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TWO LUNAR METEORITES, YAMATO-791197 AND -82192: REE ABUNDANCES AND GEOCHRONOLOGICAL DATING

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Abstract: Four antarctic meteorites (ALHA81005, Y-791197, -82192 and -82193) have been identified as lunar meteorites. We investigated the REE, Rb, Sr and Ba abundances and major element compositions in specimens spearated from Y-791197 and -82192. Furthermore, we have discussed the genesis of these lunar meteorites, using Rb-Sr systematics and Nd isotope ratios. Most REE patterns show similar features, reflecting those of anorthosites, and also show positive Ce anomalies. These Ce anomalies are considered to have been formed 3.9–4.0 b.y. ago, based on the age obtained from the Rb-Sr systematics for Y-791197 and -82192,55A. It is possible that these Ce anomalies could have been formed by an oxic alteration (T. TANAKA *et al.*, Papers presented to the 10th Symp. Antarct. Meteorites, 129, 1985) and this event might be related to the observation that the initial $^{87}Sr/^{86}Sr$ ratios are significantly low. Y-82192,63B shows a glassy feature and an age of 0.71 b.y. has been obtained from the Rb-Sr systematics for this sample. This age could indicate an event of impact partial melting (possibly, related with the formation of a crater on the moon). The Sm-Nd systematics of Y-82192,55A suggests that the REE abundances of this meteorite were differentiated from the chondritic abundances at the age 3.9 b.y. obtained from the Rb-Sr systematics. Based on the Sm-Nd data, the original formation of the parent materials of this meteorite could be traced back to around 4.3 b.y. ago.

1. Introduction

Since the first identification of the "lunar meteorite", ALHA81005 in 1982, some other lunar meteorites have been discovered in the Yamato collection. Until recently, three Yamato meteorites (Y-791197, -82192 and -82193) have been classified as meteorites of lunar origin (YANAI and KOJIMA, 1985). Several previous studies have been done for ALHA81005 and Y-791197, and the results of most of these studies confirmed the hypothesis that these meteorites were derived from the lunar highlands.

According to our previous study, the REE (rare earth elements) abundances of the samples from Y-791197 resemble those of lunar anorthositic samples, but a clast with different REE abundances from those of anorthosite exists. Rb-Sr systematics for one sample of Y-791197 gives initial $^{87}Sr/^{86}Sr$ ratios which are significantly too low, even if this meteorite is taken as having been derived from an anorthositic sample with a low Rb/Sr abundance ratio (TAKAHASHI *et al.*, 1986). Y-82192, the third lunar meteorite, has been reported to have some petrographic characteristics which are distinct from those of Y-791197 and it has been suggested that this meteorite was derived from another part of the moon (YANAI and KOJIMA, 1985, YANAI *et al.*, 1986).

In this study, we analyzed two chips from Y-791197 and two chips from Y-82192 for REE abundances, major element compositions and Rb-Sr systematics. Furthermore, the Nd isotopic ratios were measured for Y-82192 and the genesis and history of these lunar meteorites will be discussed.

2. Samples and Experimental

We received six chips, subordinate No. 108 (Sub No. 108 for brevity), Sub No. 109 and 115 of Y-791197 and Sub No. 63B, 55A and 141C of Y-82192, from the National Institute of Polar Research. We have already reported for the samples of Sub No. 108 and the clast of Sub No. 109 (TAKAHASHI *et al.*, 1986). In this work, we analyzed Sub No. 115 and the matrices of Sub No. 109 of Y-791197 and two chips, Sub No. 63B and 55A, of Y-82192. The chip, Sub No. 115 of Y-791197, consists of white clasts and the chip, Sub No. 55A of Y-82192, consists of matrix with small pieces of clasts 2–3 mm in diameter. The chip, Sub No. 63B of Y-82192, shows a glassy feature distinct from the other five chips (Sub No. 108, 109 and 115 of Y-791197 and Sub No. 55A and 141C of Y-82192) which are characterized as polymict breccias. This feature of Sub No. 63B suggests that Y-82192 was partially melted after these breccia were originally formed.

The chip, Sub No. 109, was roughly crushed and separated by the hand-picking method into three samples: (A) white colored fragments (109W), (B) black-colored

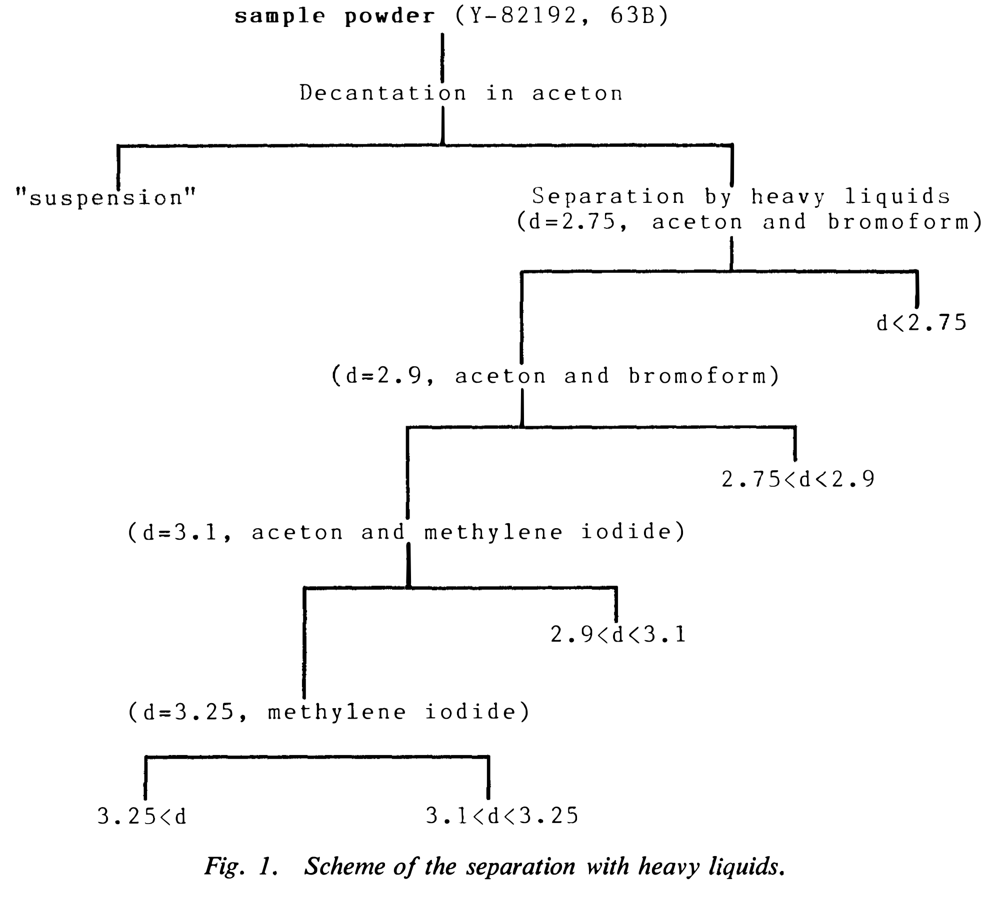

Fig. 1. Scheme of the separation with heavy liquids.

fragments (109B) and (C) the remains (109R). (The clast of Sub No. 109 is called 109CL and the clast of Sub No. 115 is called 115CL in this study). The chip, Sub No. 63B of Y-82192, was crushed and ground well to 100–200 mesh. This sample was separated into 6 fractions with heavy liquids (see Fig. 1). These separated samples and two chips, Sub No. 115 of Y-791197 and Sub No. 55A of Y-82192, were used for the determination of REE, Ba, Sr and Rb abundances, and for the measurement of the Sr isotopic compositions. One small fragment of each sample of Sub No. 109 (Y-791197) or a small amount of each fraction of Sub No. 63B (Y-82192) was used for the major element analysis. Furthermore, measurement of the Nd isotopic compositions was performed for Sub No. 55A (Y-82192). Table 1 concisely lists the samples.

Table 1. Sample list.

Sample	SubNo.	Description
I. Samples for REE abundances, Rb-Sr systematics and major element compositions		
Y-791197	109	Matrix (hand-picking separation) (109W): white colored sample (109B): black colored sample (109R): the remains
	115	(115CL): Clast
Y-82192	55A	Matrix
	63B	**Melted sapmle?** (mineral separation by heavy liquids) (This sample was separated into six fractions.) (S) suspended in acetone $d<2.75$, $2.75<d<2.9$, $2.9<d<3.1$, $3.1<d<3.25$, $3.25<d$
II. Samples for Sm-Nd systematics		
Y-82192	55A	Matrix

The REE, Ba, Sr and Rb determinations were carried out by the stable isotope dillution method, using the JEOL JMS-05RB mass spectrometer and the Sr and Nb isotopic compositions were measured, using a VG-354 (VG-Isotope, Limited). The measured $^{87}Sr/^{86}Sr$ ratios were normalized to $^{86}Sr/^{88}Sr=0.1194$ and the $^{143}Nd/^{144}Nd$ ratios were normalized to $^{146}Nd/^{144}Nd=0.7219$. NBS-SRM 987 and the Juvinas meteorite (eucrite) were measured as standards for the Sr isotopic analyses. For the Nd isotopic analyses, the La Jolla Nd standard and Juvinas were also measured as standards. The concentrations of the major elements were determined by the electron probe micro analyzer JXA-733 (JEOL). The total blanks are 0.09 ng for Sr, less than 0.005 ng for Rb and less than 0.01 ng for the REE. The uncertainties for REE, Ba, Sr and Rb abundances are less than 0.5%.

3. Results and Discussion

3.1. *Samples of Y-791197*

3.1.1. REE abundances and major element compositions

The data for the REE, Ba, Sr and Rb abundances of 4 samples from Y-791197 are shown in Table 2 and major element compositions of some spots in each sample are given in Table 3. Figure 2 shows the REE patterns of 4 samples form Y-791197 (109W, 109B, 109R and 115CL) with those of Sub No. 108, the clast from Sub No.

109 (109CL), ALHA81005 (bulk) and one lunar anorthosite. The data of ALHA-81005 (bulk) are from BOYNTON and HILL (1983) and the data of the lunar anorthosite (65702,3,6C) are from HASKIN *et al.* (1973). The other two samples of Y-791197 (Y-791197,108 and 109CL) are from our previous report (TAKAHASHI *et al.*, 1986). Roughly speaking, most of the REE patterns except 109CL, in Fig. 2b, show similar features to each other, including positive Eu-anomalies and enrichments toward the lighter REE reflecting the pattern of Ca-rich plagioclase. Especially, 115CL has the REE

Table 2. The REE abundances (ppm) in the samples from Y-791197.

	109W white	109B black	109R the remains	115CL clast	Normalyzing values
La	2.19	3.16	2.89	1.491	0.322
Ce	5.58	8.19	7.40	3.69	0.835
Nd	3.56	5.41	4.82	2.38	0.603
Sm	1.059	1.645	1.472	0.742	0.196
Eu	0.781	0.761	0.801	0.820	0.0825
Gd	1.342	2.20	1.961	0.981	0.270
Dy	1.574	2.65	2.35	1.203	0.331
Er	1.023	1.731	1.528	0.793	0.226
Yb	0.999	1.733	1.565	0.766	0.233
Lu	0.1450	0.265	0.232	0.1144	0.0362
Ba	45.9	43.6	42.7	44.5	4.21
Sr	133.6	128.5	135.5	135.6	11.47
Rb	0.406	0.934	0.731	0.362	—
Ce/*Ce	1.02	1.04	1.03	1.01	—

The Ce-deviation factors, Ce/*Ce, are the ratios between the observed Ce values and the calculated Ce values from the La-Nd join in the REE patterns.

The normalizing values are from SHIMIZU and MASUDA (1986).

Table 3. Major element compositions of some spots in each separated sample.

	109CL		115CL	109W	109B			109R
	I	II	I	I	I	II	III	I
SiO_2	44.38%	44.62%	44.91%	45.96%	37.58%	37.48%	46.25%	40.73%
TiO_2	0.03	0.12	n.d.	n.d.	0.20	0.60	0.10	0.11
Al_2O_3	34.43	23.25	34.10	34.94	0.84	5.47	30.65	20.04
Cr_2O_3	n.d.	n.d.	n.d.	n.d.	0.16	n.d.	n.d.	0.31
MnO	n.d.	n.d.	n.d.	n.d.	0.39	0.24	0.20	0.14
FeO	0.47	5.44	n.d.	0.32	26.95	21.22	3.06	17.79
CaO	19.23	16.54	18.38	18.39	0.08	2.81	16.30	12.56
MgO	0.15	8.87	0.08	0.17	34.07	32.11	3.91	6.74
Na_2O	0.56	1.18	0.81	0.79	0.29	0.93	1.10	0.29
K_2O	0.09	0.52	0.07	0.09	n.d.	0.20	0.18	0.13
NiO	n.d.	n.d.	n.d.	n.d.	0.30	n.d.	n.d.	n.d.
Total	99.41	98.66	98.45	100.66	100.86	101.56	101.75	98.84
	An 9.45		An 92.3	92.3	Fo 68.5			
	Ab 5.0		Ab 7.3	7.2	Fa 31.5			
	Or 0.5		Or 0.4	0.5				

n.d. = not detected.

The data of 109CL are from our previous report (TAKAHASHI *et al.*, 1986).

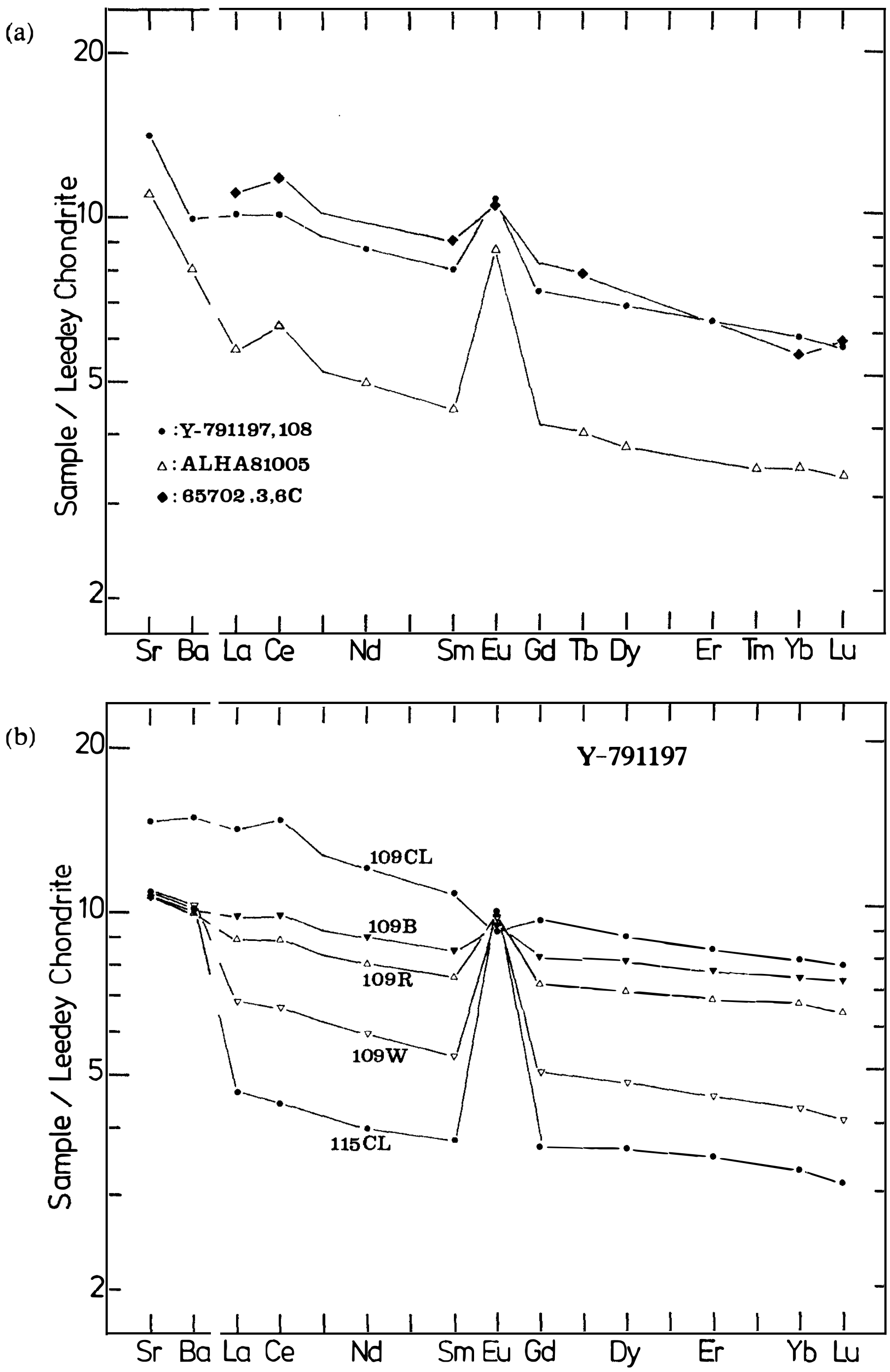

Fig. 2. The REE patterns of the samples from Y-791197, along with those of ALHA81005 and a lunar anorthosite, The data of ALHA81005 are from Boynton *and* Hill *(1983) and the data of 65702,3,6C are from* Haskin *et al. (1973). The data of 109CL and 108 in Y-791197 are from our previous study (*Takahashi *et al., 1986).*

pattern with a large Eu anomaly and relatively low REE abundances. These faetures reflect the REE patterns of anorthosites more strongly than other rock types. Although ALHA81005 has a similar level of REE abundances as 115CL or 109W, there are some differences in the fine structures (the degree of the enrichments of the lighter

REE or the degree of the Ce anomaly) of these patterns. Namely, ALHA81005 shows a larger Ce anomaly than 115CL or 109W, and the degree of the enrichments of the lighter REE is greater for ALHA81005 than for 115CL or 109W. As shown in Table 3, 115Cl and a major part of 109W consist of Ca-rich plagioclase (CaO 18–19%) and on the other hand, the bulk Ca content for ALHA81005 is known to be lower, in the rangel4–16% (BOYNTON and HILL, 1983; LAUL *et al.*, 1983). Therefore, it is supposed that the bulk sample, ALHA81005 (Fig. 2a), contains materials originating from lunar lithologies which are distinct from those in 115CL or 109W (Y-791197).

As seen in Fig. 2, the samples 109B and 109R have higher REE abundances than 107W and 115CL. As inferred from the major element compositions (Table 3), some parts of 109B or 109R consist of mafic components, such as pyroxene or olivine, and the differences in the REE patterns are controlled to a certain degree by such components. Figure 2b leads to the suspicion that the patterns of 109B, 109R and 109W could be explained as mixtures of 109CL and 115CL. If these three samples could be regarded as mixture of 109CL and 115CL, the data for these samples would form a mixing line in a Rb-Sr systematics. In order to examine this possibility we calculated some patterns as a mixture of 115CL and 109CL and compared the results with 109B, 109R and 109W. As shown in Fig. 3, the pattern of 109W is in good agreement with the calculated pattern based on the assumption that 23% of 109W might be 109CL and 77% of this sample might be 115CL. However, the REE patterns of the other two samples, 109B and 109R, cannot be explained as mixtures of 109CL and 115CL (See Fig. 3 for 109R, 109B is similar.). So these samples from Y-791197, possibly excepting 109W, are not expected to form a mixing line in the Rb-Sr diagram. (This expectation will be further supported below.)

In Fig. 2b, one can see some characteristics in the fine structures of the REE patterns. For example, the degree of the Ce anomaly seems to increase with increasing REE abundances; whereas, the Eu contents of these samples are relatively

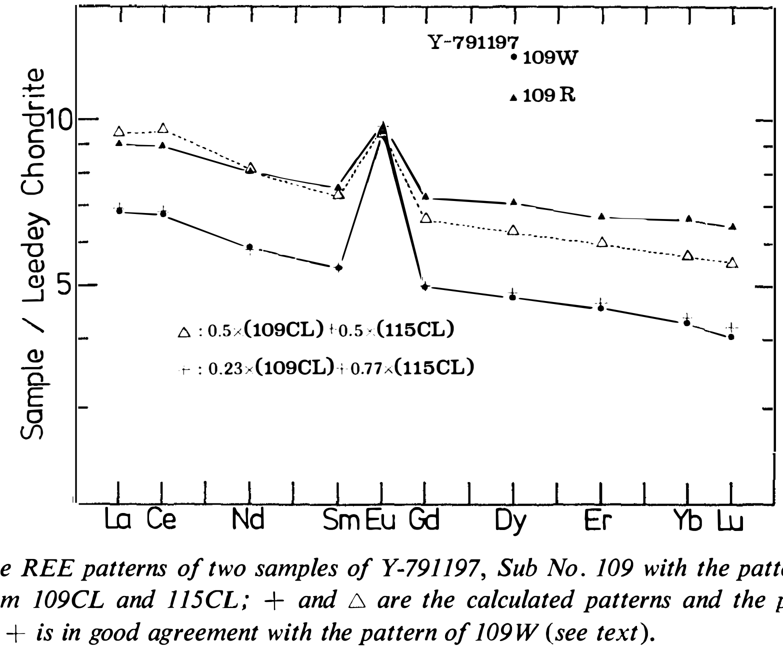

Fig. 3. The REE patterns of two samples of Y-791197, Sub No. 109 with the pattern calculated from 109CL and 115CL; + and △ are the calculated patterns and the pattern shown by + is in good agreement with the pattern of 109W (see text).

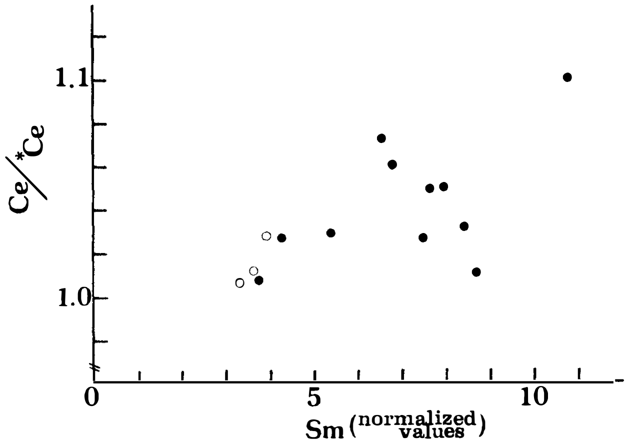

Fig. 4. A polt of the degrees of the Ce anomalies vs. the chondrite normalized values of Sm. The open circles indicate the data for Y-82192 and closed circles indicate the data for Y-791197.

uniform. As shown in Fig. 4, the extents of the Ce anomalies of the samples from Y-791197 and -82192 are different from sample to sample. As shown in Fig. 4, the extent of the Ce anomaly increases in rough proportionality to the Sm abundance. Positive Ce anomalies have been reported frequently for lunar samples by some workers (MASUDA *et al.*, 1972) and this anomaly also appears in the REE patterns of the samples of Y-791197, Sub No. 108. NAKAMURA *et al.* (1986) also reported positive Ce anomalies for Y-791197. TANAKA *et al.* (1985) examined the Ce anomalies of lunar samples in combination with a Ce-isotopic study and reported that the degree of the Ce anomaly was different among different minerals; that is, the pyroxene component has a larger Ce anomaly than the plagioclase component. The pyroxene component has higher REE abundances than the plagioclase component, so, this characteristic of lunar samples is in good agreement with that of the samples of these two lunar meteorites, Y-971197 and -82192. TANAKA *et al.* (1985) concluded that the Ce anomaly could be brought about by some oxic (hydrothermal, aqueous or ice) alteration in an early stage of lunar history. It is possible that the source materials of these lunar meteorites might be subjected to similar alteration and that this alteration might have affected the materials composed of pyroxene more strongly than the materials composed mainly of plagioclase. It is necessary that this alteration should have occurred earlier than 3.9–4.0 b.y. ago. If such alteration had taken place in a later stage than 3.9 b.y. ago, the Rb-Sr systems would have been disturbed. However, as discussed later, the disturbance related to the Ce anomaly has not been observed for the Rb-Sr systems of these meteorites. It is possible that the alteration which brought about the Ce anomaly occurred prior to 4.0 b.y. ago, and we can observe REE patterns with various degrees of the Ce anomaly in these lunar meterorites. Presumably, these meteorites are composed of some materials which had undergone alteration, possibly under oxic circumstances, to various extents.

3.1.2. The Rb-Sr systematics

Table 4 shows the results of the Rb-Sr isotopic analysis and the data of 109CL from our previous study (TAKAHASHI *et al.*, 1986). Since the $^{87}Sr/^{86}Sr$ ratio measured

Table 4. Rb-Sr system for the samples from Y-791197.

Sample name	Amount (mg)	Sr (ppm)	Rb (ppm)	^{87}Sr/^{86}Sr ($\pm 2\sigma$)	^{87}Rb/^{86}Sr
109CL	4.36	129.1	0.495	.699632±12	.01108
109B	8.25	128.5	0.934	.700235±12	.02101
109W	3.32	133.6	0.405	.699540±22	.00875
109R (the remains)	4.60	135.5	0.731	.699908±12	.01560
115CL	2.60	135.6	0.362	.699462±28	.00771
Juvinas	—	69.0	0.0965	.699279±10	.00404
NBS 987	—	—	—	.710241±14	—

The data of 109CL are from our previous study (TAKAHASHI *et al.*, 1986).

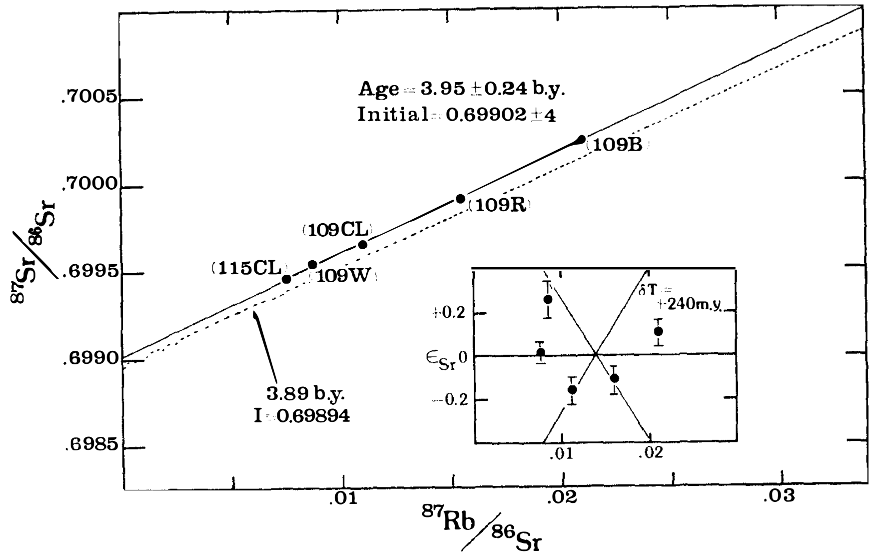

Fig. 5. The Rb-Sr isochron diagram of the samples from SubNo. 109 and SubNo. 115 (Y-791197). The dashed line is the one obtained for Y-791197, SubNo. 108 in our previous study (TAKAHASHI et al., 1986).

for NBS 987 in this study is in agreement, within error limits, with the data obtained in our previous report, it is not necessary to correct the Sr-isotopic data when we compare them with the data obtained in our previous study. Figure 5 is a plot of the ^{87}Sr/^{86}Sr ratios against ^{87}Rb/^{86}Sr atomic ratios; the analytical error limits are contained within each circle in Fig. 5. The dashed line is the line obtained for Sub No. 108 (Y-791197) in our previous study. The age corresponding to this dashed line is 3.9 b.y. and the initial ^{87}Sr/^{86}Sr ratio is 0.69894. As shown in Fig. 5, the samples of Sub No. 109 and the clast of Sub No. 115 fall on a line distinct from the dashed line for Sub No. 108. The age calculated from the slope of the line for the samples of Sub No. 109 and 115 is 3.95±0.24 (2σ) b.y. and the initial ^{87}Sr/^{86}Sr ratio is 0.69902±0.00004 (2σ), using $\lambda=1.42^{-11}\mathrm{y}^{-1}$ as a decay constant.

As mentioned above, the REE patterns suggest the possibility that 109W could be explained as a mixture of 109CL and 115CL. Figure 6 is a plot of the ^{87}Sr/^{86}Sr ratio *vs.* 1/Sr(ppm^{-1}). In Fig. 6 the point for 109W falls near the line connecting the point for 109CL and that for 115CL, and the mixing ratio is similar to that calculated from

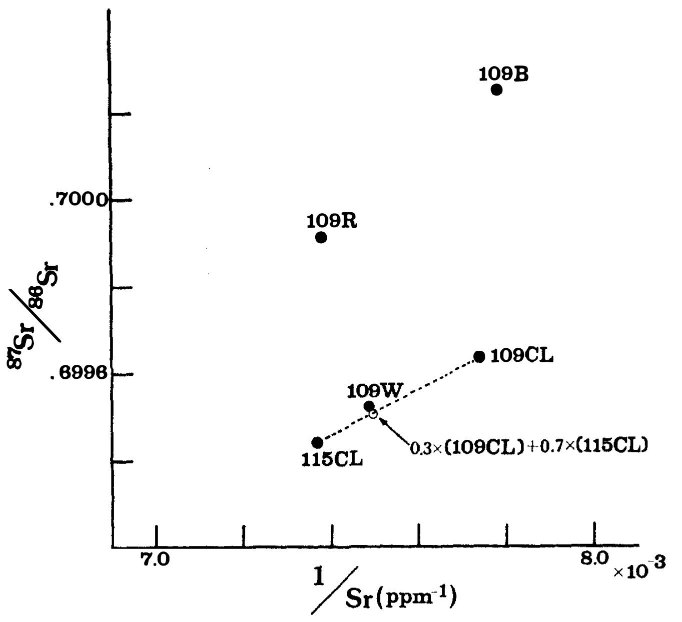

Fig. 6. A plot of $^{87}Sr/^{86}Sr$ vs. $1/Sr$ (ppm^{-1}). The data of 109W falls near the mixing line of 109CL and 115CL.

the REE abundances. However, the other points, excepting the point of 109W, do not form a line and the line in Fig. 5 can be judged to be an isochron determined by three or more components, not a mixing line determined by two components.

The inital $^{87}Sr/^{86}Sr$ ratio obtained for the samples of Sub No. 109 and 115 is distinct from that for Sub No. 108, though the ages calculated from the slope of two lines in Fig. 5 are mutually in good agreement within the error limits, and these two ages are within the range of those of lunar anorthosites. These observations suggest that this meteorite is composed of materials which were derived from distinct parts on the moon from each other and which kept individual Rb-Sr systems. These materials must have undergone an event such as brecciation or impact melting 3.9–4.0 b.y. ago. It is possible that the Rb-Sr system was not totally reset at that time, but reset partially. Furthermore, some of the source materials of this meteorite had very primitive Sr isotope ratios and low Rb/Sr abundances ratios, since the initial ratio we obtained for the samples of Y-791197 is extremely low. LUNI (the lunar initial $^{87}Sr/^{86}Sr$ ratio) has been proposed by NYQUIST (1977) to be 0.69891 when adjusted to a value of 0.71015 for the NBS 987 Sr standard. As shown in Table 4, our NBS 987 value is 0.710241, so we adopt the value 0.69901 as LUNI on our scale. In this connection, the primordial $^{87}Sr/^{86}Sr$ value 4.55 b.y. ago can be also calculated from our data for Juvinas (see Table 4) and we obtained the value, 0.69901, in very good agreement with LUNI. The initial ratio obtained for Y-791197 is within the same range as the primordial value despite its younger age. As regards this observation, two hypotheses are conceivable. One is that the source materials of this meteorite were derived from materials with very primitive Sr isotope composition, such as Allende or Angra dos Reis. Actually, some other planetary materials have been known to show "primordial" initial $^{87}Sr/^{86}Sr$ ratio despite their younger ages, for example, some of low-K mare basalts, some of the lunar anorthosites and some kinds of meteorites (Kapoeta howardite; PAPANASTASSIOU *et al.*, 1974). A second hypothesis is that the source materials had undergone an event by which the radiogenic ^{87}Sr had been taken away prior to 4.0 b.y. ago. At present, it is not clear which hypothesis would be adequate to explain the observations, but it is possible that the latter hypothesis could be related to the genesis of the Ce anomaly mentioned above. Namely, it is considered that an oxic alteration, in which H_2O might have taken part, could have brought about the Ce anomaly and at the same time could have taken away the radiogenic ^{87}Sr. If we can get further data for Rb-Sr systems and REE abundances at times prior to 3.9 b.y. ago, the relationship between the degrees of the Ce anomalies and the Sr isotope ratios is expected to be disclosed. Therefore, by accumulation of the data for Rb-Sr systems are REE abundances for many more samples formed in the early stages of lunar history, it is hoped that we can clarify the problem concerning the relationship between the genesis of the Ce anomalies and the primitiveness of the Sr isotope ratios. Further Ce-isotope studies of lunar samples formed in early stages of the lunar history, such as that by as TANAKA *et al.* (1985), will also be needed.

3.2. Y-82192

3.2.1. REE abundances and major element compositions

Sub No. 63B (Y-82192) is the part regarded as a melted sample. This chip was

Table 5. The fractions separated with heavy liquids (see Fig. 1); total amount=51.86 mg.

Density (g/cm^3)	Amount (mg)	wt%	Heavy liquid
Suspension	13.05	(26.5)	(suspended in acetone)
$d<2.75$	3.55	(7.2)	Acetone and bromoform
$2.75<d<2.9$	6.15	(12.5)	Acetone and bromoform
$2.9<d<3.1$	20.92	(42.4)	Acetone, bromoform and methylene iodide
$3.1<d<3.25$	1.93	(3.9)	Acetone and methylene iodide
$3.25<d$	3.73	(7.6)	Methylene iodide
Total	49.33	(100.1)	

Recovery 95.12%.

Table 6. REE, Ba, Sr and Rb abundances (ppm) in the samples from Y-82192.

	55A	63B					
		Whole rock	Suspension	$d<2.75$	$2.75<d<2.9$	$2.9<d<3.1$	$3.25<d$
La	1.4456	1.3120	1.1183	1.0389	1.1619	1.1752	2.338
Ce	3.682	3.091	2.772	2.804	2.930	2.916	6.045
Nd	2.387	2.078	1.843	1.7970	1.8754	1.8934	4.070
Sm	0.7040	0.6354	0.5707	0.5448	0.5742	0.5841	1.2580
Eu	0.7785	0.8402	0.8572	0.4771	0.8470	0.9158	0.6741
Gd	0.9126	0.8568	0.7902	0.7182	0.7831	0.7830	1.6548
Dy	1.0900	1.0550	0.9727	0.8771	0.9297	0.9533	2.065
Er	0.7211	0.7433	0.6837	0.5868	0.6306	0.6531	1.4054
Yb	0.7290	0.7398	0.6873	0.6104	0.6546	0.6757	1.4437
Lu	0.10922	0.10719	0.10361	0.08939	0.09588	0.09883	0.2129
Ba	33.64	32.56	20.48	18.557	36.37	42.63	30.62
Sr	140.76	143.88	140.08	115.94	145.72	147.68	126.54
Rb	0.2841	0.3899	0.4392	0.9775	0.4283	0.2968	0.5316

Table 7. Major element compositions of some spots in each separated sample.

	Suspension		$d<2.75$			$2.75<d<2.9$	
	I	II	I	II	III	I	II
SiO_2	48.17%	43.45%	87.35%	40.12%	45.21%	43.25%	44.62%
TiO_2	0.24	0.21	0.37	n.d.	0.18	0.32	0.12
Al_2O_3	27.58	27.55	4.25	34.25	24.36	24.39	23.25
Cr_2O_3	n.d.	n.d.	0.62	n.d.	0.14	0.14	n.d.
MnO	0.12	0.11	n.d.	n.d.	0.11	0.20	0.14
FeO	3.41	3.48	0.78	0.22	5.95	9.15	5.44
CaO	14.48	12.80	2.05	15.96	15.07	14.48	16.54
MgO	3.05	4.45	0.81	0.07	5.38	6.21	8.87
Na_2O	1.37	5.62	1.13	7.31	1.05	1.13	1.18
K_2O	0.65	1.84	0.96	2.40	0.15	0.19	0.52
NiO	0.13	n.d.	n.d.	n.d.	n.d.	0.42	n.d.
Total	99.23	98.06	98.32	100.33	97.60	97.41	98.66
				An 49.8			
				Ab 41.3			
				Or 8.9			

	$2.9<d<3.1$					$3.25<d$		
	I	II	III	IV	V	I	II	III
SiO_2	43.97%	43.94%	43.41%	45.58%	42.09%	37.48%	54.34%	42.58%
TiO_2	0.06	n.d.	n.d.	0.30	0.20	0.60	0.62	0.32
Al_2O_3	35.47	36.30	34.28	23.25	21.40	5.47	1.50	25.39
Cr_2O_3	n.d.	n.d.	n.d.	0.23	n.d.	n.d.	0.77	0.14
MnO	n.d.	n.d.	0.65	0.70	0.15	0.24	0.20	0.14
FeO	0.27	0.45	1.53	7.71	10.30	21.22	8.97	9.15
CaO	18.48	19.10	17.84	14.51	11.71	2.81	1.08	13.38
MgO	0.25	0.26	1.77	6.18	12.05	32.11	32.66	5.24
Na_2O	1.18	0.60	0.88	1.22	1.87	0.93	0.31	1.13
K_2O	0.21	0.03	0.11	0.28	0.31	0.20	0.13	0.19
NiO	n.d.	n.d.	n.d.	n.d.	0.30	n.d.	n.d.	n.d.
Total	100.06	100.68	100.47	99.98	101.38	101.56	100.58	97.75
An	88.5	94.5	93.1					
Ab	10.3	5.4	6.2					
Or	1.2	0.1	0.7					

n.d. = not detected.

separated into six fractions by heavy liquids (Fig. 1) and the results of this separation is shown in Table 5. The REE abundances of each fraction are given in Table 6, whereas the major element compositions of some grains in each fraction are given in Table 7. The fraction, $3.1<d<3.25$ g/cm^3, was not large enough to measure trace element abundances and Sr isotope ratios precisely. As shown in Table 7, most grains show Ca and Al-rich compositions similar to those of An(anorthite)-rich plagioclase. The compositions of the fraction suspended in acetone (here called "suspension") can be classified into two types. One is the most alkali-element rich component (Na_2O, 4.5–5.5% and K_2O, 1.5–2%) among any samples of the six fractions and another shows the relatively lower alkali-element abundances (Na_2O, 1–1.5% and K_2O, 0.5–2%). Among the grains, belonging to the suspension fraction, there are a few which show the composition of plagioclase clearly and this fraction has a composition which is alkali-element rich compared with other fractions. The fraction, of density between 2.9 and 3.1 g/cm^3, is composed chiefly of anorthite-rich plagioclase and as shown in Table 7, there is a grain that shows a variation of the major element composition among the parts in it. That is, the center of the crystal shows the composition of plagioclase clearly and near the part of its rim, the more Fe, Mg and alkali-element rich composition

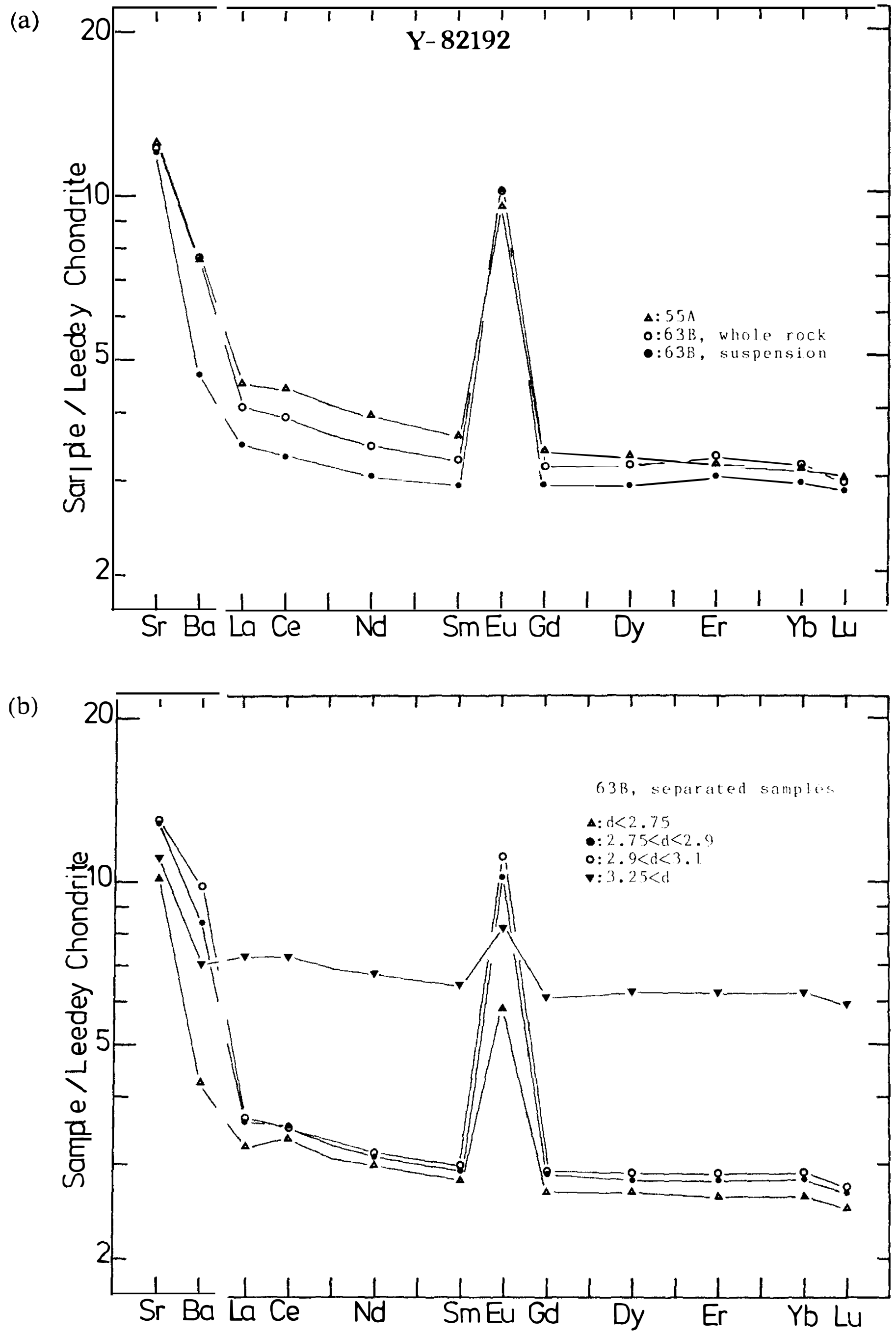

Fig. 7. The REE patterns of the samples from Y-82192. These are the separated samples by heavy liquids (see Fig. 1).

is found. This observation suggests that this meteorite has undergone a melting event, possibly impact melting. The lighter fractions, for example, those with $d < 2.75$ g/cm^3, include glassy materials and silica-rich components besides plagioclase.

The REE patterns of the samples from Y-82192, 63B are shown in Figs. 7a and 7b together with the pattern of Y-82192,55A. Generally, the REE abundances (except Eu) of the samples of Y-82192 are lower than those of the samples of Y-791197 (Fig. 2) and it is pointed out that these patterns show a relatively small Ce anomaly (maximum 6%). As mentioned above, the chip Sub No. 63B is regarded to be a melted sample and the chip Sub No. 55A is an unmelted sample. However, it is difficult to find distinct differences in the characteristics of REE patterns between Sub No. 55A and the whole rock of Sub No. 63B. In Fig. 8, we show the REE abundance ratios between the whole rock of Sub No. 63B and 55A in order to observe the fine structures of these REE patterns. The heavy REE (Gd-Lu) of Sub No. 63B can be regarded to be slightly enriched (or the lighter REE (La-Sm) slightly depleted relative to sample Sub No. 55A). Among meteorites, some of LL-chondrites have been known to show evidences for an impact melting event. According to the study by Okano *et al.* (1984) of these impact melted LL-chondrites, the Rb-Sr systems of these samples were disturbed and reset. However, the impact melted samples did not show distinct features. Likewise, one can see little difference between the melted sample (Sub No. 63B) and unmelted sample (Sub No. 55A). So it seems that REE patterns remained almost unchanged by the event which the sample, Sub No. 63B, has undergone, but the heavy REE seem to be influenced to a different degree from the light REE. Among the REE patterns of the separated samples, there are only slight differences except for the sample, with $d > 3.25$ g/cm^3. As inferred from the major element compositions (Table 6), this fraction is composed not only of Ca, Al-rich materials, but also of Fe, Mg-rich materials, such as olivine or pyroxene, and this feature would be reflected in the REE patterns also.

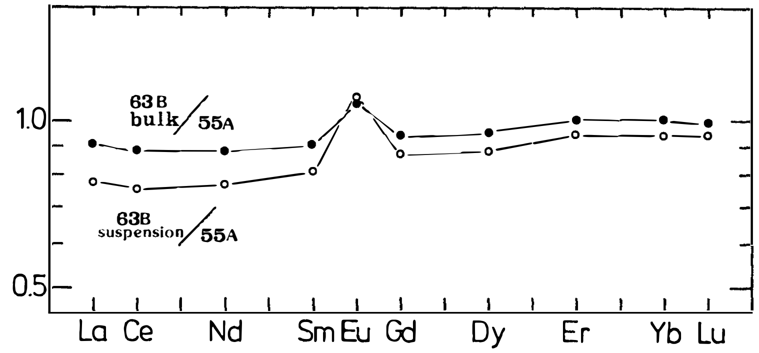

Fig. 8. The REE abundance ratios between SubNo. 55A and two samples of SubNo. 63B.

3.2.2. Rb-Sr systematics and Nd isotope ratios

Sr isotope analyses were performed for the separated samples from Sub No. 63B and for Sub No. 55A, and the results are shown in Table 8. As mentioned above, the chip Sub No. 63B is regarded as a melted part and Sub No. 55A represents an anorthositic breccia. The value of NBS 987 given in Table 8 is in good agreement

Table 8. *Rb-Sr systematics for the samples from Y-82192.*

Sample name	Amount (mg)	Sr (ppm)	Rb (ppm)	^{87}Sr/^{86}Sr ($\pm 2\sigma$)	^{87}Rb/^{86}Sr
Y-82192,63B (melted sample)					
whole rock	4.32	143.9	0.390	.699472±22	.007831
suspension	10.90	140.1	0.439	.699614±16	.009072
$d<2.75$	2.51	115.9	0.978	.699635±24	.02437
$2.75<d<2.9$	2.15	145.7	0.428	.699471±28	.008496
$2.9<d<3.1$	9.16	147.7	0.297	.699446±20	.005810
$3.25<d$	1.85	126.5	0.532	.699652±32	.012144
Y-82192,55A	132.29	140.8	0.284	.699356±20	.005832
NBS 987	—	—	—	.710237±12	—

with the value given in Table 4, so it is not necessary to adjust for biases as we compare the data in Table 7 with those in Table 4. Figure 9 is a plot of ^{87}Sr/^{86}Sr *vs.* ^{87}Rb/^{86}Sr and in this figure the solid line is the 3.95 b.y. line corresponding to the solid line in Fig. 6. The samples of Y-791197 are solid circles and those of Y-82192,63B are open triangles. Y-82192,55A lies on the 3.95 b.y. line and the whole rock of Y-82192,63B also lies near this line. However, for the separated samples from Sub No. 63B, the Rb-Sr systems are significantly disturbed. Of these six samples, four of them ($d<2.75$, $2.75<d<2.9$, $2.9<d<3.1$ g/cm^3 and the whole rock) fall nearly on a line, but two samples (suspension and the fraction $d>3.25$ g/cm^3) deviate from the line. This suggests that the Sr isotopic equilibrium in this chip had not been wholly established during the melting event. Alternatively, each of the two fractions, suspension and $d>3.25$ g/cm^3, might have belonged to separate system of the material which had been originally lying at the different positions from the whole rock or other samples of Sub No. 63B

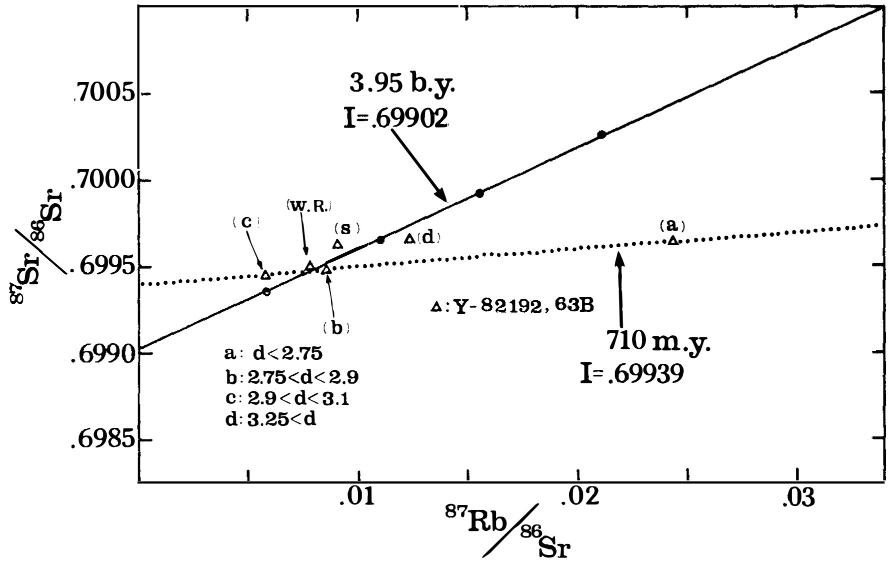

Fig. 9. *The plot of ^{87}Sr/^{86}Sr vs. ^{87}Rb/^{86}Sr for the samples from Y-791197 and -82192. The open circles indicate the data for Y-82192,55A and solid circles for Y-791197 (see Fig. 5). The dotted line is the calculated one from four samples of Y-82192, SubNo. 63B. (a: $d<2.75$, b: $2.75<d<2.9$, c: whole rock, d: $2.9<d<3.1$, W.R.: whole rock, S: suspension)*

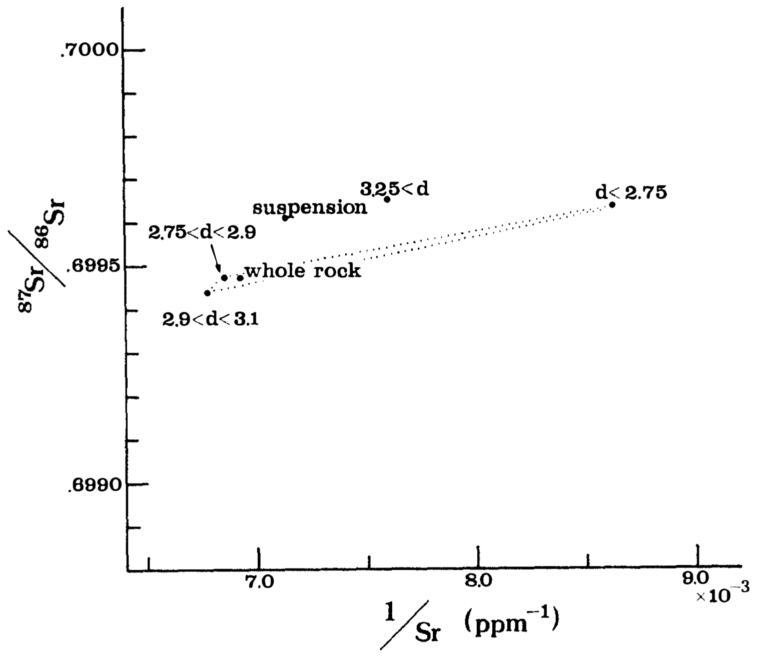

Fig. 10. The plot of $^{87}Sr/^{86}Sr$ *vs.* $1/Sr$ *(*ppm^{-1}*) for the samples of SubNo. 63B (Y-82192).*

on the 3.95 b.y. line. Four samples, except suspension and $d>3.25$ g/cm^3, define a line (dotted line in Fig. 9). The age calculated from this line is 709±114 million year and the initial ratio is 0.69939±6. As shown in Fig. 10, these samples do not fall on a line in a plot of ^{87}Sr/^{86}Sr *vs.* 1/Sr(ppm^{-1}). Therefore, the dotted line in Fig. 9 can be regarded to be an isochron and the age, 710 m.y., might be considered to indicate the age when these samples might have undergone an impact(?) melting event.

TAKAOKA also studied this chip, Sub No. 63 and reported that this sample has an ^{40}Ar-^{39}Ar age of about 4.0 b.y. (TAKAOKA, 1986). This report seems to be inconsistent with our result. We would like to propose the following interpretation: the impact melting 710 m.y. ago was not so intense and the duration of molten state was very short. As a result, loss of the radiogenic ^{40}Ar was very limited or substantially negligible for a bulk sample. For strontium isotopes, however, the isotopic homogenization was almost accomplished, followed by redistribution of Rb and Sr.

This impact melting event would not be related with the ejection of this meteorite from the surface of the moon, since no meteorites with such old exposure ages (using ^{21}Ne or ^{38}Ar etc.) are known. Possibly, an ejection event might have happened at a later stage. Among the Apollo samples, none with an age as young as 710 m.y. has ever been known. So Y-82192 appears to have originated far from the regions of the Apollo or Luna missions. Furthermore, it seems that an impact melting event affected some portions of this meteorite about 700 m.y. ago. There is a possibility that material preserving an evidence of impact melting exists around craters and that from such material the age of crater formation could be obtained.

In Table 9, we show the ^{143}Nd/^{144}Nd isotope ratio of Y-82192,55A with the ratios of the La Jolla standard and Juvinas. The data for the La Jolla standard and Juvinas are in good agreement with the data obtained by other workers (LUGMAIR and SHIMA-

Table 9. Nd-Sm systematics.

Sample name	Amount (mg)	Nd (ppm)	Sm (ppm)	$^{143}Nd/^{144}Nd$ ($\pm 2\sigma$)	$^{147}Sm/^{144}Nd$
Y-82192,55A	132.29	2.387	0.7040	.512079±10	.1783
Juvinas	185.05	3.981	1.2954	.512605± 6	.1967
La Jolla	—	—	—	.511855± 6	—

Nd isotope ratios are normalized to $^{144}Nd/^{146}Nd=0.7219$.
Y-82192,55A $\varepsilon_{Juv}(0)=-10.3\pm0.3$, $\varepsilon_{Juv}(3.9\text{ b.y.})=-1.0\pm0.3$.
$T_{ICE}=4.31\pm0.13$ b.y. ($\lambda=6.54\times10^{-12}$).

MURA, 1983 for La Jolla standard or LUGMAIR *et al.*, 1976 for Juvinas). Here let us consider the growth lines for Juvinas and Y-82192 to estimate the interception of those lines as well as the interception age, T_{ICE}. As shown in Table 9, $\varepsilon_{Juv}(0)$ is -10.3 ± 0.3, ε_{Juv}(3.95 b.y., the age from Rb-Sr systems) is -1.0 ± 0.3 and the model age, T_{ICE}, is 4.31 ± 0.13 b.y. From these data, the source material of Y-82192 is considered to have been originally formed at about 4.3 b.y. ago. If the REE patterns, especially Sm and Nd relative abundances, had been changed at 3.9 b.y. ago, the Nd model age would be changed. However, at present, the age of 3.9 b.y. obtained from the Rb-Sr system would be assumed to indicate the occurrence of a secondary alteration, perhaps caused by an intense bombardment by meteoroids, whereas the REE patterns are expected to have remained unchanged by such an event. The origin of the Ce anomaly shown in the REE patterns might be traced back to around 4.3 b.y. ago. These observations are consistent with those obtained for many lunar highland samples and it could be said that this meteorite preserves well the evidence of some events on the parental body, the moon.

4. Summary

As discussed above, the history of these two lunar meteorites, Y-791197 and -82192 might be described as follows:

(1) The Nd model age, T_{ICE}, 4.3 b.y.

At this stage, the source materials of these meteorite would have been originally formed in the same way as other lunar highland samples. Therefore, the REE patterns of these meteorites resemble closely those of other lunar highland samples. The Ce anomaly shown in the REE patterns presumably would have been brought about at this stage (by an oxic alteration?, as TANAKA *et al.*, 1985 suggests). However, it is not clear whether the Sr isotope compositions of the source materials might have been originally primitive, and similar to that in some inclusions in Allende, or whether at this stage radiogenic ^{87}Sr might have been taken away. The latter possibility would be favorable for the interpretation presented by TANAKA *et al.* (1985). Concerning this problem further study will be needed.

(2) The Rb-Sr age, 3.9–4.0 b.y.

This age would indicate a secondary event, such as bombardment by meteoroids. At this time the source materials were brecciated and mingled with other lunar highland materials, and each Rb-Sr system was reset, but on the whole (presumably on a scale of several centimeters of material) the isotopic equilibrium might not have been established.

(3) The Rb-Sr age, 710 m.y., for Y-82192,55A

At this stage, the source materials of Y-82192 would have been subjected to a partially re-melting event, possibly by an impact, and the Rb-Sr systems of some portions were disturbed. However the REE abundances would have remained almost unchanged by this event. At present, this event is not considered to be related with ejection of the meteorite from the moon.

The observations (1) and (2) can be also obtained for other lunar highland samples. Observation (3) is unique to Y-82192. This observation would suggests the possibility of measurement of ages of a crater formation. However, some problems remain, such as the primitive initial $^{87}Sr/^{86}Sr$ ratios and the Ce anomalies shown in some samples. Further studies of lunar meteorites and of the lunar samples brought back by Apollo and Luna missions will help us clarify these problems, and help us understand the history of lunar meteorites and the moon, as well.

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