REE CHARACTERISTICS OF YAMATO-82162 AND -86720 METEORITES AND THEIR INFERENCE TO CLASSIFICATION

Koshi Yamamoto and Noboru Nakamura

Department of Earth Sciences, Faculty of Science, Kobe University,
1–1, Rokkodai-cho, Nada-ku, Kobe 657

Abstract: Abundances of REE, Ba, Sr, Rb, K, Mg, Ca and Fe were determined for Yamato-82162 and -86720 carbonaceous chondrites by mass spectrometric isotope dilution. The CI-normalized REE abundance patterns for Y-82162 are nearly flat ($0.9-1.5 \times CI$), but show small negative Ce anomalies. A small fraction of the chondrite shows a clear light/heavy REE fractionation. The REE abundance patterns of Y-86720 are also almost flat ($1.4-1.9 \times CI$) and show positive Eu anomalies. The degree of Eu anomaly seems to correlate with the absolute abundance of the REE. For the abundances of elements other than REE, Y-82162 shows enrichments of Fe and Mg and Y-86720 displays depletions of the relatively volatile elements K and Rb.

From these results, the following conclusions are obtained: (1) Y-82162 may contain a high temperature component formed in the nebula. (2) Y-82162 is classified as a CI chondrite which has experienced thermal metamorphism. (3) Y-86720 is composed of a refractory-rich component and a refractory-poor component. (4) Y-86720 cannot be strictly classified into any group but is intermediate between CM and CO chondrites.

1. Introduction

Recently Yanai and Kojima (1987) reported that the meteorites Yamato-82162 (Y-82162) and -86720 (Y-86720) have petrologic features resembling CI chondrites. If these chondrites are classified as CI, they are the first CI chondrites in the large number of meteorites recovered from Antarctica. In order to investigate the detailed petrological, mineralogical, and chemical characteristics, and to classify these meteorites correctly, a research consortium was organized by the Antarctic Meteorite Research Committee of the National Institute of Polar Research (Leader: Y. Ikeda).

CI chondrites are composed primarily of hydrated phyllosilicate matrix and are devoid of chondrules and inclusions. They are commonly brecciated, and matrices from different clasts have slightly different chemical compositions (McSween and Richardson, 1977; McSween, 1979). The CI chondrites have a bulk composition similar to solar elemental abundances, except for the most volatile elements (H, He, N, C, O). They are different from other carbonaceous chondrites in showing no depletion of relatively volatile elements condensing below 1300 K (Anders *et al.*, 1976; McSween, 1979; Wolf *et al.*, 1980; Kallemeyn and Wasson, 1981). CI chondrites also show an oxygen isotopic composition that is different from the other carbonaceous

chondrites. CI chondrites have an isotopic composition which is close to the terrestrial fractionation line in a three isotope plot, while the other C-chondrites are depleted in ^{17}O (*e.g.*, MAYEDA *et al.*, 1987).

Petrologic features (WATANABE *et al.*, 1988; TOMEOKA *et al.*, 1989a), the chemical composition obtained by neutron activation analyses (NAA; KALLEMEYN, 1988), and oxygen isotopic data (MAYEDA *et al.*, 1987) show that Y-82162 belongs to CI chondrites. On the other hand, detailed petrologic studies (TOMEOKA *et al.*, 1989b) suggest that Y-86720 may be classified as CM chondrite, in spite of the CI oxygen isotopic data (CLAYTON and MAYEDA, 1989). Moreover, the chemical composition obtained by NAA (KALLEMEYN, 1988) also indicates that Y-86720 can be weakly grouped into CM chondrites, but it may be intermediate between CI and CM.

In this work, in order to study more detailed chemical characteristics of the lithophile elements, including the REE, and to chemically classify these two meteorites, we performed replicated analyses of both meteorites by isotope dilution mass spectrometry (IDMS).

2. Analytical Method

The sample chips (Y-82162, 92 mg: Y-86720, 105 mg) allocated to us were initially cleaned with 1N-HCl for about 30s in an ultrasonic bath and then washed with twice-distilled water. The samples were finally rinsed with distilled acetone and dried. Then the sample chips were broken down into 5–10 mg-size fragments in an agate mortar.

Abundances of REE, Mg, Ca, K, Rb, Sr, Ca and Fe in 5–35 mg-size fractions were determined by IDMS using a JEOL JMS 05RB mass spectrometer. The chemical
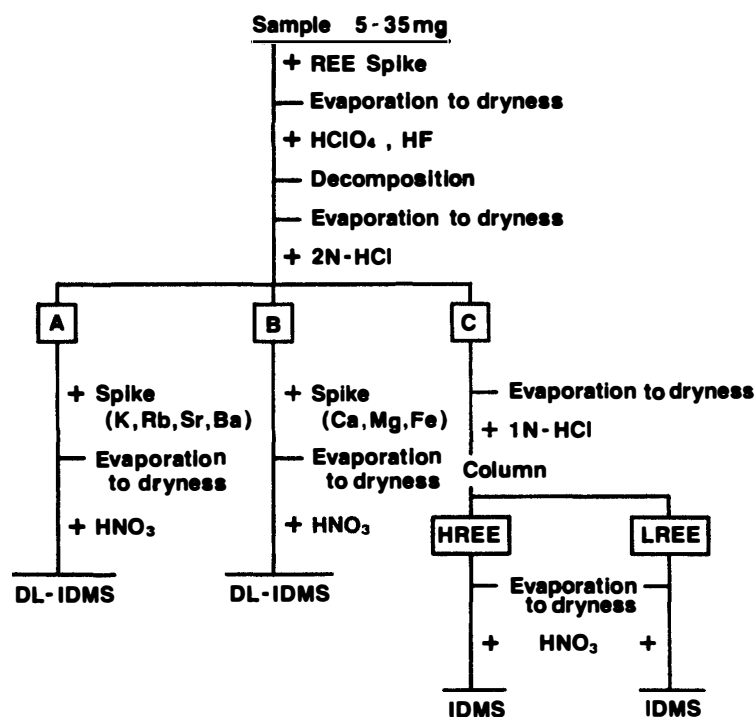

Fig. 1.   Chemical procedures.

procedures are summarized in Fig. 1. Each sample fraction was weighed and then placed into a previously cleaned teflon bomb. A REE composite spike solution was added to it. After most of the solution was evaporated to dryness, 10–60 μl HF and 5–30 μl HClO$_4$ were added. The sealed teflon bomb was heated in an oven for 8 h at 180°C. After the complete decomposition was confirmed with a binocular micro-scope, the samples were evaporated to dryness and then dissolved in about 5 ml of 2N-HCl. The samples were, moreover, split into 3 fractions, one for REE measure-ments, another for Ca, Mg and Fe, and the third for K, Rb, Sr and Ba. Composite spike solutions of K, Rb, Sr and Ba, and of Ca, Mg and Fe were added to the latter two fractions separately to avoid cross contamination by spike solutions. REEs were

Table 1. Procedural blanks. Blanks of REE are given in pg, others in ng.

K	24	La	26.3
Rb	0.038	Ce	29.3
Sr	0.22	Nd	8.3
Ba	2.7	Sm	(2.2)
		Eu	0.78
		Gd	(2.5)
		Dy	(2.5)
		Er	1.5
		Yb	(2.0)
		Lu	0.38

Blank values in parentheses are interpolated from the CI-chondrite normalized values of the neigh-boring elements.

Table 2. Analytical results for Yamato-82162 (concentrations are given in ppm, unless otherwise indicated).

Sample No.	1	2	3	4	Weighted mean	Orgueil[*2]
Weight[*1] (mg)	34.19	5.89	5.87	4.82		
Fe wt%	26.9	23.3	22.1	23.9	25.6	18.51
Mg wt%	13.0	11.7	8.42	11.5	12.2	9.53
Ca wt%	0.97	0.90	1.14	1.07	0.97	0.902
K	588	746	757	700	636	566
Rb	2.56	3.43	3.38	3.24	2.82	2.3
Sr	7.37	8.50	11.08	10.39	8.20	7.8
Ba	2.57	3.14	3.22	3.48	2.80	2.34
La	0.271	0.269	0.341	0.377	0.289	0.253
Ce	0.655	0.660	0.809	0.957	0.701	0.645
Nd	0.492	0.502	0.615	0.747	0.531	0.476
Sm	0.159	0.158	0.203	0.239	0.171	0.154
Eu	0.0618	0.0623	0.0810	0.0932	0.0670	0.0587
Gd	0.217	0.220	0.281	0.328	0.235	0.204
Dy	0.268	0.273	0.407	0.408	0.298	0.252
Er	0.179	0.174	0.274	0.259	0.197	0.166
Yb	0.176	0.176	0.270	0.259	0.195	0.168
Lu	0.0286	0.0272	0.0396	0.0389	0.0307	0.0253

[*1] Sample weight used for analyses.
[*2] Data for REE from NAKAMURA (1974), for other elements from ANDERS and GREVESSE (1989).

Table 3.   Analytical results for Yamato-86720 (concentrations are given in ppm, unless otherwise indicated).

Sample No.	1	2	3	4	
Weight (mg)	32.34	12.34	7.21	6.94	Weighted mean
Fe wt%	25.4	25.6	25.0	24.6	25.3
Mg wt%	13.6	13.4	12.2	13.9	13.4
Ca wt%	1.61	1.79	1.36	1.26	1.57
K	396	431	494	539	432
Rb	1.70	1.83	2.04	2.09	1.82
Sr	11.2	14.0	11.3	11.1	11.8
Ba	3.58	3.93	4.23	3.90	3.77
La	0.345	0.425	0.408	0.321	0.366
Ce	0.908	1.06	1.03	0.814	0.943
Nd	0.689	0.808	0.788	0.611	0.717
Sm	0.227	0.263	0.255	0.197	0.234
Eu	0.0948	0.105	0.101	0.0890	0.0970
Gd	0.304	0.358	0.338	0.265	0.315
Dy	0.381	0.457	0.419	0.340	0.397
Er	0.248	0.295	0.271	0.217	0.257
Yb	0.260		0.273	0.225	0.257
Lu	0.0389	0.0471	0.0455	0.0346	0.0409

analyzed by conventional IDMS (NAKAMURA, 1974) through column chemistry (Dowex AG 50W-X12, 200–400 mesh), and the other elements by direct loading IDMS (NAKAMURA et al., 1989). Total procedural blanks are shown in Table 1 and the analytical results corrected for blanks for Y-82162 and Y-86720 are given in Tables 2 and 3, respectively. Analytical errors for REE, Ca, Mg and Fe are less than 2%, and those for the other elements, except for Ba, less than 5%. Since the Ba contribution from the blank is about 3–20%, the accuracy for Ba is worse and the error is considered to be less than 10%.

3.   Results and Discussion

3.1.   Y-82162

Analytical data for Y-82162 are given in Table 2 and elemental abundances relative to the Orgueil CI chondrite (NAKAMURA, 1974; ANDERS and GREVESSE, 1989) are shown in Fig. 2. As shown in Fig. 2, four different parts of this chondrite have elemental abundances of about $0.9-1.5 \times CI$. Thus this chondrite seems to be very heterogeneous in the several-milligram size. Since this meteorite is composed mainly of clasts of millimeter to sub-millimeter size (WATANABE et al., 1988; TOMEOKA et al., 1989a), the chemical heterogeneity may result from different chemical compositions of clasts. The REE abundance patterns, except for that of the 5.87 mg fraction, are almost flat, but have small Ce anomalies ($-2.2 \sim -4.1\%$). Since the degree of Ce anomalies is greater than the uncertainty of REE measurement, this anomaly seems to be real. Positive or negative Ce anomalies have been reported in eucrites (NAKAMURA and MASUDA, 1980; SHIMIZU and MASUDA, 1982) and in H5 chondrites (EBIHARA,
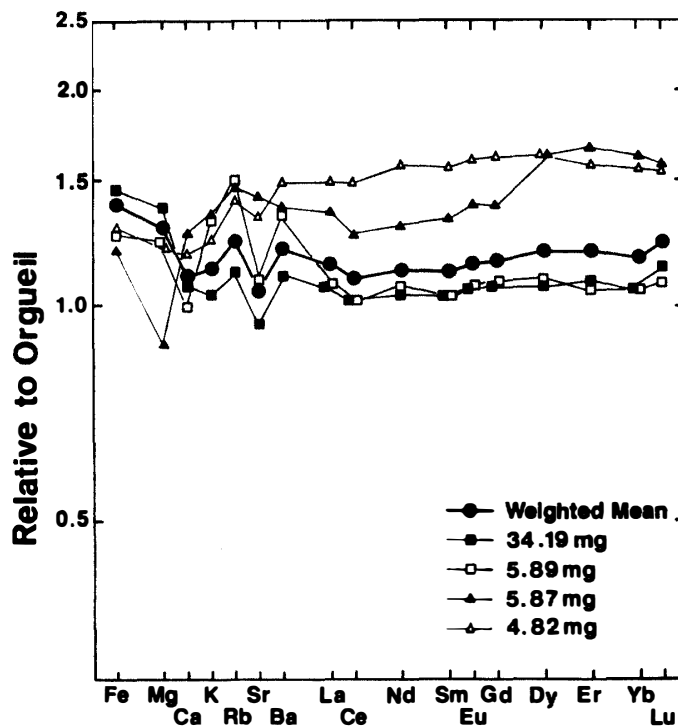
Fig. 2. Abundance patterns for different portions of Y-82162. Abundances are normalized to the Orgueil CI chondrite (NAKAMURA, 1974; ANDERS and GREVESSE, 1989).

1984) from Antarctica. Since Ce has a lower solubility than the other REEs, it is expected to behave separately from other REEs in aqueous conditions. Therefore, it may be possible that the Ce anomalies observed in Antarctic meteorites have been produced by aqueous alteration, probably due to terrestrial weathering in Antarctica (NAKAMURA and MASUDA, 1980; SHIMIZU and MASUDA, 1982). If Y-82162 has also suffered REE removal or addition during aqueous alteration in Antarctica, the abundances of more mobile elements than the REEs, such as the alkalis, should have been affected. However, the abundances of K and Rb are at the CI level (Fig. 2), suggesting that the Ce anomalies in Y-82162 may not have been produced by weathering in Antarctica. The possible explanation for the Ce anomaly is mentioned later.

For the abundances of elements other than REEs, this chondrite shows an enrichment of Mg and Fe compared with CI abundances (Fig. 2). The enrichment of the major elements Mg and Fe, is compatible with the results of TOMEOKA et al. (1989a), suggesting that volatile components such as H_2O and C had been lost during thermal metamorphism (TOMEOKA et al., 1989a).

The 5.87 mg fraction is more depleted in Mg and enriched in Ca and Sr than samples of the other fractions, and has a fractionated REE pattern. The HREEs are more abundant by about 20% than the LREEs. If the LREE/HREE fractionation was caused by aqueous alteration on the meteorite parent body, secondary hydrogenous minerals such as carbonate, sulfate and phosphate should be present. This chondrite, however, does not contain sulfate veins (TOMEOKA et al., 1989a), even though they are usually observed in non-Antarctic CI chondrites. The presence of

carbonates and phosphates may explain the enrichment of Ca and Sr. However, the REE partition coefficients of carbonates in a terrestrial marine environment (ELDER-FIELD *et al.*, 1981) and of phosphates in dacites and granites (NAGASAWA, 1970) cannot explain the LREE/HREE fractionation. Aqueous alteration in meteorites also leads to the conversion of matrix minerals into phyllosilicates. The LREE/HREE frac-tionation, as observed in the 5.87 mg sample, has not been found in terrestrial clay minerals. Terrestrial clay minerals such as montmorillonite are usually enriched in LREE relative to HREE when normalized to chondrite (*e.g.*, PIPER, 1974). It is con-sidered that the aqueous alteration on the parent body also cannot produce the HREE-enriched fractionation, although the redox and pH conditions are not clear.

The second possible explanation for the fractionation is a redistribution during a thermal event. TOMEOKA *et al.* (1989a) reported that the phyllosilicates were partially dehydrated and transformed to olivines by thermal metamorphism. Therefore, the elements should be distributed in the minerals depending on their partition coefficients. Except for Eu, almost all minerals show a smooth variation of the REE partition coef-ficients versus atomic number (*e.g.*, FUJIMAKI *et al.*, 1984), which do not explain the fractionation in the 5.87 mg fraction.

Light/heavy REE fractionations are observed in some of Ca, Al-rich inclusions (CAI's; PALME *et al.*, 1982) and isolated olivine grains (STEELE, 1986; PALME *et al.*, 1987). PALME *et al.* (1987) showed that the refractory element enrichment in isolated olivines is related to Ca, Al and Ti-rich phases. The relative enrichment of Ca and the HREE/LREE fractionation in the 5.87 mg fraction may suggest that this chondrite contains high temperature components. The possible existence of high temperature components in CI chondrites has already been suggested by NAKAMURA (1974) and BEER *et al.* (1984). REID *et al.* (1970) also reported fresh angular clasts of olivine in the Orgueil CI chondrite, showing no reaction with the surrounding matrix, which is also suggestive of high temperature components.

BOYNTON (1975) indicated that some high temperature condensates (at 10^{-3} atm) show the LREE/HREE fractionation with a large negative Yb anomaly, which is not observed in the 5.87 mg fraction. Under oxidized conditions, *e.g.* the outer shell of a supernova, Yb becomes more refractory as Lu and the first condensate does not show an Yb negative anomaly (BOYNTON, 1978; BOYNTON and CUNNINGHAM, 1981; NAGA-SAWA, 1979) but a large negative Ce anomaly. The formed high temperature con-densate under oxidizing conditions (BOYNTON, 1978; BOYNTON and CUNNINGHAM, 1981) shows HREE/LREE fractionation of two orders of magnitude with a HREE enrichment. Y-82162 shows a HREE enrichment of about 20% relative to LREE and the degree of fractionation is much smaller. This suggests that the high temper-ature component in Y-82162 is largley diluted by matrix (non-fractionated) materials and the degrees of the HREE/LREE fractionation and the Ce anomaly of the high temperature component are obscured as a result of dilution. Therefore, Y-82162 may contain small amounts of a high temperature component with a LREE/HREE fractiona-tion that formed by gas/solid reactions under modestly oxidizing conditions.

3.2. Y-86720

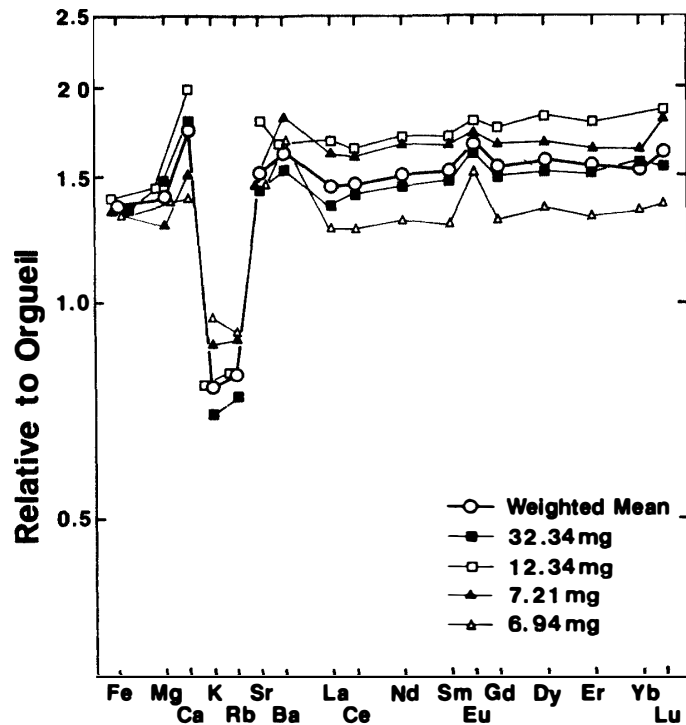Analytical results for Y-86720 are shown in Table 3 and Fig. 3, respectively. This

Fig. 3.   CI-normalized abundance patterns for different portions of Y-86720.

chondrite has elemental abundances of about $1.4–1.9 \times CI$, except for K and Rb with $0.7–0.9 \times CI$.   The depletion of moderately volatile lithophiles is well known in carbonaceous chondrites other than CI.   The REE abundance pattern of each fraction shows weak fractionation among the REEs (slight enrichment of heavier REE) and a clear Eu positive anomaly.   The degree of Eu anomaly seems to correlate with the absolute abundance levels of other REEs.

A plausible explanation for the correlation may be the mixing of two-components which are formed in nebula.   One component has low REE abundances with a large Eu anomaly, the other has high REE abundances with no or a small Eu anomaly.   It is reasonable to assume that the lower temperature component has higher abundance of Eu and low concentrations of the other REEs.   The larger positive Eu anomalies in fractions with lower REE abundances are consistent with the two-component mixing model.   High temperature components, such as inclusions and chondrules, generally have high REE abundances ($2–5 \times CI$) and negative Eu anomalies (MISAWA and NAKAMURA, 1988), thus the lower REE abundances with the large positive Eu anomaly in this meteorite may correspond to a refractory-poor component (*e.g.* matrix).

In Fig. 4, data of Y-86720 are plotted on the Sr/Mg-Eu/Mg and Ba/Mg-Sm/Mg diagrams.   As seen in Fig. 4, both Y-86720 and Y-82162 show a positive correlation between Sr/Mg and Eu/Mg, and between Ba/Mg and Sm/Mg ratios.   All these elements (Sr, Eu, Ba, and Sm) are refractory in nebular processes and expected to behave similarly at high temperatures, *e.g.* ~ 1300 K at 10^{-3} atm (KORNACKI and FEGLEY, 1986).   Therefore, the positive correlation in Fig. 4 can be explained as due to nebula processes.

On the contrary, this chondrite also underwent thermal metamorphism under re-
ducing conditions (Tomeoka *et al.*, 1989b).   Eu anomalies in Fig. 3 and the correla-
tion between Eu and Sr in Fig. 4 can be produced by thermal metamorphism under
reducing conditions, especially in the presence of plagioclase.   The correlations be-
tween Ba and Sm in Fig. 4 may also be produced by thermal metamorphism, since Ba
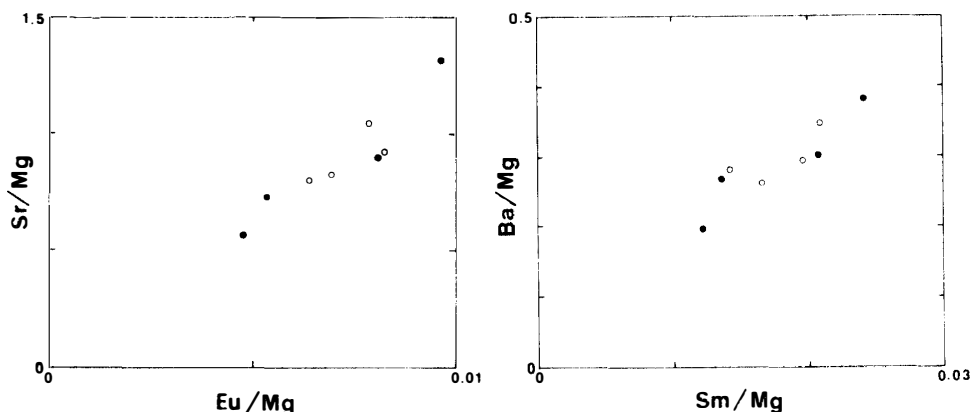and Sm are incompatible elements.

*Fig. 4.   Plots of Sr/Mg vs. Eu/Mg and Ba/Mg vs. Sm/Mg for Y-86720 (open circles) and Y-82162
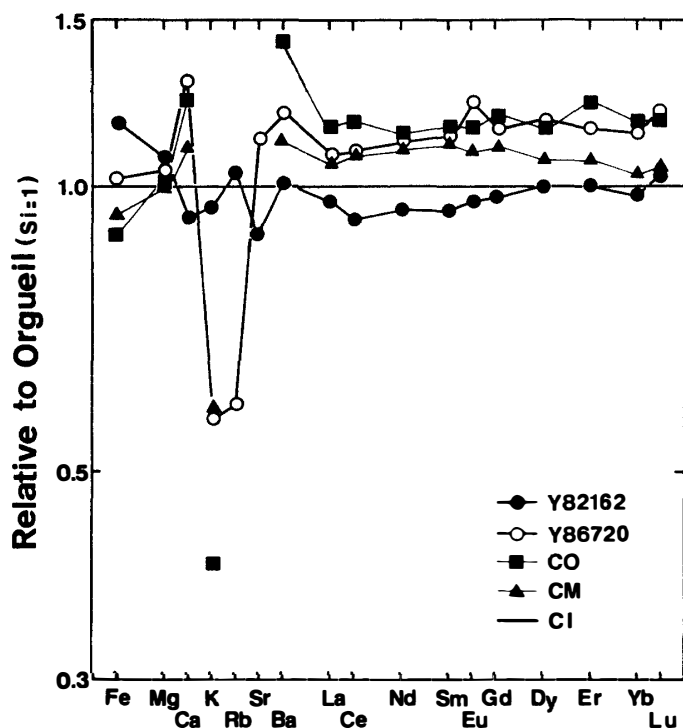(closed circles).*

*Fig. 5.   Plots of mean elemental abundances for Y-82162, Y-86720, CI, CM and CO chondrites.
Abundances are normalized to the Orgueil CI chondrite and then further normalized to
Si=1.0.   The SiO$_2$ contents of Y-82162 and Y-86720 are taken from Tomeoka et al.
(1989a, b), respectively. Data sources for CI, CM and CO chondrites are Nakamura
(1974, 1975), Evensen et al. (1978), Knab (1981) and Mason (1971).*

From the above discussion, both metamorphic and nebula (two-component mixing) models may explain the trace element chemistry of the Y-86720 chondrite. However the presence of plagioclase in Y-86720 has not been reported. Moreover, TOMEOKA et al. (1989b) reported that the thermal metamorphism is mild and the temperature is estimated to be about or over 500°C. Therefore, the nebula model seems to be favored for the explanation of the chemical features of Y-86720.

3.3. Classification

The mean values of elemental abundances for CI, CM and CO group chondrites relative to the Orgueil CI chondrite (Si= 1.0) are shown in Fig. 5 together with the weighted mean for Y-82162 and Y-86720. In this figure, data points of Y-82162 are plotted along the CI line except for lower abundances of some elements. It is possible to classify this chondrite as a CI chondrite, but the chemical compositions are more or less affected by thermal effects. Whereas Y-86720 plots intermediate between CM and CO. The abundances of LREE and K show good agreement with CM chondrites, while the HREEs and Ca agree with CO chondrites. Therefore, it is not possible to strictly classify this chondrite into the CM or CO group. If type 3 chondrites were the most primitive, and CI and CM chondrites were formed by hydrothermal alteration of type 3 C-chondrites (McSWEEN, 1979), Y-86720 may be an intermediate product formed by alteration of type 3 C-chondrites, although this model does not seem to be consistent with oxygen isotopic compositions of the meteorite.

Acknowledgments

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