REE, Ba, Sr AND Rb ABUNDANCES IN SOME UNIQUE ANTARCTIC ACHONDRITES

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Abstract: Rare-earth elements (REE), Ba, Sr and Rb were determined for an Antarctic mesosiderite and seven Antarctic achondrites including some unique ones. The meteorite samples analyzed are Y-74450 (eucrite), Y-75032 (diogenite), ALH-77256 (diogenite), ALH-78113 (aubrite), Y-74123 (ureilite), ALH-77257 (ureilite), ALH-77005 (unique) and ALH-77219 (mesosiderite).

A positive Ce anomaly (18%) is observed for Y-74450 eucrite. REE contents of Y-75032 and ALH-77256 diogenites are higher than those of Yamato recrystallized diogenites analyzed thus far. Particularly, in REE pattern of Y-75032 which is considered as intermediate between diogenites and eucrites, Leedey chondrite-normalized values are 1.8–2.7. Two ureilites, Y-74123 and ALH-77257, show curved REE patterns similar to those of diogenites and inclinations of light REE slopes of these ureilites are more gentle than those observed in Kenna, Goalpara and Novo Urei ureilites. REE patterns of ALH-77219 mesosiderite and ALH-78113 aubrite are composed of some rectilinear lines, having some deviated points, respectively.

Unique achondrite ALH-77005 shows an S-shaped REE pattern having positive Ce irregularity. The pattern of REE concentration ratios between ALH-77005 and Nakhla suggests a genetically intimate relationship between those two meteorites, indicative of coexisting solid-and-liquid relation.

1. Introduction

Since the studies by SCHMITT *et al.* (1963, 1964), knowledge of rare-earth element (REE) abundances in meteorites has provided cosmochemical information of their genesis. As for the Antarctic meteorites, MASUDA *et al.* (1977, 1979), MASUDA and TANAKA (1978), SHIMIZU *et al.* (1979) and NAKAMURA and MASUDA (1980) have investigated REE abundance patterns in seven chondrites and in six achondrites (five diogenites and one eucrite). The mineralogical and chemical studies by TAKEDA *et al.* (1979b, 1980) revealed some unique achondrite. In this study, we determined REE, Ba, Sr and Rb abundances of an Antarctic mesosiderite and seven Antarctic achondrites including some unique ones, some of which have been studied by TAKEDA *et al.* (1979b, 1980).

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2. Samples and Analytical Procedures

The samples analyzed are Yamato-74450 (eucrite), Yamato-75032 (diogenite), Allan Hills-77256 (diogenite), Allan Hills-78113 (aubrite), Yamato-74123 (ureilite), Allan Hills-77257 (ureilite), Allan Hills-77005 (unique) and Allan Hills-77219 (mesosiderite).

Y-74450 appears to be monomict breccia and is a rapidly cooled eucrite with pyroxene phenocrysts (TAKEDA *et al.*, 1979b). Y-75032 is a unique diogenite because it contains both inverted low-Ca pigeonite and primary orthopyroxene (TAKEDA and MIYAMOTO, 1977; TAKEDA *et al.*, 1979a, b). Therefore, TAKEDA *et al.* considered this meteorite as intermediate between diogenites and eucrites. TAKEDA *et al.* (1979b, 1980) have described that ALH-77256 is the only monomict diogenite found in Antarctica and it has a common texture of diogenites but is different from common Yamato diogenites in recrystallized granoblastic texture. According to MASON (1981), ALH-78113 is aubrite and ALH-77219 is mesosiderite. Descriptions of two ureilites Y-74123 and ALH-77257 have been given in TAKEDA *et al.* (1979b, 1980). ALH-77005 is a unique achondrite, being composed of olivine, pyroxene, maskelinite and opaques (TAKEDA *et al.*, 1979b). MCSWEEN *et al.* (1979a, b) suggested that this meteorite was related to shergottite. Chemical, mineralogical and petrological studies of this meteorite have been carried out by several authors (MCSWEEN *et al.*, 1979a, b; ISHII *et al.*, 1979; TAKEDA *et al.*, 1979b; WOODEN *et al.*, 1979; MA *et al.*, 1980).

REE, Ba, Sr and Rb abundances were determined by the mass-spectrometric stable isotope dilution method. The effect of impurity corrections for REE analyses due to reagents used was almost negligible except the case of ureilite, where blank contributions were 20–70% in the light REE and 2–5% in the heavy REE. Blank effects for Rb, Sr and Ba analyses were 20–40% in such samples as ureilites with lower contents of these elements. In some cases, the precisions of analyses were over 5% because of inadequate ratios between sample amounts and spike amounts added. Analyses of heavy REE in Y-75032 and ALH-77256 diogenites and Eu in Y-74123 and ALH-77257 ureilites correspond to such cases. However, the precisions of analysis are believed to be below 1% in most cases except the cases aforementioned.

3. Results and Discussion

REE, Ba, Sr and Rb abundances for eight Antarctic meteorites are tabulated in Table 1 and chondrite-normalized REE-Ba-Sr-Rb patterns are displayed in Figs. 1, 3 and 4.

3.1. Y-74450 (eucrite)

This REE pattern is characterized by a positive Ce anomaly (about 18%). Recently, it has been disclosed that the following achondrites showed Ce anomalies: Y-74136 diogenite (+17%), Y-74037 diogenite (+14%), ALH-765 eucrite (+50%) and

Table 1. Abundances (ppm) of REE, Ba, Sr and Rb in Antarctic achondrites*

	Y-74450 eucrite	Y-75032 diogenite	ALH-77256 diogenite	Y-74123 ureilite	ALH-77257 ureilite	ALH-78113 aubrite	ALH-77219 mesosiderite	ALH-77005 unique	Normalizing value
La	3.59	0.713	0.196	0.0156	0.0225	0.231	0.334	0.1812	0.378**
Ce	11.25	1.83	0.447	0.0223	0.0401	0.632	0.871	0.758	0.976**
Nd	7.43	1.35	0.286	0.0123	0.0196	0.429	0.669	0.399	0.716**
Sm	2.40	0.488	0.101	0.00433	0.00560	0.1308	0.223	0.226	0.230**
Eu	0.708	0.116	0.0296	0.000743	0.00105	0.0263	0.1051	0.1187	0.0866**
Gd	3.26	0.723	0.169	0.0108	0.0105	0.1812	0.315	0.440	0.311**
Dy	3.82	0.929	0.249	0.0254	0.0248	0.216	0.381	0.569	0.390**
Er	2.37	0.630	0.195	0.0261	0.0279	0.1357	0.255	0.336	0.255**
Yb	2.30	0.633	0.232	0.0394	0.0455	0.1485	0.261	0.315	0.249**
Lu	0.341	0.106	0.0375	0.00753	0.00870	0.0215	0.0404	0.0461	0.0387**
Ba	44.6	6.73	4.11	0.506	0.783	1.177	4.04	3.45	4.21**
Sr	78.5	12.2	3.26	0.199	0.266	2.38	15.88	8.06	11.1†
Rb	0.362	0.124	—	0.0588	0.0500	0.667	0.0813	0.633	4.21††

* No blank corrections (see text), ** Leedey chondrite by MASUDA *et al.* (1973), † GOPALAN and WETHERILL (1971), †† GOLES (1971).

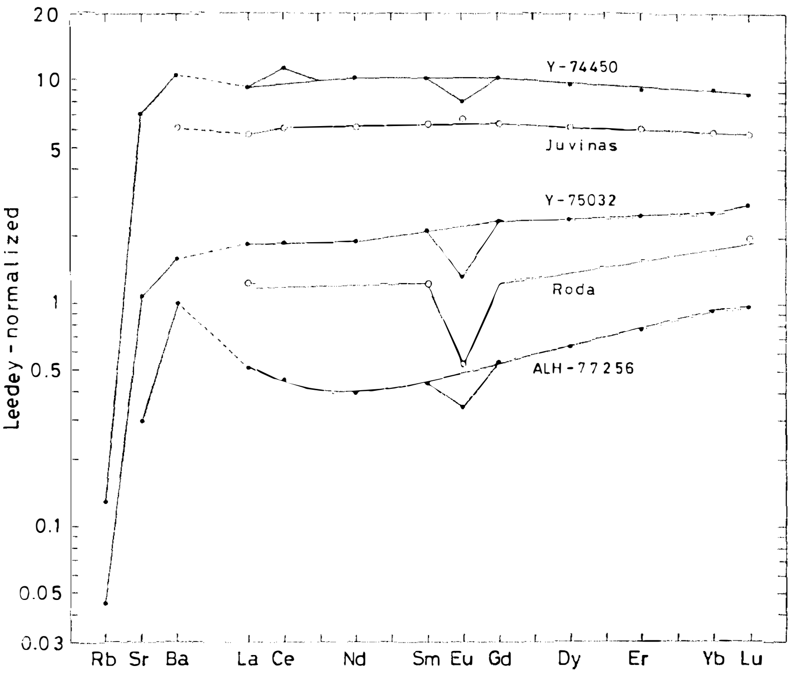

Fig. 1. Chondrite-normalized REE-Ba-Sr-Rb patterns of eucrites (Y-74450 and Juvinas) and diogenites (Y-75032, ALH-77256 and Roda). Data for Juvinas and Roda are from NAKAMURA and MASUDA (1980) and FUKUOKA et al. (1977), respectively.

Melrose-b howardite (−51%) (MASUDA *et al.*, 1979; NAKAMURA and MASUDA, 1980; MASUDA and TANAKA, 1980). The problem of Ce anomaly observed in achondrites as well as that in chondrites is understood to be related with oxygen fugacity distribution in the solar system. As stated by MASUDA and TANAKA (1980), it is considered that less reducing parts or stages existed heterogeneously in solar nebula and specific Ce fractionation took place in these parts or stages, judging from the fact that Ce anomaly is not necessarily rare as stated before. On the other hand, BOYNTON (1978) noted that Ce anomaly observed for Allende inclusions could be raised in the outer zones of supernova with oxidizing gas composition. Anyway, further study will be needed to clarify the processes of causing the Ce anomaly. It is added that Y-74450 eucrite shows a negative Eu anomaly, whereas ALH-765 eucrite shows a positive Eu anomaly. (As stated above, these two eucrites show positive Ce anomalies.)

REE pattern (excepting Ce and Eu) of Y-74450 is very similar to that of Juvinas eucrite determined by NAKAMURA and MASUDA (1980), although Y-74450 has relatively higher abundances of REE. REE patterns of Y-74450 and Juvinas display the flatness for middle REE span with rectilinear inclined lines for the light REE and heavy REE spans. These features of gross patterns and elevated concentration level compared with chondrites may be explained by separation of orthopyroxene component from chondritic liquid (MASUDA, 1968; SCHNETZLER and PHILPOTTS, 1969).

For the REE-Ba-Sr-Rb pattern of Y-74450, it is a remarkable feature that Rb has a very low normalized value compared with the corresponding values of REE, Ba and Sr. In general, the reported Rb content is low for eucrites including cumulate ones. (Rb contents compiled by GOLES (1971) are 0.0497–0.707 ppm for eucrites.) The Rb/Nd concentration ratio in eucrite is lower than that in chondrite by a factor of about 1/100. It is difficult to account for this Rb depletion by the orthopyroxene separation from the chondritic initial melt. The Rb content in materials responsible for formation of eucrite may have been low, compared with that in chondritic materials.

3.2. Y-75032 and ALH-77256 (diogenites)

REE contents of Y-75032 and ALH-77256 diogenites are higher than those of Yamato recrystallized diogenites analyzed thus far (MASUDA *et al.*, 1979). Particularly, Y-75032 has significantly high REE contents and the Leedey-normalized values are 1.8–2.7. (The corresponding values for Yamato recrystallized diogenites are 0.04–0.4.) Further, REE pattern of Y-75032 is quite different in gross features from other Antarctic diogenites, and markedly gentle compared with them. These peculiar REE features of Y-75032 may correlate with its mineralogical features intermediate between diogenites and eucrites. Roda (FUKUOKA *et al.*, 1977) has similar REE contents and pattern to those of Y-75032. Fig. 2 is a plot of abundance of Sm versus normalized value ratios between Lu and Sm. This figure shows that a slope for the Sm-Lu span of REE pattern tends to become greater with lowering of Sm

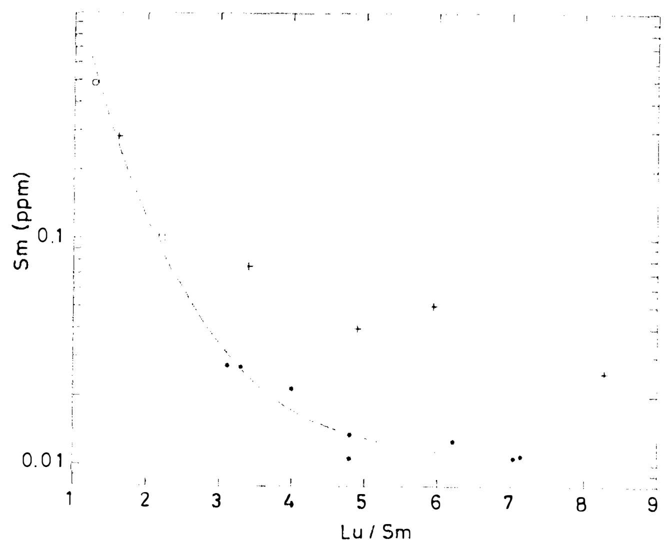

Fig. 2. A plot of Sm abundance versus normalized value ratio between Lu and Sm for diogenites including separated fractions from diogenites. Open circle is Y-75032. Open square is ALH-77256. Solid circles are Yamato recrystallized diogenites by MASUDA and TANAKA (1978) and MASUDA et al. (1979). Crosses are Roda, Johnstown and Ibbenbühren by FUKUOKA et al. (1977).

abundance. It should be noted that diogenites (crosses) other than Antarctic ones appear not to take a general trend of Antarctic diogenites (solid circles, open square and open circle).

3.3. Y-74123 and ALH-77257 (ureilites)

REE patterns of these ureilites show curved patterns having the minimum position between Nd and Sm, with the exception of Eu, and having maximum at Lu. The REE curve for the ureilites appears to be (upward) concave for light REE segment and to be (upward) convex for heavy REE segment. Although fine structures in the light REE segment are ambiguous in some aspects because of larger effects from blanks due to reagents used, it is certain that inclinations of light REE slopes of Y-74123 and ALH-77257 are more gentle than those of Kenna, Goalpara and Novo Urei ureilites reported by BOYNTON *et al.* (1976). Therefore, REE patterns of Y-74123 and ALH-77257 are not typical V-shaped ones and are rather similar to those observed for diogenites. Besides, the data presented by BOYNTON *et al.* (1976) do not show clearly recognizable Eu anomalies.

3.4. ALH-77219 (mesosiderite) and ALH-78113 (aubrite)

ALH-77219 has a rather unfractionated REE pattern with a positive Eu anomaly and its REE abundances are close in absolute magnitude to those in Leedey chondrite throughout the span from La to Lu. REE pattern of ALH-77219 appears to be com-

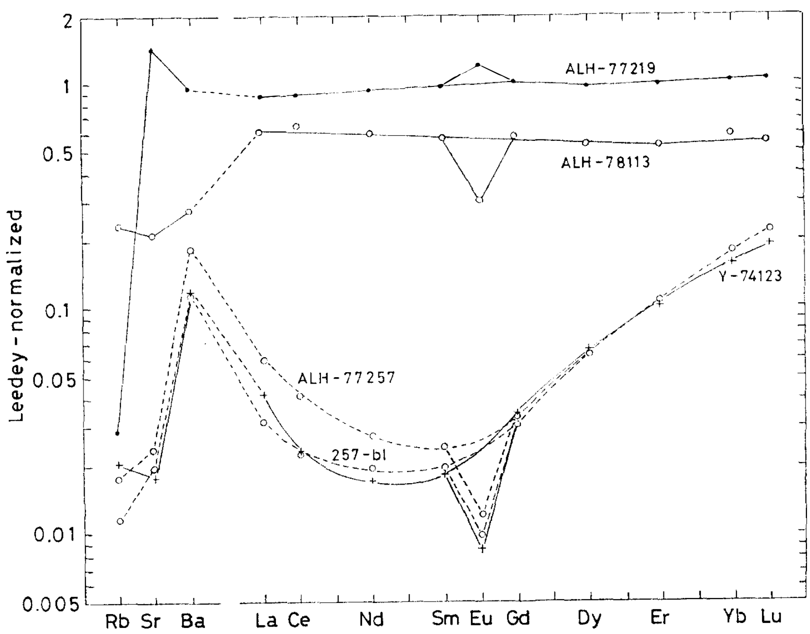

Fig. 3. Chondrite-normalized REE-Ba-Sr-Rb patterns of ALH-77219 (mesosiderite), ALH-78113 (aubrite), ALH-77257 (ureilite) and Y-74123 (ureilite). The pattern of "257-bl" is a plot corrected for blank for ALH-77257. Y-74123 pattern is drawn without blank correction. In analyses of REE, Ba, Sr and Rb for the Y-74123, however, effects of blank contribution are similar to those for ALH-77257.

posed of three rectilinear lines having small inflections at Gd and Dy. A normalized value of Rb in ALH-77219 is very small.

REE pattern of ALH-78113 aubrite shows that points for La, Nd, Sm, Dy and Er lie on a single line within the deviation of 1%, and that points for Ce, Eu and Gd deviate from the La-Nd-Sm-Dy-Er line. Extents of deviations are +7, −43 and +4% for Ce, Eu and Gd, respectively. Further, a point of Yb for this ALH-78113 deviates from a Er-Lu line; the extent of deviation is +9%. It draws our attention that REE pattern of this aubrite has no features expected for enstatite. REE partitioning for the enstatite in this aubrite may not have been a typical one but a relatively unfractionated one. Alternatively, other minerals, whose REE partitioning is unfractionated, may have crystallized first and these minerals may have been transformed into enstatite without REE pattern change. Here, our attention is turned to features in Rb-Sr-Ba pattern of ALH-78113 aubrite. They are different from those of other Antarctic achondrites analyzed in this study. That is, in ALH-78113, the normalized values of Rb, Sr and Ba are relatively similar to each other, whereas in other achondrites of this study, the value for a certain element (Rb in most cases) is considerably distinct from those for the other two elements.

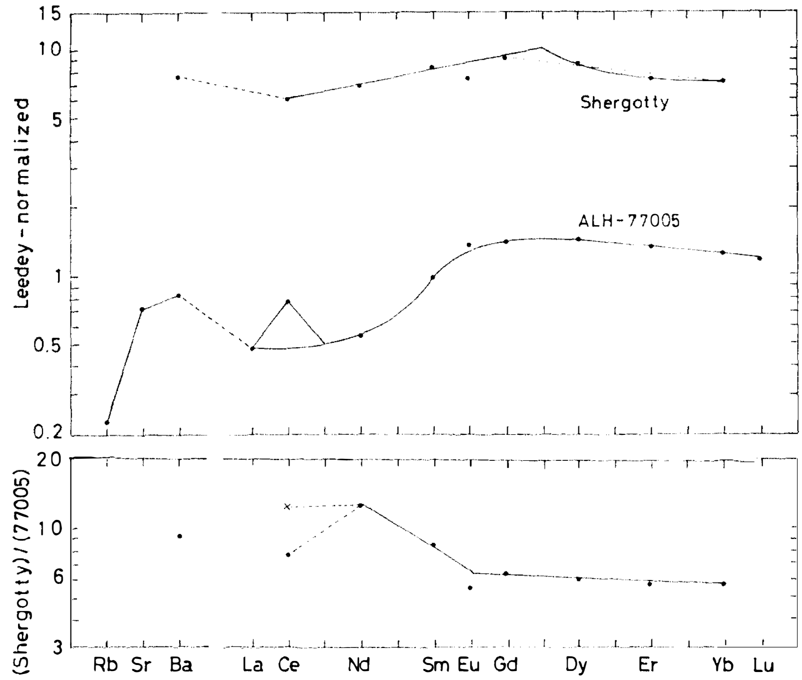

Fig. 4. Chondrite-normalized REE-Ba-Sr-Rb patterns of ALH-77005 (this study) and Shergotty (SCHNETZLER and PHILPOTTS, 1969), with REE and Ba concentration ratio pattern between those two metorites. The point marked by cross shows a ratio between Ce value observed for Shergotty and Ce value interpolated from La and Nd values in ALH-77005 pattern.

3.5. *ALH-77005 (unique)*

ALH-77005 displays an S-shaped REE pattern and a positive Ce anomaly (60%) is observed (Fig. 4). In Fig. 4, REE pattern of Shergotty by SCHNETZLER and PHILPOTTS (1969) is also shown. Both of these patterns have a maximum position at middle REE. The pattern of REE abundance ratios between Shergotty and ALH-77005 is also presented in Fig. 4. This relation of REE concentration ratios between these two meteorites may provide us with a clue to understanding some genetic relationship between them. (MCSWEEN *et al.* (1979a, b) indicated a genetical relationship between the two meteorites.)

REE pattern of ALH-77005 can be hardly formed directly from horizontal REE patterns as far as peculiar complicated REE partition coefficient pattern is not considered. We assume rectilinear REE pattern having an inflection point at Tb as a REE pattern "A" in Fig. 5a. REE concentration ratio between ALH-77005 and the REE pattern "A" in Fig. 5a is terrace-shaped with inflection points at Nd and Tb (Fig. 5b) and some features of this terrace-shaped pattern in Fig. 5b resemble those of partition coefficient pattern "B-3" obtained experimentally by MASUDA *et al.* (1977); that is, the patterns are terrace-shaped with inflection points at Nd and Tb. One of the

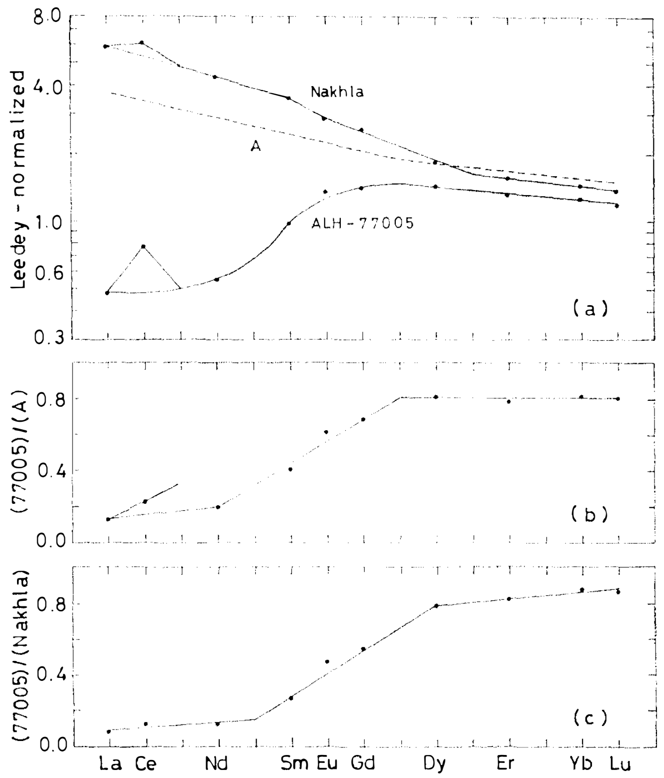

Fig. 5. Chondrite-normalized REE patterns of Nakhla (NAKAMURA and MASUDA, 1973), ALH-77005 (this study) and "A" (assumed pattern in this study), with REE concentration ratio patterns among them.

possible interpretations for the REE pattern of ALH-77005 is that ALH-77005 was produced as a solid phase separated from a source material having REE pattern like "A" in Fig. 5a under the operation of the partition coefficient pattern shown in Fig. 5b. REE pattern of Nakhla (NAKAMURA and MASUDA, 1973) is rather similar to that of "A" in Fig. 5a. Particularly, both patterns resemble each other in the slope of light and heavy REE lines. Further, Nakhla shows a positive Ce anomaly. Fig. 5c shows REE concentration ratios between ALH-77005 and Nakhla. This relation may suggest a genetically intimate relationship between these two meteorites, indicative of coexisting solid-and-liquid relation. (STOLPER *et al.* (1979) have suggested that the basaltic achondrite, shergottite and nakhla-chassignite source peridotites may have been related.)

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