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Rb-Sr ISOTOPIC STUDY OF YAMATO-794046 CHONDRITE AND ITS INCLUSION

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Abstract: The Yamato-794046 H chondrite and its inclusion were dated by the Rb-Sr method as part of a consortium study of unique inclusions in ordinary chondrites. Although the inclusion recorded an approximate 3.9 Ga-melting event, the age of the impact event of the host chondrite was unclear. The inclusion is not depleted in volatile elements such as Rb and the alkalis, even though the host is depleted. Therefore, when they were impacted, they should have been in different places. The host might have been impacted under low confining pressures, and the inclusion, in contrast, was melted under relatively high confining pressures.

1. Introduction

In the consortium study of unique inclusions in ordinary chondrites, we participated in a Rb-Sr study of the Yamato (Y)-794046 chondrite and its inclusion. The host chondrite is an H chondrite and incorporates a gray-colored, lithic inclusion of the same type. The host is severely brecciated, and inclusion seems to have once melted. We do not know the chronological relationship between the brecciation and melting events, however. The inclusion might have been melted prior to the brecciation of the host or the host might have been brecciated before the inclusion was melted. When the inclusion was incorporated into the host is also unknown. All might have happened at the same time, or separately. It should be significant to date the events not only to clarify the chronological relationship between the brecciation and/or shock events, melting event, and the incorporation into the host but to understand the history of the meteorite parent body as well (*e.g.*, BOGARD *et al.*, 1976; GOPALAN and WETHERILL, 1971; NAKAMURA and OKANO, 1985; FUJIMAKI *et al.*, 1992, 1993). Therefore, we analyzed Sr isotopic compositions, and determined Rb and Sr concentrations of the fractions separated from the host and inclusion to date the time of brecciation of the host chondrite as well as melting of the inclusion. Although the purpose of this study is to examine the chronological order of those events, we intend to contribute to the study of the genetical relationships between the host and inclusion.

2. Sample and Experimental Procedure

Samples are Y-794046,61 (host, 0.605 g) and 794046,94 (inclusion, 0.474 g).

The host is an H5 chondrite, and the inclusion is of the same type (NIPR Catalog, 1987; NAKAMURA *et al.*, 1993; YANAI and KOJIMA, 1993). SACK and LIPSCHUTZ (1993) reported that both the host and inclusion suffered from severe shock heating. The host chondrite is reddish-brown and seems to be severely altered. In contrast, the inclusion seems fresh and compact. Mineralogical descriptions of the host and inclusion have been reported elsewhere (NAKAMURA *et al.*, 1993; SACK and LIPSCHUTZ, 1993; WANG *et al.*, 1993; YANAI and KOJIMA, 1993). Although their appearances and alteration are totally different, NAGAO (1993) reported that their K-Ar ages are similar (1.9–2.0 Ga). The experimental procedures of our Rb-Sr analysis are essentially the same as those of FUJIMAKI *et al.* (1992) with some insignificant modifications. This method uses the diversity of Rb-Sr concentrations in the glasses produced by impact melting to construct a Rb-Sr isochron. Since the host chondrite seemed to be so altered, we repeatedly rinsed it in an ultrasonic cleaner until the ultrapure water remained clean, even after one-hour cleaning. Such an assessment for cleanliness is simply empirical. More than 200 mg was stripped off and leached out from the host chondrite. In contrast, only a small amount was removed from the inclusion. After drying, each sample was crushed to less than 100-mesh size, and metallic iron, the extremely fine powder (less than 300 mesh), and suspended materials in acetone were excluded. Remaining powders were separated into five fractions according to their magnetic susceptibility. Only a small amount of metallic iron was separated from the crushed inclusion. To avoid sample loss, we intentionally did not thoroughly exclude the metallic iron from the host. Sr and Rb were extracted by a cation-exchange resin column technique, and the eluted HCl solutions were collected for partial analysis of major elements.

3. Analytical Results

The recovered weight percentages of the fractions are presented in Table 1. The least magnetic fractions (H4, H5, I4 and I5) are largest for both the host and inclusion. The most magnetic fraction (H1) of the host is large as well. These

Table 1. Weight (mg) and partial analytical results (%) of recovered fractions.

	H-1	H-2	H-3	H-4	H-5	I-1*	I-2*	I-3*	I-4*	I-5
mg	96.77	9.54	9.53	30.01	125.5	23.26	33.83	40.53	77.52	178.0
Fe**	50.4									
FeO		18.7	20.1	16.2	18.0					10.7
MnO	0.14	0.29	0.36	0.28	0.33					0.32
MgO	10.5	20.6	20.8	21.4	25.3					24.7
CaO	0.37	1.00	1.14	0.89	1.12					0.73
Na_2O	0.38	0.86	1.11	0.85	0.78					0.34
K_2O	0.06	0.14	0.28	0.13	0.07					0.07

H: fractions of host chondrite, I: fractions of inclusion.
* I-1 to I-4 were not analyzed because of some comtamination.
** Iron content is expressed as metallic iron.

Table 2. Rb and Sr abundances (ppm), and $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ ratios.

	Rb	Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	2σ mean
H-1	0.39	3.15	0.3591	0.73171	0.00002
H-2	0.73	8.72	0.2426	0.72501	0.00003
H-3*					
H-4	0.41	5.77	0.2060	0.72743	0.00003
H-5	0.24	3.86	0.1801	0.72223	0.00002
I-1	11.2	32.6	0.9999	0.76836	0.00003
I-2	8.60	27.3	0.9165	0.76408	0.00002
I-3	11.0	32.2	0.9942	0.76833	0.00001
I-4	2.93	21.6	0.3945	0.76184	0.00003
I-5	4.84	16.7	0.8428	0.75948	0.00002

H: fractions of host chondrite, I: fractions of inclusion.
* H-3 was not analyzed.

tendencies contrast with examples we experienced in similar Rb-Sr isotopic studies of other shock-melted Yamato chondrites (FUJIMAKI *et al.*, 1992; 1993). In previous studies we could control the amount of each fraction by adjusting the magnetic intensity, but not this time. The host was only brecciated and altered so much that the magnetic separation did not function well. The inclusion does not contain appreciable amounts of glass (YANAI and KOJIMA, 1993; NAKAMURA *et al.*, 1993), and therefore the magnetic separation does not seem effective.

Analytical results of some of the major elements are shown in Table 1. The eluted solutions of the most magnetic through the 4th magnetic fraction of the inclusion (I1–I4) were not analyzed because some contamination was found while drying on a hot plate. Fe in the most magnetic fraction (H1) is expressed as metallic iron. Since metal removal before separation was not perfect, H1 contains a large amount of metallic iron. In contrast, I1 is small (Table 1) due to scarcity of metallic iron. These data seem consistent with the analytical results reported by FUKUOKA (1993). Table 2 includes the analytical results of Rb and Sr concentrations as well as Sr isotopic compositions of each fraction. However, we failed to analyze the Sr isotopic composition of the third magnetic fraction (H3).

4. Discussion

4.1. Age and initial ratio

The analytical results of the host fractions are plotted on $^{87}Sr/^{86}Sr$ versus $^{87}Rb/^{86}Sr$ diagrams (Figs. 1 and 2a). Regression and the corresponding slopes of lines were calculated in a method similar to YORK (1969). We use 2 sigma errors in the calculations (0.8% for $^{87}Rb/^{86}Sr$ and 0.016% for $^{87}Sr/^{86}Sr$), and the uncertainties of the results are expressed at the 2 sigma level. The ^{87}Rb decay constant used was $1.42 \times 10^{-11} y^{-1}$ (STEIGER and JÄGER, 1977).

The calculated regression line of the host chondrite is shown in Fig. 1 and compared with the 4.55-Ga reference isochron. Compare the regression line with the

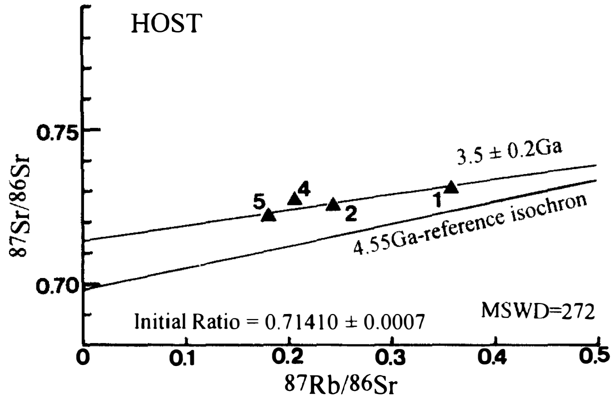

Fig. 1. $^{87}Rb/^{86}Sr$ *vs.* $^{87}Sr/^{86}Sr$ *plot of the fractions from Y-794046 host chondrite. The numbers associated with the solid triangles correspond to the fraction number in Table 2 (H-1 to H-5). The regression line was calculated in a similar manner to that of* YORK *(1969).*

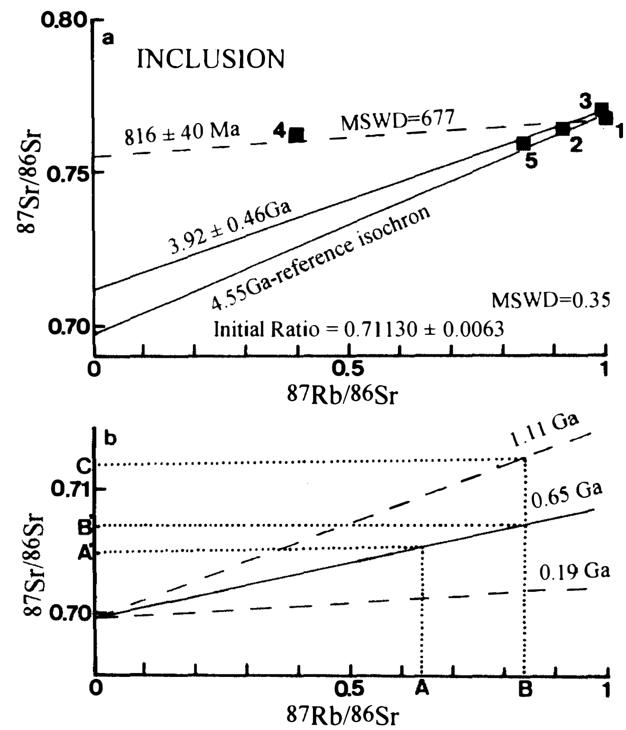

Fig. 2. (a) $^{87}Rb/^{86}Sr$ *vs.* $^{87}Sr/^{86}Sr$ *plot of the fractions from the inclusion in the Y-794046 chondrite. The numbers associated with the solid squares correspond to the fraction number in Table 2 (I-1 to I-5). The 3.9-Ga isochron is shown and compared with the 4.55-Ga reference isochron. Fraction number 4 was not included in the isochron calculation.*
(b) Rb-Sr evolution of chondritic material. The $^{87}Rb/^{86}Sr$ *ratio of chondritic material is assumed to be between points A and B, 4.55 Ga years ago. After 0.65 Ga, chondritic* $^{87}Sr/^{86}Sr$ *ratio will reach points A′ and B′. After 1.11 Ga, the ratios could reach point C (0.71223).*

4.55-Ga reference line; all the data points are shifted in the direction of Rb loss. Such loss is probably due to Rb-vaporization by the severe impact (*e.g.*, SACK and LIPSCHUTZ, 1993), or possibly Rb-loss by weathering. Assuming that the regression line is an isochron of the impact age of the host chondrite, the age (3.5±0.2 Ga) and initial $^{87}Sr/^{86}Sr$ ratio (0.71410±0.0007) were calculated. Although the errors associated with the age and initial ratio seem small, the mean square weighted deviation (MSWD) is as large as 272. It is possible that either strong alteration has distorted the Rb-Sr system of the host, the Rb-Sr chronometer was reset incompletely by the impact, the separation method might have been inadequate to exclude altered parts as well as unmelted parts, or there was some combination of these factors. It is also conceivable that the host had been impacted prior to the 3.5-Ga event, and the 3.5-Ga impact might have partly disturbed the previous isochron. Whichever the case, we would like to interpret the age to indicate the approximate time of an asteroidal impact on the parent body.

The analytical results of the inclusion are plotted in Fig. 2a. The fourth magnetic fraction (I4) plots away from the other collinear data points. Therefore, two different isochrons of the inclusion are shown. When all the fractions are included in the calculation, the age is 816 ± 40 Ma with a large MSWD = 677 and very high initial $^{87}Sr/^{86}Sr = 0.7548$. Since the inclusion is unaltered and might have experienced near-total melting (YANAI and KOJIMA, 1993; NAKAMURA *et al.*, 1993), we have no excuse to ignore I4. However, the calculated MSWD is not acceptable, and the Rb and Sr abundances as well as Sr isotopic composition were probably disturbed much; possibly Rb might have been leached out to some extent. When I4 is excluded from the calculation, the age is 3.92 ± 0.46 Ga with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7113 ± 0.0063, and the MSWD is rather small (0.35). The inclusion might have been impacted prior to the 3.92-Ga event, and 3.92-Ga event could have only partly reset the Rb-Sr chronometer of the inclusion; this could be the reason of the scattering of the data in Fig. 2a as well. Although we cannot disregard I4, we prefer 3.92 ± 0.46 Ga as the age of impact-induced melting of the inclusion, 0.19–1.11 Ga after the primitive planets of the solar system were formed.

We have drawn Rb-Sr evolution lines (solid and dashed lines) of chondritic material in Fig. 2b to evaluate the validity of the isochron. The solid line is a 0.65 Ga reference isochron and the dashed lines are 0.19- and 1.11-Ga reference isochrons, respectively. The $^{87}Sr/^{86}Sr$ ratio evolves counterclockwise depending on its $^{87}Rb/^{86}Sr$ ratio during the 0.19 to 1.11 Ga time interval, starting at 0.69899 (PAPANASTASSIOU and WASSERBURG, 1969). Although the present Rb/Sr abundance ratio of chondritic material is not clear, we believe it should be within the range from 0.21 (average value of H chondrites analyzed by MINSTER and ALLEGRE, 1979) to 0.28 (for CI chondrites, WASSON, 1985). Both values will be used as chondritic Rb/Sr abundances to test how $^{87}Sr/^{86}Sr$ evolves. Three billion and nine hundred million years ago, the $^{87}Rb/^{85}Rb$ ratio was approximately 0.4077, and the chondritic $^{87}Rb/^{86}Sr$ ratios are roughly from 0.63 (point A in Fig. 2b) to 0.84 (point B in Fig. 2b). The dotted lines indicate those ratios on the horizontal axis. Since the changes in the Rb/Sr abundance ratio and those of the atomic weights of Sr and Rb, due to decrease of ^{87}Sr and increase of ^{87}Rb for 0.65 Ga, are insignificant, they are disregarded in the calculation. Within 0.65 Ga the chondritic $^{87}Sr/^{86}Sr$ ratio evolved and ranges from 0.7049 (point A′) to 0.7067 (point B′). The calculated ratio (0.7113 ± 0.0063) is outside this possible range. However, after 1.11 Ga and assuming that the $^{87}Rb/^{86}Sr$ ratio is 0.84, the $^{87}Sr/^{86}Sr$ ratio can reach 0.71223 (point C), similar to the calculated value. The model calculation is consistent with the determined age and initial $^{87}Sr/^{86}Sr$.

Considering the young age obtained by the K-Ar method (1.9 Ga; NAGAO, 1993) for the same inclusion, it appears that the inclusion might have been subjected to repeated impacts since the 3.9-Ga melting event. A final event might have happened at 1.9 Ga, resetting its K-Ar age; but not strong enough to reset the Rb-Sr chronometer. The disagreement of the ages obtained by the two isotopic methods implies a complicated thermal history for this sample, and the age data should be treated with great care.

4.2. *Melting conditions*

The host chondrite and inclusion seem to have similar Rb-Sr ages, and possibly were shocked by the same impact at the same time. The host and inclusion might have been in close association in or on the parental body. Their chemical features should provide us with information about the relationship between the host and inclusion. All the analytical results are plotted except the fourth magnetic fraction (I4) of the inclusion (Fig. 3). The data were plotted to the left of the 4.55-Ga reference line. Assuming that the parent body was formed at 4.55 Ga, the deviation of the data from this line should be attributed to Rb vaporization during impact at 3.6–3.9 Ga. Most of the inclusion fractions are very close to the reference line, but those of the host are not. The impact effect seems more severe to the inclusion than to the host. FUKUOKA (1993) reported that the inclusion in Y-794046 was more depleted in siderophile elements than the host, and the losses were due to removal of metal, or sulfide, or both when the host was heated up. In contrast, Rb loss from the inclusion is less than that of the host chondrite. It should be pointed out that although the inclusion has lost siderophile elements, it could have kept Rb during melting. On the other hand, the host chondrite lost Rb, but could have kept siderophile elements. The analytical results of Y-794046 also revealed that the inclusion is more enriched in K and Na than the host chondrite (FUKUOKA, 1993). If they were impacted under the same conditions, such geochemical inconsistencies would not be conceivable. Assuming that the alkali elemental abundances in the host were not much modified by alteration, the host and inclusions probably impacted under different conditions. The host rock might have impacted under low confining

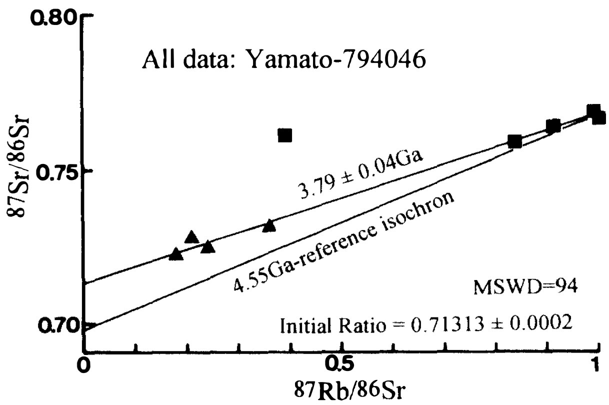

Fig. 3. $^{87}Rb/^{86}Sr$ vs. $^{87}Sr/^{86}Sr$ plot of all the fractions from the Y-794046 chondrite. Symbols are the same as those in Figs. 1 and 2a. The line corresponds to the 3.79-Ga isochron calculated using all the points excluding the fourth magnetic fraction from the inclusion (I4). The 4.55-Ga reference isochron is also shown.

pressure and melting was incomplete, and in contrast, the inclusion was once totally molten under rather high confining pressure.

If the age is calculated using all the analytical results plotted in Fig. 3, excluding the I4 fraction, the result is 3.79 ± 0.04 Ga with again a large MSWD (94). Although the Rb-Sr system of Y-794046 might not have been reset perfectly to erase out the previous history, and the system might have been distorted much, the obtained age could be a secondary isochron indicating the age of impacting.

5. Conclusion

The inclusion in the Y-794046 H chondrite reveals a melting event that occurred at approximately 3.9 Ga. The host meteorite might have been impacted at a similar time as well. The volatile element abundances are largely different between them, and therefore when they were impacted, they should have been in different places. The host might have been impacted under low confining pressure, and the inclusion was melted under rather high confining pressure.

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