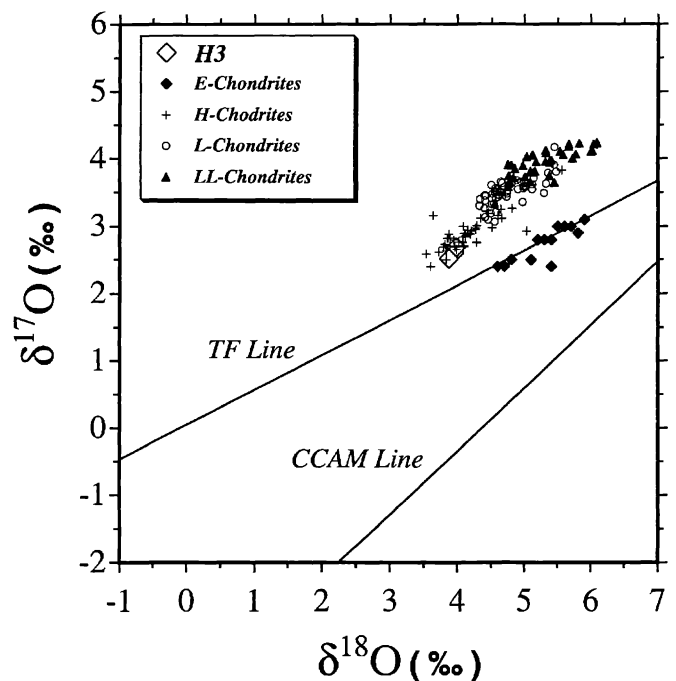


FIG. 9. Three oxygen isotopic plot of whole-rock samples of Y-792947, Y-793408 and Y-82038 (H3). The data overlap with the range of H chondrites. TF = terrestrial fractionation line. CCAM = carbonaceous chondrite anhydrous mineral line.

The whole-rock oxygen isotopic compositions indicate that the three meteorites are H chondrites. The chemical compositions (*e.g.*, Mg/Si, Al/Si and Fe/Mg ratios) agree with this classification. The trace element abundances are also typical of H chondrites.

The small chondrule size distributions (0.32 mm average apparent size) in the three chondrites are within the range of both H (0.3 mm) and CO chondrites (0.2–0.4 mm) (Grossman *et al.*, 1988). The abundances of textural and chemical types of chondrules are also consistent with those in O chondrites, as mentioned before. The modal abundances of matrices, 12–17%, in the Yamato meteorites are typical of O chondrites (Grossman *et al.*, 1988). The abundance of opaque minerals (8–13%),

TABLE 6. Oxygen isotopic compositions of Y-792947, Y-793408 and Y-82038.

Meteorite	Sample	Type	Position	$\delta^{17}\text{O}$ (‰)*	$\delta^{18}\text{O}$ (‰)*	$\Delta^{17}\text{O}$ (‰)*†	Comment
Y-792947	Whole-rock	—	—	2.61	3.95	0.56	Acid washed
Y-793408	Whole-rock	—	—	2.52	3.87	0.51	Acid washed
Y-82038	Whole-rock	—	—	2.69	3.98	0.62	Acid washed
Y-792947	Inclusion-17	Spinel-rich	1	5.4 ± 3.6	9.3 ± 4.2	0.6 ± 2.2	Cr-rich spinel; outer-most part
			2	1.4 ± 3.4	3.3 ± 4.1	-0.4 ± 1.8	Sodalite-rich; inner part
			3	2.4 ± 3.4	0.5 ± 4.1	2.1 ± 2.0	Cr-rich spinel; outer part
	Inclusion-10	Olivine-rich	4	-0.6 ± 3.6	3.3 ± 4.1	-2.3 ± 2.2	Olivine (Fo ₇₆)
	Inclusion-21	Olivine-rich	5	-31.7 ± 3.4	-30.3 ± 4.2	-16.0 ± 2.0	Fine-grained olivine (Fo ₇₀)
	Inclusion-9	Spinel-rich	6	-7.8 ± 3.3	-6.7 ± 4.1	-4.4 ± 1.8	Fine-grained spinel + anorthite
			7	-2.1 ± 3.6	-1.8 ± 4.1	-1.2 ± 2.2	Diospide rim

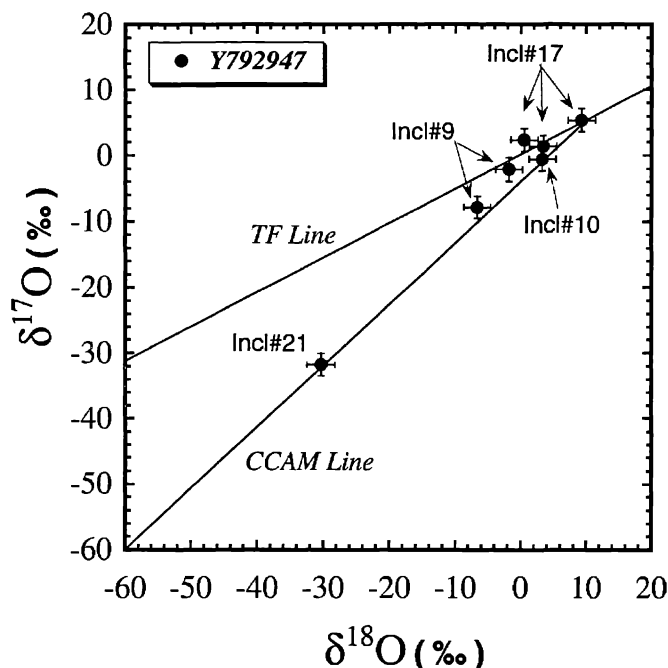
*Errors are 2σ .† $\Delta^{17}\text{O} = \delta^{17}\text{O} - 0.52 \times \delta^{18}\text{O}$ (‰).

FIG. 10. Three oxygen isotopic plot of refractory inclusions in Y-792947. A fine-grained olivine inclusion (#21) plots just on the CCAM line. The other inclusions plot near the TF line.

and the higher amount of Fe-Ni metal than troilite, are typical of H chondrites (Keil, 1962). The average Co content of kamacite (0.51 wt%) is close to that in H3 chondrites (0.46, after Rubin, 1990).

The petrologic type of Y-792947, Y-793408 and Y-82038 is very low, based on the following observations: (1) chondrules are sharply defined; (2) olivine and pyroxene show wide ranges of compositions; the PMD of olivines in all samples is 75, suggesting petrologic subtypes lower than 3.4 (Sears *et al.*, 1991); (3) the three chondrites contain abundant opaque matrices, clinoenstatite and clean glass in chondrules; (4) some chromites are nearly pure FeCr_2O_4 . Such chromites are only

found in chondrites of type lower than 3.4 (Kimura, 2000). Benoit *et al.* (2002) also classified Y-792947, Y-793408 and Y-82038 into subtypes 3.4, 3.3 and 3.2, respectively, based on thermoluminescence data.

From all these data, we conclude that Y-792947, Y-793408 and Y-82038 are H chondrites of petrologic type 3.2–3.4 and shock stage S1. The most primitive H chondrite so far found is Roosevelt County 075 (H3.2(S2)) (McCoy *et al.*, 1993). This meteorite is, however, heavily weathered (W4) resulting in the loss of most Fe-Ni metal. The abundances of most siderophile and chalcophile elements in this chondrite are severely affected by weathering (Fig. 8). The three Yamato meteorites studied here show much less effects of weathering (W2 or degree B). These chondrites essentially preserve the primordial compositions of H chondrites. Therefore, Y-792947 and others represent the most primitive H chondrites known to date.

Unusual Features of Yamato 792947, 793408 and 82038

Although Y-792947, Y-793408 and Y-82038 are undoubtedly H3 chondrites, the abundance of refractory inclusions is extraordinarily high in comparison with any known O chondrites. Bischoff and Keil (1984) found only 12 inclusions from 39 sections of 30 O-chondrite samples. Noonan (1975) discovered five inclusions from Sharps (H3.4), 10 from Clovis (H3.6) and five from Dimmitt (H4). Although the areas of these meteorites investigated were not reported, it is clear that inclusions in O chondrites are rare. Semenenko *et al.* (2001) found a fragment containing many tiny refractory inclusions in Krymka (LL3.1). However, the bulk of Krymka does not appear to have abundant refractory inclusions. Kimura *et al.* (2001) systematically searched for refractory inclusions from H, L and LL chondrites with petrologic types 3.0 to 4 by using the same technique as used here. The abundance they reported is very low: 0.00–3.9 inclusions/cm² in 20 samples (0.8 in average). The abundances of refractory inclusions in Y-792947, Y-793408 and Y-82038 are, on the other hand, 16.1–25.9 (average 22.3) inclusions/cm², more than 20× the abundance in normal type 3 chondrites.

The average modal abundance of refractory inclusions is 0.19 vol% in these H3 chondrites. On the other hand, C chondrites contain 0.9–17.6 vol% refractory inclusions according to McSween (1979). Thus, the abundance of inclusions in Y-792947, Y-793408 and Y-82038 is intermediate between O and C chondrites.

The matrices of the H3 chondrites studied here seem to have similar compositions to those of CO chondrites, but are different from matrix of UOCs. Especially, Na is depleted in the matrices of Y-792947 and other chondrites (Fig. 7). Ikeda *et al.* (1981) reported UOCs with C-chondritic matrices. However, it is also possible that terrestrial weathering affected the matrix. The average matrix Na₂O content of these chondrites (0.31%) is lower than that (1.9%) of Allan Hills (ALH) 77299 (H3) (Ikeda *et al.*, 1981). This difference corresponds to depletion of 0.2% of Na₂O for the bulk rock composition, based on the matrix modal compositions. Actually, Y-792947 and others have bulk Na₂O contents of ~0.2 wt% lower than normal H chondrites (see Table 4).

Features of Refractory Inclusions

Refractory inclusions studied here and in other UOCs are small in size, like those in CO chondrites. However, this size distribution is not the result of secondary fragmentation, because many inclusions show primary structures with rims like those in C chondrites.

Primary minerals in inclusions in H3 chondrites studied here and other UOCs are spinel, olivine, high-Ca pyroxene, hibonite and perovskite. Such mineral assemblages and textures resemble spinel-pyroxene and spinel-hibonite inclusions in CO and CM chondrites (MacPherson *et al.*, 1988), and spinel-rich inclusions in E chondrites (Guan *et al.*, 2000; Fagan *et al.*, 2000; Kimura *et al.*, 2000). On the other hand, secondary feldspathoids are highly abundant in most of inclusions studied here and other UOCs. Primary Ca-rich phases, such as melilite, perovskite and anorthite, are rarely encountered in the inclusions (Nelen *et al.*, 1978; Bischoff and Keil, 1984; this work). FeO-rich olivine and spinel and abundant ilmenite also support the secondary alteration. The alteration degrees in UOC inclusions are commonly compatible with "heavily altered" in CO inclusions (Tomeoka *et al.*, 1992). On the other hand, phyllosilicates and sulphates encountered in CM inclusions are not observed in UOCs, which were not subjected to aqueous alteration.

It is not yet evident why the H3 chondrites studied here contain such an extraordinarily high number of refractory inclusions. However, Kimura *et al.* (2000) found that an EH3 chondrite, Sahara 97159, also contain a huge number of inclusions (20.8 inclusions/cm²). Apparently, the distribution of refractory inclusions is much more heterogeneous in O and E chondrites than thought before.

At any rate, similarities in mineralogy, bulk chemistry and oxygen isotopic compositions of the inclusions in UOCs to those in CO and E chondrites supports the idea that all inclusions formed in a single reservoir, and were later delivered to local

reservoirs where the various groups of chondrites formed (*e.g.*, McKeegan *et al.*, 1998; Guan *et al.*, 2000; Fagan *et al.*, 2000; Kimura *et al.*, 2000). Through this process, some O and E chondrites may have sampled extraordinarily abundant inclusions.

CONCLUSIONS

(1) The petrological and chemical data strongly suggest that Y-792947, Y-793408 and Y-82038 are members of a single H3 chondrite.

(2) The three meteorites were only slightly thermally metamorphosed and suffered almost no shock metamorphism. Their low petrologic type is similar to that of Roosevelt County 075. However, since the primary features of the Yamato meteorites are much better preserved, we consider them the most primitive H chondrites known to date.

(3) The unusual feature of these chondrites is the extraordinarily large number of refractory inclusions, with abundances intermediate between those of O and C chondrites. The distribution of the inclusions may have been highly heterogeneous in the primitive solar nebula.

(4) The characteristic features of the inclusions, such as mineralogy, chemistry and oxygen isotopic compositions, are similar to those in CO and E chondrites, although most inclusions in UOCs are heavily altered to form feldspathoids and FeO-rich phases.

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