REE ABUNDANCES AND Rb-Sr GEOCHRONOLOGY OF YAMATO-791197

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Abstract: The REE abundances and the Sr isotopic compositions were determined for the separated samples and the clast sample of the "lunar meteorite", Yamato-791197. Most of the features of the REE patterns are similar to those of the lunar highland samples, especially a kind of anorthosites. And the positive Ce-anomalies, shown in all REE patterns, appear characteristic of the lunar origin. The age obtained from the Rb-Sr system is 3.89 ± 0.36 b.y. and it is considered that this age shows the time when these materials underwent an event, such as brecciation or impact melting. However, as a noticeable point, the initial $^{87}Sr/^{86}Sr$ is significantly low, even lower than BABI or LUNI. This result suggests that the source material of these samples might have had very low $^{87}Sr/^{86}Sr$ and Rb/Sr abundance ratios. The clast sample from the chip subordinate No. 109 has the distinct REE pattern and Sr-isotope ratio. Therefore, this clast can be considered to have been formed by different evolution process from the other samples, and was mingled later with them.

1. Introduction

Since 1969, more than thousands of meteorites have been recovered from the Antarctic. Of these "Antarctic meteorites", some meteorites have been recognized to belong to the rare or unique types. Among such unique type meteorites, Yamato-791197 is one of the most interesting meteorites. As pointed out by YANAI and KOJIMA (1984), this meteorite has been classified as an anorthosite breccia and it has features similar to the lunar highland samples in mineralogy and chemical compositions. Likewise, ALHA81005 has been reported by MARVIN (1983) to have a lot of similarities to the lunar highland samples and it was identified as of lunar origin. The REE abundances in ALHA81005, analyzed by some groups (BOYNTON and HILL, 1983; or LAUL *et al.*, 1983), also sustained that this meteorite had derived from the highlands on the moon.

In this study we measured the REE abundances and major elements in Y-791197 to compare with ALHA81005 or some lunar samples. Furthermore, by using ^{87}Rb-^{87}Sr system, we examined geochronological data to discuss the genesis of Y-791197.

2. Sample and Experimental

Three chips, subordinate No. 108 (Sub No. 108 will be used for brevity), Sub No.

109 and Sub No. 115, of Y-791197 were delivered from National Institute of Polar Research. In this work we analyzed Sub No. 108 and a portion of the clast from Sub No. 109. A 31-mg chip, Y-791197,108, resembles the bulk sample of this meteorite. A 60-mg chip, Y-791197 Sub No. 109, includes a clast, which is gray to white in color and 2–3 mm in diameter. The sample, Y-791197,108, was roughly crushed, so that each fragment was the size of about 0.2–0.5 mm. And among them, a small fragment was used for only the REE, Sr and Ba analysis as a "bulk sample". Other fragments were separated by the hand-picking method under a binocular microscope into four samples: (A) white-colored fragments, (B) black-colored, (C) grayish ones, (D) the remains. According to the mineralogical description by YANAI and KOJIMA (1984), Y-791197 consists of many clasts and mineral fragments (olivine, pyroxene, plagioclase etc.) in dark brown matrix. We expected that most of the fragments belonging to (A) would be composed of plagioclase, most of (B) of olivine or pyroxene, and most of (C) and (D) of other minerals or glass. These four samples and a portion from the clast in Sub No. 109 were used for determination of REE, Ba, Sr and Rb abundances, and for the measurement of the Sr isotopic composition. One small fragment of each sample was for the major element analysis. The REE, Ba, Sr and Rb abundances were determined by the isotope dilution method using the JEOL JMS-O5RB mass spectrometer and the Sr isotopic compositions were measured by the VG-354. The measured $^{87}Sr/^{86}Sr$ ratios were normalized to $^{86}Sr/^{88}Sr=0.1194$. In the work of Sr-isotopic analyses, NBS-SRM 987 and Juvinas meteorite (eucrite) were also measured as a standard or reference sample. The concentrations of the major elements were determined by the electron probe micro analyzer JCXA-733.

3. Results and Discussion

3.1. REE abundances

The data of the REE, Ba, Sr and Rb abundances are shown in Table 1 and major

Table 1. REE Ba, Sr and Rb abundances (ppm) and the Ce deviation factors in the samples from Y-791197.

	"Bulk"	(A) white	(B) black	(C) gray	(D) ?	The clast	Normalizing values
La	3.236	4.507	2.714	3.160	2.801	4.573	0.322
Ce	8.408	10.722	7.164	8.155	7.318	12.388	0.835
Nd	5.258	6.369	4.344	5.067	4.503	7.337	0.603
Sm	1.5564	1.6998	1.2885	1.5005	1.3340	2.115	0.196
Eu	0.8889	0.8148	0.7590	0.7792	0.8010	0.7657	0.0825
Gd	1.9599	2.107	1.6602	1.9508	1.6752	2.569	0.270
Dy	2.277	2.331	1.8642	2.151	1.9166	2.980	0.331
Er	1.4347	1.5061	1.1797	1.3336	1.4347	1.9263	0.226
Yb	1.3951	1.5372	1.1429	1.2482	1.1983	1.8815	0.233
Lu	0.2072	0.2157	0.16871	0.18757	0.17638	0.2864	0.0362
Ba	43.17	56.71	34.99	31.58	38.81	55.55	4.21
Sr	161.26	148.89	137.67	135.98	143.19	129.12	11.47
Rb	n.d.	0.5548	0.8411	0.9683	0.9507	0.4652	—
Ce/*Ce	1.05	1.01	1.07	1.05	1.06	1.10	—

n.d.: not detected.

Table 2. Major element compositions of some spots in each separated sample.

	(A) Pl	(B)-I	(B)-II Px	(B)-III Ol	(C)-I	(C)-II	(D)-I	(D)-II	Clast-I Pl	Clast-II
SiO_2	44.62%	45.66%	51.70%	35.40%	43.02%	48.85%	40.73%	45.18%	44.38%	44.62%
TiO_2	0.06	0.10	0.31	n.d.	0.31	1.60	0.11	0.21	0.03	0.12
Al_2O_3	34.46	29.09	0.54	0.54	30.71	11.89	20.04	28.90	34.43	23.25
Cr_2O_3	n.d.	n.d.	0.44	n.d.	0.47	0.16	0.31	0.07	n.d.	n.d.
MnO	n.d.	0.08	0.44	0.41	0.09	0.22	0.14	0.11	n.d.	n.d.
FeO	0.27	5.12	27.19	39.86	3.99	17.12	17.79	3.38	0.47	5.44
CaO	19.63	16.35	1.43	0.30	17.70	10.28	12.56	17.26	19.23	16.54
MgO	0.14	4.51	16.10	22.48	4.18	4.98	6.74	5.62	0.15	8.87
Na_2O	0.47	0.41	0.11	n.d.	0.64	0.45	0.29	0.21	0.56	1.18
K_2O	0.07	n.d.	n.d.	n.d.	0.11	0.55	0.13	0.08	0.09	0.52
NiO	n.d.	n.d.	n.d.	n.d.	n.d.	0.28	0.11	n.d.	n.d.	n.d.
Total	98.19	101.46	100.27	98.99	101.30	96.38	98.95	101.06	99.41	98.66
	An 95.5		Wo 3.0	Fo 50.1					An 94.5	
	Ab 4.1		En 52.6	Fa 49.9					Ab 5.0	
	Or 0.4		Fs 44.4						Or 0.5	

n.d.: not detected.

element contents are in Table 2. In addition, Fig. 1 shows the REE pattern of the "bulk sample" from Y-791197 normalized by the "Leedey-84" with the patterns of ALHA81005 and some lunar samples. The REE abundances in the Leedey chondrite, including the monoisotopic REE, were obtained from MASUDA *et al.* (1973) and MASUDA (1975), and they had been used as the normalizing values. Here we call these values "Leedey-73". Recently SHIMIZU and MASUDA (1984) reported new data named "Leedey-84", and we have employed the values "Leedey-84" as the normalizing values, because the same spike solutions are employed here. For the monoisotopic REE, we estimated as follows:

$$[\mathrm{Pr}]_{\mathrm{Leedey\text{-}84}} = F_{\mathrm{Pr}} \times [\mathrm{Pr}]_{\mathrm{Leedey\text{-}73}}, \quad (F_{\mathrm{Pr}})^2 = F_{\mathrm{Ce}} \times F_{\mathrm{Nd}}.$$
$$(F_{\mathrm{Ce}} = [\mathrm{Ce}]_{\mathrm{Leedey\text{-}84}} / [\mathrm{Ce}]_{\mathrm{Leedey\text{-}73}}).$$

For the other elements, Tb, Ho and Tm, we calculated in the same way, and obtained the following values (ppm):

$$[\mathrm{Pr}]=0.115, \quad [\mathrm{Tb}]=0.0506, \quad [\mathrm{Ho}]=0.0770, \quad [\mathrm{Tm}]=0.0351.$$

As shown in Fig. 1, all patterns have some common features, reflecting the pattern of Ca-rich plagioclase. Namely, all patterns are characterized by the positive Eu anomalies and the enrichments toward the lighter REE. It has been known that the REE patterns for the lunar highland rocks might be classified roughly into two types. One has the patterns with the negative Eu anomaly and the higher REE abundances (Leedey $\times$ 50–Leedey $\times$ 100), such as those of the Fra Mauro basalts. The other has the patterns with the positive Eu anomaly and relatively low REE abundances (Leedey $\times$ 5–Leedey $\times$ 10), such as those of the gabbroic anorthosites (TAYLOR, 1975). Apparently the patterns for samples under consideration (Fig. 1) are similar to the latter type. These observations support the hypothesis that Y-791197 and ALHA81005 might have originated from the lunar highland material, possibly gabbroic anorthosite. It is one more characteristic that some patterns including Y-791197 have the positive Ce

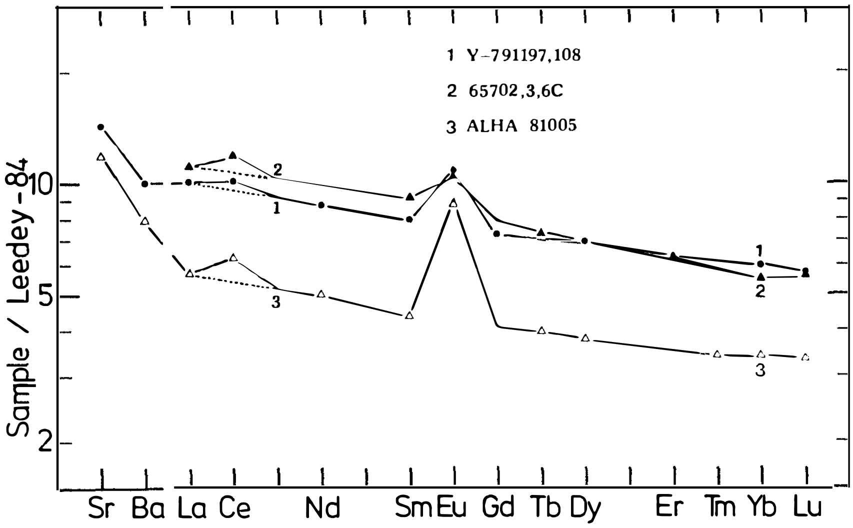

Fig. 1. The REE, Ba and Sr patterns of the "bulk sample" of Y-791197,108, ALHA81005 and a lunar sample 65702,3,6C. They are all normalized by "Leedey-84" (see text). The data of ALHA81005 are from Boynton *and* Hill *(1983), and the data of 65702,3,6C are from* Haskin *et al. (1973).*

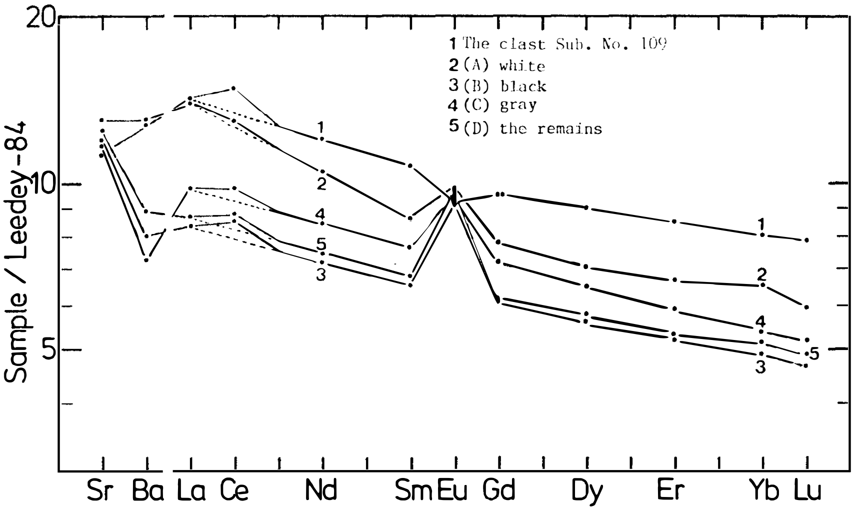

Fig. 2. The REE patterns of the separated samples and the clast in Sub No. 109.

anomalies. On this point we discuss later on.

In Fig. 2 are shown the REE patterns of four samples separated from Y-791197,108 and of the clast from Y-791197 Sub No. 109, and the major element compositions are presented in Table 2. Among the patterns in Fig. 2, the pattern of the clast is distinct from the others. This pattern shows the negative Eu anomaly and the REE abundances are higher than the others. These features resemble those of the Fra Maulo basalts or the soil samples. As shown in Table 2, this clast does not consist of the Ca-rich plagioclase only but also of Mg, Fe-rich mafic parts. It is known that such components exist with the anorthositic samples. In Fig. 3, the REE patterns for some samples of Apollo 16 determined by Nakamura *et al.* (1973) and the pattern of the clast, Sub No. 109 are shown. The negative Eu anomaly of the REE pattern of the 61016,

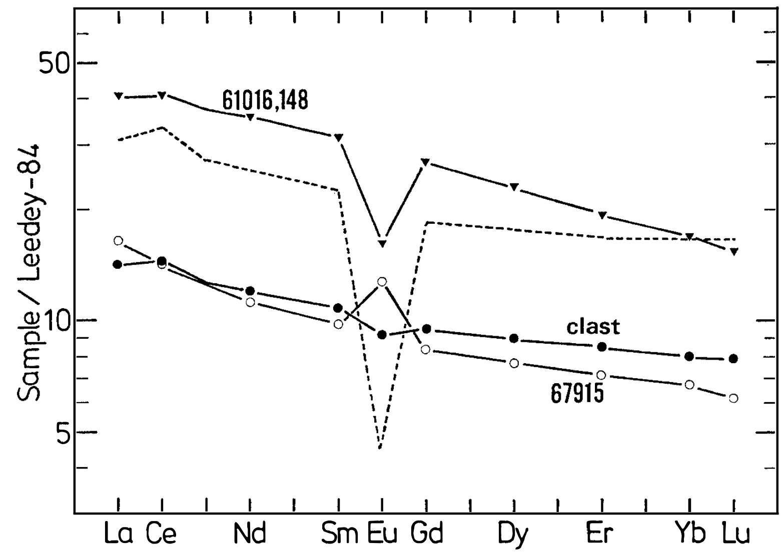

Fig. 3. The REE patterns of our clast and some lunar samples (NAKAMURA et al., 1973). The pattern shown by a broken line is a calculated one (see text).

148 Apollo sample is much larger than that of the clast under consideration and the REE abundances in 61016,148 are higher than those in the clast. In Fig. 3, the broken line is the calculated pattern. That is, an assumption that about 80% of the clast might be plagioclase component, such as the "bulk sample" in Fig. 1, brings about the REE pattern as shown by the broken line, for the rest. The calculated pattern has similar features to the Fra Mauro basalts. So it seems that this clast could be the mixture of the two components. Namely one of the two components is derived from anorthositic material and the other has the REE pattern which is like those of the Fra Mauro basalts. As regards this clast, we shall discuss in more detail.

Roughly speaking, all patterns except the clast in Fig. 2 are similar to the "bulk sample" in Fig. 1. However, for them, the REE concentrations and the degrees of the Eu anomalies are different from each other. Sample (A) has the highest REE concentration and the smallest positive Eu anomaly among the four separated samples. The other samples show the similar patterns, although the REE concentrations decrease slightly. As shown in Table 2, sample (A) seems to consist of the Ca-rich plagioclase only. With respect to sample (B), it seems that its major part is composed of the Ca-rich plagioclase, and that the minor part is pyroxene and olivine. As for samples (C) and (D), they also have the Ca, Al-rich part as a major one and have the other part, which chiefly includes Fe, Mg-rich mafic mineral mixture. So against our expectation, most of samples represent the complex materials, and are rather similar in the REE patterns. The data of the major element compositions are those for the small fragment among many fragments, so it is considered that the data on each sample do not represent the bulk of each sample.

Here let us pay our attention to Ce-anomaly. Five patterns show possitive Ce-anomalies, but their extents are more or less variable. The values of the Ce-deviation factors are shown in Table 1 with the data of the REE abundances. These values are the ratios between the observed Ce values and the calculated Ce value from La and

Nd in the patterns normalized by the "Leedey-84". The Ce-deviation factors of six samples from Y-791197 are 1.01–1.10. Except the clast, sample (A) has the smallest Ce-anomaly and sample (B) has the largest one. The REE patterns of the lunar rocks have been known to show the positive Ce-anomalies frequently (MASUDA *et al.*, 1972). And according to the review about the positive Ce-anomalies of the lunar samples by NAKAMURA (1974), the highland basalts, such as the Apollo 14 samples, often show the larger positive Ce-anomalies from 5 to 10%. On the other hand, the mare basalts scarcely exhibit the Ce-anomalies and most of the anorthosites also exhibit little anomalies. But as shown in Fig. 1, a few anorthositic samples studied here have the REE patterns with several per cent positive Ce-anomalies. These Ce-anomalies have not been explained clearly. TANAKA *et al.* (1985) examined the Ce-anomaly of the lunar samples and reported that the extent of the positive Ce-anomaly is different among the minerals. For example, plagioclase has a smaller Ce-anomaly than pyroxene. As described above, sample (A), consisting chiefly of plagioclase, has the smallest anomaly. And sample (B), including mafic materials, has the largest one. Accordingly our results are in agreement with those by TANAKA *et al.* All these features for the REE patterns of Y-791197 are conformable with those of the lunar samples, in particular, anorthosites, and the positive Ce-anomalies are considered to have been formed by the same process on the moon as that for the lunar samples.

3.2. *Rb-Sr geochronology*

Table 3 shows the results of the Rb-Sr isotopic analyses. As inferred from the Sr concentrations and the sample amounts, the amounts of Sr analyzed are 300–1000 ng. Each of $^{87}Sr/^{86}Sr$ ratios of NBS 987 and Juvinas is in good agreement with the data obtained by some workers. Samples (C) and (D) have the higher $^{87}Sr/^{86}Sr$ and Rb/Sr ratios, suggesting that these samples contain the material with high Rb contents, for example, the silica minerals.

Table 3. Results of the Rb-Sr system.

Sample name	Amount (mg)	Sr (ppm)	Rb (ppm)	$^{87}Sr/^{86}Sr(\pm 2\sigma)$	$^{87}Rb/^{86}Sr$
Black (B)	8.80	137.67	0.8411	.699962±20	.01766
White (A)	2.55	148.89	0.5548	.699554±22	.01078
Gray (C)	4.09	135.98	0.9683	.700103±12	.02065
The remains (D)	4.68	143.19	0.9507	.700024±22	.01919
Clast (109)	4.36	129.12	0.4652	.699632±12	.01108
NBS 987 (I)	—	—	—	.710245±12	—
Juvinas	—	69.01	0.0965	.699286±10	.00404

Figure 4 shows the plot of the $^{87}Sr/^{86}Sr$ ratios against the $^{87}Rb/^{86}Sr$ atomic ratios. The analytical errors are within each circle in Fig. 4. The errors in the $^{87}Rb/^{86}Sr$ ratios are below 0.5%. All points except the point for a clast fall on a linear line. The age calculated from the slope of this line is $3.89\pm0.36(2\sigma)$ b.y. and an initial $^{87}Sr/^{86}Sr$ ratio is $0.69894\pm.00004$, using $\lambda=1.42\times10^{-11}$ y^{-1} as a decay constant of ^{87}Rb. Figure 5 is a plot of $^{87}Sr/^{86}Sr$ *vs.* 1/Sr (ppm^{-1}) and we inspected the possibility that the line in Fig. 4 might be a mixing line, not an isochron. Apparently these points in Fig. 5 do not form a line. Therefore, the line in Fig. 4 can be judged to be an isochron. The

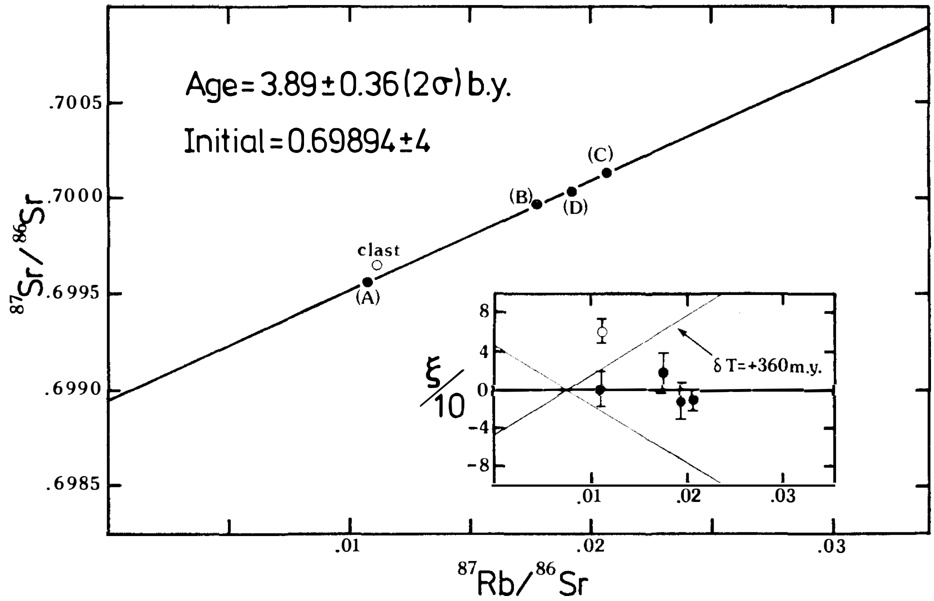

Fig. 4. The Rb-Sr isochron diagram of Y-791197 Sub No. 108. In calculation of age, the clast is omitted.

$$\xi=\frac{(^{87}Sr/^{86}Sr)_{measured}-(^{87}Sr/^{86}Sr)_{calculated}}{(^{87}Sr/^{86}Sr)_{measured}}\times 10^{4}\ .$$

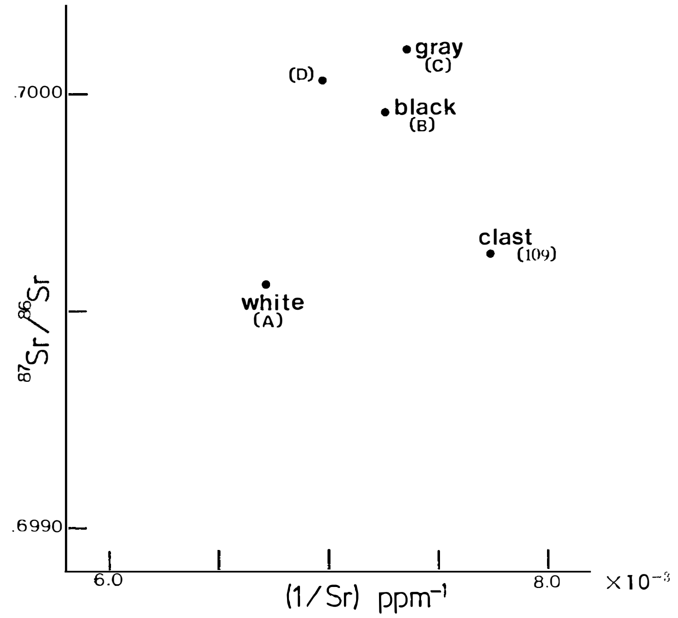

Fig. 5. A plot of $^{87}Sr/^{86}Sr$ vs. $1/Sr\,(ppm^{-1})$.

clast does not fall on the line shown in Fig. 4. As mentioned above, the REE pattern of this clast is also distinct from the others. So it is considered that the clast from the chip Sub No. 109 was formed by the different evolution process from the other samples, and both were mingled in the brecciation process.

It is believed that the highlands were formed at the earliest stage, about 4.5 b.y. ago, and believed that they were destroyed by the intense bombardment about 4.0 b.y. ago (BASALTIC VOLCANISM STUDY PROJECT, 1981). Most of the isotopic systems of the highland samples were reset by the brecciation, shock metamorphism, and/or partial or complete melting. So most of the ages obtained for the highland samples cluster around 4.0 b.y. The age 3.89 b.y., which we obtained for Y-791197, falls in the range with the highest frequency for the ages of the highland samples.

On the following discussions about the initial Sr ratios, the data corrected by comparison with the standard (NBS 987) data are employed. NYQUIST (1977) proposed that the value of LUNI was 0.69891 in adjustment with the NBS 987 value, 0.71015 and as shown in Table 3, our value for NBS 987 is 0.710245. Our observed value for the initial value of Y-791197 is 0.69894, which turns out to be 0.69884 as a corrected value when the bias between 0.71015 and 0.710245 for NBS 987 is taken into account. It is a noticeable point here that the initial $^{87}Sr/^{86}Sr$ ratio is significantly low. As shown in Fig. 6, even the value of BABI or LUNI is higher than that we obtained for Y-791197 Sub No. 108. And not only this sample, but some clasts form Kapoeta (howardite) were also reported that the initial $^{87}Sr/^{86}Sr$ ratios were very primitive despite their young ages (PAPANASTASSIOU *et al.*, 1974). It is possible that the source material

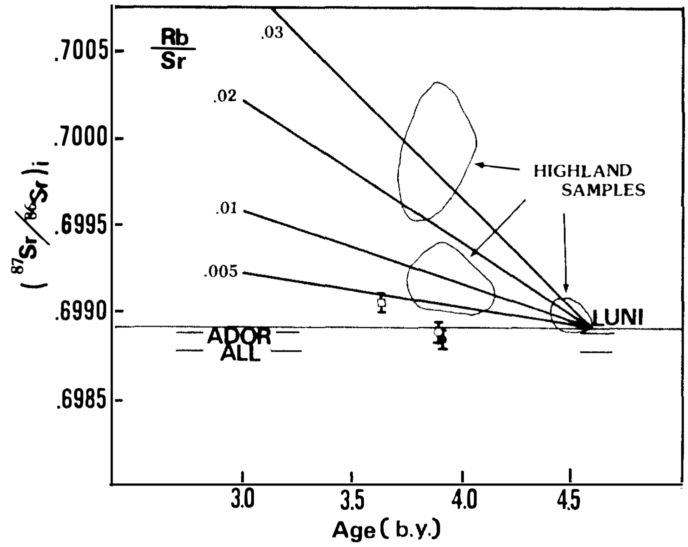

Fig. 6. Rb-Sr evolution diagram, the age vs. initial $^{87}Sr/^{86}Sr$. The data of LUNI (lunar initial) are from NYQUIST (1977), and the data of ALL (Allende) and ADOR (Angra dos Reis) are from PAPANASTASSIOU and WASSERBURG (1976)
○: Kapoeta clast A, □: Kapoeta clast B, ●: Y-791197 Sub No. 108.

of this sample, Sub No. 108, had the very primitive Sr-isotope composition, such as Allende, and the extremely low Rb/Sr abundance ratio (lower than 0.002), and it is possible that 3.9 b.y. ago this material underwent an event, perhaps brecciation or impactmelting, with the increase of Rb/Sr ratio. This hypothesis suggests the heterogeneity of the Sr-isotopic composition in the early moon. However, such heterogeneities of any isotope compositions have not been observed for the lunar samples yet. Hence, there remains a problem of the initial ratio, and more analyses of Rb-Sr systems may be needed for other chips of Y-791197.

As mentioned above, the positive Ce-anomalies exist in the REE patterns. There have not been any evidences showing the relationship between these anomalies and the

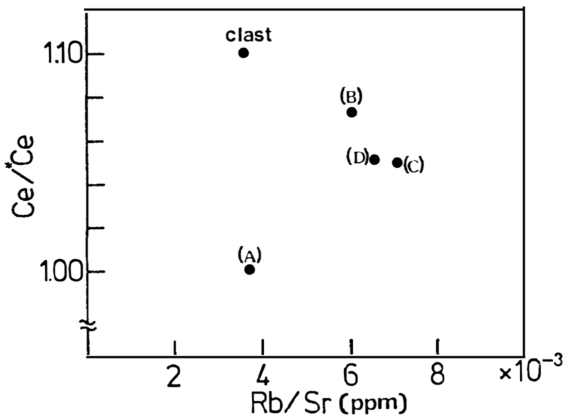

Fig. 7. A plot of the Ce deviation factor vs. Rb/Sr abundance ratio.

event, 3.9 b.y. ago calculated from Rb-Sr system. For an example, as shown in Fig. 7, one cannot recognize a correlation between the Ce-deviation factors and the Rb/Sr abundances ratios.

In conclusion, both the REE patterns and the age obtained from Rb-Sr system, of Y-791197 Sub No. 108 are consistent with the lunar highland origin of this meteorite. However, there remain some problems as follows;

(1) The clast in the chip, Sub No. 109, shows the different REE pattern, and in the Rb-Sr system, this clast is distinct from the other samples from Y-791197.

(2) The initial $^{87}Sr/^{86}Sr$ ratio obtained for the Sub No. 108 is lower than most of the corresponding ratios of the lunar samples studied thus far, even lower than LUNI or BABI.

(3) The positive Ce-anomalies exist in the REE patterns of most of the samples from Y-791197 as well as the lunar samples. However, the origin of these anomalies has been still unknown. It is hoped that further studies will help us make these problems clear and help us elucidate ambiguous aspects concerning the genesis of this meteorite.

Acknowledgments

We thank the National Institute of Polar Research, for offering the valuable samples of Y-791197.

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(*Received August 13, 1985; Revised manuscript received January 18, 1986*)