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# $^{40}Ar$-$^{39}Ar$ ANALYSES OF YAMATO-75097 (L6) CHONDRITE FROM ANTARCTICA

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***Abstract:*** $^{40}Ar$-$^{39}Ar$ analyses were performed on the host phase of an H-clast bearing chondrite Yamato-75097 (L6). The result indicates a typical U-shaped age spectrum, suggesting that the serious degassing event occurred at about 490 Ma or slightly younger age for this meteorite. Since the meteorite shows a sign of shock, this event might have been a collisional event. It is estimated that more than 99% of radiogenic $^{40}Ar$ was degassed during this event. For this degassing, it requires prolonged time of at least a few hours even at 1200°C, and a longer time is required if the ambient temperature is lower and the diffusion mainly controls the degassing process.

## 1. Introduction

The Yamato-75097 (Y-75097) (L6) chondrite has been known to include some unique inclusions. One of the inclusions has a shiny black fusion crust and a fine-grained granular texture, consisting mainly of olivine with minor amounts of plagioclase and merrillite (YANAI *et al.*, 1983) and is similar to that of Brachina meteorite (JOHNSON *et al.*, 1977; NEHRU *et al.*, 1983). Oxygen isotope study has revealed that the inclusions belong to H-type chondrite (PRINZ *et al.*, 1984). Thus this meteorite is very unique in that the host rock and its inclusions are classified into different groups.

The host rock has a chondritic structure. Chondrules and chondrule fragments show extensive integration with the granular groundmass which consists of olivine and pyroxene as major components. Further, the meteorite is observed to have been traversed by thin black veinlets probably produced by shock (YANAI *et al.*, 1983). In order to reveal the thermal history of this unique meteorite, we analyzed the host rock by the $^{40}Ar$-$^{39}Ar$ method as a first step.

## 2. Sample and Experimental Procedures

A portion of the host rock of Y-75097 meteorite (Y-75097,82) was prepared for $^{40}Ar$-$^{39}Ar$ analyses. No clast nor fusion crust was included in this portion. The meteorite appears to be unweathered and is classified as an L6 chondrite (YANAI *et al.*, 1983).

The experimental procedures are almost the same as those reported in KANEOKA and TAKAOKA (1986). A chip with the amount of 0.752 g was prepared as a bulk sample for neutron irradiation. The sample was cleaned with acetone, wrapped in aluminium foil, and stacked together with age standard samples MMhb-I (hornblende, K-Ar age: $519.5 \pm 2.5$ Ma) (ALEXANDER *et al.*, 1978) in a vacuum-sealed quartz vial. The sample was irradiated in the JMTR of Tohoku University with the total fast neutron fluence of about $8 \times 10^{18}$ nvt/cm$^2$. Ar gas was extracted and purified after the conventional procedures at the Isotope Center of the University of Tokyo and the Ar isotopes were measured on a Nier-type mass spectrometer with a multiplier, having a resolving power of about 600 (TAKAOKA, 1976) at Yamagata University.

Nine temperature fractions (600–1600°C) were taken for analyses, each of which was kept for 45 min for degassing. System blanks were in the range of $(1\text{–}1.4) \times 10^{-8}$ cm$^3$ STP$^{40}$Ar for the fractions below 1300°C, but increased up to $2.1 \times 10^{-8}$ cm$^3$STP$^{40}$Ar in the 1600°C fraction. Blanks and K-derived interference isotopes were corrected to calculate an age by using the correction factors determined before (KANEOKA, 1983). No Ca-derived interference isotopes were corrected, however, because the Ar analyses were made after the irradiation of the sample for more than two years and most of $^{37}Ar(T_{1/2}=35.1$ days) already decayed. As shown later, the effect of Ca-derived interference isotopes on the calculated age is estimated to be less than 1% for each temperature fraction except for the highest temperature fraction (1600°C).

Since the present sample has been revealed to contain mostly cosmogenic components for $^{36}Ar$ and $^{38}Ar$ (TAKAOKA *et al.*, 1981), the following values were used to calculate an $^{40}Ar$-$^{39}Ar$ age:

$$^{40}Ar/^{36}Ar=0.15 \text{ and } ^{38}Ar/^{36}Ar=1.5 \text{ for the cosmogenic Ar.}$$

The amounts of $^{40}Ar$ were estimated by the peak height method with the uncertainty of about 20% by using the calibrated air standard.

## 3. Results

Ar isotopes observed in each temperature fraction are shown in Table 1 together with the amount of $^{40}Ar$. The calculated $^{40}Ar$-$^{39}Ar$ ages are also included in Table 1. The age spectrum and the $^{40}Ar/^{36}Ar$-$^{39}Ar/^{36}Ar$ plot are shown in Fig. 1.

As shown in Fig. 1, the meteorite Y-75097,82 indicates a characteristic young age of about 500 Ma, which is included in the typical age ranges for shocked L chondrites (*e.g.*, TURNER, 1969; BOGARD *et al.*, 1976). The age spectrum of this meteorite shows a U-shaped pattern, indicating higher $^{40}Ar$-$^{39}Ar$ ages in the lower and higher temperature fractions with the minimum value at 800°C. In the intermediate temperature fractions (800 and 900°C), which cover about 69% of total $^{39}Ar$, the apparent $^{40}Ar$-$^{39}Ar$ ages become about 500 Ma. The 800°C fraction shows a still younger age of $489 \pm 3$ Ma than the 900°C fraction ($505 \pm 3$ Ma), the difference of which exceeds the experimental uncertainty. Hence, the event which reset the K-Ar system would have occurred at around 489 Ma or slightly younger age. The apparent older $^{40}Ar$-$^{39}Ar$ ages observed in the lower temperature fractions might have been due to the inherited $^{40}Ar$ remaining slightly at loose sites at the time of the event. The apparent older age in the higher

*Table 1. Ar isotopes in a neutron-irradiated meteorite (Y-75097,82) from Antarctica.*
0.7520 g, $J=0.09403\pm0.00046$

| T (°C) | [$^{40}$Ar] ($\times10^{-8}$cm$^3$ STP/g) | $^{36}$Ar/$^{40}$Ar ($\times10^{-3}$) | $^{38}$Ar/$^{40}$Ar ($\times10^{-2}$) | $^{39}$Ar/$^{40}$Ar ($\times10^{-2}$) | $^{40}$Ar*/$^{39}$Ar* | Age (Ma) |
|---|---|---|---|---|---|---|
| 600 | 3.4 | 3.931 ±0.023 | 13.49 ±0.36 | 12.81 ±0.34 | 7.632 ±0.207 | 975.9 ±20.8 |
| 700 | 28.9 | 1.443 ±0.017 | 3.131 ±0.039 | 23.11 ±0.24 | 4.165 ±0.045 | 596.2 ±6.0 |
| 800 | 77.9 | 1.027 ±0.006 | 3.216 ±0.011 | 28.77 ±0.08 | 3.314 ±0.016 | 489.4 ±3.0 |
| 900 | 54.1 | 1.216 ±0.008 | 4.271 ±0.014 | 27.79 ±0.09 | 3.437 ±0.012 | 505.2 ±2.7 |
| 1000 | 25.7 | 2.753 ±0.009 | 13.05 ±0.14 | 24.12 ±0.26 | 3.981 ±0.045 | 573.6 ±6.1 |
| 1100 | 7.8 | 8.231 ±0.135 | 39.43 ±0.68 | 12.28 ±0.30 | 7.951 ±0.199 | 1007 ±20 |
| 1200 | 11.5 | 13.07 ±0.20 | 61.06 ±0.77 | 6.414 ±0.097 | 15.33 ±0.24 | 1610 ±17 |
| 1300 | 4.7 | 18.83 ±0.66 | 163.4 ±1.5 | 9.330 ±0.212 | 10.46 ±0.24 | 1236 ±21 |
| 1600 | 16.9 | 65.32 ±1.03 | 351.4 ±6.0 | 10.08 ±0.19 | 9.445 ±0.187 | 1147 ±17 |
| Total | 230.9 | 7.248 | 37.42 | 23.64 | 4.055 | 582.7 |

N.B. 1) All tabulated data have been corrected for the blanks, but do not include other corrections.
2) $^{40}$Ar*/$^{39}$Ar* indicates a ratio of the radiogenic $^{40}$Ar from the decay of $^{40}$K ($^{40}$Ar*) to the K-derived $^{39}$Ar by a reaction of $^{39}$K($n, p$) ($^{39}$Ar*).
3) To calculate an age, the following correction factor for K-derived interference Ar isotopes was used (KANEOKA, 1983).
$(^{40}Ar/^{39}Ar)_K=(19.6\pm0.4)\times10^{-2}$.
However, no corrections were made for Ca-derived interference Ar isotopes due to the decay of $^{37}$Ar after more than two years since the irradiation of the sample.
4) The $^{38}$Ar/$^{40}$Ar ratios in this table seem to have been affected by the addition of H$^{37}$Cl to the $^{38}$Ar peak in each temperature fraction, because the decay of $^{37}$Ar to $^{37}$Cl would easily form H$^{37}$Cl with the presence of hydrogen around a Ca site. Since the present sample contains mostly cosmogenic components for $^{36}$Ar and $^{38}$Ar (TAKAOKA *et al.*, 1981), no serious effect would occur in a calculated age.
5) Uncertainties in the measured ratio represent those of the mass spectrometric analyses. For the $^{40}$Ar*/$^{39}$Ar* ratios and calculated ages, however, 20% of blank correction and other uncertainties are included.

temperature fractions would represent inherited $^{40}$Ar trapped at much more retentive sites.

As mentioned before, the correction for the Ca-derived interference isotopes could not be applied in the present case. However, based on the relatively constant production rate for K-derived $^{39}$Ar and Ca-derived $^{37}$Ar in the same reactor and the information on K and Ca contents in the bulk sample of this meteorite, we can evaluate the maximum effect of Ca-interference isotopes on the calculated age. For the present case, Ca and K contents were reported to be 1.3 and 0.066%, respectively (YANAI *et al.*, 1983). For the JMTR, we have observed the following relationship (KANEOKA, 1983).

$$(K/Ca)=(0.5\pm0.1)(^{39}Ar^*/^{37}Ar),$$

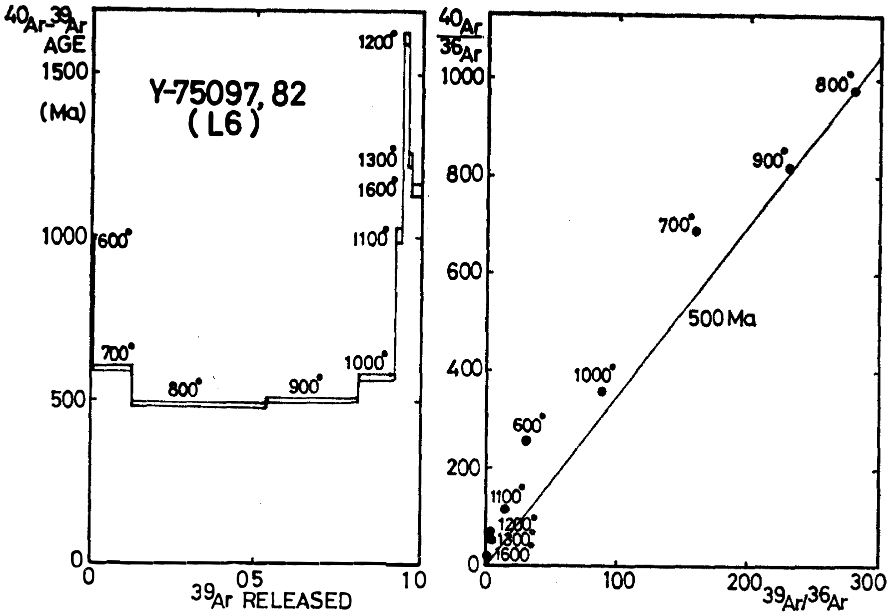


*Fig. 1. The $^{40}Ar$-$^{39}Ar$ age diagram and the $^{40}Ar/^{36}Ar$-$^{39}Ar/^{36}Ar$ plot for the sample Y-75097,82. The number at each column indicates the degassing temperature in degree Celsius. The uncertainty is indicated by 1σ. In the $^{40}Ar/^{36}Ar$-$^{39}Ar/^{36}Ar$ plot, a reference isochron of 500 Ma is shown.*

where $^{39}Ar^*$ indicates K-derived $^{39}Ar$. Thus, we can roughly estimate the amount of $^{37}Ar$, which should have been produced during the neutron irradiation in this meteorite as follows:

$$(^{37}Ar) \simeq (0.98 \pm 0.2)(^{39}Ar^*).$$

Although this indicates only the total amount of $^{37}Ar$ in this meteorite, we have known that more than half of $^{37}Ar$ are degassed in the highest fraction of similar meteorites in many cases (KANEOKA, 1984). Further, we know that it correlates roughly with cosmogenic and/or neutron produced $^{36}Ar$ and $^{38}Ar$. As shown in Fig. 2, the present sample degasses about 70% of $^{36}Ar$ and $^{38}Ar$ in the 1600°C fraction. Thus, the effect of Ca-derived interference would appear only in the 1600°C fraction for the present sample. For the lower temperature fractions, the effect on the calculated age is evaluated to be less than 1%.

As shown in Fig. 2, the $^{40}Ar$ and $^{39}Ar$ are mostly degassed at 800°C, being quite different from $^{36}Ar$ and $^{38}Ar$. Hence, these components would mostly represent radiogenic $^{40}Ar$ and K-derived $^{39}Ar$ retained in crystals such as plagioclase in this meteorite.

The amounts of $^{36}Ar$ and $^{40}Ar$ are calculated to be 1.67 and 221 in the unit of $10^{-8}$ cm$^3$STP/g, which are in good agreement with the reported data ($^{36}Ar$, 1.80; $^{40}Ar$, 220; unit: $10^{-8}$ cm$^3$STP/g) by TAKAOKA *et al.* (1981). Further, the K content estimated on the basis of the amount of $^{39}Ar$ becomes about 830 ppm, which is slightly larger than the value reported by YANAI *et al.* (1983), but similar to that reported by NAKAMURA *et al.* (1984). Hence, such a situation would probably reflect the heterogeneity of mineral distributions in this meteorite.

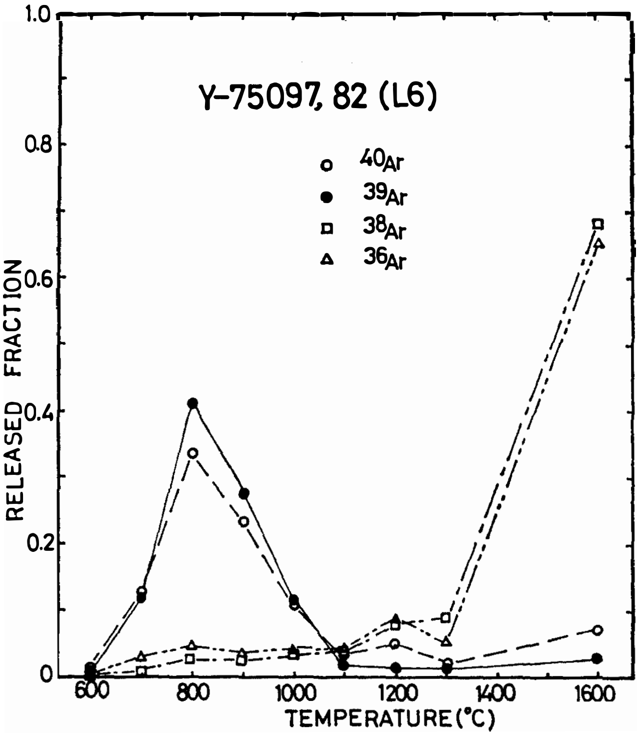


*Fig. 2. The release patterns of Ar isotopes for the sample Y-75097,82.*

## 4. Discussion

For the present meteorite, the integrated amounts of $^{36}Ar$, $^{38}Ar$ and $^{40}Ar$ are plotted against the integrated amount of $^{39}Ar$ for each temperature fraction in Fig. 3. In such

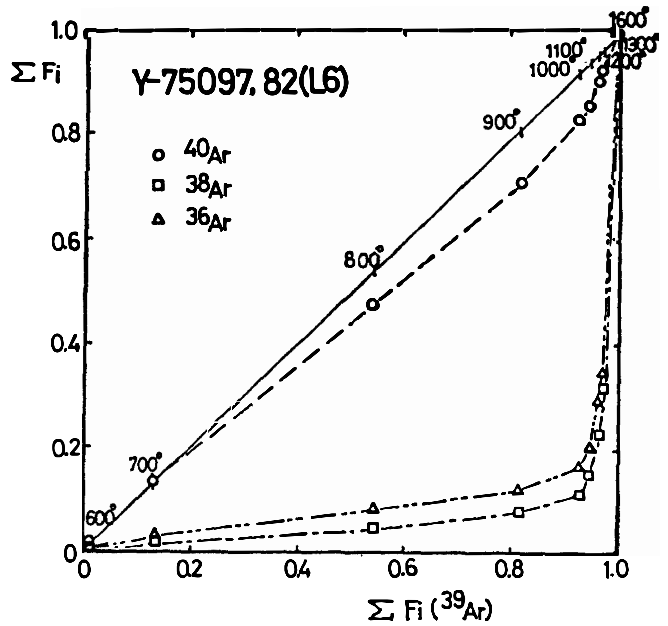


*Fig. 3. The integrated fraction of Ar ($^{36}Ar$, $^{38}Ar$, $^{40}Ar$) vs. the integrated fraction of $^{39}Ar$ for the sample Y-75097,82.*

a diagram, we can classify the degassing patterns of Ar in neutron-irradiated meteorites and identify a sample which might have lost its radiogenic $^{40}Ar$ due to weathering, and not by any thermal event (KANEOKA, 1984). According to the classification by KANEOKA (1984), the degassing pattern of Y-75097,82 is classified as Type B, which is a typical pattern for ordinary chondrites, having received no serious effect of Ar degassing due to weathering. This result is compatible with the macroscopic observation that the meteorite seems to have been unweathered (YANAI *et al.*, 1983). Hence, we can conclude that the Ar degassing from this meteorite occurred mostly at the time of secondary event about 489 Ma or slightly younger.

Based on the degassing rate of Ar in each fraction to the total amount of Ar, we can calculate a diffusion parameter $D/a^2$ ($D$: diffusion coefficient, $a$: grain size) for each temperature and make an Arrhenius plot as shown in Fig. 4. Since the estimated degassing temperature includes some uncertainty (up to 30°C), the figure should be read as showing only a general trend. As shown in Fig. 4, $^{39}Ar$ and $^{40}Ar$ seem to deviate from the line which corresponds to an activation energy of about 55 kcal/mole above 1000–1100°C. This may be caused probably by a phenomenon that the trapping sites

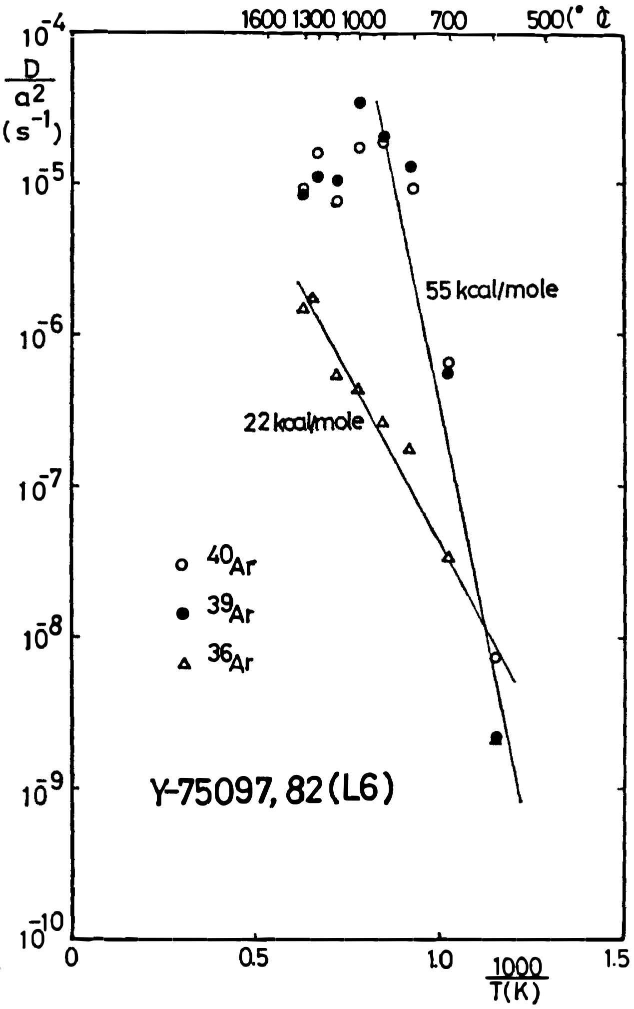


*Fig. 4. Arrhenius plot for the sample Y-75097,82.*

for $^{39}Ar$ and $^{40}Ar$ might be different from those degassed at lower temperatures as revealed in the release patterns in Fig. 2. Whereas the data of $^{36}Ar$ lie on a line indicating an activation energy of about 22 kcal/mole, which is clearly different from those of $^{39}Ar$ and $^{40}Ar$. This implies that these components were trapped at different sites in this meteorite, which are also seen in the release patterns of each Ar isotope (Fig. 2). The scattered points of $^{39}Ar$ and $^{40}Ar$ above 1000–1100°C may suggest that they might have been caused due to the incomplete redistribution of elements in relatively high temperature minerals such as olivine and pyroxene.

As explained before, the meteorite Y-75097 contains some inclusions which are composed mainly of olivine with minor amounts of plagioclase and merrillite and shows a possible cumulate texture (YANAI *et al.*, 1983). This would imply that the host meteorite would have not exceeded the temperatures of 1300–1400°C during the secondary event. Since the meteorite has a sign of shock, the degassing event would probably reflect a collision between meteorites or on the parent body.

Assuming that the degassing from the meteorite is controlled by the diffusion processes we can get a rough idea about the relationship between the temperature and the required time to degas the observed rate of Ar from the meteorite. Based on the estimated age for the degassing event by the $^{40}Ar$-$^{39}Ar$ method and the total amount of radiogenic $^{40}Ar$ observed, we can evaluate the degree of degassing rate at the probable collisional event (BOGARD *et al.*, 1976). For the present meteorite, assuming that it was formed at 4550 Ma and degassed at 490 Ma by a shock event, the degree of degassing rate of radiogenic $^{40}Ar$ is calculated to be more than 99.3% at the time of the event. In Fig. 5, the relationship between the temperature and the required time to degas Ar is shown for the meteorite Y-75097,82 as a function of the degassing rate. The values

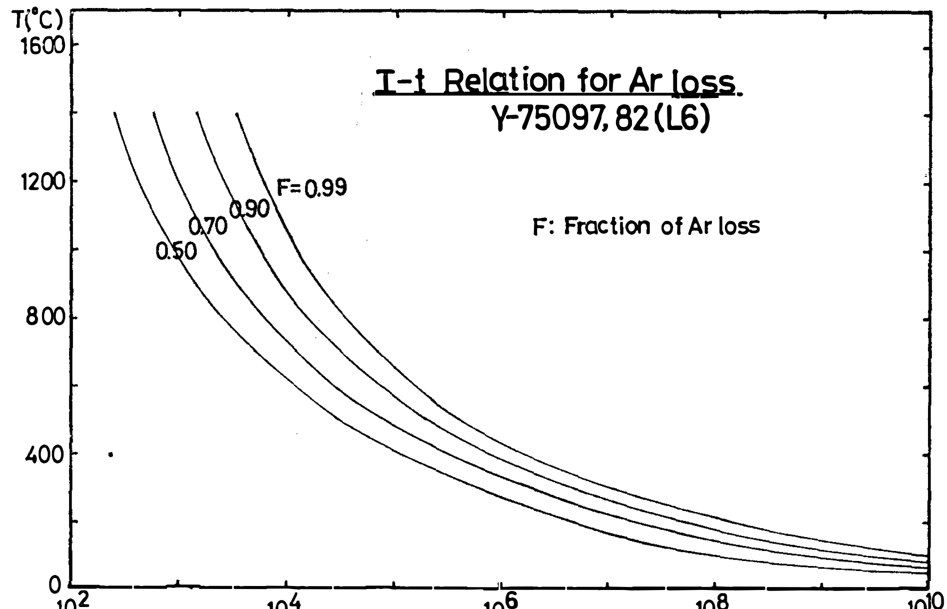


*Fig. 5. The relationship between the degassing temperature (T) and the required time (t) to degas a certain amount of Ar from the sample Y-75097,82. "F" indicates the fraction of Ar loss from the sample. Diffusion parameters ($D/a^2$) estimated from Fig. 4 are used for these calculations.*

$(D/a)^2$ have been estimated on the basis of the data deduced from Fig. 4. Diffusion characteristics might change before and after the shock event for this meteorite and it may be not appropriate to use the data observed in Fig. 4 to calculate such values in a strict sense. Further it includes some uncertainties about the values above 1000–1100°C. However, the present calculations aim to show only the general trend about the degassing characteristics and do not aim to give exact numbers. Hence, even if they include some uncertainties, such treatments would be still valid for this purpose.

From Fig. 5, it is easily realized that at least a few hours are necessary to degas more than 99% of radiogenic $^{40}Ar$ from the meteorite if it was exposed at the temperatures of even 1200°C. Since this relationship is based on the assumption that the same temperature is maintained for the period, the time indicates the minimum value. However, the meteorite might have been shock-heated at a lower temperature actually. In such a case, a much longer time is required to degas effectively from the meteorite. Hence, as long as the diffusion processes are concerned, it is necessary for this meteorite to be kept at relatively high temperatures for a long time (at least a few hours).

This situation might be different from that of carbonaceous chondrites. Laboratory experiments for serpentine and other hydrated minerals indicate that large amounts of water can be degassed by a shock (BOSLOUGH *et al.*, 1980), suggesting a shock-induced degassing from carbonaceous meteorites. However, such degassing would occur due to the phase change of serpentine and hydrated minerals and dehydration would accompany it. Since ordinary chondrites do not contain significant amounts of hydrated minerals, such mechanism cannot be expected during a shock event. Instead, it may be expected that the loss of Ar from such meteorites may be caused during the passage of a shock wave. However, experimental data do not support the conjecture and it is required that the materials reside for prolonged periods of time at elevated temperatures in a relatively hot circumstance (BOGARD *et al.*, 1987). This conclusion is the same as that we get in the present study.

In this context, it is worth analyzing the inclusion of this meteorite by the $^{40}Ar$-$^{39}Ar$ method, because it still keeps its original texture. For the clast of Y-75097, NAKAMURA *et al.* (1984) have reported a model Rb-Sr whole rock age of 3.91 Ga. This indicates a later disturbance or resetting of Rb-Sr systematics in the clasts. However, the apparent age is much older than the age estimated as a shock event for this meteorite based on the $^{40}Ar$-$^{39}Ar$ analyses for the host phase. Such difference would have been caused due to different mobilities between Sr and Ar at elevated temperatures and/or different thermal profiles in the host phase and the clasts. In order to solve the problem, we are planning to analyze the clast by the $^{40}Ar$-$^{39}Ar$ method and the result will reveal the thermal history of the meteorite more clearly.

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