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TRACE ELEMENT AND ISOTOPIC CHARACTERISTICS OF INCLUSIONS IN THE YAMATO ORDINARY CHONDRITES Y-75097, Y-793241 AND Y-794046

Noboru NAKAMURA[1], Noritoshi MORIKAWA[1], Robert HUTCHISON[2], Robert N. CLAYTON[3], Toshiko K. MAYEDA[3], Keisuke NAGAO[4], Keiji MISAWA[1], Osamu OKANO[5], Koshi YAMAMOTO[1], Keizo YANAI[6] and Yukio MATSUMOTO[7]

[1] *Department of Earth and Planetary Sciences, Faculty of Science, Kobe University, Nada, Kobe 657*

[2] *Department of Mineralogy, The Natural History Museum, Cromwell Road, London SW7 5BD, England*

[3] *Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637, U.S.A.*

[4] *Institute for Study of the Earth's Interior, Okayama University, Misasa, Tottori 682-01*

[5] *Department of Geosciences, Faculty of Science, Okayama University, Tsushima, Okayama 700*

[6] *National Institute of Polar Research, 9-10, Kaga, 1-chome, Itabashi-ku, Tokyo 173*

[7] *13-25, Beppu 2-chome, Jonan-ku, Fukuoka 814-01*

Abstract: Igneous inclusions and hosts of the Yamato ordinary chondrites Y-75097 (L6), Y-793241 (L6) and Y-794046 (H5) were analyzed for lithophile trace elements, and Rb-Sr, rare gas and oxygen isotopes, together with preliminary petrographic examinations. On a three oxygen-isotope plot, all the inclusions lie near the H-chondrite field. The Y-75097 host and inclusion were severely shocked and the Rb-Sr systematics were disturbed by a 500 Ma event which was defined by the K-Ar age. The Y-793241 host and inclusion are unshocked and have an old K-Ar age of 4270 ± 170 Ma and undisturbed Rb-Sr systematics for the bulk meteorite. Both Y-75097 and Y-793241 inclusions have similar chemical compositions and mineral assemblages consisting mainly of olivine (Fa_{25}), and minor plagioclase (An_{12-19}), chlor-apatite, merrillite and chromite. Olivines in both inclusions equilibrated with those of their L6 hosts. The two inclusion mantles consisting of mainly olivine and plagioclase show a highly fractionated REE pattern with middle REE depletion and a large positive Eu anomaly (50–100 times chondritic) (V-shaped). A model calculation suggests that this remarkable REE fractionation was produced by thermal equilibration with the phosphate-rich cores of inclusions during the igneous formation and the metamorphic event. The Y-794046 inclusion comprises abundant anhedral olivines ($Fa_{20.5}$), fractured pyroxenes ($Fs_{14-16.5}$) and microcrystalline plagioclase ($An_{3-5}Ab_{81-96}Or_{0-16}$). The inclusion did not equilibrate with its host which has less Fe-rich olivines (Fa_{19}) and more Fe in pyroxenes ($Fs_{17.5}$). The inclusion shows an unfractionated REE pattern. We suggest that the three inclusions formed by melting of differentiated precursor materials carrying unfractionated REE. They were then incorporated into the L- or H-chondrite parent bodies and subjected to the early thermal metamorphism, which eventually overprinted the fractionated REE in the Y-75097 and Y-793241 inclusions by solid/solid equilibrium partitioning. The Y-794046 inclusion was subjected to less extensive equilibration, so that REE abundances remained unfractionated.

1. Introduction

Various kinds of angular clastic rocks have been found in chondritic and achondritic meteorites (KEIL, 1982; BUNCH and RAJAN, 1988; LIPSCHUTZ *et al.*, 1989). They are called lithic fragments, lithic inclusions, lithic clasts, xenoliths, etc. It is considered that they are products of impact and consolidation on small planetary bodies (mostly asteroids). The inclusions, however, occasionally show chemical, isotopic and petrologic features distinctly different from their host meteorites (see LIPSCHUTZ *et al.*, 1989), indicating that they represent different sources of meteoritic materials. One chondritic meteorite, Barwell, (L6) contains an igneous inclusion which may represent a planetary differentiate formed prior to the accretion of an equilibrated chondrite (HUTCHISON *et al.*, 1988). One lithic inclusion from the Hedjaz (L4) chondrite shows unusual REE fractionations indicative of a nebular signature (NAKAMURA *et al.*, 1990; MISAWA *et al.*, 1993). Lithic inclusions may thus provide important information regarding early planetary and nebular processes.

Large igneous-like inclusions (a few cm in size) have been identified in two Yamato L6 ordinary chondrites Y-75097 and Y-793241 (see YANAI and KOJIMA, 1987). YANAI *et al.* (1983) reported preliminary results of chemical and petrographic investigation of the Y-75097 inclusion. This is olivine-rich and similar to Brachina in texture and mineral assemblage (YANAI *et al.*, 1983). NAKAMURA *et al.* (1984) found an unusual REE fractionation (V-shaped REE pattern with a large positive Eu anomaly) for both inclusions. They have the oxygen isotopic composition of H-group chondrites (MAYEDA *et al.*, 1987). PRINZ *et al.* (1984) noted that Na/Ca in plagioclase of the mantles, but not the cores, of inclusions had equilibrated with their hosts, and found a relic barred olivine (BO) chondrule in the core of the Y-793241 inclusion. It was suggested that the meteorites are paired and that the formation of the inclusions was related to chondrules. On the other hand, based on their INAA results, WARREN and KALLEMEYN (1989) suggested that the high P content in the core and "U-shaped REE pattern" for the outer part is not explained by partial melting but that the inclusions most likely originated as an achondrite containing cumulus olivine, plagioclase and phosphate.

From these previous works, the inclusions seem to be a new type of material in ordinary chondrites and thus more comprehensive studies of these materials are very important. During the preliminary sample description, a similarly large inclusion in the Y-794046 chondrite caught our attention. In order to investigate the origins and chemical-petrologic evolution of the three inclusions, consortium studies were organized. We aim to obtain evidence of their origins either in nebular or planetary setting, the petrogenetic processes, the time of formation and evolution, the relationship between inclusions and their host meteorites and their relationship with other meteoritic materials such as chondrules.

We initiated preliminary studies of trace elements, Rb-Sr systematics and K-Ar in the early stage of this work (NAKAMURA *et al.*, 1984). In addition to the early results, we report here results of consortium studies (NAKAMURA *et al.*, 1993) for trace elements, Rb-Sr isotopes, K-Ar ages and oxygen isotopes as well as preliminary petrographic descriptions, and present interpretations of REE and other chemical, petrological and isotopic characteristics of the inclusions and their host meteorites.

2. Experimental Procedures

The samples Y-75097,65 (inclusion: 0.094 g) and Y-75097,84 (host: 0.95 g) and Y-793241,81 (inclusion: 0.22 g) and Y-793241,77 (host: 0.70 g) were provided by the NIPR. All these specimens appeared fresh but were subjected to our normal cleaning processes (a brief wash with 1N HCl and distilled water, and rinse with acetone) before trace element and isotope analyses. The specimen of Y-794046,100 (inclusion: 0.10 g) also appeared fresh, but the host meteorite (Y-794046,60: 0.138 g) had a rusty appearance and may be severely weathered. They were also washed as described above.

The ~100 mg specimens of inclusion and host were broken and ground in an agate mortar. Part of each sample was set aside for rare gas analyses (for the hosts of Y-75097 and Y-793241) and the remainder was pulverized and split into a few parts for trace element and Sr isotopic analysis. The general procedures are described elsewhere (TORIGOYE *et al.*, 1993). Analyses of REE, Ba, Sr, Rb, K, Ca, Mg and Fe were carried out by isotope dilution (NAKAURA *et al.*, 1989) at Kobe University. The procedural blanks for trace elements were mostly negligible (<0.5%) for all samples. Analytical precision was normally better than 3% but was 5–10% for extremely low REE such as the middle REE in the inclusions of Y-75097 and Y-793241.

During the course of this study, we carried out Rb-Sr isotopic analyses of inclusions and hosts of Y-75097 and Y-793241 using three different mass spectrometers at the Institute for the Study of Earth's Interior (ISEI), Okayama University (Misasa); U.S. Geological Survey (USGS) (Denver); and Institute for Cosmic-Ray Research (ICRR), University of Tokyo (Tanashi). There exists machine bias between the institutes. The repeated measurements of the NBS 987 Sr standard indicated good reproducibility at different institutes; see NAKAMURA *et al.* (1985) for USGS data, TORIGOYE *et al.* (1993) for ICRR, University of Tokyo data, and OKANO *et al.* (1990) for ISEI, Okayama University data. The Sr isotopic ratios obtained for the samples are then sufficiently reliable.

Analyses of Ar and other rare gases were carried out at Okayama University for two host specimens (Y-75097 and Y-793241) which had been analyzed for trace elements and Rb-Sr isotopes. The procedures were described by NAGAO *et al.* (1993). The oxygen isotopic ratios of the Y-794046 inclusion and the host chondrite were measured at University of Chicago using the procedures of CLAYTON and MAYEDA (1983).

3. Results and Discussion

3.1. *Petrographic descriptions*

Chemical and petrological studies have been undertaken at the Natural History Museum, London. Presented here are preliminary results of petrographic examinations.

Yamato-75097: A troctolitic inclusion lies within an L6 host. Pyroxene is completely absent. Shock veins of green to dark brown isotropic glass (10–30 μm thick) run within the inclusion. The host is heavily shocked; the olivines are commonly fractured and show undulose extinction, and the plagioclases are now maskelynite. There is no change in the grain-size at the contact. Near the host, the inclusion is composed of euhedral to subhedral olivines ($<400\,\mu$m long). Feldspar is intergrown with granular olivine and chromite. Chromites are anhedral, round to elongate ($5\times50\,\mu$m), along margins of olivines. Olivines may be enclosed in poikilitic chlor-apatite or merrillite. Phosphates are unevenly distributed, being completely absent in most of the inclusion but comprising ~10 vol% of part of the coarser area. The composition of olivine is uniform ($Fa_{24.8}$) and indistinguishable from that in the host. The composition of maskelynite is $An_{12-18}Ab_{78-86}Or_{3-5}$. Chromite has 2–4 wt% TiO_2, 6.8% Al_2O_3 and 2% MgO.

Yamato-793241: A troctolitic inclusion lies within an L6 host. Both are unshocked. An arcuate, granular textured zone, 200–500 μm wide, separates host from inclusion. In part of the inclusion, olivines about 50 μm in size form an interlocking to granular mesh with interstitial crystalline feldspar ($An_{12-19}Ab_{83-78}Or_{7-3}$) and metal droplets. Poikilitic chlor-apatite occurs in an elongated zone 3 mm $\times250\,\mu$m bordering the edge of the inclusion. Olivines ($Fa_{24.7}$) are in equilibrium with those of the host ($Fa_{25.2}$).

According to preliminary examinations (YANAI and KOJIMA, 1987; and PRINZ *et al.*, 1984), there exists a relic barred olivine chondrule in the core of the inclusion. Plagioclase is zonally distributed in the inclusion; plagioclase (An_{10}) in the outer part is equilibrated with that (An_{10}) of the host, but the core is more calcic (An_{36}).

Yamato-794046: A harzburgitic inclusion is associated with an H5 host. The host is coarse-grained, like type 6, but "striated" pyroxene is common and there are some fine-grained areas. Metal-sulfide veins and fractures are present. The inclusion contains abundant anhedral olivines (25–150 μm in size), commonly in granular clusters. The olivines are enclosed within poikilitic plates of twinned, low-Ca pyroxene with augite rims ($Wo_{27}En_{59}Fs_{13}$). The pyroxenes ($<2000\times500\,\mu$m) are fractured, usually perpendicular to the *c* axis. A few large low-Ca pyroxenes have cores ($<250\times100\,\mu$m) with abundant polysynthetic twins and numerous fractures perpendicular to the *c* axis. The cores (probably protopyroxene) co-precipitated with olivine before the poikilitic pyroxene crystallized. The interstices are filled with turbid, grey-green to brown microcrystalline plagioclase (devitrified maskelynite?) with variable compositions ($An_{3-5}Ab_{81-95}Or_{0-16}$). Anhedral chromite and Fe-sulfide are minor phases. A few small (60 μm) areas have a granular texture, with grains

2–15 μm in diameter. These areas are considered to be recrystallized melt-pockets. The host and inclusion are not in equilibrium. In the host, olivines ($\sim Fa_{19}$) are less Fe-rich and pyroxenes ($Fs_{17.5}$) are more Fe-rich than those in the inclusion ($Fa_{20.5}$ and $Fs_{14-16.5}$). The inclusion probably formed by slow crystallization from high temperature, followed by rapid cooling and/or reheating and quenching, and then brittle deformation.

3.2. *Oxygen isotopic composition*

Results of oxygen isotopic measurements for the Y-75097 and Y-793241 inclusions have been reported previously (MAYEDA *et al.*, 1987). Both inclusions have oxygen isotopic compositions similar to those of H-chondrites (MAYEDA *et al.*, 1987; CLAYTON *et al.*, 1991). Results for Y-794046 are shown in Table 1 and Fig. 1, together with the previous analyses for Y-75097 and Y-793241. In a three oxygen-isotope plot (Fig. 1), data points of both inclusion and host of Y-794046 lie within the range of bulk H-chondrites.

Table 1. Oxygen isotope compositions of inclusions from Yamato meteorites.

Sample		$\delta^{18}O$	$\delta^{17}O$ (‰ relative to SMOW)	$\Delta^{17}O$	Class†
Y-75097,93*	host	4.53	3.55	1.19	L
Y-75097,111*	inclusion	4.54	3.05	0.69	H
Y-793241,85*	host	4.32	3.30	1.05	L
Y-793241,82*	inclusion	3.75	2.42	0.47	H?
Y-793241,83*	inclusion	4.02	2.48	0.39	H?
Y-794046,64	host	4.01	2.83	0.74	H
Y-794046,95	inclusion	3.96	2.61	0.58	H

* Data are from MAYEDA *et al.* (1987).
† The assignments of H and L are based on comparison with the mean values for equilibrated chondrites (CLAYTON *et al.*, 1991), mean H: $\delta^{18}O=4.08$, $\delta^{17}O=2.85$, $\Delta^{17}O=0.73$, mean L: $\delta^{18}O=4.70$, $\delta^{17}O=3.52$, $\Delta^{17}O=1.07$.

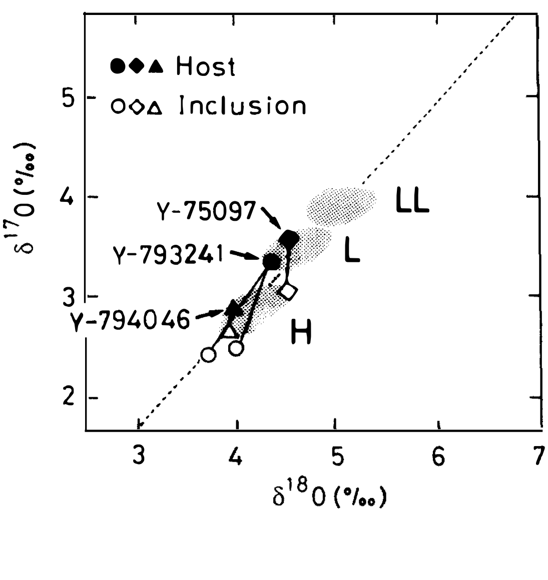

Fig. 1. Oxygen isotopic compositions of three inclusions and their host Yamato ordinary chondrites. Shaded areas indicate the ranges of the compositions of H-, L- and LL-chondrites. The hosts are L-chondrites, Y-75097 and Y-793241, and H-chondrite, Y-794046, whereas all three inclusions lie near the H-chondrite field. Data of Y-75097 and Y-793241 are from MAYEDA et al. (1987).

Oxygen has a lower diffusivity than most common silicate-forming elements (FREER, 1981) and may thus provide key information on the parent materials of the inclusions, typically their relationship to the groups of meteorites (CLAYTON *et al.*, 1991). All the inclusions studied here lie near the H-chondrite field and show no relationship with any achondrites so far reported. It is also noted that the Y-793241 inclusion shows a slight deviation to a lower $^{17}O/^{16}O$ ratio from the typical range of bulk H-chondrites (CLAYTON *et al.*, 1991). Therefore, if the inclusions are achondritic (WARREN and KALLEMEYN, 1989), they represent a new type of achondrite which has not yet been reported. This isotopic composition, however, is well within the range of chondrules from unequilibrated ordinary chondrites (UOC's) (CLAYTON *et al.*, 1991). It is thus possible that the precursor materials of inclusions are more related to UOC chondrules in their oxygen isotopic composition.

3.3. *Chronology of the inclusions*

K-Ar ages: The results of Ar and rare gases are presented in Table 2. The K-Ar age is calculated to be 583±50 Ma for the Y-75097 host. This is somewhat higher than the well defined Ar-Ar plateau age (490 Ma) obtained by KANEOKA *et al.* (1988). They also reported a total Ar-Ar age of 583 Ma which is in good agreement with this work. From the Ar-release pattern, it is clear that the older total Ar-release age is caused by incomplete degassing of ^{40}Ar mostly in high temperature components. Therefore, the slightly younger Ar-Ar age (490 Ma) may represent that of a real event more closely. NAGAO (1994) reported 485±30 Ma for the Y-75097 inclusion, which is in agreement with that of its host. The concordant ages of host and inclusion of the Y-75097 meteorite indicate a severe thermal event at 490 Ma, which may be assigned to the intensive degassing event commonly known for L-chondrites (TAYLOR and HEYMANN, 1969).

The K-Ar age of the Y-793241 host is 4270±170 Ma. This value is substantially in agreement with those recently obtained by the same worker (NAGAO, 1993). The age of the host is again in good agreement with that of the Y-793241 inclusion (4270 ±120 Ma) reported by NAGAO (1994). The host and inclusion of the meteorite are found to have a concordant old age which is quite different from that of Y-75097. The K-Ar ages are in accordance with the petrological textures as described above

Table 2. Results of rare gas analyses for the host samples from Y-75097 ahd Y-793241.

Sample	^{3}He	^{4}He	$^{3}He/^{4}He$	^{20}Ne	^{21}Ne	^{22}Ne	$^{20}Ne/^{22}Ne$
Y-75097,84	41.7	351	0.1187±0.0007	8.25	9.04	9.85	0.8378±0.0013
Y-793241,77	45.0	1180	0.03813±0.00022	6.45	6.16	7.53	0.8571±0.0021

Sample	$^{21}Ne/^{22}Ne$	^{36}Ar	^{38}Ar	^{40}Ar	$^{38}Ar/^{36}Ar$	$^{40}Ar/^{36}Ar$
Y-75097,84	0.9185±0.0084	1.12	0.887	231	0.7922±0.0026	206.65±0.43
Y-793241,77	0.8188±0.0075	1.74	0.952	5050	0.5472±0.0080	2904±61

^{3}He, ^{4}He, ^{20}Ne, ^{21}Ne, ^{22}Ne, ^{36}Ar, ^{38}Ar, ^{40}Ar: 10^{-8} cm^{3}STP/g.

and also with the Rb-Sr systematics described later. It can be concluded that the meteorites are not paired but are different falls. This conclusion is supported by the different cosmic-ray exposure ages of two meteorites (NAGAO, 1994).

NAGAO (1994) reported young K-Ar ages of 2020±190Ma and 1870±80 for Y-794046 host and clast, respectively. This agreement of K-Ar ages is surprising because the host samples are generally severely weathered. KANEOKA (1983) found that weathered outer parts of the ALH-761 (L6) and ALH-77288 (H6) meteorites gave older Ar ages compared with inner fresh specimens. We suggest that the age of the inclusion is more reliable and represents a real thermal event in the parent body. Nevertheless, the rough agreement in age for both inclusion and host suggests that they experienced a common degassing event significantly later than the early formation and metamorphism.

Rb-Sr systematics: Because the K-Ar system of Y-75097 was completely reset, it is interesting to determine whether the more refractory Rb-Sr isotopes were also reset. In an attempt to obtain an internal Rb-Sr isochron for the meteorite, mineral separates were analyzed as well as the whole-rock of the Y-75097 meteorite. In an ^{87}Rb-^{87}Sr evolution diagram (Fig. 2), the data points of mineral separates and

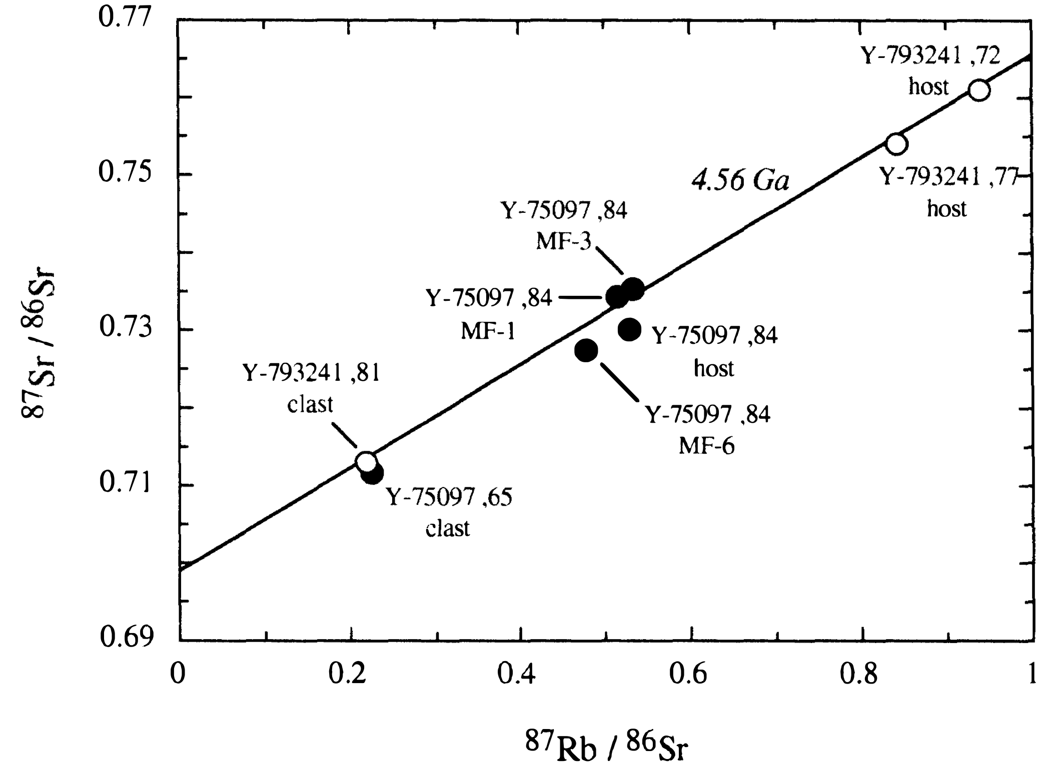

Fig. 2. ^{87}Rb-^{87}Sr evolution diagram for the inclusions and the hosts of the Y-75097 (L6) and Y-793241 (L6) chondrites. The mineral separates (MF-1, MF-3 and MF-6) and a host specimen of Y-75097 do not form an isochron, indicating a late Rb-Sr isotopic perturbation, which also affected the Y-75097 inclusion. The data of two whole-rocks and the inclusion from Y-793241 form an isochron corresponding to an age of 4510 ±240Ma and an initial ^{87}Sr/^{86}Sr ratio of 0.6985 ±0.0035, indicating no perturbation since their early formation and/or metamorphism.

whole-rock are distributed on both sides of a 4.56 Ga reference line, indicating that the Rb-Sr system was perturbed by a later event. This data point distribution does not resemble those of shocked L-chondrites (GOPALAN and WETHERILL, 1971; MINSTER and ALLÈGRE 1979); owing to Rb losses, the data points of shocked meteorites usually lie to the left side of a 4.56 Ga line in an ^{87}Rb-^{87}Sr evolution diagram. Scatter around the 4.56 Ga reference line was also found for a series of Yamato-79 shock-melted LL-chondrites (OKANO et al., 1990). The event responsible for the Rb-Sr perturbation in Y-75097 is considered to be the 490 Ma impact event which reset the K-Ar system and may have produced the abundant shock features: fracturing of crystals and presence of maskelynite. Similar isotopic and petrologic characteristics have been well documented for the series of Y-79 shocked LL chondrites (OKANO et al., 1990).

In Fig. 2, the three data points of the Y-793241 host (,72 and ,77) and inclusion show relatively large variations in ^{87}Rb/^{86}Sr and ^{87}Sr/^{86}Sr ratios, and form a linear trend. The slope of the regression line corresponds to an age of 4.51±0.24 Ga and an initial ^{87}Sr/^{86}Sr ratio of 0.6985±0.0035. The calculated age is in agreement with the K-Ar age and may roughly represent the time of the early formation and/or metamorphism. However, only three samples were analyzed and the error associated with the age is too large to specify the chronological meaning. Model ages can be calculated using the Rb-Sr data of the bulk samples and the Allende ^{87}Sr/^{86}Sr initial ratio (see Table 3). The calculated model ages (so-called ALL-model ages) are 4.51 ±0.03 and 4.48±0.03 Ga for the two host specimens and 4.45±0.03 Ga for the inclusion. The three model ages are similar and consistently very old. We, therefore, suggest that the Rb-Sr system of Y-793241 as a whole was not perturbed signifi-

Table 3. Results of Rb-Sr isotopic analyses for the Y-75097 and Y-793241 meteorites.

Sample		Rb (ppm)	Sr (ppm)	^{87}Rb/^{86}Sr**	^{87}Sr/^{86}Sr	Model age$^{\#}$ (Ga)
Y-75097,84	host	2.001	10.93	0.5309	0.729990¶±31§	4.01
Y-75097,84	MF-1*	1.474	8.315	0.5142	0.734338† ±22	
Y-75097,84	MF-3*	0.9407	5.138	0.5312	0.735164† ±22	
Y-75097,84	MF-6*	9.587	58.05	0.4788	0.727380† ±24	
Y-75097,65	inclusion	1.513	19.40	0.2257	0.711770¶±40	3.92
Y-793241,72	host	2.018	6.251	0.9389	0.760944† ±36	4.51
Y-793241,77	host	2.716	9.377	0.8417	0.754044‡ ±21	4.48
Y-793241,81	inclusion	1.317	17.45	0.2185	0.713113¶±36	4.45
NBS 987 standard	ISEI (Misasa)				0.710236 ±33	
	USGS (Denver)				0.710242 ±20	
	ICRR (Tanashi)				0.710124 ±17	

* MF-1, MF-3, and MF-6 are mineral separates.
** Errors are estimated to be ~0.5%.
§ Errors are 95% confidence limit.
¶ Using a mass spectrometer model MAT 261 at ISEI, Okayama University.
† Using a mass spectrometer model VG Isomass 54-R at U.S. Geological Survey, Denver.
‡ Using a mass spectrometer model VG 354 at ICRR, University of Tokyo.
\# Model ages are calculated using the Allende initial value (^{87}Sr/^{86}Sr=0.69877, GRAY et al., 1973; $\lambda=1.42\times10^{-11}\,y^{-1}$). Machine bias is corrected using the NBS 987 value of 0.71014.

cantly since the early formation and/or the thermal metamorphism.

FUJIMAKI *et al.* (1993) reported that the Rb-Sr systematics of both the Y-794046 host and inclusion were also perturbed by a late event. In view of the young K-Ar age of ~1.9 Ga, the petrographic texture of fractured pyroxenes, and the presence of melt pockets, it is possible that the Rb-Sr system was also perturbed by the same impact event. Nevertheless, it must be borne in mind that the host samples are severely weathered and the alkalis were leached out significantly possibly during the burial of the meteorite in Antarctica, as discussed later, and the effect of weathering on the Rb-Sr system as well as on the K-Ar system is important for weathered Antarctic meteorites (KANEOKA, 1983; NISHIKAWA *et al.*, 1990).

3.4. *Lithophile element abundances*

Results of isotope dilution analyses are given in Table 4 and shown in Figs. 3 and 4. In the early stage of the work, iron was not analyzed and no data were

Table 4. Results of mass spectrometric isotope dilution analyses (values are in ppm unless otherwise indicated).

Sample		Mg (%)	Ca (%)	Fe (%)	K	Rb	Sr	Ba	La	Ce
Y-75097,84	host	15.1	1.32	n.d.	870	2.00	10.93	3.74	0.420	1.21
		(0.2)	(0.01)		(13)	(0.01)	(0.01)	(0.03)	(0.003)	(0.003)
Y-75097,65	inclusion	17.4	0.42	n.d.	950	1.52	19.22	5.21	0.051	0.064
		(0.3)	(0.01)		(20)	(0.01)	(0.01)	(0.05)	(0.001)	(0.001)
Y-793241,77	host	15.0	1.29	22.6	756	2.72	9.377	3.56	0.323	0.889
		(0.2)	(0.01)	(0.2)	(5)	(0.01)	(0.002)	(0.04)	(0.005)	(0.012)
Y-793241,81	inclusion	18.1	0.46	n.d.	526	1.32	17.46	3.52	0.084	0.107
		(0.2)	(0.01)		(5)	(0.01)	(0.01)	(0.01)	(0.001)	(0.001)
Y-794046,60	host	15.7	1.28	31.5	691	1.26	10.3	3.78	0.297	0.712
		(0.6)	(0.01)	(0.3)	(4)	(0.01)	(0.1)	(0.02)	(0.004)	(0.003)
Y-794046,100	inclusion	21.3	1.71	13.6	1780	5.14	13.5	5.31	0.412	1.05
		(0.4)	(0.02)	(0.1)	(10)	(0.03)	(0.1)	(0.03)	(0.002)	(0.01)

Sample		Nd	Sm	Eu	Gd	Dy	Er	Yb	Lu
Y-75097,84	host	0.825	0.267	0.0852	0.365	0.446	0.296	0.279	0.0436
		(0.003)	(0.002)	(0.0006)	(0.004)	(0.006)	(0.002)	(0.004)	(0.0003)
Y-75097,65	inclusion	0.0205	0.0035	0.134	0.0044	0.0060	0.0086	0.0280	0.0069
		(0.0002)	(0.0001)	(0.008)	(0.0001)	(0.0002)	(0.0001)	(0.0004)	(0.0002)
Y-793241,77	host	0.679	0.222	0.0754	0.307	0.378	0.244	0.238	0.0362
		(0.004)	(0.003)	(0.0007)	(0.002)	(0.002)	(0.002)	(0.001)	(0.0003)
Y-793241,81	inclusion	0.0297	0.0060	0.118	0.0067	0.0065	0.022	0.077	0.016
		(0.0002)	(0.0001)	(0.002)	(0.0008)	(0.0002)	(0.003)	(0.002)	(0.001)
Y-794046,60	host	0.526	0.170	0.0685	0.237	n.d.	0.188	0.190	0.0296
		(0.002)	(0.001)	(0.0005)	(0.001)		(0.003)	(0.003)	(0.0003)
Y-794046,100	inclusion	0.779	0.246	0.0898	0.342	n.d.	0.275	0.273	0.0426
		(0.004)	(0.001)	(0.0005)	(0.003)		(0.002)	(0.003)	(0.0004)

n.d. denotes "not analyzed".
Errors are in parentheses.

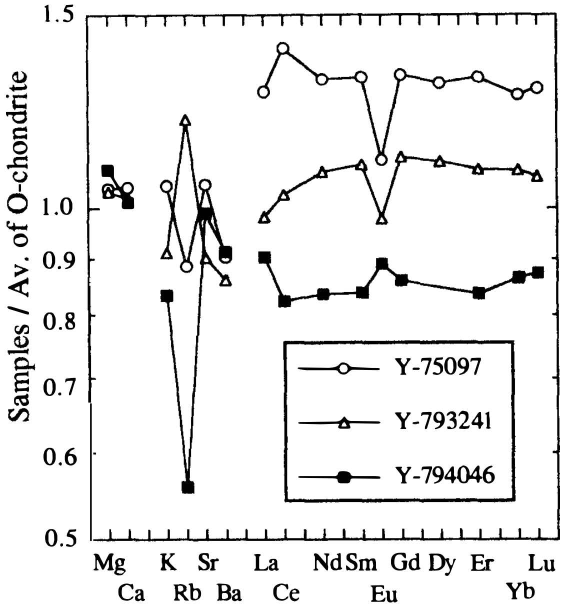

Fig. 3. Chondrite-normalized lithophile element patterns for host samples of the Y-75097 (L6), Y-793241 (L6) and Y-794046 (H5) chondrites. The Y-75097 meteorite has higher REE abundances, a minor positive Ce anomaly and a negative Eu anomaly. The Y-793241 meteorite shows a slightly fractionated REE pattern with a minor negative Eu anomaly. The weathered host specimen Y-794046 shows a depletion of Rb and K. Particularly, a large Rb depletion and the irregularity of La are unusual for an H-chondrite, and may be caused by the terrestrial weathering in Antarctica.

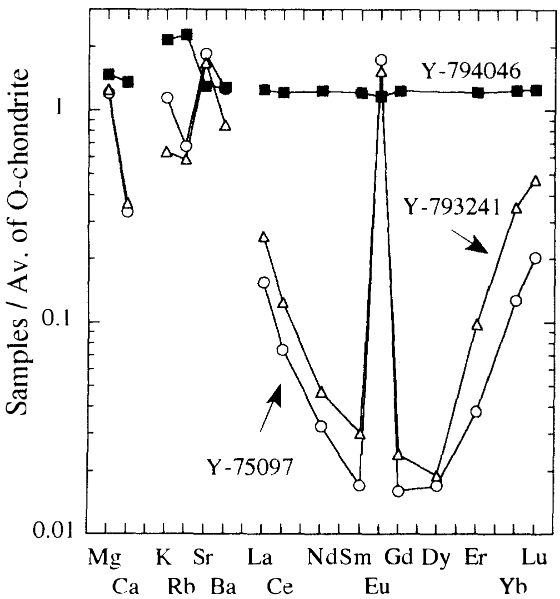

Fig. 4. Chondrite-normalized lithophile element patterns for inclusions from the Y-75097 (L6), Y-793241 (L6) and Y-794046 chondrites. The Y-795097 and Y-793241 inclusions show an extremely fractionated (V-shaped) REE pattern with middle REE depletion and large positive Eu anomaly. The Y-794046 inclusion has an unfractionated lithophile pattern except for its higher alkali contents (~2×O-chondrites).

obtained for Y-75097 specimens and the Y-793241 inclusion. The analyses of Dy for Y-794046 samples were not successful due to misleading mass spectrometry. Except for these two cases, precise analyses were performed for the specimens.

Host meteorites: The host meteorites of Y-75097 and Y-793241 have abundances of Mg, Ca and K (and Fe) typical of L-chondrites (KALLEMEYN *et al.*, 1989). In Fig. 3, the lithophile element abundances are normalized to the average of ordinary chondrites (NAKAMURA, 1974). Both Y-75097 and Y-793241 hosts show somewhat higher REE abundances compared with average L6 chondrites (KALLEMEYN *et al.*, 1989) and indicate a negative Eu anomaly. The Y-75097 host shows a small positive Ce anomaly. The Y-793241 host shows a minor REE fractionation from light to middle REE. Lower Ba and Sr abundances are parallel with the negative Eu anomaly. In spite of the higher common REE, the Eu abundance is within the range of normal L6 chondrites (KALLEMEYN *et al.*, 1989).

NISHIKAWA *et al.* (1990) investigated the weathering effect on REE abundances in Antarctic H-chondrites including heavily weathered ones (weathering categories: A–D) and compared with non-Antarctic H-chondrites. While Antarctic H-chondrites show systematic depletion of alkalis with increasing degree of weathering, they indicate the tough resistance of REE. In addition, it is pointed out that the lithophile trace element features as mentioned above has been commonly found in non-Antarctic ordinary chondrites (MASUDA *et al.*, 1973; NAKAMURA 1974). Although systematic examinations of weathering effect on REE in Antarctic L-chondrites have not yet been carried out, we believe that the lithophile element features as mentioned above are not due to the weathering but to a sampling problem because of the relatively small-sized ($\sim$100 mg) samples analyzed in this work: heterogeneous distribution of phosphates for the common REE and homogeneous distribution of plagioclase for Eu.

The weathered host specimen of the H5 chondrite Y-794046 has slightly higher abundances of Mg and Fe but a lower abundance of alkalis. From analogy with the weathered Antarctic H-chondrites investigated by NISHIKAWA *et al.* (1990), the significantly lower Rb (0.57 times ordinary chondrites; Fig. 3) is suggested to be due to the terrestrial weathering. On the other hand, considering the small sample sizes used for analyses, lower abundances of common REE and normal abundances of Eu, Sr and Ba in the meteorite may not necessarily be assigned to the weathering effect (see NISHIKAWA *et al.*, 1990).

Inclusions: Both inclusions from Y-75097 and Y-793241 have similar Mg, Ca and K contents. Compared with their L6 hosts or with H-chondrites, they are higher in Mg and lower in Ca. Apparently their chemical composition reflects the olivine-rich nature of the inclusions. Nevertheless, the specimens analyzed in this work indicate a lower Mg content and higher Ca and K compared with the chemical compositions given by YANAI *et al.* (1983). As noted in the previous section, the major minerals appear to be zonally distributed: generally more phosphate-rich in the core and more plagioclase-rich in the mantles of the inclusions. The reported mineral contents are: olivine 82–91%, plagioclase 2.5–14%, merrillite 0–11% (YANAI *et al.*, 1983; PRINZ *et al.*, 1984). Using the metal contents (assuming similar mineral assemblage), we have estimated the mineral composition of the inclusions analyzed in this work. The specimens analyzed here show quite lower olivine (75%) and phosphates ($<$0.1%), and higher plagioclase (25%).

In Fig. 4, the ordinary chondrite-normalized abundance patterns of lithophile elements are shown for the inclusions of Y-75097, Y-793241 and Y-794046. As noted by NAKAMURA *et al.* (1984) and by WARREN and KALLEMEYN (1989), the former two clasts show an extreme REE fractionation with light and heavy REE enrichment, middle REE depletion but a large positive Eu anomaly (so-called V-shaped or W-shaped pattern). The degree of the Eu anomaly is calculated to be 100 for Y-75097 and 51 for Y-793241 inclusions. The observed Eu anomalies are among the highest observed in meteoritic and planetary materials such as lunar anorthosites. The most extremely positive Eu anomaly (~300 times chondritic) in solar system materials has been reported for mesosiderite clasts (MITTLEFEHLDT *et al.*, 1992). They suggest that the extreme REE ratios in mesosiderites were produced by multiple igneous processes in some asteroids. In order to interpret the observed REE pattern for the inclusions, we did a model calculation which is discussed later.

The Y-794046 inclusion shows higher Mg, Ca and K contents than those of ordinary chondrites. It shows an unfractionated REE pattern with normal absolute lithophile abundances (~1.2 times ordinary chondritic) for H-chondritic material, except for the alkalis. The abundances of K and Rb are ~2 times chondritic. These high alkalis are due to a higher content of albitic plagioclase in the inclusion.

4. Early Igneous Formation and Metamorphism

4.1. Equilibrium solid/solid REE partitioning during the thermal metamorphism

Both Y-75097 and Y-793241 inclusions have distinctly different oxygen isotopic compositions from their hosts. However, they indicate equilibrium partitioning of Fe/Mg in olivines and partial equilibration of Na/Ca in plagioclase with their hosts, and the complete resetting of the K-Ar system. The major and minor element chemical compositions of the inclusions are considered to have been affected by the early thermal metamorphism and/or a late impact event. Hence, the bulk major chemical compositions of the inclusions do not tell us directly the nature of the precursor materials of the inclusions. A question then arises as to whether the remarkable REE fractionations observed for Y-75097 and Y-793241 inclusions were created by an igneous event or by a metamorphic process.

As noted by TORIGOYE *et al.* (1993), V-shaped REE patterns with a positive Eu anomaly have been found for a barred-olivine chondrule of an equilibrated ordinary chondrite (Bjurböle L4), winonaites and for silicate inclusions of IAB irons. They are generally related to metamorphosed materials in chondritic mineral assemblages. Therefore, we did a model calculation for the solid/solid equilibrium by following the mass balance equation given by TORIGOYE *et al.* (1993). Among the constituent minerals of the Y-75097 and Y-793241 inclusions, phosphates are the most important minerals which control the REE partitioning. In addition, apatite/melt partition coefficients for REE vary systematically with changing temperature and melt composition (WATSON and GREEN, 1981). Therefore, the partition coefficients obtained for basic to acidic melts (SiO_2=40–68%) at higher temperatures (900–1120°C) must be applied to the metamorphosed chondritic material with care. Nevertheless, it was demonstrated that REE distributions in L6 chondrites can be interpreted by using normal solid/melt partition coefficients (CURTIS and SCHMITT, 1979). In the following calculations, we tentatively employed a set of apatite/melt partition coefficients obtained at 950°C.

First, we tested an open system equilibrium model: assuming ordinary-chondritic REE abundances and mineral assemblage (except for metal/troilite) and equilibrium partitioning of REE between the minerals in the whole meteorite and an inclusion, the material with the mineral assemblage of the inclusions (75% olivine and 25% plagioclase) is found to have a V-shaped REE pattern (see Fig. 5a). In Fig. 5a, the V-shaped pattern was calculated by using the apatite/melt partition coefficients given by WATSON and GREEN (1981) but is less fractionated than that observed.

Next, we tested a closed system equilibrium model: assuming that the inclusion has ordinary chondritic REE abundances and "troctolitic" mineralogy (+phosphate) and the equilibrium partitioning occurred among minerals within the inclusion, then the REE pattern was calculated for the mineral assemblage of the inclusion mantle. As shown in Fig. 5b, the REE abundances in the mantle decrease and become more fractionated with increasing phosphate content in the bulk inclusion. Our model calculation indicates that the best fit of the calculated to observed REE patterns was obtained for ~5% phosphate, 5% plagioclase and 90% olivine in the bulk inclusion when using partition coefficients of WATSON and GREEN (1981) (see Fig. 5b). The phosphate content estimated here is solely dependent on the partition coefficients of phosphate. The metamorphic temperatures of the inclusions were estimated to be 700°C from the Fe/Mg distributions between olivine-orthopyroxene pairs by SACK and LIPSCHUTZ (1993). Hence, the phosphate REE partition coefficients are considered to be higher at the metamorphic temperature (700°C) than those employed here, which in turn suggests that the phosphate content in the bulk inclusion is even lower than 5%. For example, using the partition coefficients of phosphate/melt given by FUJIMAKI (1986), the phosphate content is estimated to be ~1% in the bulk inclusion. In the same way, employing higher apatite/melt partition coefficients for the open system model, a more highly fractionated V-shaped REE pattern is obtainable. Although both models yield a V-shaped REE pattern similar to those observed for the inclusions, the closed system model (Fig. 5b) can give a better fit to the observed one and thus may be more important.

The results of our calculation imply that the observed V-shaped REE pattern of the inclusion mantles was established by a thermal equilibrium during the early thermal metamorphism within a material with "chondritic" REE abundances but with a troctolitic mineralogy (+phosphates). If this is the case, it follows that, compared with Na/Ca and oxygen, the refractory REE diffused more easily through the inclusion and/or between host and inclusion during the thermal event. Is this possible, considering the diffusivities of these elements? Ca^{2+} and Na^{+} are cations in solid solution in plagioclase. A Na/Ca diffusive exchange reaction may have occurred with charge compensation; thus, the CaAl-NaSi interdiffusion must be accompanied by coupled diffusion of tetrahedral coordinated Al and Si (GROVE *et al.*, 1984).

In order to understand the thermal diffusivities of trivalent rare earths, Na/Ca and oxygen in the inclusions, a simple diffusion calculation was performed. The diffusion coefficients of the cations and oxygen in olivine and plagioclase have been measured only at higher temperatures (>1000°C) (*e.g.*, BUENING and BUSECK, 1973 for Fe-Mg in olivine; GROVE *et al.*, 1984 for CaAl-NaSi in plagioclase; JAOUL *et al.*, 1980 for oxygen). Then the coefficients obtained in the range of 1000–1500°C

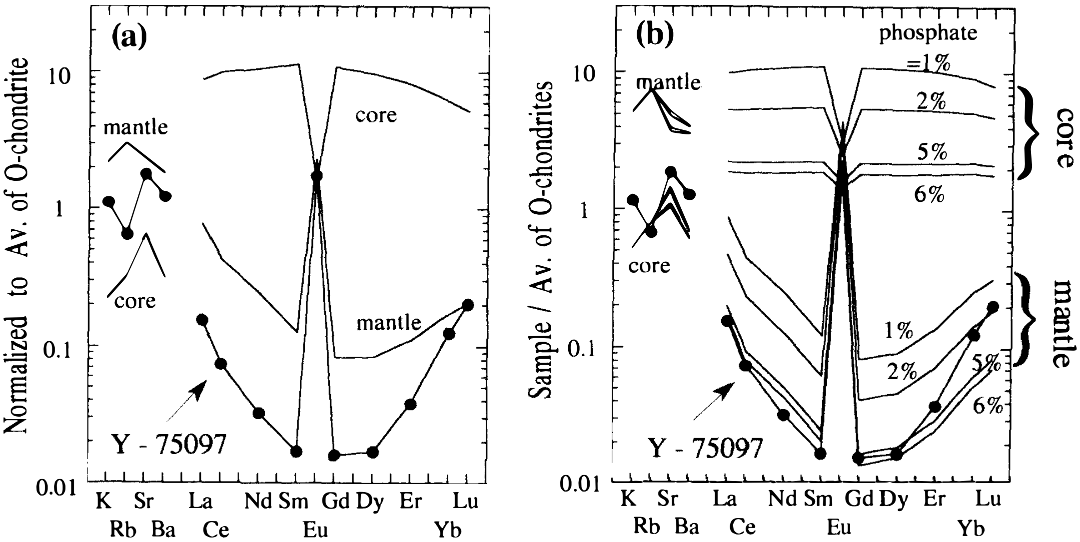

Fig. 5. Calculated REE patterns for the mineral assemblages of the core and mantle of the Y-75097 inclusion, based on solid/solid equilibrium partitioning (TORIGOYE *et al.*, 1993).

(a) Open system equilibrium model: assuming ordinary chondritic REE abundances and mineral assemblage (except for metal/troilite) and equilibrium partitioning of REE between the minerals in the whole meteorite and an inclusion, the REE patterns are calculated for the materials with the mineral assemblage of the mantle (75% olivine and 25% plagioclase) and the core (87% olivine, 3% plagioclase and 10% phosphate).

(b) Closed system equilibrium model: assuming that the inclusion has a troctolitic mineral assemblage with zonal distributions (89–94% olivine, 5% plagioclase and 1–6% phosphate) and the overall elemental abundances of ordinary chondrites and that the constituent minerals were equilibrated within the inclusion, the REE pattern was calculated for the mantle and the core. The closest fit to the observed REE pattern for the mantle was obtained for a bulk composition of 90% olivine, 5% plagioclase and ~5% phosphate. Mass balance requires that the inclusion core has a REE pattern complimentary to that of the mantle.

were extrapolated to 700°C. The estimated coefficients are $\sim 10^{-13}$ cm^{2}s^{-1} for Fe-Mg and $\sim 10^{-22}$ cm^{2}s^{-1} for oxygen in olivine, and $\sim 10^{-27}$ cm^{2}s^{-1} for CaAl-NaSi in plagioclase. Therefore, the diffusion rate of Na/Ca in plagioclase is even slower than that of oxygen in olivine. Using the diffusion coefficients estimated here, the diffusion time required for equilibration of Fe/Mg in 100 μm-cm size olivines is calculated to be 10^3–10^6 years and those of oxygen in olivine and Na/Ca in plagioclase are $\geq$100 m.y. Therefore, it is clear that during the early thermal metamorphism for ~100 m.y. (GÖPEL *et al.*, 1993), the Mg/Fe in olivines easily equilibrated between inclusions and hosts but not for oxygen in olivine and Na/Ca in plagioclase. On the other hand, the presence of shock veins of isotropic glass in the Y-75097 suggests that the inclusion and the host experienced a local melting at peak temperature of >1200°C at 490 Ma which caused almost complete degassing of Ar and perturbation of the Rb-Sr system. Because of the very short duration (< one day) of shock heating at 700–1200°C (KANEOKA *et al.*, 1988), the impact was not strong enough to greatly change the distributions of Na/Ca and Fe/Mg in the inclusion.

Since no diffusion coefficients of REE have been reported for olivine and plagioclase, a direct comparison of diffusivity of trivalent REE with Na/Ca and oxygen may not be possible for these minerals. However, it has been shown that REE in L6 chondrites mostly equilibrated among the constituent minerals (CURTIS and SCHMITT, 1979) and that an equilibrated BO chondrule from Bjurböle (L4) has a V-shaped REE pattern (NAKAMURA *et al.*, 1989) similar to that of the inclusions. Therefore, it is likely that the trivalent REE mostly equilibrated among the constituent minerals of equilibrated (type 6) ordinary chondrites. If the REE abundances in the bulk inclusions prior to the metamorphism were about ordinary-chondritic, mass balance requires that a complimentary REE pattern with higher REE abundances and a negative Eu anomaly is present in the core of the inclusions (87% olivine, 3% plagioclase and 10% phosphate; YANAI *et al.*, 1983), as illustrated in Figs. 5a and 5b.

4.2. *Igneous formation and metamorphic overprinting*

From the above calculation, the bulk mineral composition of the Y-75097 and Y-793241 inclusions is calculated to be 90% olivine, 5–8% plagioclase and $<5\%$ phosphate. The low contents of siderophile/chalcophile elements in the Y-793241 and Y-794046 inclusions (FUKUOKA, 1993) indicate that they are poor in metal/troilite. In addition a large ^{129}Xe excess was observed for the Y-75097 and Y-793241 inclusions (NAGAO, 1993; OTT *et al.*, 1993). Therefore, the igneous event that produced the troctolitic mineralogy occurred when ^{129}I was still alive.

If the inclusions were formed from the ordinary-chondritic material, the metal/silicate separation and solid/melt fractionation of silicate must have occurred during the igneous event. Assuming that the inclusions represent a cumulate or partial melting residue, then a light-REE depleted pattern (La/Sm$=\sim$0.3 times chondritic) could be attained for the bulk inclusions. Although detailed REE distributions in the bulk inclusions have not yet been obtained, we believe that REE abundances in the bulk inclusions were chondritic. If this is the case, it is considered that melting and/or crystallization occurred in a closed system of the silicates; in other words, the removal of silicate melt from solid did not occur during the igneous event. The unfractionated REE pattern of the harzburgitic inclusion Y-794046 also indicates that it formed without solid/liquid fractionation of the silicate, but the silicate melt must have been lost metal/sulfide.

The presence of a relic BO chondrule in the Y-793241 inclusion suggests a close genetic relation between inclusions and BO chondrules (PRINZ *et al.*, 1984). Since the chemical composition of the Y-75097 inclusion (mantle) (YANAI *et al.*, 1983) is well within the range of BO chondrules from UOC's, it may be possible that the inclusion was formed as a "giant BO chondrule". HUTCHISON *et al.* (1988) mentioned that the formation of Y-75097 and Y-793241 "clasts" may be linked to the formation of BO chondrules. The phosphate content (up to 11%) in the inclusion core was considered to be too high for a chondrule (WARREN and

KALLEMEYN, 1989). However, from our model calculation the phosphate content is probably considerably lower than that considered previously. Due to uncertainties of phosphate/melt partition coefficients of REE applicable to the inclusion, a precise estimate is not obtained here. One possibility is that the inclusion is a giant chondrule, in which the precursor had troctolitic major element chemistry and chondritic REE. It solidified in a closed system (probably in space), developing a mineralogical zoning with plagioclase enriched in the mantle and with phosphate enriched in the core, and hence a zoned and complimentary REE pattern. The inclusions were incorporated into an L-chondrite parent body, and then thermal metamorphism served to equilibrate Fe/Mg and REE totally, but played only limited roles for Na/Ca and oxygen.

From the above consideration, it is concluded that the igneous (solid/melt) REE distributions which might have been recorded in the Y-75097 and Y-793241 inclusions were mostly replaced by the metamorphic overprinting. The validity of the closed system equilibrium model envisioned above may be tested by more detailed REE distribution data for the inclusions. Therefore, in future work, it will be important to obtain more systematic REE analyses for samples from the inner to the outer parts of inclusions.

5. Summary

(1) Based on oxygen isotopic compositions, two troctolitic inclusions from the Y-75097 and Y-793241 L6 chondrites and a harzburgitic inclusion from Y-794046 H5 were formed from materials related to H-chondrites.

(2) Both the Y-75097 inclusion and host were severely shocked, but the Y-793241 host and inclusion were not.

(3) Both Y-75097 and Y-793241 inclusions (mantles) are similar in chemical composition and mineral assemblage and have similar REE fractionations, with light-heavy REE enrichment and middle REE depletion and a large positive Eu anomaly.

(4) For both meteorites, the Fe/Mg in olivines have equilibrated between inclusion and host, Na/Ca in plagioclase has partially equilibrated, but oxygen has not.

(5) The harzburgitic inclusion from Y-794046 H5 shows unfractionated REE abundances and is not equilibrated with the host.

(6) The shock age for Y-75097 is defined by the K-Ar age of 500 Ma. The Rb-Sr systems of both host and inclusion were perturbed significantly. The Rb-Sr systems of the Y-793241 host and inclusion were not perturbed, yielding a 4.5 Ga-ALL model age.

(7) The petrographic and isotopic features suggest that Y-75097 and Y-793241 are not paired.

(8) A model calculation of equilibrium solid/solid partitioning indicates that the Y-75097, Y-793241 and Y-794046 inclusions had been formed from a material comprising fractionated precursor with unfractionated REE abundances within a

time span of the half-life of ^{129}I, and that the V-shaped REE pattern of the mantles of the Y-75097 and Y-793241 inclusions was produced during the early igneous formation and thermal metamorphism.

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