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Rb-Sr FEATURES OF THE IMPACT-MELTED LL-CHONDRITES FROM ANTARCTICA: YAMATO-790723 AND YAMATO-790528

Hirokazu FUJIMAKI[1], Ken-ichi ISHIKAWA[2] and Ken-ichiro AOKI[1]

[1] *Institute of Mineralogy, Petrology, and Economic Geology, Tohoku University, Aoba, Sendai 980*

[2] *College of General Education, Tohoku Univeristy, Kawauchi, Sendai 980*

Abstract: Rubidium and strontium abundances as well as Sr isotopic compositions were analyzed for the impact-melted meteorites (LL-chondrite: Yamato-790723 and -790528) from Antarctica to clarify their Rb-Sr features and to date the impact events. The samples were separated according to the magnetic property. The less magnetic and glass-rich portions of Y-790723 approximate an isochron of 1.27±0.19 Ga. The obtained age should indicate the impact event. The magnetic portions and fine-grained one largely deviate from the isochron. Y-790528 is rather depleted in K_2O and Rb, but not in Na_2O; this may be due to scarcity of the K-rich fragments. The $^{87}Sr/^{86}Sr$ ratios of the separated portions from Y-790528 are low and less variable. The five less magnetic portions of the Y-790528 chondrite seem to form the isochron of 4.36±0.76 Ga as the time of the impact event. The large errors may have derived from local reset of the Rb-Sr chronometer and incomplete separation into the portions.

1. Introduction

The impact events recorded in ordinary chondrites have been dated by the K-Ar and ^{40}Ar-^{39}Ar methods (*e.g.*, PODOSEK, 1972; BOGARD *et al.*, 1976; BOGARD and HIRSCH, 1980; TAKIGAMI and KANEOKA, 1987). In contrast, the successful results are rare in the age determination of the impact by the Rb-Sr method (GOPALAN and WETHERILL, 1971; MINSTER and ALLÈGRE, 1979; NAKAMURA and OKANO. 1985; NAKAMURA *et al.*, 1990). This may be due to a near-total reset of the K-Ar chronometer, but an incomplete reset of the Rb-Sr one. Although the asteroid impacts on the parent bodies could have heated up enough to release Ar, complete or near-complete fusion might not have been achieved to redistribute Rb and Sr. Since many deformed chondrules and lithic fragments can be observed in most of the impact-melted chondrites, the Rb-Sr chronometer might not have been fully reset by the impact events in most cases. Undoubtedly, the Rb-Sr method is not advantageous to date the impact events. The K-Ar method, however, involves such difficulties as the Ar loss during the penetration into the atmosphere and by the following impact with the earth. The ^{40}Ar-^{39}Ar method has also some problems associated with the irradiation since ^{39}Ar may be lost by recoil (*e.g.*, TURNER and CADOGAN, 1974). Therefore, the impact events must be dated not only by the ^{40}Ar-^{39}Ar (K-Ar) method, but by the Rb-Sr method as well to examine whether both ages agree within an acceptable difference. This contributes to the chronological investigation of the impacts. In this paper, we report the Rb-Sr features of the partially-melted LL-chondrites from Antarctica and discuss the significance of the obtained Rb-Sr isochrons.

2. Samples and Experiments

Two LL-chondrites (Y-790723 and Y-790528) from Antarctica were selected for experiments; both are melted to some extent and have many vesicles. The general description of the Yamato-79 chondrites was already reported (YANAI, 1981; YANAI *et al.*, 1981; SATO *et al.*, 1982; HARAMURA *et al.*, 1983). OKANO *et al.* (1984, 1990) also described Y-790723. Y-790723 is believed to be included in the group of Yamato-79 shock-melted chondrites (OKANO *et al.*, 1984). They tried to date the impact event recorded in Y-790723 by the Rb-Sr method as well, but it was not successful. In comparison with the other chondrites, their appearances do not differ much. Each is slightly altered and has some slightly reddish-brown stains. All the chondrules and lithic fragments are deformed and set in rather glassy fine-grained matrices. Sulfide mineral is hardly found.

The water used in each experiment in this report was prepared by the MILLI-Q purification system of MILLIPORE. HF and HCl were sub-boiled to lower the blanks. $HClO_4$ used in this experiment was MERCK Ultrapur reagent. The abundances of Rb and Sr were measured by the isotope dilution method using ^{87}Rb and ^{86}Sr spikes. The measured $^{87}Rb/^{85}Rb$ and $^{86}Sr/^{88}Sr$ ratios were corrected for mass fractionation. The Rb and Sr blanks for the isotope dilution analysis are 10 picograms and 80 picograms, respectively. The errors with mass spectrometry of Rb and Sr abundances are better than 0.2%. The total errors, however, are little larger than 0.2%, including the standard and spike preparations, the weight measurements of the spike and the samples, and aliquoting the samples. The blank correction was applied to the analytical results.

The NBS 987 Sr standard has been analyzed repeatedly for the last three years and the $^{87}Sr/^{86}Sr$ ratios normalized to $^{86}Sr/^{88}Sr=0.1194$ are 0.71023 ± 2. The error associated with each analytical run is as small as 10^{-6} level on the basis of 95% confidence level, but the reproducibility is worse. Usual Sr impurity associated with the isotope composition analysis is less than 180 picograms, and it was lowered to less than 100 picograms for this experiment. Since more than 800 nanogram (usually more than 1 microgram) Sr was used for the composition analyses, the effect of the blanks may not be so serious. The reported results here, however, are corrected for the blanks.

The samples provided by NIPR were washed for six hours in hot water in an ultrasonic cleaner to leach out water-soluble impurities. The leached substances were too small to measure their weights. After the samples were dried, they were softly crushed to smaller than 100 mesh. The crushed samples were then put in acetone to exclude exceedingly fine powder. A pinch of the fine powder suspended in acetone was collected. Since the recent successes are the results of good sample preparation mostly by the magnetic separation (NAKAMURA and OKANO, 1985; NAKAMURA *et al.*, 1990), we also employed a similar technique. Using a hand magnet the crushed sample powder was separated into six portions in alcohol. First we removed metal grains using a very weak magnet. The most magnetic portions, however, contain fine-grained metallic globules that we could not separate. The magnet intensity was controlled by the number of thin plastic films covering the magnet. We checked the separation by microscopic observation and by an X-ray diffraction method. The magnetic portions (M1 of Y-790723 and 790528 and M2 of Y-790723) contain olivine with a smaller amount of orthopyroxene and a much smaller amount of clinopyroxene. Those magnetic portions contain nearly no glass. In a rough estimate, the amount of olivine decreases from M1 to M3 and does not change from M3 to M6. Pyroxenes do not change significantly in quantity among the separated portions. Glass is included in all the less magnetic portions.

The 80–140 mg samples were decomposed in clean HF with HNO_3, and a few drops of $HClO_4$. After the solutions were evaporated, the dried cakes were dissolved in 1.8 N HCl. Then each was divided into two; the Rb and Sr composite spike was added to an aliquot of each sample. Sr and Rb were extracted by the cation exchange columns. The analysis has been carried out with a MAT 261 mass spectrometer.

The eluted HCl was collected and FeO, MnO, MgO, CaO, Na_2O, and K_2O were further analyzed by the conventional methods such as flame photometry and atomic absorption spectrometry. The analysis has been performed rigidly and the precision is better than 2 percent for CaO, MnO, Na_2O, and K_2O, and better than

Table 1. Rb, Sr abundances (ppm) and Sr isotopic compositions for the separated fractions from Y-790723.

Fraction	Rb	Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	2 sigma
M1	5.52	11.99	1.347	0.82483	±0.00004
M2	9.93	13.46	2.169	0.87450	±0.00004
M3	10.39	14.15	2.170	0.92296	±0.00003
M4	14.69	16.02	2.709	0.92166	±0.00004
M5	7.02	5.46	3.799	0.93619	±0.00003
M6	20.70	25.87	2.362	0.91358	±0.00006
S	12.95	24.56	1.544	0.83347	±0.00004
W				0.77641	±0.00035

Table 2. Rb, Sr abundances (ppm) and Sr isotopic compositions for the separated fractions from Y-790528.

Fraction	Rb	Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	2 sigma
M1	0.879	11.52	0.211	0.71284	±0.00005
M2	0.945	15.42	0.177	0.71430	±0.00004
M3	1.216	17.73	0.199	0.71569	±0.00004
M4	1.277	20.64	0.179	0.71451	±0.00006
M5	1.330	15.93	0.242	0.71846	±0.00006
M6	0.979	15.90	0.178	0.71449	±0.00005
S	2.113	23.54	0.260	0.71598	±0.00004
W				0.71765	±0.00008

a few percent for MgO and FeO as far as the instrumental reproducibility is concerned. Some of the solution might have been lost during chemical procedures, however. Sometimes a tiny droplet remains in a micro pipette and in a centrifuge tube. Thus those problems with the aliquoting and extraction procedures will double, or may triple the error and lower the accuracy. We tried to recover all the droplets, but could not perfectly overcome those difficulties. The analytical results of the major elements should be treated for a rough and general examination.

3. Results

The analytical results of the Sr isotopic compositions with the Rb and Sr concentrations are shown in Table 1 for Y-790723 and Table 2 for Y-790528. The errors associated with the Sr isotopic compositions are 2 sigma mean. The results of the major element are in Tables 3 and 4. M1 is the most magnetic portion, and M6 is the least magnetic portion. S is the fine-grained powder suspended in acetone. W indicates hot-water soluble impurities.

Y-790723

The most magnetic portion (M1) is highly rich in iron probably due to unremoved fine metal grains. Less magnetic portions are less iron-rich. The K_2O content does not vary much among the portions. The iron contents seem to be roughly correlated with the order of magnetic intensity. The calculated $^{87}Rb/^{86}Sr$

Table 3. Some major elements (wt%) in the separated fractions from Y-790723

Sample	CaO	MnO	MgO	FeO	Na_2O	K_2O
M1	0.95	0.31	13.5	68.4	0.78	0.16
M2	1.58	0.33	22.6	29.3	1.12	0.21
M3	1.66	0.34	22.6	25.6	1.15	0.22
M4	1.56	0.35	24.5	24.9	1.04	0.23
M5	1.51	0.33	24.1	23.4	0.99	0.21
M6	1.48	0.33	22.8	22.9	1.02	0.18
S	1.86	0.30	21.1	33.0	1.69	0.25

Table 4. Some major elements (wt%) in the separated fractions from Y-790528

Sample	CaO	MnO	MgO	FeO	Na_2O	K_2O
M1	1.17	0.25	16.0	48.0	0.71	0.02
M2	1.61	0.32	24.2	28.0	1.07	0.07
M3	1.61	0.34	25.1	25.9	1.07	0.07
M4	1.36	0.36	25.2	26.1	0.88	0.08
M5	1.50	0.36	25.9	26.3	0.93	0.03
M6	1.73	0.34	23.7	26.7	0.97	0.10
S	2.01	0.30	20.0	31.8	1.44	0.13

ratios appear to be positively correlated with the FeO content, and so do the $^{87}Sr/^{86}Sr$ ratios. The $^{87}Sr/^{86}Sr$ ratios of Y-790723 are as high as those reported by OKANO *et al.* (1990). Figure 1 is the isochron plot of the analytical results for Y-790723.

M1 and M2 contain abundant olivine and a minor amount of pyroxenes. Under the microscope, small amounts of cryptocrystalline materials (and metal in M1) and glass can be noticed in both portions, but nearly no glass was detected by the X-ray examinations. The mineral fragments in M1 and M2 seem mostly free from glass or cryptocrystalline materials. This may indicate that although both relict and recrystallized minerals must be included, M1 and M2 consist mainly of abundant relict mineral fragments. Thus they are not expected to be on the isochron of the impact age. M3, M4, M5, and M6 consist mainly of cryptocrystalline to microcrystalline materials and glass. Clear mineral fragments are rare in those portions. Some glass may be the primary glass included in the deformed and relict chondrules as OKANO *et al.* (1990) indicated. Such primary glass is small in amount in the thin sections. Although we could not exclude the primary glass from the less magnetic portions, we believe that the effect may not be so serious. M3, M4, M5, and M6 are expected to lie around an isochron indicating the impact age. Since both reset of the Rb-Sr clock and the separation seem incomplete, we imposed rather large errors on the results in the age calculations (0.015% for $^{87}Sr/^{86}Sr$ and 2% for $^{87}Rb/^{86}Sr$). The isochron was drawn by M3, M4, M5, and M6 in Fig. 1, The calculated age is 1.27 Ga, but the associated uncertainty is as large as 0.19 Ga (2 sigma). The initial ratio is 0.8751±0.0035. Although the uncertainty is con-

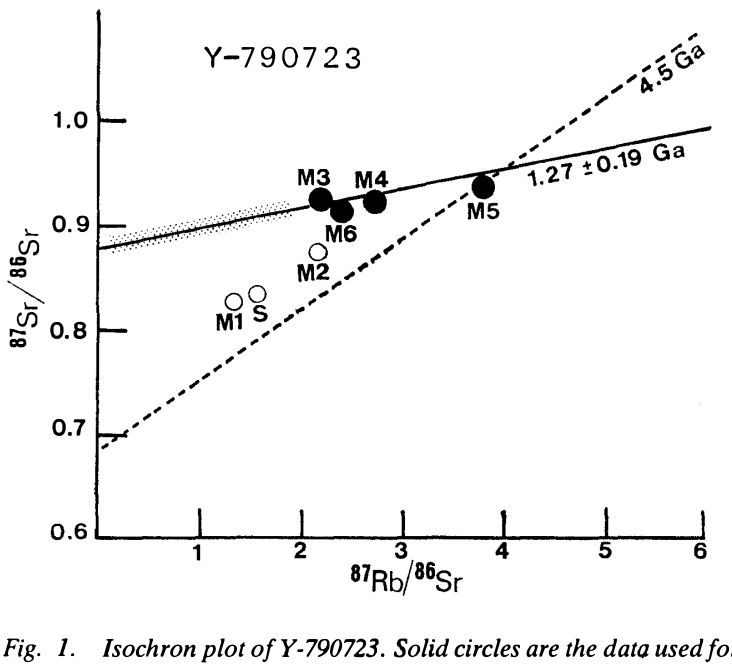

Fig. 1. Isochron plot of Y-790723. Solid circles are the data used for age calculation. Open circles are not included in the calculation. The age is 1.27±0.19 Ga and its initial ratio is 0.8751±0.0035. The dashed line is 4.5 Ga reference line that has 0.699 as the initial $^{87}Sr/^{86}Sr$ ratio. See text for the shaded area.

siderable, the calculated age is similar to that obtained for Y-790964 by NAKAMURA and OKANO (1985) and TAKIGAMI and KANEOKA (1987). The large uncertainty may be due to incomplete separation and to local reset of the Rb-Sr clock by the impact.

OKANO *et al.* (1990) reported the whole rock $^{87}Sr/^{86}Sr$ ratios for the different chips of Y-790723. One is rather low, but the other is high, and the reported highest value of the separated portion is 1.01430 (OKANO *et al.*, 1990). The Y-790723 chondrite has considerably variable $^{87}Sr/^{86}Sr$ ratios. The obtained $^{87}Sr/^{86}Sr$ ratios are high and this indicates that the analyzed chips were enriched in Rb, and thus the sample chip included the abundant K-rich fragments such as indicated by WLOTZKA *et al.* (1983).

It should be pointed out that the isochron is not a mixing line of the unmelted materials and the melted products. Note the 4.5 Ga reference isochron in Fig. 1; if the isochron is a mixing line, the unmelted materials should be around the crossing point of the 1.27 Ga and 4.5 Ga lines, and the melted products should plot somewhere in the shaded area along the 1.27 Ga line (Fig. 1). This leads to such an assumption as follows; the unmelted materials have high Rb/Sr ratios, but the melted materials have low Rb/Sr ratios. When an impact melts the rock on the parental body, the easily melted areas in the rock should be enriched in the low-temperature melting components such as K and Rb. Therefore, the melted areas in the sample chip must have been more enriched in Rb and should have had higher Rb/Sr ratios than the unmelted areas. Accordingly, melted material have higher Rb/Sr and $^{87}Sr/^{86}Sr$ ratios than the unmelted materials. All those expectations disagree with the assumption mentioned above, and thus the 1.27 Ga isochron in Fig. 1 is not a mixing line.

Y-790528

The most iron-rich portion should contain many metal globules like M1 of Y-790723. M1 and S of Y-790528 seem rich in FeO, and M3 is poorest in FeO among all. The order of magnetic intensity is not exactly correlated with the FeO content if no loss can be assumed during the chemical procedures. The analyzed major element abundances are similar to those of Y-790723 except K_2O (Table 4). Y-790528 is rather poor in K_2O in comparison with Y-790723, and is also poor in Rb but not Na_2O. If K_2O and Rb have vaporized when the asteroid hits the parent body, first of all Na_2O should vaporize from the surface rocks. It would not be easy to vaporize K_2O and Rb but not Na_2O by such a process. Therefore, the cause of the relative depletion of Rb and K_2O may be due to scarcity of the K-rich fragments (WLOTZKA *et al.*, 1983).

The $^{87}Sr/^{86}Sr$ ratios of the separated portions of Y-790528 are rather low and the variations are narrow compared with Y-790723 because of the low Rb abundance and its small variation. The lowest $^{87}Sr/^{86}Sr$ ratio has been obtained from the analysis of the most magnetic portion. This is coincident with Y-790723. The X-ray examination made clear that M1 contained nearly no glass, but M2 of Y-790528 includes abundant glass. The other portions contain glass as well. The variations of the $^{87}Sr/^{86}Sr$ ratios are also narrow. M2, M4, and M6 have nearly the similar

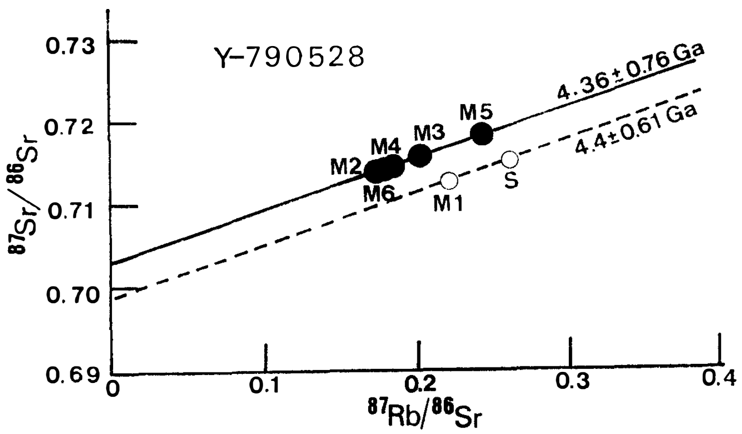

Fig. 2. Isochron plot of Y-790528. Solid circles are the data used for the impact age calculation. Open circles are not used in the calculation. The obtained age is 4.36±0.76 Ga with the initial $^{87}Sr/^{86}Sr$ ratio of 0.7030±0.002. The dashed line is to connect the remaining points of M1 and S. The inclination of the line corresponds to 4.4 Ga and the line intersects at 0.6992±0.004. The error was estimated separately using the deviations.

$^{87}Sr/^{86}Sr$ and $^{87}Rb/^{86}Sr$ ratios and accordingly they are plotted in almost the same area in Fig. 2. The data are plotted in Fig. 2 to check whether they make an isochron. Line 1, consisting of the five data points of M2, M3, M4, M5, and M6, is possibly an isochron indicating the impact age of 4.36±0.76 Ga. The estimated errors in the age calculation are the same as those used in the impact age calculation for Y-790723. The obtained initial ratio is 0.7030±0.002. Line 2 is not a regression line and was drawn to connect the two points. The obtained age may reveal that Y-790528 memorizes an impact right after its parent body formation. Line 2 may not be significant, but the inclination of line 2 corresponds to the age of 4.4±0.6 Ga and the intersection with the vertical axis 0.6992±0.004. The error was separately calculated using the estimated deviations. The errors associated with ages and initial ratios are so large, and this should be attributed to either local reset of the Rb-Sr chronometer or incomplete separation, or both. Furthermore, the age difference between lines 1 and 2 is so small. Thus we admit that although line 1 seems to form an isochron, it may not make sense.

4. Conclusion

Antarctic LL-chondrites (Y-790723 and Y-790528) have been investigated by means of Rb-Sr systematics. The less magnetic portions from Y-790723 seem to form an isochron corresponding to the age of 1.27 Ga. Since the less magnetic portions consist mainly of the abundant glass and mixtures of the recrystallized phases, the age should indicate the impact event. Considering that the high initial ratio of Y-790723, K- and Rb-rich portions might have been selectively melted in the impact event. The large uncertainty may be due to the incomplete separation and to local reset of the Rb-Sr clock. Y-790528 is rather poor in K_2O and Rb.

The $^{87}Sr/^{86}Sr$ ratio of every portion from Y-790528 is low and less variable in comparison with Y-790723. Five less magnetic portions of Y-790528 make a line with an inclination comparable to 4.36 Ga. Although the obtained line can be interpreted as an isochron indicating the time of the impact event right after the formation of its parent body, the significance of the age is not clear yet.

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