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Rb-Sr isotopic systematics of lherzolitic shergottite Yamato-793605

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Abstract: We have undertaken a Rb-Sr isotopic study of the lherzolitic shergottite, Yamato (Y)- 793605. The acid-leaching experiment designed to remove secondary Pb contamination during previous work with U-Th-Pb systematics did not significantly affect the Rb-Sr systematics. A Rb-Sr internal isochron obtained for combined data of leachates and residues yielded an age of 173±14 Ma with an initial $^{87}Sr/^{86}Sr$ ratio of 0.71042±0.00007, using $\lambda(^{87}Rb) = 1.402 \times 10^{-11} y^{-1}$. The Rb-Sr age, initial $^{87}Sr/^{86}Sr$ ratio and trace element abundance pattern of Y-793605 are all similar to those of lherzolitic shergottites, ALH 77005 and LEW 88516. We favor the 173 Ma age for the time of igneous crystallization, because this interpretation is more consistent with characteristics of both the isotopic systematics and mineral chemistry. A minor disturbance of U-Pb systems observed in residue fractions indicate that shock event(s) occurred more recently, without affecting Rb-Sr system.

1. Introduction

One of the most characteristic features of Martian meteorites is their young crystallization ages. The nakhlites and Chassigny give a concordant age of about 1.3 Ga using Ar-Ar, Rb-Sr, Sm-Nd and U-Th-Pb isotopic systems (*e.g.*, Podosek, 1973; Gale *et al.*, 1974; Bogard and Husain, 1977; Wooden *et al.*, 1979; Nakamura *et al.*, 1982a, b; Shih *et al.*, 1996). On the other hand, numerous chronological studies on the shergottites, another clan of Martian meteorites, gave younger ages of 153–474 Ma (Bogard *et al.*, 1979; Nyquist *et al.*, 1979, 1995, 2000; Shih *et al.*, 1982; Chen and Wasserburg, 1986, 1993; Jagoutz, 1989; Jagoutz and Wänke, 1986; Borg *et al.*, 1997, 1998, 2000; Misawa *et al.*, 1997; Bogard and Garrison, 1999). The interpretation of younger ages for shergottites is controversial, because subsequent shock metamorphism affected the isotopic systematics. The younger ages for shergottites are important towards understanding the latest igneous activity on the parent body, possibly Mars.

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Yamato (Y)- 793605 is the third lherzolitic shergottite identified and shows close similarity to Allan Hills (ALH) 77005 and Lewis Cliff (LEW) 88516 in its mineralogy and petrology (Yanai, 1995, 1996; Mikouchi and Miyamoto, 1996a, b). Both K-Ar (Nagao *et al.*, 1997) and ^{39}Ar-^{40}Ar (Bogard and Garrison, 1999) ages for Y-793605 yield 1.4–1.9 Ga. These are, however, interpreted as apparent ages because of the presence of trapped ^{40}Ar components. We have previously undertaken U-Th-Pb isotopic analysis (Misawa *et al.*, 1997). Using a modified concordia diagram (Tera and Wasserburg, 1972), a chord through the data for both the pyroxene leachate and residue fractions intersects concordia at 4439 ± 9 Ma and 212 ± 62 Ma, suggesting a young disturbance event resulting in Pb loss.

As part of a consortium study, we have undertaken a Rb-Sr isotopic study of Y-793605 to understand the younger event and reveal the genetic relationship between Y-793605 and the other lherzolitic shergottites.

2. Experimental procedure

The samples used in this study were the same ones used earlier by Misawa *et al.* (1997) and were, therefore, subject to three-step, acid-leaching experiments to remove secondary Pb contamination. In order to make the following discussion clear, we will briefly describe the procedures for mineral separation and the leaching experiments.

The sample was crushed and divided into three size-fractions ($<63\,\mu$m, 63–150 μm, 150–300 μm). Olivine (OL) was hand-picked from the 150–300 μm fraction. Three separates (two pyroxene-rich phases: PX1 and PX2, and maskelynitized plagioclase: PL) were obtained from the 63–150 μm fraction using a Frantz isodynamic separator. The PX1 fraction is more magnetic than PX2 and contains shock-melt. The finest fraction ($<63\,\mu$m) was used as the whole-rock fraction (WR). The four separates and the whole-rock sample were first leached three times in 0.01 M HBr (L1), then leached three times in 0.1 M HBr (L2) and finally leached twice in 1 M HNO_3 (L3).

The leachates and residues were spiked with three (^{233}U-^{236}U-^{230}Th-^{205}Pb, ^{87}Rb-^{84}Sr, and ^{149}Sm-^{150}Nd) mixed tracer solutions. After complete decomposition, the samples were passed through an anion exchange column for U, Th, and Pb separation. All eluate before and after U, Th and Pb fractions were recovered, and dried down. Rubidium and Sr were separated from major elements by Dowex AG 50W-X12 cation exchange columns with HCl and HNO_3. Owing to the use of large amounts of reagents for previous U-Th-Pb analyses, the total blanks are larger than those of conventional Sr analyses. For residue samples, the analytical blanks of Rb and Sr are 60 pg and 280 pg, respectively. The blanks for leachate samples are about 4–6 times lower than that for residue samples. However, the blank contributions to age calculations and initial ^{87}Sr/^{86}Sr ratios are negligible, because most of Rb and Sr reside in this residue and blank contributions to the residue phases are typically less than 0.2%.

Rubidium and Sr isotopes were measured at Kobe University on a Finnigan MAT 262 mass spectrometer equipped with one fixed and four movable Faraday cups and an electron multiplier. All isotopic data were acquired in the single static mode. Strontium was measured using single W-filaments with Ta-oxide + H_3PO_4 activator (Birck, 1986). Samples with at least 10 ng of Sr were measured with $^{88}Sr^+$ ion beam intensities of 1×10^{-11}A. Some leachate samples, with typically less than 10 ng Sr available, were run with $^{88}Sr^{+}$ beam intensities of $0.5–1\times10^{-11}$A. Each mass spectrometer run consists of forty blocks of eleven ratios. The $^{87}Sr/^{86}Sr$ ratio was corrected using a simultaneously determined $^{85}Rb/^{86}Sr$, assuming natural Rb isotopic composition. ^{85}Rb were not observed during the course of Sr measurement (less than 1×10^{-14}A). After on-line correction for ^{87}Rb interference, the raw data were further corrected for instrumental mass fractionation and spike contribution. Strontium isotopic compositions were normalized to $^{88}Sr/^{86}Sr=8.37521$. Thirty analyses of NIST SRM 987 during the course of this study gave an average normalized $^{87}Sr/^{86}Sr$ value of 0.710268 ± 0.000014 (2σ).

Rubidium was loaded with concentrated HNO_3 on an outgassed Ta-filament with phosphoric acid and measured on a Re-Ta double filament mode. The $^{87}Rb^{+}$ beam intensities were kept at $0.7–2\times10^{-11}$A. Quoted uncertainties in the $^{87}Rb/^{86}Sr$ ratios reflect only the precision of the mass spectrometer analyses. For leachate samples, the $^{87}Rb/^{85}Rb$ ratios exceed 10, sometimes up to 78 ($^{87}Rb/^{85}Rb$ ratio of the spike solution was 117). The large errors observed for some leachate samples are mainly due to the expansion of errors because of the correction for spike contributions. Each mass spectrometer run consists of five blocks of eleven ratios. The raw data were corrected for an instrumental mass fractionation of 2.3 ± 0.3 per mil, based on twelve analyses of NIST SRM 984 (Steiger and Jäger, 1977) during the course of this study.

The decay constant for ^{87}Rb used in this paper is $\lambda(^{87}Rb)=1.402\times10^{-11}y^{-1}$ (Begemann *et al.*, 2001). The Rb-Sr isochrons were defined using algorithms of Ludwig (1991) which use the regression methods of York (1969).

3. Results and discussion

3.1. *Sr isotopes*

3.1.1. Leaching experiment

Preferential extraction of U and Th occurred during acid leaching experiments (Misawa *et al.*, 1997). We thus have to examine whether Rb-Sr fractionation also occurred or not.

The Sr and Rb analytical results are given in Table 1. As shown in Fig. 1, 94–97% of Rb remained in the residues in all mineral concentrates and the whole-rock sample, which contrast with the situation reported for U, Th and Pb. Strontium proved to be more leachable (8–23%) than Rb, especially in 0.01 M HBr. In the OL, PX1 and PX2 fractions, 10–16% of Sr was leachable in 0.01 M HBr. In the PL and WR fractions, small amounts (2–7%) of Sr were removed during the 0.01 M HBr treatment. The $^{87}Rb/^{86}Sr$ ratios vary from 0.053 to 0.138 in the leachates, and these values are always lower than those of their corresponding residues (Fig. 2), indicating that Sr was selectively leached out and/or a phase with low Rb/Sr was dissolved during the leaching process.

The Rb-Sr isotopic systematics of the Y-793605 residue and leachate fractions are shown in Fig. 3. If the best-fit line is drawn using the residue data only, a 165 ± 10 Ma (MSWD$=13.1$) age with an initial $^{87}Sr/^{86}Sr$ ratio of 0.71043 ± 0.00007 is obtained. The data points of all the leachates plot at the lower left portion of Fig. 3a and are

Table 1. Rb-Sr data for leachates and residues of Y-793605 mineral separates.

Sample	Weight(g)	Rb(ng)	Sr(ng)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
1st leachates					
OL	0.11344	0.69	31.0	0.064 ± 0.004[$]	0.710994 ± 0.000018[$]
PX1	0.03093	0.26	11.4	0.054 ± 0.008	0.710692 ± 0.000023
PX2	0.0691	0.43	19.5	0.064 ± 0.006	0.710825 ± 0.000019
WR	0.10199	1.20	60.2	0.0577 ± 0.0009	0.710838 ± 0.000021
PL	0.00609	0.484	25.4	0.055 ± 0.005	0.710607 ± 0.000016
2nd leachates					
OL	0.11344	0.29	9.7	0.088 ± 0.013	0.710573 ± 0.000018
PX1	0.03093	0.26	7.8	0.098 ± 0.011	0.710748 ± 0.000041
PX2	0.0691	0.25	5.1	0.14 ± 0.02	0.710842 ± 0.000065
WR	0.10199	1.61	81.1	0.0576 ± 0.0008	0.710724 ± 0.000014
PL	0.00609	0.384	14.9	0.075 ± 0.003	0.710630 ± 0.000026
3rd leachates					
OL	0.11344	0.28	7.2	0.11 ± 0.01	0.710657 ± 0.000041
PX1	0.03093	0.27	5.63	0.14 ± 0.02	0.710597 ± 0.000032
PX2	0.0691	0.23	5.1	0.13 ± 0.04	0.710309 ± 0.000071
WR	0.10199	1.08	29.4	0.106 ± 0.002	0.710605 ± 0.000017
PL	0.00609	0.496	19.3	0.074 ± 0.004	0.710551 ± 0.000016
Residues					
OL	0.11047	39.9	150	0.768 ± 0.001	0.712227 ± 0.000016
PX1	0.02644	13.0	108	0.349 ± 0.002	0.711239 ± 0.000022
PX2	0.06227	21.7	101	0.619 ± 0.002	0.711853 ± 0.000013
WR	0.09424	94.6	1030	0.266 ± 0.001	0.710982 ± 0.000023
PL	0.00473	22.3	692	0.0962 ± 0.0002	0.710660 ± 0.000011
Total					
OL	0.11344	41.2	198	0.601 ± 0.001	0.711896 ± 0.000016
PX1	0.03093	13.8	135	0.296 ± 0.002	0.711128 ± 0.000022
PX2	0.0691	22.6	131	0.499 ± 0.003	0.711600 ± 0.000013
WR	0.10199	98.5	1030	0.237 ± 0.001	0.710948 ± 0.000023
PL	0.00609	24.4	751	0.0939 ± 0.0003	0.710655 ± 0.000011

[$] Errors for concentration ratios and Sr isotopic compositions are 2 sigma and 2 sigma of the mean, respectively.

scattered around the best-fit line. The data points of first leachates define a linear array (Fig. 3b). When the $^{87}Sr/^{86}Sr$ ratios are plotted against 1/Sr (ppm^{-1}), the data show a linear trend, strongly indicating a two component mixing. Considering that most of U and Th and large amounts of Sr were present in the leachates, one possible end member with a low $^{87}Sr/^{86}Sr$-ratio and $^{87}Rb/^{86}Sr$-ratio (high Sr-concentration) is explained by the dissolution of phosphate. Phosphates were observed, but now altered, in Y-793605 (Ikeda, 1997; Mittlefehldt *et al.*, 1997). The high $^{87}Sr/^{86}Sr$ ratios of the OL, L1, PX2, L1 and WR, L1 fractions may have been inherited from the high $^{87}Sr/^{86}Sr$ ratios of olivine and/or pyroxene. It is possible that Sr was selectively leached out from these minerals. The other end member with a high $^{87}Sr/^{86}Sr$ ratio and low Sr-

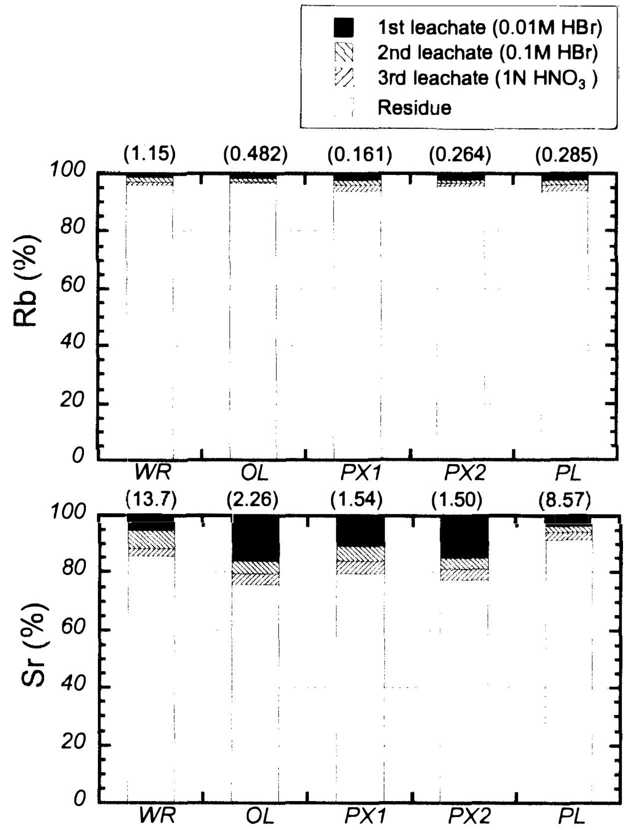

Fig. 1. Abundances of Rb and Sr in the four mineral concentrates and a whole-rock fraction from Y-793605 at different leaching steps. Values in parentheses are total amounts of Rb and Sr (in nanomoles). Up to 97% of the Rb and 85% of the Sr reside in the residue fractions, which is in contrast to the U and Th (Misawa et al., 1997).

concentration is thus considered to correspond to the extracted component from the olivine or pyroxene fractions.

Borg *et al.* (1998) showed that the LEW 88516 mineral separate-leachate pairs appeared to define an age of about 90 Ma. Tie lines between each first leachate and corresponding residue of Y-793605 define an age between 120–130 Ma from their inclination. However, these ages are uncertain in view of the selective leaching of Sr into leachates, causing obvious fractionation during leaching experiments.

Because small Rb-Sr fractionations took place during the leaching experiment, the best-fit line defined by residue data is not necessarily a useful isochron and its corresponding age may not be meaningful. Corrections for the Rb-Sr fractionations must be undertaken before a meaningful isochron age can be obtained.

3.1.2. Rb-Sr systematics

We have to correct for the effect of Rb-Sr fractionation by combining the residue data with that of each leachate for all fractions. The combined whole-rock data of Y-793605 is shown in Fig. 4 together with the data from other shergottites. The whole-rock data for the shergottites define BABI model ages of approximately 4.5 Ga, which has been interpreted to represent the time of planetary differentiation (*e.g.*, Shih *et al.*, 1982). The whole-rock datum of Y-793605 plots on the right side of the 4.5-Ga

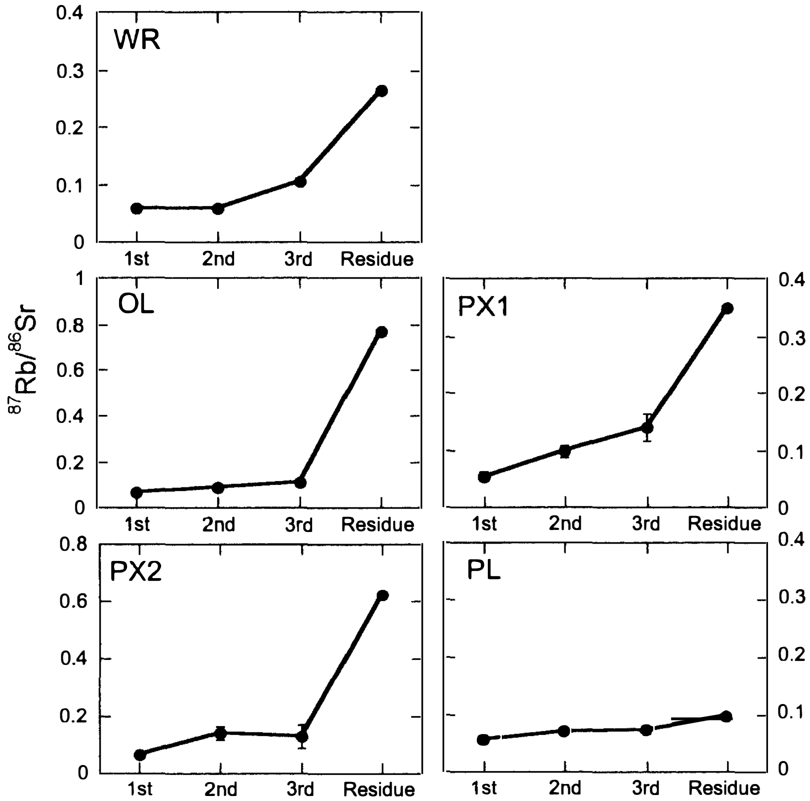

Fig. 2. *$^{87}Rb/^{86}Sr$ ratios in the five fractions from Y-793605 at different leaching steps. $^{87}Rb/^{86}Sr$ ratios in the leachates are always lower than those in the corresponding residue phases.*

reference line and yields a model age of 3.46±0.01 Ga by using the initial Sr isotopic ratio of BABI (Papanastassiou and Wasserburg, 1969). This model age for Y-793605 does not correspond to the older intercept age of the U-Pb concordia diagram (4.4 Ga; Misawa *et al.*, 1997) and may not be meaningful at all. The whole-rock data of ALH 77005, Shergotty, Zagami, Elephant Moraine (EET) 79001, and Queen Alexandra Range (QUE) 94201, are scattered and thus show various model ages (Shih *et al.*, 1982; Wooden *et al.*, 1982; Jagoutz, 1989; Borg *et al.*, 1997). There are two possible explanations for the deviation of whole-rock data of shergottites. One explanation is that the whole-rock samples exhibit open system behavior. The other is that sampling heterogeneity exists within whole-rock portions from these meteorites. In the case of sampling heterogeneity, the whole-rock data for ALH 77005, Shergotty, and Zagami all plot on, but are shifted along, their internal isochron lines (see Fig. 4). Heterogeneous distribution of maskelynitized plagioclase (Ikeda, 1997) with low Rb/Sr ratio may be responsible for the whole-rock Rb-Sr heterogeneity. Although there is only one whole-rock datum, we suggest that the young model age for Y-793605 can be attributed to the sampling heterogeneity by analogy with the other meteorite data.

When the Rb and Sr data for the leachates are combined with those for the residues for each fraction, the combined data yield an isochron age of 173±14 Ma (MSWD= 12.5) using λ (^{87}Rb) = $1.402\times10^{-11}y^{-1}$ and an initial ratio of 0.71042±0.00007 (Fig. 5). Table 2 summarizes the Rb-Sr internal isochron ages and initial $^{87}Sr/^{86}Sr$ ratios for

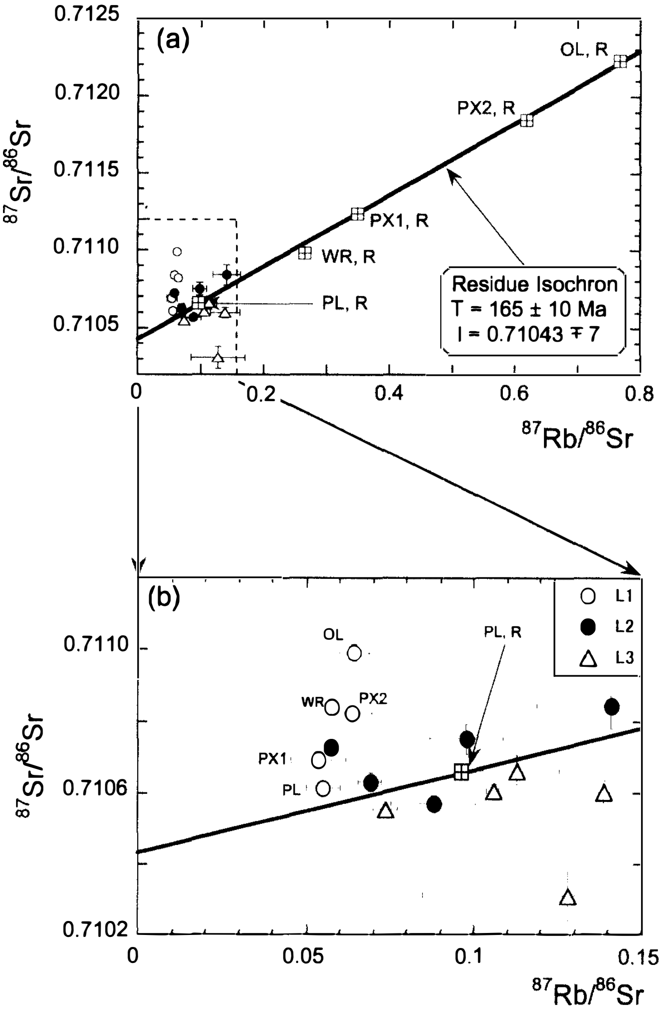

Fig. 3. $^{87}Sr/^{86}Sr$ vs. $^{87}Rb/^{86}Sr$ diagram of Y-793605 for leachate and residue fractions. The best-fit line was drawn using the residue data and yields a 165 ± 10 Ma age with an initial ratio of 0.71043 ±0.00007. Uncertainties are reported at the 95% confidence limit. The data points of all the leachates plot in the lower left portion (a) and are scattered around the best-fit line.

shergottites. All ages are recalculated using the decay constant for ^{87}Rb of $1.402 \times 10^{-11} y^{-1}$. The Rb-Sr internal isochron age of 170 Ma for Y-793605 is in good agreement with that obtained for ALH 77005 (Shih *et al.*, 1982) and for LEW 88516 (Borg *et al.*, 1998), but slightly older than the age of ALH 77005 (Jagoutz, 1989). The U-Th-Pb isotopic data for ALH 77005 and LEW 88516 also indicate that a young event occurred at 170–180 Ma (Chen and Wasserburg, 1986, 1993). The initial $^{87}Sr/^{86}Sr$ ratio of Y-793605 is in excellent agreement with that of ALH 77005, but about 170 ppm lower than that of LEW 88516 (Borg *et al.*, 1998). The internal isochron ages of three basaltic shergottites, EET 79001, Los Angeles, Shergotty and Zagami, are similar to those of lherzolitic shergottites (Nyquist *et al.*, 1979, 1995, 2000; Shih *et al.*, 1982; Wooden *et al.*, 1982; Jagoutz and Wänke, 1986), but that of QUE 94201 (327 ± 12 Ma; Borg *et al.*, 1997) and the Sm-Nd age of Dal al Gani (Dag) 476 (474 ± 11 Ma; Borg *et al.*, 2000) are exceptionally older than other shergottites. The Rb-Sr age of Dag 476

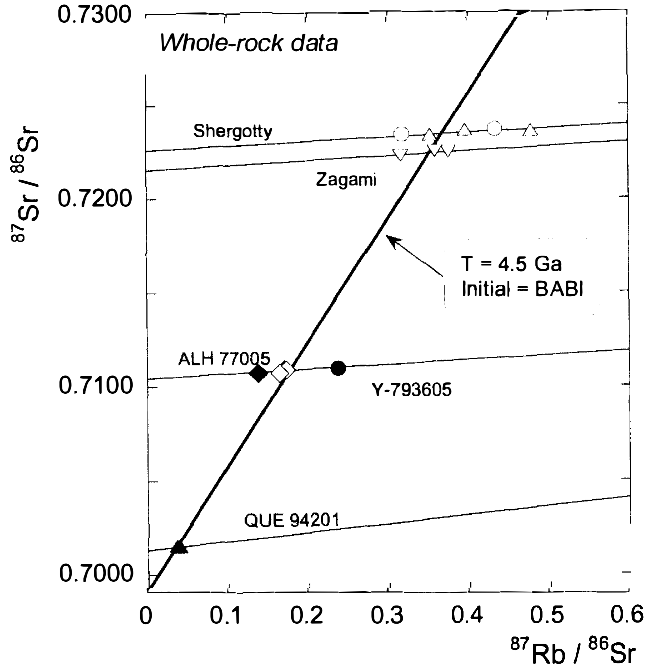

Fig. 4. Whole-rock Rb-Sr data for Y-793605, ALH 77005, QUE 94201, Shergotty and Zagami with individual mineral isochrons and the 4.5 Ga reference line relative to BABI (Papanastassiou and Wasserburg, 1969). BABI = 0.69918 on our scale. Data shown by open triangles and open circles for Shergotty are from Nyquist et al. (1979) and Jagoutz and Wänke (1986), respectively. Data shown by open and filled diamonds for ALH 77005 are from Shih et al. (1982) and Jagoutz (1989), respectively. The data of Zagami are from Shih et al. (1982), and of QUE 94201 are from Borg et al. (1997). Reference isochrons are also shown for the 164 Ma internal isochron age of Shergotty, the 178 Ma of Zagami and the 185 Ma of ALH 77005 (Nyquist et al., 1979; Shih et al., 1982).

could not be obtained because this meteorite was affected by terrestrial calcite contamination (Borg *et al.*, 2000).

The combined olivine datum has the highest Rb/Sr ratio among data from all the fractions of Y-793605. Considering the partition coefficient between olivine and there should be a low Rb/Sr ratio. Magmatic inclusions are commonly observed in Y-793605 olivine (Ikeda, 1997; Mikouchi and Miyamoto, 1997). The EPMA data indicate that some inclusions show high concentration of K_2O. This finding suggests that the high Rb/Sr ratio of our olivine fraction reflects the characteristics of magmatic inclusions as discussed by Jagoutz (1989) for ALH 77005.

3.2. Genetic relationships among lherzolitic shergottites (Y-793605, ALH 77005 and LEW 88516)

From mineralogy and petrology, Mikouchi and Miyamoto (1997) suggested that Y-793605 would have followed a crystallization history similar to ALH 77005 and LEW 88516 as proposed by Harvey *et al.* (1993), who concluded that Y-793605 originated from the same igneous body or rock as ALH 77005 and LEW 88516. For Y-793605, both REE elemental abundances and their pattern (Ebihara *et al.*, 1997; Warren and Kallemeyn, 1997; Morikawa *et al.*, 1998) are similar to those of ALH 77005 and LEW

Table 2. The Rb-Sr internal isochron ages and initial Sr isotopic rations of shergottites.

Meteorite	Age (Ma)#	Initial $^{87}Sr/^{86}Sr^{\$}$	Reference
Lherzolitic shergottites			
Y-793605	173±14	0.71042 ± 0.00007	This Work
ALH 77005	185±12	0.71037 ± 0.00005	Shih *et al.* (1982)
	153± 6	0.71042 ± 0.00002	Jagoutz (1989)
LEW88516	183±10	0.71052 ± 0.00006	Borg *et al.* (1998)
Basaltic shergottites			
EET 79001	172±10	0.71217 ± 0.00003	Wooden *et al.* (1982)
	183±25	0.71243 ± 0.00007	Wooden *et al.* (1982)
Los Angeles	165±11	0.72100 ± 0.00005	Nyquist *et al.* (2000)
QUE94201	327±12	0.70130 ± 0.00001	Borg *et al.* (1997)
Shergotty	163±11	0.72260 ± 0.00012	Nyquist *et al.* (1979)
	166	0.72263 ± 0.00005	Jagoutz and Wänke (1986)
	357±12	0.72188 ± 0.00005	Jagoutz and Wänke (1986)
Zagami	178± 4	0.72145 ± 0.00005	Shih *et al.* (1982)
	186± 5	0.72227 ± 0.00005	Nyquist *et al.* (1995)
	183± 6	0.72160 ± 0.00006	Nyquist *et al.* (1995)

: These ages are recalculated, applying the decay constant of ^{87}Rb for $1.402 \times 10^{-11} y^{-1}$.
$: Not corrected the machine bias.

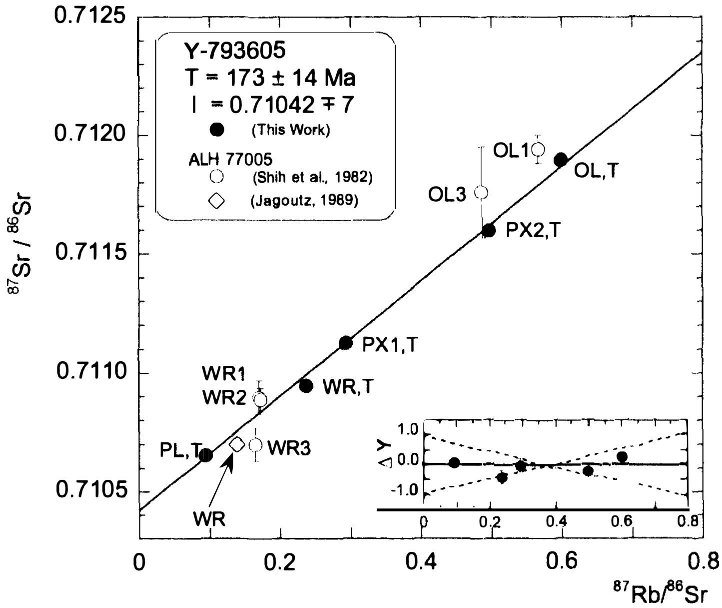

Fig. 5. $^{87}Sr/^{86}Sr$ vs. $^{87}Rb/^{86}Sr$ diagram for the combined data of Y-793605. The best-fit line is drawn using the combined data and yields an 173±14 Ma age with an initial ratio of 0.71042±0.00007. Uncertainties are reported at the 95% confidence limit. Insert shows deviations of measured $^{87}Sr/^{86}Sr$ ratios from the best-fit line, in parts in 10^4. For comparison, the data of whole-rock and olivine fractions from ALH 77005 (Shih et al., 1982; Jagoutz, 1989) are also plotted together.

88516 (*e.g.*, Shih *et al.*, 1982; Dreibus *et al.*, 1992; Treiman *et al.*, 1994; Warren and Kallemeyn, 1996; Gleason *et al.*, 1997), and also imply that these three meteorites originated from similar parent melts.

The olivine fraction in Y-793605 has similar Rb/Sr and $^{87}Sr/^{86}Sr$ ratios to the ALH 77005 (see Fig. 5) and LEW 88516 olivine (Borg *et al.*, 1998). Olivine appears first during the crystallization sequence of lherzolitic shergottites (*e.g.*, Harvey *et al.*, 1993; Ikeda, 1997; Mikouchi and Miyamoto, 1997) and could have trapped parent melt. If this was the case, the Rb/Sr ratio of olivine reflects the characteristics of the parent melt. Thus, similar Rb/Sr ratios in olivine suggest that olivines from Y-793605 crystallized from a compositionally similar melt as those from ALH 77005 and LEW 88516.

Similarities among three lherzolitic shergottites are also shown in their post-formation history. The average cosmic-ray exposure age (4.4 ± 1.0 Ma) of Y-793605 based on cosmogenic ^{3}He, ^{21}Ne and ^{38}Ar agrees with that of ALH 77005 and LEW 88516 (Eugster and Polnau, 1997). The ejection time from Mars of Y-793605 was calculated to be 4–5 Ma, and agrees within errors with that obtained for ALH 77005 and LEW 88516, suggesting that these three meteorites were ejected from the parent body by the same ejection event (Eugster and Polnau, 1997).

Unfortunately, there is no evidence to conclude that Y-793605 is paired with ALH 77005 and LEW 88516. Trace element and isotopic signatures imply that these three lherzolitic shergottites originated from a similar geological source on Mars as suggested by Harvey *et al.* (1993) and Mikouchi and Miyamoto (1997). The 170-Ma event of interest must have recorded the same event either by igneous crystallization or shock-related thermal metamorphism (and/or melting).

3.3. *Ages for Y-793605 and lherzolitic shergottites*

There are many arguments on the age of shergottites, because chronological data obtained showed extremely young (170–180 Ma) ages and these ages are not concordant with different isotopic systems. In order to resolve this, the model that the 180-Ma age reflected shock metamorphism was introduced by Bogard *et al.* (1979) and Nyquist *et al.* (1979). Jones (1986) argued for the diffusion of major and trace elements; since olivine remained strongly zoned, it is reasonable to expect that any subsolidus thermal metamorphism experienced by the shergottites would have been insufficient to have reset Rb-Sr and U-Th-Pb chronometers. He also suggested that zonation of Na in maskelynite could not be supported for Sr resetting model by thermal metamorphism. For Y-793605, Ikeda (1997) and Mikouchi and Miyamoto (1997) observed Cr-Al-Ti or Mg-Fe zoning in chromite and zonation of Ca in pyroxene. Wadhwa *et al.* (1999) reported Fe-Mg zoning within the poikilitically enclosed olivine. According to the diffusion arguments by Jones (1986), these observations for Y-793605 indicate that thermal metamorphism was not intense enough to reset the Rb-Sr and U-Pb isotopic systems. Considering the nearly complete resetting of the Rb-Sr systematics, the 170-Ma age seems to record the time of crystallization. Formation by crystallization from a magma is more plausible than derivation from shock-induced melt in order to explain the observed chemical zoning and cumulative texture.

Rubidium-Sr internal isochron ages of about 170 Ma are also reported for ALH 77005 (Shih *et al.*, 1982) and LEW 88516 (Borg *et al.*, 1998). A concordia plot using the data from the whole-rock residue and its leachates also yields an age of about 170 Ma for ALH 77005 and LEW 88516 (Chen and Wasserburg, 1986, 1993). We interpret that the concordance of the Rb-Sr and U-Pb age seems to record the time of crystallization.

For U-Pb systematics of Y-793605, a young disturbance event (212 ± 62 Ma) resulting in Pb loss was inferred from Tera-Wasserburg concordia diagram (Misawa *et al.*, 1997). We previously interpreted the 212 ± 62 Ma-age as resulting from shock disturbance. This age overlaps, within error limits, with the Rb-Sr internal isochron age presented here. If the Pb loss and the resetting of Rb-Sr systematics recorded the same event, certain mechanisms are required to redistribute Rb and Sr only, but not affect the U-Th-Pb systematics and other major elements, because only PX1 fractions define the 212 ± 62 Ma-line. On a $^{207}Pb/^{206}Pb$-$^{204}Pb/^{206}Pb$ diagram, many leachate data lie off a tie line between a 210-my-old radiogenic Pb and the olivine residue, and shift towards the data point of the blank (See Figs. 4 and 8 in Misawa *et al.*, 1997). If our leaching procedure was effective to remove terrestrial Pb contamination, the intrinsic Pb isotopic composition of each mineral phase would be represented by the residue data. Even for the residue data, not all data points plot on this tie line, indicating a disturbance of U-Pb systems.

It is difficult to judge whether or not a concordant age between Rb-Sr and U-Pb systematics was obtained for Y-793605. However, we prefer a derivation by igneous crystallization because this model is more consistent with the mineral chemistry and the fact that a concordant age between Rb-Sr and U-Pb systematics was obtained from other lherzolitic shergottites. If the 173-Ma event records the time of igneous crystallization, the event(s) that disturbed the U-Pb systems in Y-793605 residue fractions probably occurred more recently, without affecting the Rb-Sr system.

4. Conclusion

We have undertaken Rb-Sr isotopic studies for the samples after acid-leaching experiments of Y-793605 lherzolitic shergottite. The results are as follows:

(1) In contrast to the U-Th-Pb systems, extreme preferential extractions of elements during leaching were not observed within the Rb-Sr systematics.

(2) The Rb-Sr internal isochron obtained for the calculated combined data of leachates and residues yields an age of 173 ± 14 Ma with an initial $^{87}Sr/^{86}Sr$ ratio of 0.71042 ± 0.00007.

(3) The Rb-Sr age and initial $^{87}Sr/^{86}Sr$ ratio of Y-793605 are very similar to those of ALH 77005 and LEW 88516 lherzolitic shergottites. The similarities of isotopic feature in conjunction with trace element features imply that these three lherzolitic shergottites originated from a similar source, as also suggested by mineralogical evidence (Mikouchi and Miyamoto, 1997).

From these results, the 170-Ma age observed in all lherzolitic shergottites probably record the same event. We prefer the 173-Ma age for the time of igneous crystallization, because the igneous crystallization model consistently explains the features of both the isotopic systems and the mineral chemistries of these three lherzolitic shergottites. If the 170-Ma event records the time of igneous crystallization, the event(s) that disturbed the U-Pb systems in Y-793605 residue fractions probably occurred more recently, without affecting the Rb-Sr system.

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