REE, Rb-Sr and Pb ISOTOPIC CHARACTERISTICS OF THE YAMATO-791197 METEORITE: EVIDENCE FOR A LUNAR HIGHLAND ORIGIN

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Abstract: Rb-Sr systematics, Pb isotopic composition, and REE, Ba, Sr, Rb, K, Ca, Mg and Fe concentration analyses were carried out for matrix and clasts from the anorthositic breccia, Yamato-791197 meteorite. Major and trace element abundances in the matrix and clasts are similar to those in lunar anorthositic rocks. The estimated initial $^{87}Sr/^{86}Sr$ ratio for two anorthositic clasts at 4.55 b.y. is similar to the lunar initial ratio (LUNI) and lower than BABI, which is consistent with lunar origin of the meteorite. The LUNI model ages for two split of the matrix are 4.0 and 4.1 b.y., indicating that the Rb-Sr system of the matrix was perturbed by a late event. One matrix sample shows very high $^{207}Pb/^{204}Pb$ (=118–129) and high $^{207}Pb/^{206}Pb$ (=1.05) ratios which are characteristic of lunar anorthosite Pb, and which are unique among solar system samples thus far analyzed. One anorthositic clast shows a Pb isotopic composition similar to that of lunar soils or mare basalts. Consequently, the Pb data provide strong evidence for a lunar origin of the meteorite. Chemical compositions including high Pb concentrations together with very low $^{87}Sr/^{86}Sr$ ratios and unique Pb isotopic compositions suggest that the meteorite represents an unsampled type of lunar highland rock which may have formed at 4.55 b.y. and brecciated at $<$4.0 b.y.

1. Introduction

The Yamato-791197 meteorite is an anorthositic regolith breccia consisting of many white, gray and black clasts ($<$5 mm in diameter) in a black to brown glassy matrix (YANAI and KOJIMA, 1984a). Chemical characteristics, in particular the low MnO/FeO ratio in pyroxene and olivine, have led to the speculation that the meteorite may be of a lunar origin (YANAI and KOJIMA, 1984b). Since the first discovery of a similar unusual type of meteorite, ALHA81005 (18 papers published in the issue of Geophys. Res. Lett., **10** (9)), considerable work has been focussed on the chemical and petrologic nature of the ALHA meteorite. This work led to the conclusion that the meteorite may have been derived from the lunar highland crust. Unfortunately, ALHA81005 is rather small and so the isotopic and/or age characteristics have not been sufficiently examined. In order to obtain a better understanding and firm isotopic constraints on the source of the same type of meteorite, we have carried out Rb-Sr, and Pb, isotopic analyses together with chemical analyses for the matrix and two clasts from the Y-791197 meteorite.

2. Experimental

Three samples (subscript Nos. 74, 80 and 84) were allocated to us. Sample 74 (0.471 g) included numerous tiny clasts, sample 80 is a large gray clast (203 mg) and sample 84 (30 mg) consists of a white clast ($\sim$5 mg) and matrix. One part of sample 74 was used for Pb isotopic analyses and the rest was used for Rb-Sr and chemical examinations. During the initial stage of this work, we tried mineral separations for clast-80 and matrix-74 for Rb-Sr isotopic analyses by means of hand-picking and heavy liquids but we found that both the clast and matrix were primarily composed of glassy material and even when mineral grains were identified, the grain size was too small to enable us to collect sufficient pure separates. Finally, we performed analyses of only bulk matrix and clasts in this work.

All the chemical analyses in this work were carried out by the isotope dilution technique similar to that of NAKAMURA (1974b), except for K, Rb, Ca, Mg and Fe for which a direct-loading technique was applied. The samples were briefly washed with 1 N-HCl and distilled acetone before analyses. Except for Ba in two sample (matrix-74,1 and clast-80) blank contributions during chemical processes are less than 2%. Blanks on Ba for the two samples were $\lesssim$20%. Blanks for Rb-Sr system analyses were less than 1.5% for Rb and 0.05% for Sr. All the data (Tables 1 and 2) are corrected for the blanks.

Sr isotopic analyses were performed using a VG ISOMASS-54R mass spectrometer at the USGS (Denver). The $^{87}Sr/^{86}Sr$ ratios for the NBS 987 Sr standard were 0.71023–0.71026 with typical inrun precission of $\pm$0.000017–0.000030 for ^{88}Sr intensity of 2×10^{-12} A to 1.1×10^{-11} A (Fig. 1). No linearity corrections were required over

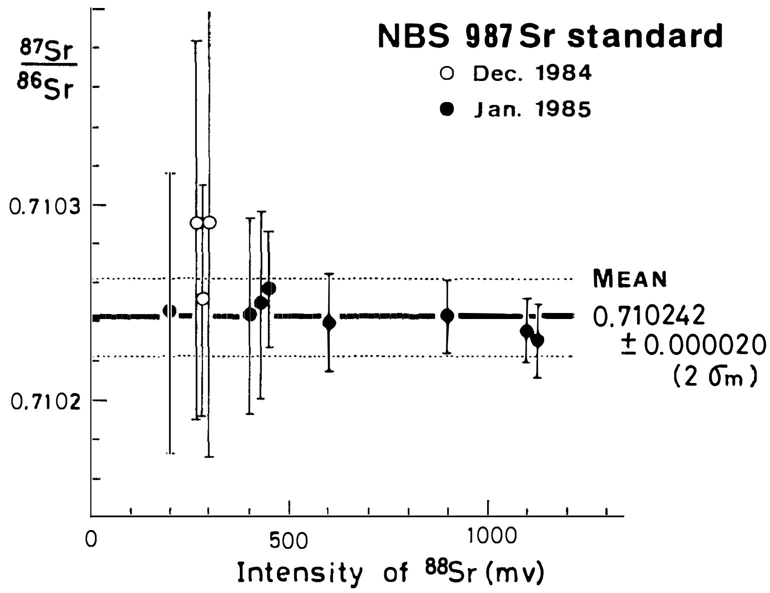

Fig. 1. Diagram for $^{87}Sr/^{86}Sr$ ratio vs. ^{88}Sr intensity obtained for NBS 987 Sr standard using a VG Isomass-54R mass spectrometer at USGS (Denver) during the period of this work.

this intensity range. The mean $^{87}Sr/^{86}Sr$ ratio was 0.710242±0.000020 ($2\sigma_m$) for 8 separate runs.

The specimens for Pb isotopic analyses were washed in 1.2 N-HBr for 10 min at room temperature prior to dissolution with $HF-HNO_3$. Both the acid leaches (L) and residues (R) were analyzed (TATSUMOTO and UNRUH, 1976).

The Pb blanks were 0.05 and 0.07 ng for clast-80 leach and residue, respectively, and 0.08 and 0.13 ng for the matrix leach and residue, respectively. The higher blanks for the matrix were traced to a contaminated HBr storage bottle. Blank uncertainties are ±20% as determined from duplicate blank analyses for each sample analysis. The ^{206}Pb blank/sample ratios were 0.02–0.05 for clast-80 and 0.012–0.013 for the matrix. Mass fractionation corrections of 0.12±0.03%/mass unit were applied to the Pb isotope data based on analyses of NBS standard SRM-982.

3. Results and Discussion

3.1. Chemical composition

Results of chemical analyses are given in Table 1 and Fig. 2. REE, Ba and Sr abundances in two matrix splits and clast-80 are quite similar to each other and to those of lunar anorthositic breccias, *e.g.* Apollo 64435 (HUBBARD *et al.*, 1974; JAMES *et al.*, 1984). The positive Eu anomaly of clast-80 is more prominent compared with the matrix, indicating that the clast is more anorthositic. The clast-84 sample shows a large positive Eu anomaly typical of lunar anorthosites. However, as for the case of the clast-80 and two matrix splits mentioned above, the general REE pattern is rather flat, which is not typical for most crystalline anorthosites such as Apollo 60025 (NAKAMURA *et al.*, 1973), but rather similar to those of cataclastsic ferroan anothosites.

Table 1. Chemical composition of matrix and clasts from the Y-791197 meteorite (concentrations are expressed in ppm unless otherwise stated).

Element	Y-791197,74	Y-791197,80	Y-791197,84	
	Matrix-1	Clast-80	Matrix-4	Clast-84
CaO (%)	15.0	17.2	—	19.6
MgO (%)	5.5	6.8	—	0.92
FeO (%)	5.6	6.0	—	0.96
K	—	—	208	52.1
Rb	0.705	0.313	0.515	0.0340
Sr	135.1	122.3	130.0	157.2
Ba	31	28	25.9	11.4
La	—	—	1.812	0.250
Ce	5.39	4.40	4.92	0.553
Nd	3.46	2.90	3.07	0.317
Sm	1.027	0.888	0.923	0.093
Eu	0.750	0.924	0.718	0.821
Gd	—	—	1.170	0.117
Dy	1.520	1.386	1.341	0.134
Er	0.980	0.916	0.883	0.087
Yb	0.950	0.935	0.865	0.082
Lu	0.1460	0.134	0.1300	—

The chemical compositions of the clasts, including major elements (Ca, Mg and Fe) and other trace elements are quite similar to those of anorthosites Apollo 67535, 67536 and 67539 (North Ray Crater; PALME *et al.*, 1984). Although the Ca abundance in this clast is the highest among lunar anorthositic rocks, relatively higher Mg and Fe abundances suggest that the clast contains a minor but significant amount of mafic minerals such as pyroxene which might contain relatively heavier REE. Therefore, the large positive Eu anomaly and the lower and flat REE pattern of the clast may be understood as the result of early crystallization of the anorthosite and minor pyroxene from a melt with chondritic relative REE abundances.

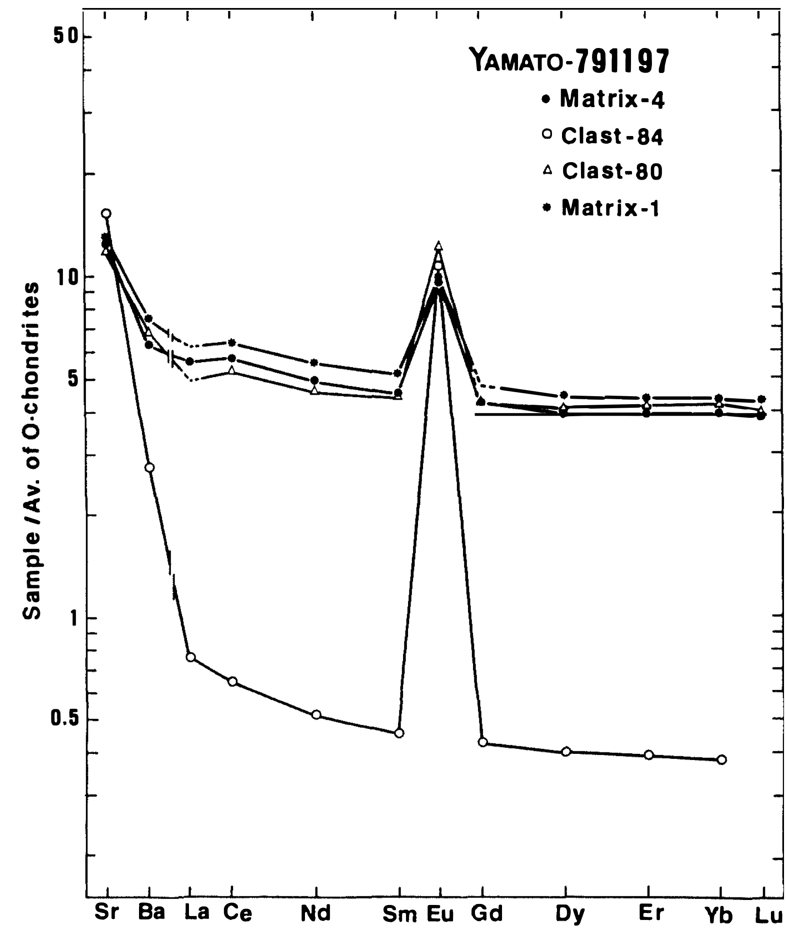

Fig. 2. Chondrite-normalized REE, Ba and Sr abundance patterns for matrix and clasts (−80 and −84) from the Y-791197 meteorite. Abundances are normalized to average of ordinary chondrites (NAKAMURA, 1974b).

In Fig. 2, it is worth noting that matrix-4 with similar absolute REE abundances shows positive Ce anomaly, but clast-84 with a highly anorthositic nature does not. NAKAMURA (1974a) pointed out that most lunar highland samples except anorthosite showed minor positive Ce irregularities, which is consistent with the present results if the meteorite represents a lunar sample. Similar Ce irregularities are also noted by TAKAHASHI *et al.* (1985).

Table 2. Results of Rb-Sr isotopic analyses for the Y-791197 meteorite.

Sample	Weight (mg)	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$*1	$^{87}Sr/^{86}Sr$*2	LUNI Model age*3
Matrix-1	1.19	0.705	135.1	0.0151	0.699945±33	4.14±0.23
-2	1.22	0.680	136.3	0.0145	0.699886±17	4.04±0.13
Clast-80	1.22	0.313	122.3	0.00728	0.699496±22	4.37±0.21
-84	0.39	0.108	175.2	0.00178	0.699142±18	4.30±0.81
Moore County (plag)	1.62	0.0591	135.9	0.00178	0.699066±17	
NBS 987 Sr standard (mean of 8 runs)					0.710242±20	

*1 Estimated errors are 1–3%.

*2 Ratios are nomalized to $^{86}Sr/^{88}Sr=0.1194$. Errors correspond to last digits and are the 95% confidence limit.

*3 Calculated using the lunar initial $^{87}Sr/^{86}Sr$ ratio (LUNI)=0.69903±3 (NYQUIST *et al.*, 1977) (re-normalized to NBS $^{87}Sr/^{86}Sr=0.710242$) and the decay constant $\lambda_{87}=1.42\times10^{-11}y^{-1}$.

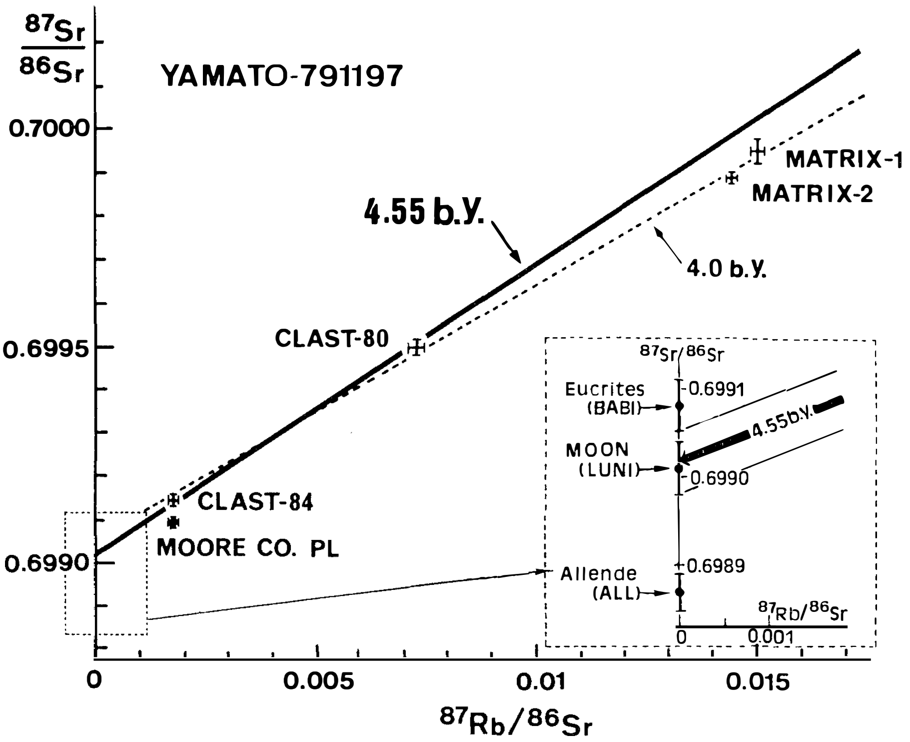

Fig. 3. $^{87}Rb/^{86}Sr$ evolution diagram for the Y-791197 meteorite. The data points of the clasts plot on the 4.55 b.y. reference line but the two matrix splits deviate to the right of the line. The linear array of four data points (matrix and clasts) yields an apparent isochron age of 4.03±0.23 (2σ) b.y. and an initial $^{87}Sr/^{86}Sr$ ratio of 0.69905±0.00003 (2σ). The inserted diagram shows comparison of initial $^{87}Sr/^{86}Sr$ ratios of Y-791197 meteorite with those of planetary materials. The initial $^{87}Sr/^{86}Sr$ ratio at 4.55 b.y. calculated from data sets of clasts (−80 and −84) is 0.699017±0.000016 (2σ), in agreement with the lunar initial $^{87}Sr/^{86}Sr$ ratio (bias-adjusted LUNI=0.69903±0.00003; NYQUIST et al., 1977). BABI from PAPANASTASSIOU and WASSERBURG (1969). ALL from GRAY et al. (1973).

3.2. Rb-Sr systematics

Results of Rb-Sr isotopic analyses are presented in Table 2 and Fig. 3. As found in Table 2, Rb abundances are rather variable from sample to sample. In particluar, the low Rb abundance in clast-84 is remarkable. Sr abundances (122–175 ppm) are normal for anorthositic rocks. Consequently, the $^{87}Rb/^{86}Sr$ ratios are extremely low, as typically found in the lunar anorthositic rocks (NYQUIST, 1974). In Fig. 2, it appears that the data points form a linear array. The slope of the line corresponds to an age of 4.03 ± 0.24 (2σ) b.y. and the intercept to an initial $^{87}Sr/^{86}Sr$ ratio of 0.69905 ± 0.00003 (2σ). On the other hand, the data points of the two clasts also plot on the 4.55 b.y. reference line whereas the two matrix samples deviate to the right of the line. We wish to point out that any data points on the 4.55 b.y. line between $^{87}Rb/^{86}Sr$ of 0.002 and 0.01 could yield a poorly defined apparent age of 3.8–4.1 b.y. which is similar to that calculated for these four data sets. In addition, in view of chemical and petrological features obtained here and by YANAI and KOJIMA (1984a), individual clasts, in general, do not appear to be co-genetic and to be sufficiently in equilibrium with each other as well as with the matrix. Hence, the apparent isochron age of 4.0 b.y. obtained here may be accidental and have no age significance. However, because the LUNI model ages of two matrix samples (Table 2) are significantly lower than 4.55 b.y., we suggest that the Rb-Sr system of these samples was perturbed by a later event (possibly at <4.0 b.y.), for example a strong impact which might have resulted in formation of glassy matrix materials.

Although most samples examined in this work are strongly-shocked and glassy, the primitive nature of the samples as shown by the Rb-Sr system and REE abundances of two clasts is important to estimate an initial isotopic ratio of the planetary source of the samples. Assuming that the Rb-Sr isotopic systems of these samples were closed since their initial formation at 4.55 b.y., and using two data sets of clast-80 and 84, a precise $^{87}Sr/^{86}Sr$ ratio at 4.55 b.y. is calculated to be 0.699017 ± 0.000016 (2σ) (Fig. 3). This value is in complete agreement with the lunar initial $^{87}Sr/^{86}Sr$ ratio (the bias adjusted LUNI$=0.69903 \pm 0.00003$) given by NYQUIST (1977), and is lower than the BABI ($=0.69907 \pm 3$; PAPANASTASSIOU and WASSERBURG, 1969) but significantly higher than the Allende initial (ALL$=0.69886 \pm 2$; GRAY *et al.*, 1973), when the inter-laboratory bias is adjusted.

3.3. Pb isotopic composition

The Pb isotopic compositions determined from clast-80 (20 mg chip) and matrix are shown in Table 3 and Fig. 4, together with the data from selected lunar samples taken from the literature. Also shown are the data fields for mare basalts and unequilibrated chondrites (UC), terrestrial oceanic basalts, and Nakhla. The geochron (4.55 b.y.) is defined primarily by eucrites and equilibrated ordinary chondrite (EOC) data.

Growth curves for $\mu=700$ and $\mu=180$ ($\equiv {}^{238}U/^{204}Pb$) are shown for reference in Fig. 4. The Pb isotopic ratios in a rock that formed 4.55 b.y. ago with $\mu=700$ and that remained a closed system throughout its history would evolve along the curve shown and would eventually reach the geochron at $^{206}Pb/^{204}Pb=727$ at T=0. Different μ values will, of course, produce different growth curves that intersect the geochron at

Table 3. Results of Pb isotopic analyses for Y-791197 meteorite.

Sample	Pb (ppm)	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	$^{207}Pb/^{206}Pb$	$^{208}Pb/^{206}Pb$	S. stage model age** (m.y.)
Clast-80-L*	0.0348	65.6±1.5	59.7±1.5	79.3±1.5	0.9104±10	1.2085±78	5053
R*	0.0920	178.4±6.9	116.4±4.8	188.8±7.8	0.6524±8	1.0584±41	4573
(total)	0.1268						
Matrix-74							
-L*	0.427	109.6±1.8	129.1±2.3	114.8±1.5	1.1774±13	1.0469±33	5457
-R*	0.861	108.2±1.9	118.0±2.3	113.6±1.8	1.0904±10	1.0493±32	5356
(total)	1.287						

* L and R represent 1.2 N-HBr leach (cold) and residue fractions, respectively.
** Single stage model age calculated using Pb isotopic composition of Canyon Diablo troilite. (TATSUMOTO *et al.*, 1973).

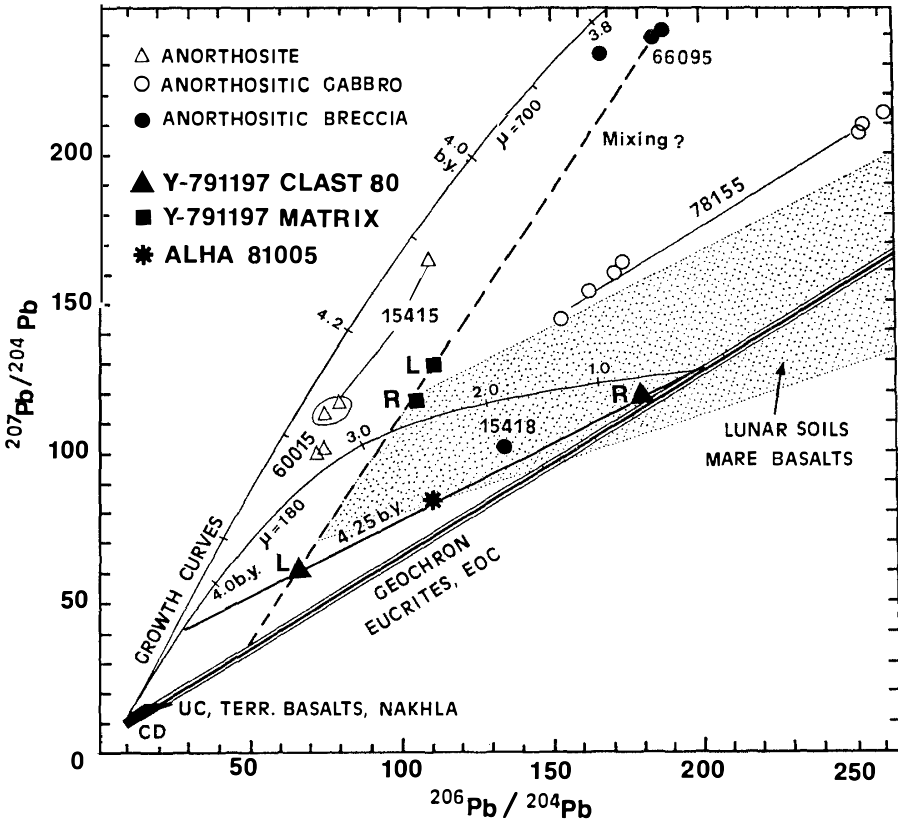

Fig. 4. $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ diagram for the Yamato-791197 meteorite and selected lunar samples. The L and R represent 1.2 N-HBr leach and residue fractions, respectively. (UC=unequilibrated ordinary chondrite; EOC=equilibrated ordinary chondrite; CD= Canyon Diablo troilite). Growth curves for μ=700 and 180 are shown for reference. The tie-line connecting L and R of clast-80 yields an apparent age of 4.25 b.y. that intersects the 4.25 b.y. primary isochron at a point corresponding to an initial μ of 180.

various $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ values. Most meteorites have evolved in such a manner so that virtually all meteorite data plot within the small envelope surrounding the geochron or the UC, terrestrial basalt, Nakhla field.

Both the clast-80 and matrix data plot significantly above the geochron which indicates a minimum two-stage history involving evolution in a high μ environment followed by a drastic decrease in μ. This type of evolution has been observed only among lunar samples, in particular lunar anorthosites and anorthositic breccias. Thus we believe the Pb data provide the most compelling evidence to date for a lunar origin for Y-791197.

The leach fraction of clast-80 plots significantly above the geochron in the direction of lunar anorthositic rocks, but its Pb is not as radiogenic as that in typical lunar samples. The residue fraction is much more radiogenic, but plots only slightly above the geochron. The total Pb abundance of clast-80 is 0.127 ppm, about half that in anorthosite 15415, but similar to that in breccia 15418 (TATSUMOTO *et al.*, 1974).

Both the leach and residue of the matix have quite high $^{207}Pb/^{204}Pb$ and high $^{206}Pb/^{204}Pb$ ratios similar to lunar anorthosite Pb. However, the Pb abundance (1.29 ppm) is 5–7 times higher than that of Apollo 15415 and 60005 (TATSUMOTO *et al.*, 1974) and 10 times higher than that in clast-80. However, anorthositic breccia Apollo 66095 (rusty rock) is still 10 times more enriched in Pb (15 ppm) than the matrix (NUNES and TATSUMOTO, 1973).

The line connecting the leach and residue of clast-80 corresponds to an age of 4.25 b.y. (Fig. 4) and an initial $^{238}U/^{204}Pb$ ratio (4.55–25 b.y.) of 180. This inital μ value is at least a factor of 2 lower than in most lunar samples. Thus, if the meteorite did come from the moon, there must be still a significant amount of non-radiogenic non-lunar Pb or Pb from unsampled lunar material in the meteorite.

As noted above, the clast has a much lower Pb content than the matrix. Thus, the clast is much more susceptible to terrestrial Pb contaminations than the matrix, and the possibility of contamination during sample processing and handling should be considered. Given this possibility, then most of the terrestial Pb would probably have been removed by the leaching and the apparent 4.25 b.y. age would represent a maximum age. However, we note that the Pb data from clast in ALHA81005 analyzed by CHEN and WASSERBURG (1985) plot on the tie-line for clast-80 within experimental error. Thus, we tentatively conclude that terrestrial Pb contamination in the clast is probably not significant, and that the non-radiogenic component in the clast was derived either from the projectile or an unsampled, low-μ portion of the moon. In any case, the evidence in Fig. 4 for at least three isotopic components in Y-791197 (80-L, 80-R, and matrix) suggests that the apparent 4.25 b.y. age has no rigorous significance. It is quite possible that the clast-80 leach Pb is a mixture of matrix Pb and projectile Pb (brokenline in Fig. 4), whereas the clast-80 residue Pb represents indigenous lunar Pb that is not genetically related directly to the matrix Pb, *i.e.* the target material was a breccia or regolith prior to the impact. This interpretation is consistent with that obtained from the REE data previously discussed.

In summary, the chemical compositions obtained in this work for the Yamato-791197 meteorite indicate that the meteorite represents an anorthositic breccia which contains clasts similar to lunar cataclastic ferroan anorthosites. The initial $^{87}Sr/^{86}Sr$ ratio for the meteorite is similar to the lunar initial ratio (LUNI). The Rb-Sr model age calculated from the matrix data suggests that the meteorite may have been brecciated at $<$4.0 b.y. Both the matrix and clast of the meteorite have high $^{207}Pb/^{204}Pb$

and $^{207}Pb/^{206}Pb$ ratios similar to those of lunar samples, particularly lunar anorthosites. Because the isotopic characteristics of lunar anorthositic rocks are distinct among solar system materials thus far analyzed, the Pb data provide convicing evidence for a lunar origin for Y-791197. However, the limited data accrued to date do not provide any strict information regarding the age of the breccia or the impact event.

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