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A PRELIMINARY STUDY OF REE ABUNDANCES IN CHONDRULES, AN INCLUSION AND MINERAL FRAGMENTS FROM YAMATO-793321 (CM2) CHONDRITE

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Abstract: In order to examine REE distributions in components of CM chondrites, eight spherical silicate materials (four chondrules [PO, POP and GO], one CAI, two olivine fragments and one unknown inclusion [chondrule?]) were separated from the Yamato (Y)-793321 meteorite, one of the least altered CM2 chondrites, and have been analyzed for REE, Ba, Sr, Rb, K, Ca, Mg and Fe by isotope dilution, together with petrographic examination.

The olivine fragments (YO-1, YO-2) (Fo>99%) with rounded metal inclusions show depletion of alkalis ($\sim 10^{-2} \times$ CI), low refractory element abundances (Sr, Ba and REE=0.2–0.5×CI) and a fractionated (V-shaped) REE pattern, indicative of solid/liquid partitioning of REE. It is suggested that YO-1 and YO-2 formed from melt. The CAI (YI-5) consisting of olivine, fassaite and euhedral spinel shows no sign of aqueous alteration. It has low alkali (<0.1×CI) and high refractory element abundances (2–20×CI) and indicates a light REE depletion and generally smooth pattern with a light/heavy REE discontinuity. The unaltered PO chondrule (YC-7) shows alkali depletion and unfractionated abundances of REE, Ba, Sr and Ca. The altered PO and GO chondrules (YC-8, YC-38) and unknown spherule (Y-9) indicate a light-REE depleted pattern with a negative Eu anomaly and low Ba, Sr and alkalis (~0.1×CI). This REE fractionation seems to be a new type for a chondrule, indicating that a unique REE fractionation occurred during the formation and/or evolution of the Y-793321 CM meteorite.

1. Introduction

The abundances of rare earth elements (REE) in meteoritic and planetary materials can be a unique tool to determine the formation processes of the materials. Chondrite-normalized abundances indicate generally a smooth function (fractionated pattern) against ionic radii (or atomic number) owing to partitioning between solid and liquid during igneous processes. Such elemental features (geochemical fractionations) are found typically for igneous rocks of the earth, moon and achondritic meteorites. On the other hand, rare earths indicate irregular behavior due to gas/solid (or gas/liquid) fractionation during high temperature processes. The volatility controlled abundance feature has been well documented for primitive materials such as Ca, Al-rich inclusions (CAIs) and chondrules (*e.g.* MASON and TAYLOR, 1982; NAKAMURA, 1993) from chondritic meteorites.

The REE analyses for chondrules have been carried out by instrumental neutron activation analysis (INAA) and have generally shown a flat REE pattern relative to CI-chondrites (*e.g.* for Ornans (CO) chondrules by RUBIN and WASSON (1988), for Semarkona (LL3) by GROSSMAN and WASSON (1983)). More recently, precise isotope dilution technique has been applied to analyses of chondrules from Allende (CV) (MISAWA and NAKAMURA, 1988a), Felix (CO) (MISAWA and NAKAMURA, 1988b, c) and unequilibrated ordinary chondrites (UOCs) (NAGAMOTO *et al.*, 1987; NAKAMURA *et al.*, 1990). The isotope dilution technique has disclosed new REE features of chondrules. Many Allende chondrules indicate anomalies of Ce, Eu, Yb and light(L)/heavy(H) REE irregularities; one Felix chondrule indicates a remarkable REE fractionation (group II REE pattern) (MISAWA and NAKAMURA, 1988a, c). Such REE features have been found for chondrules and/or inclusions from a UOC, Hedjaz (NAKAMURA *et al.*, 1990). These elemental features are consistent with volatility-controlled fractionations in the early solar nebula during the formation of precursor materials of chondrules. As a very rare case, a geochemical REE fractionation has been found for Al-rich chondrules from the Ybbsitz (H4) chondrite analyzed by INAA (BISCHOFF *et al.*, 1989).

On the other hand, chondrules from CM chondrites have rarely been analyzed for REE since SCHMITT *et al.* (1968). This is mainly due to analytical difficulties because of small size and scarcity. We, therefore, initiated analyses of REE in chondrules from CM chondrites. Since the CM meteorites have been more or less subjected to aqueous alteration (*e.g.* MCSWEEN, 1979) in their parent body or in the nebula, effects of aqueous alteration on chemical and mineralogical properties are very important and have been extensively studied (*e.g.* BUNCH and CHANG, 1980; TOMEOKA and BUSECK, 1985; ZOLENSKY and MCSWEEN, 1988). In particular, detailed examinations of chondrule mesostasis of CM chondrules have clarified a general trend of elemental redistribution during aqueous alteration (RICHARDSON, 1981; IKEDA, 1983; KOJIMA *et al.*, 1984).

The Y-793321 chondrite is one of the least altered CM chondrites, composed of abundant chondrules, CAIs and mineral fragments. The matrix and components include many alteration products (serpentine, chlorite, smectite, *etc.*) indicative of early aqueous alteration in the parent body or in the nebula (KOJIMA *et al.*, 1984). In this work, we have applied a more refined direct-loading isotope dilution technique (NAKAMURA *et al.*, 1989) to trace element (particularly REE) analyses as well as petrographic and major-element chemical examinations of micro components (chondrules, a CAI and mineral fragments) of the Yamato-793321 CM2 chondrite, and present a combined discussion.

2. Samples and Experimental Procedures

A few pieces of the Y-793321 whole rock fragments (total weight: 1.42 g) and chondrule specimens (46 mg) were allocated to us from NIPR for trace element study. The specimens of olivine fragments (YO-1 and YO-2), a Ca, Al-rich inclusion (CAI) (YI-5), chondrules (YC-7, YC-8 and YC-10) and an unknown spherical silicate (Y-9) were separated from the whole rock fragments by hand-picking through freeze-thaw processing. The rest sample removed spherical materials was used as "whole rock". The chondrule YC-38 had been collected by NIPR (by H. K.) and was transferred to Kobe University. Individual specimens were washed with distilled acetone, briefly washed with 1N HCl and rinsed with water and acetone, and then split into two parts: One half was for polished thin section preparation and the other half was for precise analysis of lithophile elements. Chemical compositions of constituent minerals and the effect of aqueous alteration were examined by an electron probe microanalyzer (EPMA) at NIPR using a focused beam operated at 15 kV acceleration voltage and 10 nA beam current (for samples of YO-1, YO-2, YI-5 and YC-7, YC-8, YC-10) or by a scanning electron microscope-energy dispersive spectroscopy (SEM-EDS) at Kobe University using a 15 kV, 1.2 nA beam (for sample of YC-38).

Abundances of REE, Ba, Sr, Rb, K, Mg, Ca and Fe were determined by isotope dilution using a mass spectrometer model JEOL-05RB. Because the sizes of individual specimens for trace element analysis were too small for conventional procedures, all the specimens studied here were analyzed by the Direct Loading technique (DL-IDMS) (Misawa and Nakamura, 1988a; Nakamura *et al.*, 1989). Except for a few cases, the uncertainties of concentrations due to mass spectrometric measurements were better than ~5% for K, Ca, Fe, Rb, Sr and Ba, and were better than ~10% (~20% in a few cases) for Mg and REE. During the course of this study, one set of chemical procedure blanks was determined. The general blank level was somewhat higher than our normal (Nakamura *et al.*, 1989; Misawa and Nakamura, 1988a). The contributions of blanks to K, Rb, Sr and Ba concentrations in chondrules were ~5%, ~8%, ~8% and ~30%, respectively. The blank effects on REE analyses for chondrules were smaller than 3% for most elements but that for La was ~5%. In this work, the blank levels of major elements, Mg, Ca and Fe, were not determined, but from our experience in this laboratory (*c.f.* Misawa *et al.*, 1992), the effects of major element blanks on analytical data are believed to be negligible ($\ll$0.1%). All the concentration data except for Mg, Ca and Fe presented here are corrected for the blanks. For analyses of specimens with low REE concentrations (olivine grains YO-1, and YO-2; chondrule YC-8), the blank corrections were more serious: ~15% for La and Ce, ~3% for other REE.

For precise REE analyses for the whole rock sample (103 mg was used for acid decomposition), conventional chemical treatment was carried out using cation exchange resin (Dowex 50W-X12 200–400 mesh). For the analysis of trace elements other than REE, the DL-IDMS was employed. The analytical precisions of elements for whole rock are better than 3%.

3. Results and Discussion

3.1. *Petrography and major element chemistry*

In this work, eight spherical silicates separated from the meteorite were analyzed for trace elements. The petrographical features of the specimens are presented in Table 1, and chemical compositions of their constituent minerals and bulk (Mg, Ca and Fe) are shown in Tables 2 and 3. Petrographic textures (SEM-BEI) of specimens studied here are also shown in Figs. 1a–1f. The specimens, YO-1 and YO-2 (Fig. 1a), appeared to be chondrules under a binocular microscope but were found to be almost pure forsterite grains (Fo=99.7) carrying spherical metal inclusions. The Mg content (24%) in bulk YO-1 is too low for forsterite grain, which is not understood here. The specimen YI-5 (Fig. 1b) was also spherical in shape and was thought to be a chondrule. But from the mineral assemblage (olivine, fassaite and spinel), texture and chemical compositions, it is now classified as a coarse-grained type B2 Ca, Al-rich inclusion (CAI) (WARK and LOVERING, 1977). The two forsterite grains and one CAI appeared quite fresh and no alteration products were noted in their thin sections. The four specimens, YC-7, YC-8, YC-10 and YC-38, are olivine-rich chondrules with porphyritic (PO, POP) and granular (GO) textures (Table 1 and Figs. 1c–1f). The specimen Y-9 was not examined for

Table 1. Petrographic descriptions of chondrules, CAI and mineral grains from Y-793321 (CM2).

Sample	Total weight (mg)	Description	Alteration*
YO-1	0.228	Pure forsterite grain (Fo=99.7) including spherical metal inclusions.	unaltered
YO-2	0.160	Pure forsterite grain (Fo=99.7) including spherical metal inclusions.	unaltered
YI-5	0.063	Coarse grained type B2 Ca, Al-rich inclusion (CAI) composed of forsterite (Fo=99.0), fassaite and euhedral spinel.	unaltered Stage I
YC-7	0.099	Prophyritic olivine (PO) chondrule (Fo=65.2) with true glass in mesostasis.	Stage II
YC-8	0.059	Porphyritic olivine (PO) chondrule (Fo=99.3) with Fe-rich phyllosilicate in mesostasis.	
Y-9	0.116	**	Stage II
YC-10	0.089	Porphyritic olivine pyroxene (POP) chondrule (Fo=99.1) with Fe-rich phyllosilicate in mesostasis.	Stage II
YC-38	0.328	Granular olivine (GO) chondrule (Fo=99.1) composed of olivine including mesostasis of anhydrous mineral, two spherical Fe, Ni-sulfides (partly altered to PCP) and Fe-rich phyllosilicate rim.	

* Degree of alteration of chondrules based on criteria given by IKEDA (1983);
Stage I = No alteration or very weak alteration.
Stage II = Alteration of chondrule mesostasis.

** The sample was lost during thin section preparation and was not examined for the texture.

Table 2. Chemical compositions of constituent minerals of CAI and interstitial phases of chondrules (values in wt%).

	YI-5			YC-7		YC-8	YC-10	YC-38		
	Ol	Fas	Sp	Gl		Phyl	Phyl	Ahy	Sul	
SiO_2	41.9	42.4	0.1	59.8	55.3	23.7	21.8	48.0	1.6	0.0
TiO_2	0.0	2.2	0.2	0.4	0.6	0.1	0.1	1.3	0.1	0.2
Al_2O_3	0.1	15.9	72.0	14.2	11.4	7.5	6.0	10.1	0.4	0.5
Cr_2O_3	0.2	0.5	2.4	0.1	0.2	0.8	0.1	1.3	1.6	1.2
FeO	1.1	0.2	0.7	9.4	15.1	41.3	49.7	0.5	47.6	59.3
MnO	0.0	0.0	0.1	0.2	0.3	0.2	0.3	0.2	0.2	0.3
NiO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	11.4	14.6
MgO	57.7	13.4	28.2	0.9	1.6	10.1	7.0	16.3	2.7	2.4
CaO	0.7	25.3	0.0	6.1	12.0	0.5	0.3	19.9	0.1	0.1
Na_2O	0.0	0.1	0.0	8.6	4.5	0.8	0.5	0.0	0.0	0.0
K_2O	0.0	0.0	0.0	0.4	0.2	0.1	0.1	0.0	0.1	0.0
SO_3	—	—	—	—	—	—	—	0.0	28.4	36.9
P_2O_3	—	—	—	—	—	—	—	0.0	0.9	0.1
Total	101.7	100.0	103.7	100.1	101.2	85.1	85.9	97.9	95.1	115.6

Ol = olivine, Fas = fassaite, Sp = spinel, Gl = glass, Phyl = phyllosilicate, Ahy = anhydrous mineral. Sul = mixture of Fe, Ni-sulfide and PCP (poorly characteristic phase).
"—" denotes "not determined".

Table 3. Results of isotope dilution analyses for whole rock (W.R.), olivine fragments, CAI and chondrules from the Y-793321 chondrite.

	YO-1	YO-2	YI-5	YC-7	YC-8	Y-9	YC-10	YC-38	W.R.
wt (mg)*	0.159	0.057	0.039	0.060	0.037	0.081	0.058	0.212	(103.3)
Mg (%)	24	34	10.8	10.9	26.8	29	22.7	—	10.7
Ca (%)	0.332	0.361	10.4	1.17	0.297	1.18	1.02	1.37	1.25
Fe (%)	1.25	2.26	0.65	31.3	17.7	3.8	5.75	4.86	22.0
K (ppm)	4.9	11	22	511	58.8	78.1	70.5	79.2	376
Rb (ppm)	0.028	0.029	0.052	0.856	0.156	0.313	0.210	0.297	1.69
Sr (ppm)	3.6	3.7	27.4	15.3	0.754	2.91	1.1	3.6	9.70
Ba (ppm)	0.35	0.48	0.34	3.3	0.43	0.32	0.19	1.23	3.31
La (ppm)	0.13	0.069	0.44	0.30	0.04	—	—	0.12	0.357
Ce (ppm)	0.14	0.14	4.06	0.998	0.12	0.76	—	0.556	0.921
Nd (ppm)	0.089	0.124	5	0.72	0.123	0.72	—	0.512	0.662
Sm (ppm)	—	—	2.7	0.240	—	—	—	—	0.215
Eu (ppm)	0.00959	0.0112	0.277	0.096	0.0076	0.073	—	0.036	0.0839
Gd (ppm)	0.049	—	—	0.36	—	—	—	0.37	0.283
Dy (ppm)	0.074	—	2.1	0.42	—	—	—	—	0.342
Er (ppm)	0.061	0.081	1.8	0.263	—	0.47	—	—	0.231
Yb (ppm)	—	—	—	0.28	—	—	—	—	0.231
Lu (ppm)	0.010	—	0.14	0.032	—	0.058	—	—	0.0343

* Sample weight used for DL-IDMS. Cation exchange treatment was carried out for the whole-rock specimen (W.R.).
"—" denotes "not determined".

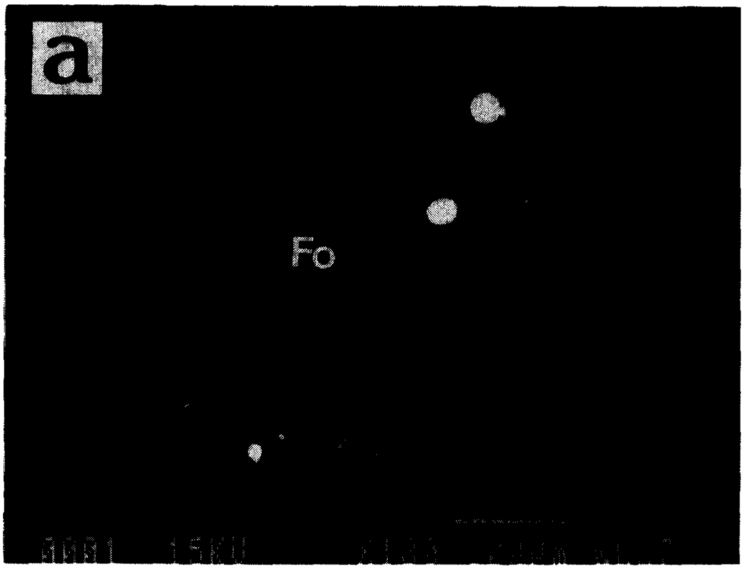

Fig. 1a. A back scattered electron image (SEM-BEI) of an olivine fragment (YO-2) from Y-793321, consisting of homogeneous olivine (Forsterite [Fo]=99.7) with spherical metal inclusions (white dots).

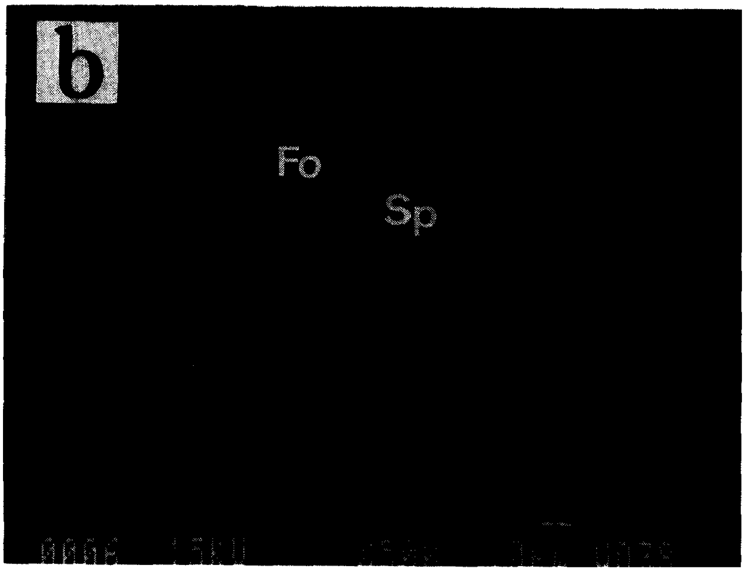

Fig. 1b. A type B2 Ca, Al-rich inclusion (YI-5) from Y-793321. The specimen was originally spherical in shape. Euhedral spinel (Sp) grains are surrounded by forsterite (Fo) and fassaite (Fas).

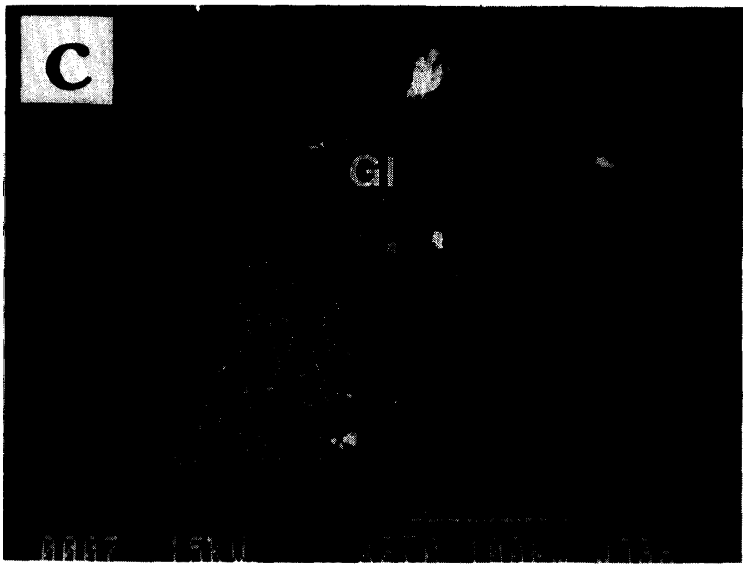

Fig. 1c. A porphyritic olivine chondrule (YC-7) from Y-793321 consisting of olivine (Ol) phenocrysts and the least altered mesostasis glass (Gl).

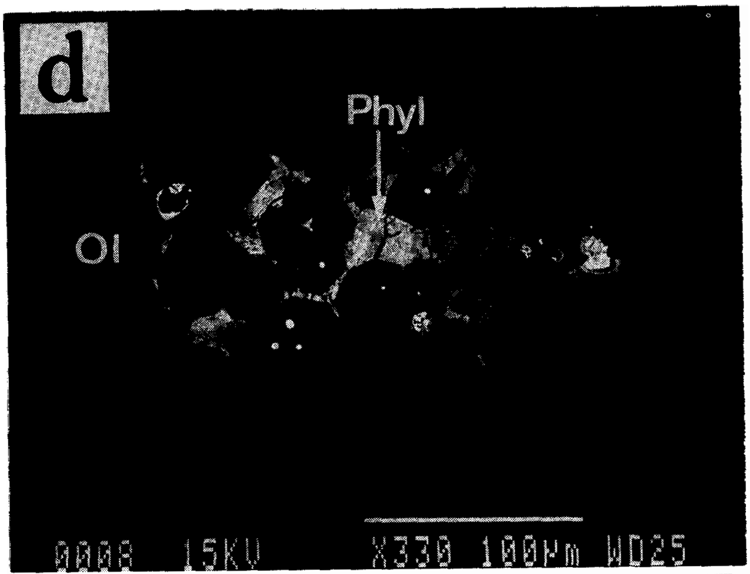

Fig. 1d. A porphyritic olivine chondrule (YC-8) from Y-793321 consisting of olivine (Ol) phenocrysts and altered Fe-rich mesostasis (Phyl).

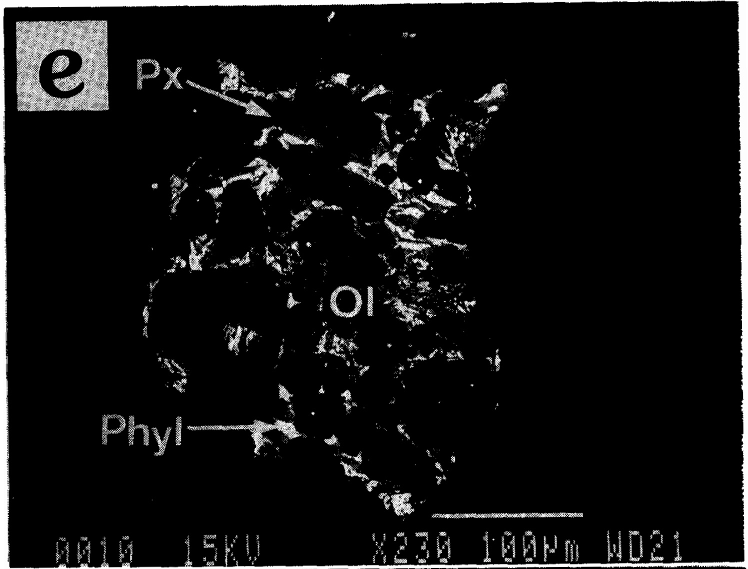

Fig. 1e. A porphyritic olivine pyroxene chondrule (YC-10) from Y-793321 consisting of olivine (Ol), minor Ca-rich pyroxene (Px) phenocrysts and altered Fe-rich mesostasis (Phyl).

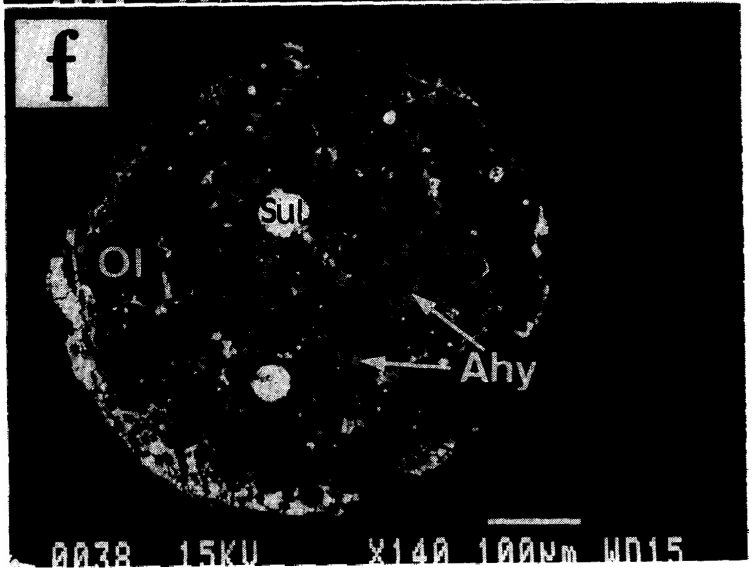

Fig. 1f. A granular olivine chondrule (YC-38) from Y-793321. Two spherical Fe, Ni-sulfides (partly altered to PCP) (Sul) and mesostasis of anhydrous mineral (Ahy) are included in the interstitial area of homogeneous olivine (Ol) grains.

texture owing to failure of the thin section preparation. The chondrule YC-7 has interstitial glass, and almost no alteration products were noted in the mesostasis. The two chondrules YC-8 and YC-10 have altered mesostasis with neither Fe, Ni-metal nor sulfide, and look rather porous in appearance. The GO chondrule YC-38 includes large rounded Fe, Ni-sulfide grains which were partly altered. Based on criteria defined by IKEDA (1983), the degrees of aqueous alteration of these four chondrules are assigned to the relatively weak alteration stages I and II (see Table 1). While most chondrules, a CAI and inclusions show very high Fo content in olivine (>99%), only the YC-7 chondrule shows low Fo (65.2%) in olivine. As mentioned below, this chondrule has unaltered mesostasis. It is thus suggested that the origin and alteration evolution of YC-7 was different from other chondrules examined here.

In Figs. 2a and 2b, chemical compositions of groundmass in porphyritic chondrules are compared with previous chondrule data of Y-793321 (KOJIMA *et al.*, 1984). In the diagrams, the glass compositions of YC-7 are nearly in the region previously reported for those of unaltered chondrules from the other CM meteorites (KOJIMA *et al.*, 1984). On the other hand, for the altered chondrules, phyllosilicate compositions of groundmass are relatively Fe-rich compared with those of chondrules from Y-793321 and other CM chondrites, but they are distinctly different from those of unaltered chondrules of YC-7 and other meteorites. Compositions of altered mesostasis are more Fe, Mg-rich and Si, Al-poorer than those of unaltered glass. In addition to these elements, Ca depletion is notable in altered mesostasis (CaO <1 wt%) compared to those of unaltered mesostasis (6–12 wt%). Such compositional variations of mesostasis may be understood as being due to substitutions of major elements during the alteration process (IKEDA, 1983).

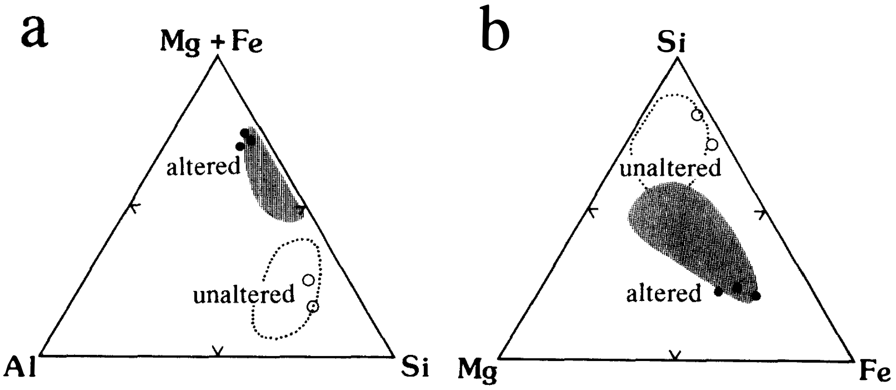

Fig. 2. Comparison of chemical compositions (atomic %) of interstitial phases of porphyritic chondrules from Y-793321 with those of previous data (KOJIMA et al., 1984). Open circles show true glasses of an unaltered chondrule, YC-7 and solid circles represent mesostasis of other chondrules, YC-8 and YC-10. The shaded areas and the dotted circles show the ranges of groundmass compositions of altered (Y-793321) and unaltered (Y-791717, Y-74135) chondrules from KOJIMA et al. (1984), respectively.

3.2. *Lithophile trace element abundances*

The results of isotope dilution analyses for eight individual specimens and a whole rock sample are given in Table 3 and Figs. 3–6. In the diagrams, elemental abundances are normalized to the CI-chondrites (K, Rb, Sr and Ba; ANDERS and

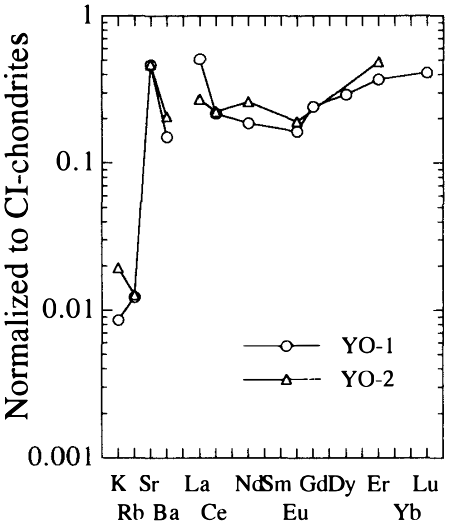

Fig. 3. CI-normalized lithophile element patterns of olivine fragments, YO-1 and YO-2 (both unaltered) from Y-793321. Slightly fractionated (V-shaped) REE patterns are found for the specimens.

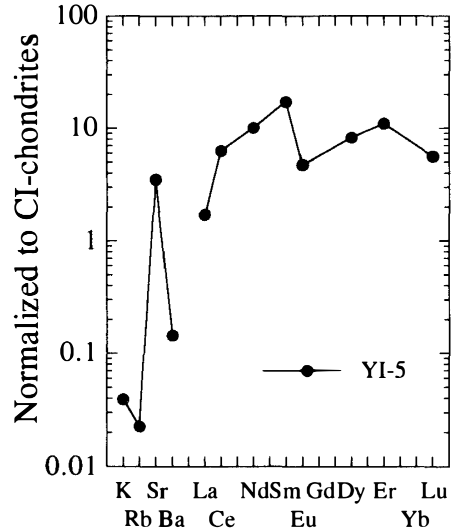

Fig. 4. CI-normalized lithophile element pattern of an unaltered B2 CAI, YI-5 from Y-793321. A peculiar REE fractionation of light-REE depletion and light/heavy REE discontinuity.

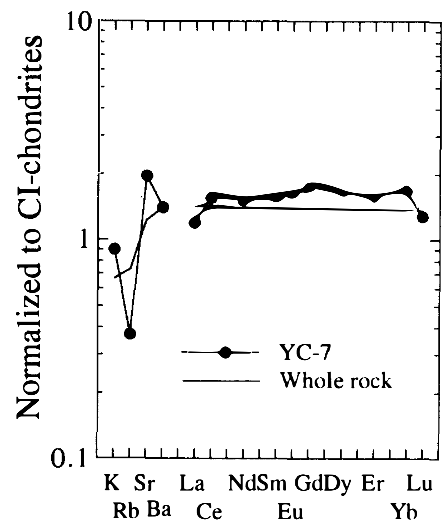

Fig. 5. CI-normalized lithophile element patterns of unaltered chondrule, YC-7 and a whole rock sample from Y-793321.

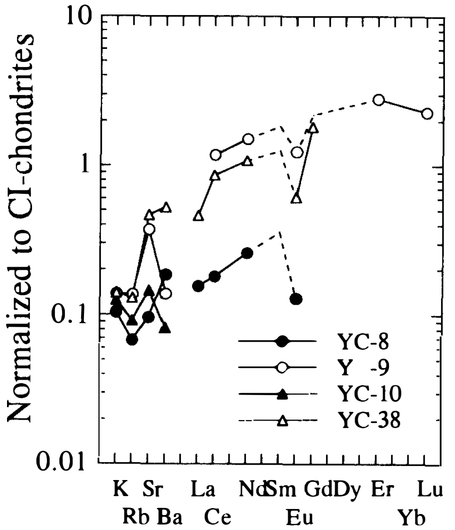

Fig. 6. CI-normalized lithophile element patterns of chondrules, YC-8, YC-10, YC-38 and Y-9 from Y-793321. The light-REE depleted pattern with a negative Eu anomaly is noted in two altered chondrules and one unknown spherical silicate, though the REE data are not complete.

GREVESSE, 1989; REE, NAKAMURA, 1974) and plotted *versus* atomic number.

3.2.1. Olivine fragments

In Fig. 3, Olivine fragments YO-1 and YO-2 show a similar abundance pattern with very low alkalis K, Rb ($\sim 10^{-2}\times$CI) and lower abundances of refractory elements (Sr, Ba, REE=0.2–0.5×CI) compared with CI chondrites. The Ca abundances (0.37–0.40×CI) in YO-1 and YO-2 are comparable to Sr and heavier REEs. Europium and Ba have similarly the lowest abundances of the refractories analyzed here. In Fig. 3, the patterns appear grossly flat but are found to be slightly enriched in lighter REEs and more enriched in heavier REEs. As a result, a slightly fractionated (V-shaped) pattern is recognized for the specimens. Such an REE trend is similar to those of solid/liquid partition coefficients of olivine (see review by IRVING, 1978), or of olivines from achondrites and equilibrated chondrites (NAKAMURA *et al.*, 1982; CURTIS and SCHMITT, 1979). Therefore, we suggest that these olivine grains probably formed from melt by trapping metallic melt under a reducing condition. It is thus possible that YO-1 and YO-2 represent isolated olivines fragmented from some chondrules (RICHARDSON and MCSWEEN, 1978).

3.2.2. CAI

In general, it has been well documented that Ca, Al-rich inclusions (CAIs) have high REE abundances (10–50×CI) together with fractionated REE patterns (*e.g.* MASON and TAYLOR, 1982) indicative of high-temperature processes such as condensation and/or vaporization in the nebula. Nevertheless, the complicated nebula processes have been inferred from their chemical, petrological and isotopic properties. Therefore, their origins, specifically related to other meteoritic components such as chondrules, still remain a major unsolved problem.

The type B2 CAI YI-5 studied here also shows high Ca and REE abundances (2–17×CI) and light (L) to heavy (H) REE irregularity (Fig. 4). Because of high concentration of refractory major elements (typically Ca), the DL-IDMS of this sample encountered analytical difficulties, resulting in rather poor precisions for Nd and Sm. Nevertheless, the general REE pattern is believed to be reliable. The L/H REE fractionations have been reported for group II CAIs from Allende (CV) (TANAKA and MASUDA, 1973) and have been interpreted to have originated by high-temperature nebula condensation (BOYNTON, 1975; DAVIS and GROSSMAN, 1979). The pattern of YI-5 shows similar REE (especially HREE) fractionation to those of inclusions, in particular, MUR7-753 (IRELAND *et al.*, 1991) and SH-4 (EKAMBARAM *et al.*, 1984) from Murchison (CM). The LREE depleted feature found for the spherical CAI YI-5 can not be simply explained only by the volatility control common for REE patterns of group I and III–VI observed in CAIs (MASON and TAYLOR, 1982).

Two alternative formation processes are considered here from these REE constraints. First, YI-5 formed as the solid phase produced by separation of melt from an inclusion precursor with a group II pattern. Second, the mixing of some LREE depleted components was produced by the solid/liquid separation and other components formed by the condensation (/vaporization) processes. For two alternative mechanisms, the separation of liquid from the inclusion precursor in the nebula may be required to interpret this peculiar REE pattern. Although the former process may be favored, these possibilities should be further studied after detailed petrographic examination.

3.2.3. Chondrules

It has been clarified that a majority of chondrules from unequilibrated ordinary chondrites so far reported show a flat REE pattern (GOODING *et al.*, 1983; KURAT *et al.*, 1984). However, the precise IDMS analyses demonstrated that there exist occasional anomalies of Ce, Eu and Yb as well as L/H REE irregularity in their REE patterns (see details in the review by NAKAMURA, 1993). It is thus suggested that chondrules (precursors) had formed through gas/solid (or gas/liquid) distribution processes in the nebula (MISAWA and NAKAMURA, 1988a). It is then interesting to determine whether the CM chondrules also have such nebula REE signatures or other elemental features produced by the parent body processes.

In Figs. 5 and 6, the CI-normalized trace element patterns for chondrules and an unknown spherical inclusion of Y-793321 are shown. In Fig. 5, the PO chondrule YC-7 is compared with the whole rock. The whole rock specimen of Y-793321 shows an unfractionated REE-Ba-Sr pattern (1.4×CI) and low alkalis like most other CM chondrites (NAKAMURA, 1974; EVENSEN *et al.*, 1978). The chondrule YC-7 also shows a flat REE-Ba-Sr pattern, lower K and depletion of Rb. In the REE pattern, Lanthanum (or Ce) and Lu (or Yb) appear to be irregular. Except for the lower alkalis, such refractory element features are quite similar to those of CV and CO chondrules. The GO chondrule (YC-38), PO chondrule (YC-8) and unknown type (Y-9) (Fig. 6) indicate a smoothly fractionated REE pattern with a large negative Eu anomaly, although their abundance data (particularly for heavy REE) are incomplete. This was mainly due to incorrect heating procedures employed for the elements (denoted "—" in Table 3) during DL-IDMS. Other elemental abundances obtained are precise enough to evaluate structures of REE patterns. The low Ba and Sr, and depleted alkali metal abundances, appear to be consistent with the depletion of light REE and/or with negative Eu anomaly. It is thus likely that the light REE depletion and smoothly fractionated pattern with a negative Eu anomaly are common features of chondrules from this meteorite. These REE features have not been found in the chondrules from UOC, E, CV, CO chondrites. Therefore, this REE pattern is unique for this meteorite and/or for CM chondrites. It is thus very important to confirm the new REE fractionation by additional analyses and to explore the implications for origins and evolution of CM chondrules. Because the analytical data presented here, particularly for heavy REE, are not good compared to our chondrule data previously reported, in future work, more complete trace-element data should be obtained to establish the REE fractionation features of CM chondrules.

4. Summary

Eight micro (0.037–0.212 mg) components (four chondrules, a coarse-grained type B2 inclusion (CAI), two olivine fragments and an unknown spherical inclusion) and one whole rock sample were analyzed for REE, Ba, Sr, Ca, Mg, Fe, Rb and K by precise isotope dilution (DL-IDMS) together with petrographic examination. The following results were obtained:

(1) The olivine fragments indicate generally low lithophile element abundances with slightly fractionated (V-shaped) REE pattern, suggesting formation from melt.

(2) The CAI shows peculiar REE abundances with a generally smooth, light-REE depletion pattern and light/heavy REE discontinuity.

(3) The chondrules indicate generally weak aqueous alteration (categories I and II). They indicate two types of REE pattern. An almost unfractionated REE pattern was found for an unaltered PO chondrule. On the other hand, the low alkali and fractionated REE features (light-REE depleted and smoothly fractionated pattern with negative Eu anomaly) were found for two other (PO and GO) chondrules. In addition, one unknown spherical silicate shows similar REE and other lithophile element abundances to these chondrules.

Some of the REE fractionations observed here are rather rare and/or unique for this and/or CM meteorites and thus are very important in order to understand nebula and/or parent body processes. Therefore, further combined trace-element chemical and petrographic research for these CM components is desirable.

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