^{40}Ar–^{39}Ar AGE STUDIES OF FOUR YAMATO-74 METEORITES

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***Abstract*:** ^{40}Ar–^{39}Ar ages have been obtained for four Yamato-74 meteorites (Yamato-74640, -74190, -74159 and -74097) from Antarctica.

Yamato-74640 (H5–6) shows a plateau age of 4407±71 m.y. (1 σ) at higher temperatures. This age probably corresponds to the time of formation or a very intense metamorphism for this meteorite.

Yamato-74190 (L6) indicates a ^{40}Ar–^{39}Ar age spectrum with a low temperature plateau-like age of 357±32 m.y. The apparent ^{40}Ar–^{39}Ar age increases up to about 1300 m.y., but does not reach a high temperature plateau. The apparent young age would reflect the time of degassing due to the collisional process of the parent body, which has been observed in many L-chondrites.

Yamato-74159, which is a eucritic polymict breccia, has a similar age spectrum to that of Pasamonte obtained by PODOSEK and HUNEKE (Geochim. Cosmochim. Acta, **37**, 667, 1973), indicating a plateau age of 4075±49 m.y. at intermediate temperatures (850–1250°C). This age may reflect the time of the later degassing event such as the impact of meteoroids on the parent body of the eucrite.

Yamato-74097 (Diogenite) seems to show a relatively young ^{40}Ar–^{39}Ar age of about 1100 m.y., though the uncertainty in the obtained age is larger for this diogenite than those for the other samples due to its low K-content. From both the value of the age and the age spectrum, this diogenite seems to have a different history from those of ordinary chondrites and achondrites known to date.

1. Introduction

After the accidental discoveries of meteorites in 1969 and 1973 on bare ice near the Yamato Mountains, East Antarctica (YOSHIDA *et al.*, 1971; KUSUNOKI, 1975), more than 600 new meteorites have been found in the same area during the period from November to December 1974 by the meteorite search team of the 15th Japanese Antarctic Research Expedition. These meteorites were named "Yamato-74 meteorites" (YANAI, 1978).

In order to clarify the origin and genetic relationships of each meteorite, the ages of meteorites are indispensable information. However, we have so far very limited data on the ages of Yamato meteorites. In the course of rare gas analyses, SHIMA *et al.* (1973) and TAKAOKA and NAGAO (1978) reported the results of gas retention ages together with cosmic-ray exposure ages for Yamato-69 and Yamato-73 meteorites, respectively. KAMAGUCHI and OKANO (1978) reported the K–Ar age on a Yamato-74 meteorite. Since the gas retention age often shows the mixture of the ages for more than two events, being directly affected by gas losses, we should take it as a measure of the averaged value for these events. Hence, in order to get more definite values of the ages for these meteorites, it is necessary to apply other dating methods which can distinguish the age of each event or keep a record of the age of the event without being affected by later disturbances.

In this respect, the ^{40}Ar–^{39}Ar method has been successfully applied to extraterrestrial materials such as meteorites and lunar samples, which enables us to deduce not only the solidification ages but also the detailed secondary effects even if some partial Ar loss occurred from the samples (*e.g.*, MERRIHUE and TURNER, 1966; TURNER, 1969). In this method, ages are obtained by comparing the radiogenic ^{40}Ar to ^{39}Ar ratio between a sample and a standard whose age is known, where ^{39}Ar is artificially produced by irradiating them with fast neutrons with the ^{39}K(n, p)^{39}Ar reaction. The application of stepwise degassing enables us to get detailed structure of Ar distribution in a sample, thus making it possible to evaluate the obtained age by itself.

In the present study, we have applied the ^{40}Ar–^{39}Ar method to four Yamato-74 meteorites of different kinds in order to clarify their properties from chronological points of view.

2. Samples

Four Yamato-74 meteorites of different kinds were analyzed in this study.

Yamato-74640 (H5–6) and Yamato-74190 (L6) are ordinary chondrites (YANAI, 1978), whereas Yamato-74159 and Yamato-74097 are achondrites classified as eucritic polymict breccia and diogenite, respectively (TAKEDA *et al.*, 1978). These meteorites were sent to us as brecciated blocks ranging from about 1 mm to 15 mm in size by the curator of Yamato meteorites. Larger blocks were carefully broken to pieces of less than 8 mm in size so that any terrestrial contamination should be avoided. However, they were never powdered in order to avoid Ar loss and/or atmospheric contamination during the procedure.

The detailed petrological descriptions for Yamato-74190 are given in KIMURA *et al.* (1978) and for Yamato-74159 and -74097 in TAKEDA *et al.* (1978), respectively.

3. Experimental

Each sample of about 0.5–0.8 grammes was wrapped in Al-foil. Two samples were stacked in a quartz ampoule ($10\phi \times 70$ mm) paired with two standard samples at both sides in order to assign proper J-values for the samples involved. USGS standard LP-6 (biotite) was used as the age monitor, which has the K–Ar age of

128 m.y. (ENGELS and INGAMELLS, 1973). In order to determine the correction factors for K- and Ca-derived Ar isotopes, K_2SO_4 and CaF_2 crystals were also irradiated in the same quartz ampoules.

Samples were irradiated in the JMTR reactor of the Tohoku University with the fast neutron flux of about 10^{18} nvt/cm^2. The irradiated sample was degassed in the extraction system, which is separated from the mass spectrometer. The sample was loaded in a well-degassed Mo-crucible in the extraction system and preheated for several hours at about 250°C. Ar gas was extracted in a series of 60 minute heatings at successibly higher temperature in the Mo-crucible heated by the HF induction coil. Crucible temperatures above about 800°C were measured by an optical pyrometer. Below 800°C, temperatures were inferred from the current of the HF induction coil. Hence, absolute temperatures estimated in this study have an uncertainty of about 50°C.

Extracted gases were removed to the purification system, and exposed to a Ti–Zr getter at 800°C for fifteen minutes. The Ti–Zr getter was then cooled to absorb all active gases. The remaining gases were mostly rare gases, especially Ar. The purified gases were collected in a collector tube with the charcoal trap at liquid nitrogen temperature, which was then cut off for mass spectrometry.

Ar isotopes were analyzed by a Reynolds type mass spectrometer (60°, 15 cm radius) with a Farady cage. All masses from 35 to 40 were measured, but mass 35 is almost negligible compared to the other masses and no effects on masses 36 and 38. Isotopic ratios have been obtained to lie the zero-time intercept of a least-squares fit to a linear variation of the ratios with time.

In principle, we can calculate the ^{40}Ar–^{39}Ar age from the Ar isotopic ratios alone and do not necessarily need to know the absolute amount of Ar. With the knowledge of the absolute amount of Ar isotopes, however, we can infer the K- and Ca-contents of a sample by comparing its K- and Ca-derived ^{39}Ar and ^{37}Ar isotopes with those of a standard whose K- and Ca-contents are known. Furthermore, it also serves to evaluate the state of gas retention in each meteorite. Hence, even the approximate values of the amounts of Ar isotopes in meteorites are very useful information. So, the amount of Ar in the present samples was determined by assuming the constant sensitivity of the mass spectrometer throughout the analyses and complete recovery of degassed Ar for all samples. However, the extraction and purification of gases were made separately from the mass spectrometry in this study, which causes the ambiguity in the above assumptions. Judging from the reproducibility of the total output voltage for radiogenic ^{40}Ar of the standard sample, which was estimated from four independent analyses, we assign about 20% uncertainty in the estimated amount. Mass discrimination among Ar isotopes was found to be only 0.08% per atomic mass unit favoring lighter isotopes by measuring the atmospheric Ar isotopes and corrected for the obtained data in the present study.

The obtained data were corrected for the background in the mass spectrometer and the sample gas introducing system. Since extraction and purification procedures were made separately, it was difficult to evaluate properly the contribution from these sources due to its variability. Hence, no corrections were made from these sources. However, on the ^{40}Ar/^{36}Ar—^{39}Ar/^{36}Ar correlation diagram our data mostly lie on a correlation line which passes through the origin and not through the air composition (Fig. 1). This indicates that the effects from our extraction and purification procedures were insignificant. The validity of the present procedures may also be supported from the reasonable results obtained in this study.

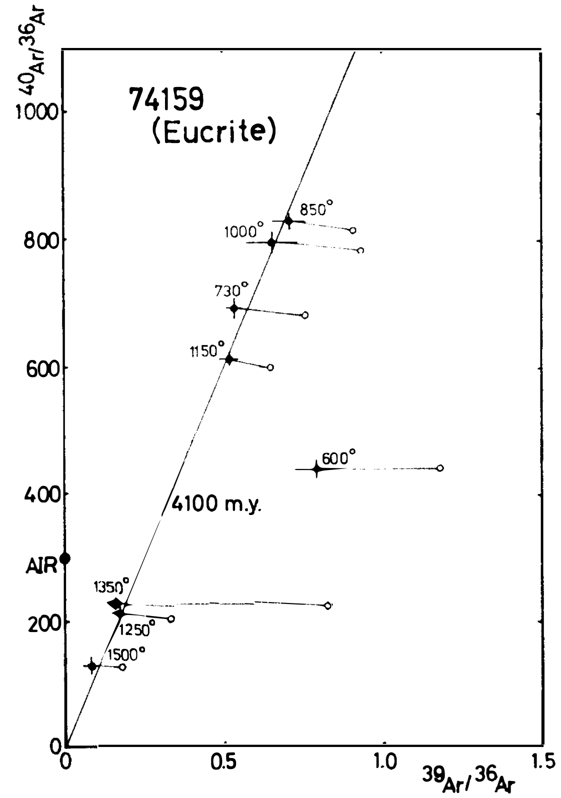

Fig. 1. The ^{40}Ar/^{36}Ar–^{39}Ar/^{36}Ar plot for Yamato-74159 (Eucrite). Open symbols indicate the values before correction for interfering isotopes and the background of the mass spectrometer. Closed symbols show the values after these corrections. Note that the closed symbols except for the 600°C fraction nearly lie on a reference isochron of 4100 m.y. which goes through the zero point. This probably implys that the atmospheric contamination is not significant for this sample.

4. Data Analysis

In order to calculate the ^{40}Ar–^{39}Ar age of a sample from the obtained data, we need many processes for data reduction. The background of the mass spectrometer and the sample introducing system only affect the Ar isotopes at masses 37, 38 and 39 due to memory effects. Hence they are subtracted from each mass peak for a set of data. We have no observable background at mass 36. Although the background at mass 40 is always observed, it is much smaller compared with the observed value for a sample. Then mass discrimination is corrected.

^{37}Ar and ^{39}Ar are corrected for radioactive decay both during and after the irradiation. However, the decay constant for ^{39}Ar ($\lambda_{39}=7.2\times10^{-6}$ day^{-1}) is relatively small compared with the time period between the neutron irradiation and the mass analyses of Ar isotopes. Hence, only the correction for the decay of ^{37}Ar is significant in the present study.

After these corrections, the data represent all measured Ar, including all ^{37}Ar and ^{39}Ar produced by the neutron irradiation. In order to get the necessary information from the data, we need further correct for interfering Ar isotopes. The correction factors were determined as follows by analyzing the neutron irradiated CaF_2 and K_2SO_4: $(^{39}Ar/^{37}Ar)_{Ca}=7.0\times10^{-4}$, $(^{38}Ar/^{37}Ar)_{Ca}=3.9\times10^{-3}$, $(^{36}Ar/^{37}Ar)_{Ca}=5.5\times10^{-4}$, $(^{40}Ar/^{39}Ar)_{K}=7.0\times10^{-2}$, and $(^{38}Ar/^{39}Ar)_{K}=6.7\times10^{-2}$.

We estimate the amount of trapped and spallogenic components by assuming that the ^{38}Ar/^{36}Ar ratios for trapped and spallogenic components are 0.187 and 1.5, respectively. ^{40}Ar is then corrected for trapped (^{40}Ar/^{36}Ar$=0.5$) and spallogenic (^{40}Ar/^{38}Ar$=0.15$) contributions. In the case of ^{38}Ar/^{36}Ar≥1.5, the excess ^{38}Ar is presumed to ^{37}Cl(n, $\gamma\beta$)^{38}Ar, and the remainder presumed spallogenic. However, memory effects for ^{38}Ar were relatively large than the other isotopes in the present study, which reduces the reliability of the obtained value for the amount of ^{38}Ar. Hence, exposure ages were not reported in this paper.

After these corrections, the only remaining ^{40}Ar is assigned to be radiogenic ^{40}Ar* from the decay of ^{40}K. ^{39}Ar has also been corrected for all contributions other than ^{39}K(n, p)^{39}Ar, which is denoted as ^{39}Ar*. The ^{40}Ar*/^{39}Ar* ratio is used for the age calculation.

5. Results

The results of observed Ar isotopic ratios are shown in Table 1 together with the amount of ^{40}Ar for each temperature fraction. They represent the raw data of Ar isotopes after the irradiation of samples and no correction has been made except for the background in the mass spectrometer+gas introducing system and radioactive decay of ^{37}Ar between irradiation and analysis. The assigned uncertainties in the observed Ar isotopic ratios are only statistical (1 σ).

5.1. ^{40}Ar–^{39}Ar ages

In Table 1, the ^{40}Ar–^{39}Ar ages for each temperature fraction are also included,

Table 1. Ar isotopes in neutron-irradiated Yamato-74 meteorites.

Yamato-74640 (H5-6) 0.5201 g $J=0.006518$

T(°C)	[^{40}Ar] ×10^{-8}ccSTP/g	^{36}Ar/^{40}Ar	^{37}Ar/^{40}Ar	^{38}Ar/^{40}Ar	^{39}Ar/^{40}Ar	^{40}Ar*/^{39}Ar*	age (m.y.)
600	24.3	0.00215 ±0.00006	−0.00183 ±0.00030	0.00905 ±0.00078	0.00198 ±0.00050	504.3 ±139.8	2626 ±383
750	180	0.00012 ±0.00001	−0.00004 ±0.00023	0.00043 ±0.00011	0.00140 ±0.00037	712.3 ±190.9	3122 ±398
850	663	0.00006 ±0.00000	0.00038 ±0.00024	0.00010 ±0.00004	0.00086 ±0.00007	1163 ± 95	3878 ±130
1000	1540	0.00005 ±0.00000	0.00043 ±0.00012	0.00009 ±0.00002	0.00064 ±0.00005	1576 ±124	4370 ±129
1150	356	0.00024 ±0.00001	0.00056 ±0.00034	0.00035 ±0.00008	0.00065 ±0.00005	1542 ±118	4334 ±126
1250	1150	0.00013 ±0.00000	0.00270 ±0.00022	0.00082 ±0.00003	0.00060 ±0.00002	1684 ± 62	4479 ± 61
1350	491	0.00018 ±0.00001	0.00554 ±0.00019	0.00205 ±0.00004	0.00062 ±0.00009	1614 ±252	4409 ±257
1500	1130	0.00059 ±0.00004	0.01515 ±0.00052	0.00116 ±0.00002	0.00050 ±0.00010	2029 ±397	4790 ±328
Total	5534.3	0.00021	0.00435	0.00070	0.00066	1526	4317

1) Tabulated data have been corrected for the background in the mass spectrometer and radioactive decay of ^{37}Ar between irradiation and analysis, but include no other corrections.

2) ^{40}Ar*/^{39}Ar* ratios were corrected for all contributions other than the decay of ^{40}K or ^{39}K$(n, p)^{39}$Ar.

Yamato-74190 (L6) 0.7034 g $J=0.006727$

T(°C)	[^{40}Ar] ×10^{-8}ccSTP/g	^{36}Ar/^{40}Ar	^{37}Ar/^{40}Ar	^{38}Ar/^{40}Ar	^{39}Ar/^{40}Ar	^{40}Ar*/^{39}Ar*	age (m.y.)
600	7.70	0.00402 ±0.00025	0.04004 ±0.01459	0.00538 ±0.00026	0.03106 ±0.00195	32.15 ± 2.07	353.2 ± 20.7
700	13.7	0.00205 ±0.00010	0.05536 ±0.00447	0.00476 ±0.00022	0.03257 ±0.00370	30.67 ± 3.52	338.4 ± 35.5
880	36.1	0.00155 ±0.00007	0.03454 ±0.00141	0.00410 ±0.00030	0.02992 ±0.00255	33.38 ± 2.89	365.3 ± 28.6
920	39.6	0.00130 ±0.00005	0.02538 ±0.00472	0.00314 ±0.00042	0.02438 ±0.00177	40.98 ± 3.05	439.3 ± 30.2
1050	31.6	0.00204 ±0.00005	0.03343 ±0.00297	0.00520 ±0.00026	0.02235 ±0.00075	44.72 ± 1.60	474.5 ± 14.9
1150	12.9	0.00657 ±0.00014	0.03903 ±0.00342	0.02674 ±0.00035	0.01369 ±0.00080	73.12 ± 4.55	721.7 ± 37.1
1270	4.43	0.00484 ±0.00057	0.03142 ±0.00452	0.02597 ±0.00130	0.01566 ±0.00430	63.88 ± 7.71	644.9 ±150.3
1350	4.97	0.03589 ±0.00199	0.5429 ±0.0143	0.07783 ±0.00079	0.02033 ±0.01020	50.02 ±25.50	523.3 ±231.9
1450	7.72	0.04523 ±0.00122	1.2950 ±0.0081	0.16100 ±0.01190	0.00708 ±0.00069	161.9 ±17.4	1329 ±103
Total	158.72	0.00545	0.11164	0.01659	0.02419	41.40	443.2

Table 1. (*continued*)

Yamato-74159 (Eucrite) 0.7199 g J=0.007104

T(°C)	[^{40}Ar] ×10^{-8} ccSTP/g	^{36}Ar/^{40}Ar	^{37}Ar/^{40}Ar	^{38}Ar/^{40}Ar	^{39}Ar/^{40}Ar	^{40}Ar*/^{39}Ar*	age (m.y.)
600	81.0	0.00230 ±0.00008	0.05207 ±0.00063	0.00129 ±0.00010	0.00185 ±0.00012	552.4 ± 37.8	2876 ±98
730	402	0.00146 ±0.00002	0.04374 ±0.00095	0.00235 ±0.00005	0.00080 ±0.00003	1301 ± 51	4197 ±64
850	538	0.00123 ±0.00002	0.03680 ±0.00054	0.00195 ±0.00004	0.00088 ±0.00006	1170 ± 82	4025 ±113
1000	494	0.00127 ±0.00002	0.03700 ±0.00049	0.00188 ±0.00004	0.00084 ±0.00008	1214 ±125	4085 ±166
1150	802	0.00166 ±0.00001	0.04649 ±0.00026	0.00247 ±0.00003	0.00088 ±0.00003	1178 ± 45	4036 ± 62
1250	264	0.00478 ±0.00005	0.12010 ±0.00090	0.00691 ±0.00008	0.00090 ±0.00008	1219 ±111	4092 ±147
1350	53.2	0.00448 ±0.00008	0.10640 ±0.00270	0.00544 ±0.00017	0.00076 ±0.00008	1464 ±173	4391 ±194
1500	163	0.00791 ±0.00007	0.20330 ±0.00130	0.01142 ±0.00069	0.00082 ±0.00017	1471 ±378	4398 ±423
Total	2797.2	0.00221	0.05994	0.00321	0.00087	1183	4043

Yamato-74097 (Diogenite) 0.7542 g J=0.007036

T(°C)	[^{40}Ar] ×10^{-8} ccSTP/g	^{36}Ar/^{40}Ar	^{37}Ar/^{40}Ar	^{38}Ar/^{40}Ar	^{39}Ar/^{40}Ar	^{40}Ar*/^{39}Ar*	age (m.y.)
700	6.7^{+} (~22)	0^{+} (~0.00310)	—	~0.070^{+} (0.00650)	~0.0069^{+} (0.000640)	~146^{+} (~1560)	~1270^{+} (~4480)
850	5.12	0.00377 ±0.00020	−0.00012 ±0.00058	0.00390 ±0.00045	0.00701 ±0.00122	142.7 ±24.8	1254 ±157
1000	6.15	0.00328 ±0.00023	0.2627 ±0.1033	0.00297 ±0.00030	0.00725 ±0.00075	141.5 ±14.6	1247 ± 94
1200	5.35	0.00465 ±0.00037	0.5810 ±0.0598	0.00426 ±0.00108	0.00887 ±0.00095	118.1 ±12.7	1091 ± 89
1250	3.86	0.00312 ±0.00020	0.3974 ±0.0063	0.00680 ±0.00028	0.00848 ±0.00134	121.9 ±20.7	1117 ±142
1350	~1.1	~0.015	~2.22	~0.015	~0.0098	~120	~1110
1500	1.95	0.01529 ±0.00113	1.845 ±0.115	0.01846 ±0.00093	0.00977 ±0.00101	117.9 ±12.2	1090 ± 87
Total	30.23 (45.53)	0.00481 (0.00319)	0.4347 (0.2883)	0.00397 (0.00263)	0.00783 (0.00519)	132.8 (200.3)	1190 (1586)

Numerical figure with a cross has been calculated with the asssumption that all ^{36}Ar observed in this fraction is of atmospheric origin and the amounts of ^{40}Ar and ^{38}Ar have been corrected for atmospheric component. Numerical figure in the parenthesis represents, however, the value without correction for atmospheric component. Refer the text for discussion.

which have been calculated after the following formula,

$$t=\frac{1}{\lambda}\ln\left\{1+J\left(\frac{^{40}\mathrm{Ar}^*}{^{39}\mathrm{Ar}^*}\right)\right\},$$

where J is a constant, depending on the state of neutron irradiation. The J-value can be obtained by measuring the ^{40}Ar*/^{39}Ar* ratio of the standard sample whose K-Ar age is known. The J-value is expressed as $(e^{\lambda t_m}-1)/(^{40}\mathrm{Ar}^*/^{39}\mathrm{Ar}^*)_m$. Hence, the uncertainty in the calculated age should reflect those of both the measured (^{40}Ar*/^{39}Ar*) ratio and the J-value. The J-value also includes the uncertainty of the calculated age for the (^{40}Ar*/^{39}Ar*) ratio and the K–Ar age of the standard sample. Present results include these uncertainties in the calculated age, whose derivation is the same as those described by DALRYMPLE and LANPHERE (1971). When the neutron flux has a gradient along the length of the ampoule in which samples are loaded, it directly affects the J-value. Such difference in the J-value is estimated from the paired standard sample at both ends of each ampoule and the J-value for each sample is estimated by interpolating them. At both ends, the difference in the J-value amounted up to 8%.

In the present study, ^{40}Ar–^{39}Ar ages were calculated by using the decay constants newly recommended by the IUGS Subcommission on Geochronology (STEIGER and JÄGER, 1977). This implies that the calculated age reduces by about 100 m.y. for a sample of about 4500 m.y. than that calculated using the older decay con-

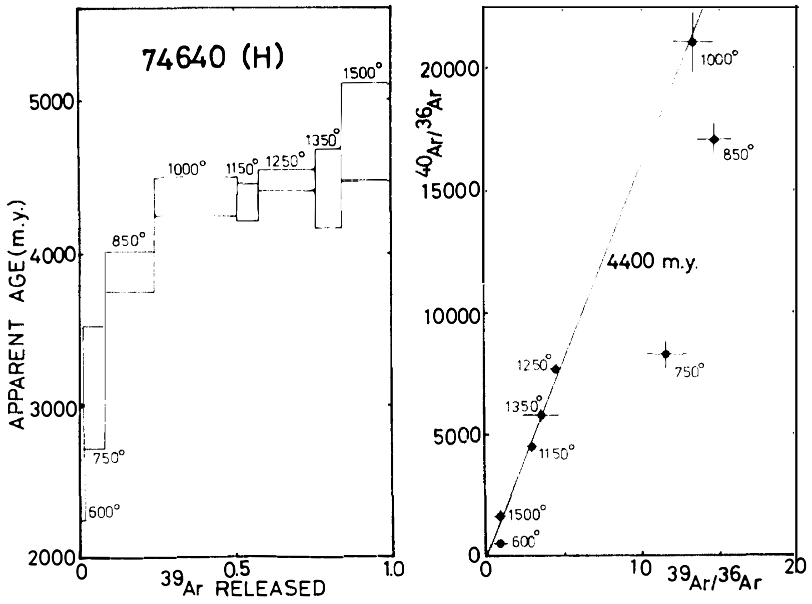

Fig. 2. The ^{40}Ar–^{39}Ar age diagram and the ^{40}Ar/^{36}Ar–^{39}Ar/^{36}Ar plot for Yamato-74640 (H5–6). The numerical figure at each column indicates the degassing temperature in °C. The uncertainties correspond to 1 σ. In the right figure, the line of 4400 m.y. is drawn as a reference which goes through the zero point.

stants.

The results of ^{40}Ar–^{39}Ar age spectra are also shown in Figs. 2–5 together with the ^{40}Ar/^{36}Ar—^{39}Ar/^{36}Ar isochron plot. As seen in these figures, the four samples show quite different age, reflecting their different histories.

The Yamato-74640 (H5–6) has an age spectrum typical of a meteorite which had been slightly affected by secondary partial Ar loss. As shown in Fig. 2, the apparent ^{40}Ar–^{39}Ar age increases gradually to a plateau age of about 4400 m.y. The plateau age is based on about 61% of the released ^{39}Ar, covering the 1000°–1350°C fractions. The 1500°C fraction shows an apparently higher age of about 4800 m.y. with relatively large uncertainty (330 m.y.). Contamination from the blank may be one possibility to cause such a high apparent ^{40}Ar–^{39}Ar age. As shown in Fig. 6, however, the release pattern of ^{36}Ar for this sample almost correlates with that of spallogenic ^{38}Ar, including the 1500°C fraction. This suggests that the observed ^{36}Ar is mostly spallogenic, but not atmospheric. Hence, atmospheric contamination is probably not a main cause for the high value in the 1500°C fraction. Another possibility may be an inadequate correction for K- and Ca-derived Ar isotopes. In this case, however, this should affect the other fractions in this sample and the other samples, too. Furthermore, minor change in the correction factors for these interfering Ar isotopes does not alter the observed value significantly. Since the assigned uncertainty in this fraction is large, we cannot give much weight to this apparent high value. The plateau age of about 4400 m.y. corresponds to about 4500 m.y., if old decay constants are used in the calculation of the ages. In the ^{40}Ar/^{36}Ar—^{39}Ar/^{36}Ar plot, ^{40}Ar/^{36}Ar and ^{39}Ar/^{36}Ar ratios are corrected for K- and Ca-derived interference Ar isotopes, but include

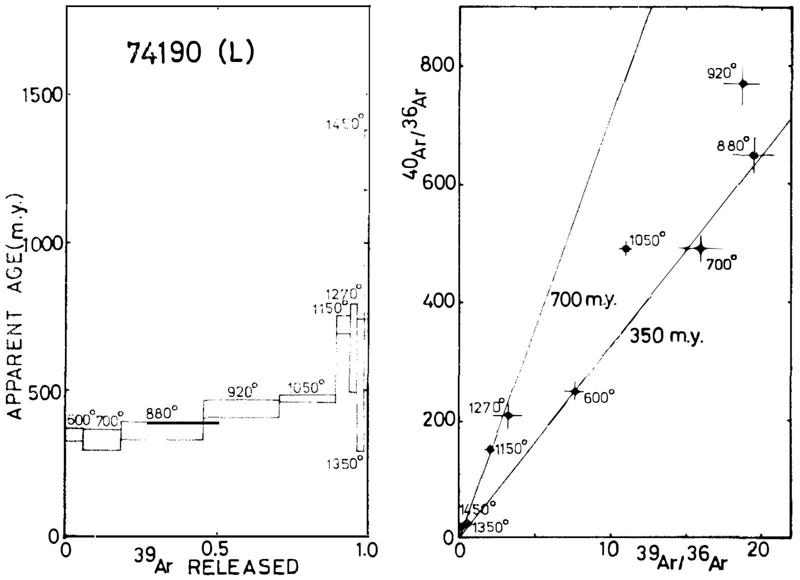

Fig. 3. The ^{40}Ar–^{39}Ar age diagram and the ^{40}Ar/^{36}Ar–^{39}Ar/^{36}Ar plot for Yamato-74190 (L6).

trapped and spallogenic components. As shown in the right figure in Fig. 2, except for lower temperature fractions, they almost lie on a correlation line of about 4400 m.y., which nearly goes through the zero point. This is concordant with the result of the age spectrum, in which the atmospheric ^{40}Ar has been assumed to be insignificant compared to the radiogenic ^{40}Ar.

The sample Yamato-74190 (L6) shows a quite different age spectrum from the previous one, indicating a much younger apparent ^{40}Ar–^{39}Ar age and with a plateau-like age of about 360 m.y. for the lower three fractions (600–880°C). These fractions cover about 46% of the released ^{39}Ar. The ^{40}Ar–^{39}Ar age then increases up to about 1300 m.y. In the ^{40}Ar/^{36}Ar—^{39}Ar/^{36}Ar plot, this situation seems to be reflected in the apparent scattering of data points. However, the data points for lower fractions seem to lie on an isochron of about 350 m.y., whereas those of higher fractions are on an isochron of about 700 m.y., both of which nearly go through the zero point. The total ^{40}Ar–^{39}Ar age is only 442 m.y. Hence, this sample clearly lost the radiogenic ^{40}Ar due to secondary effects after its formation. The apparent young age for lower temperature fractions will probably have a significant meaning, which will be discussed in the following section.

The Yamato-74159 (Eucrite) shows an intermediate plateau age of 4075 m.y. for the 850–1250°C fractions which cover about 75% of the released ^{39}Ar. The lowest temperature fraction (600°C) shows a much younger age of 2876 m.y., reflecting the slight Ar loss from the sample. The higher temperature fractions (1350°C and 1500°C) show a higher ^{40}Ar–^{39}Ar age of about 4400 m.y., though the

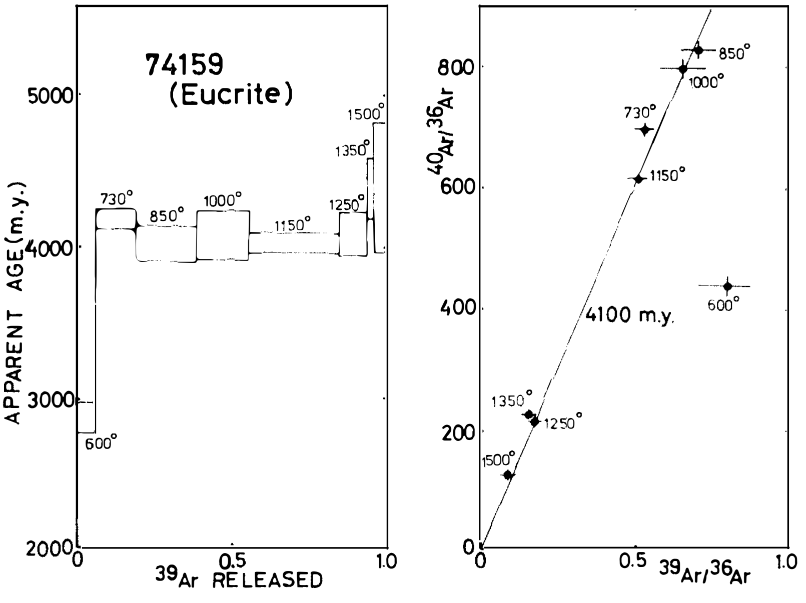

Fig. 4. The ^{40}Ar–^{39}Ar age diagram and the ^{40}Ar/^{36}Ar–^{39}Ar/^{36}Ar plot for Yamato-74159 (Eucrite). Note that the plateau age is younger than that of Yamato-74640. The line of 4100 m.y. is drawn as a reference.

uncertainty in these fractions is relatively large (300–400 m.y.). The total ^{40}Ar–^{39}Ar age becomes 4043 m.y. Since the fractions for the intermediate plateau include most released ^{39}Ar, the age will reflect a significant event for the sample. The apparent higher ^{40}Ar–^{39}Ar ages for the higher temperature fractions may also reflect an older event in the history of the sample. These points will also be discussed in the following section.

The result of the Yamato-74097 (Diogenite) is also quite different from the other samples both in its age and the age spectrum. The total ^{40}Ar–^{39}Ar age is 1090 m.y. The age spectrum seems to show a plateau age of 1100 m.y., though the lower temperature fractions indicate slightly older ^{40}Ar–^{39}Ar ages than those for the higher temperature fractions. Since the two fractions (700°C, 1350°C) could not be analyzed so precisely as the other fractions due to insufficient experimental procedures, we could not assign the same reliability for the data in these fractions as for the others. In spite of this, the 700°C fraction demonstrates a quite different character from the other fractions. If we follow a hypothesis that all ^{40}Ar in this fraction was derived from the sample itself, the apparent ^{40}Ar–^{39}Ar age indicates about 4500 m.y., distinctly older than all the other fractions. If it was the case, however, about half of ^{40}Ar in the sample should be degassed in the 600°C fraction. Although the uncertainty in each fraction for this sample is

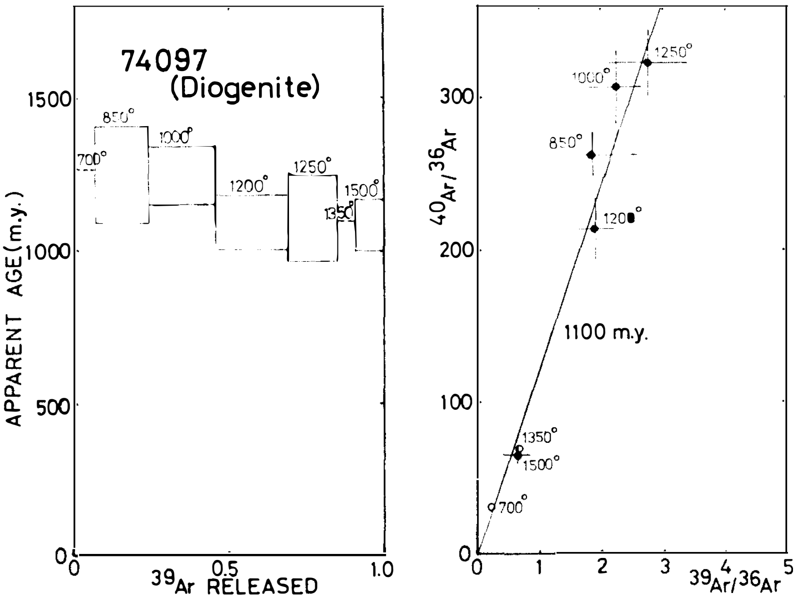

Fig. 5. The ^{40}Ar–^{39}Ar diagram and the ^{40}Ar/^{36}Ar–^{39}Ar/^{36}Ar plot for Yamato-74097 (Diogenite). The line of 1100 m.y. is drawn as a reference. The data for the 700 and 1350°C fractions should be regarded as approximate due to the insufficient experimental conditions for these fractions. The data for the 700°C fraction have been corrected for atmospheric component.

relatively large due to its low K-content, the general trend of relatively younger plateau-like age at higher temperatures should be real. Hence, it is questionable whether the ^{36}Ar observed in the 600°C fraction could be attributed to the original sample. Instead, if we assume that the ^{36}Ar observed in this fraction reflects the atmospheric one, we can obtain a ^{40}Ar–^{39}Ar age of 1270 m.y. after the atmospheric correction. Furthermore, the total amount of ^{40}Ar which is regarded to be mostly radiogenic reduces to about two thirds after subtracting the assumed atmospheric components. Such a situation is clearly reflected in the ^{40}Ar/^{36}Ar—^{39}Ar/^{36}Ar diagram for this sample (Fig. 5). If the observed value for the 600°C fraction is plotted in this diagram, it largely deviates from the other points which roughly lie on an isochron. When the 600°C fraction is corrected by assuming atmospheric contamination, however, the corrected value almost lies on the same isochron. Hence, it is more likely that the 600°C fraction for Yamato-74097 might have been affected by atmospheric contamination. It is not yet clear why only the 600°C fraction for this sample was seriously affected by atmospheric contamination. Since the sample is reported to be relatively weathered among the Yamato meteorites (H. TAKEDA, personal communication, 1978), weathering effects may be a possibility. Since diogenite generally contain very little potassium, the obtained ages have larger uncertainty than the other samples. Even if we take the low potassium into account, the relatively low ^{40}Ar–^{39}Ar age for this sample seems to be significant.

5.2. *Release patterns of Ar isotopes*

In order to demonstrate the different characteristics of degassed Ar of different origin, two examples are shown in Figs. 6 and 7.

In Fig. 6, the release patterns of Ar for Yamato-74640 are shown against degassing temperature. As shown in this figure, the release pattern of ^{40}Ar is similar to that of ^{39}Ar, suggesting that the observed ^{40}Ar is mostly of radiogenic origin. The release pattern of ^{40}Ar has peaks at 1000°C, 1250°C and 1500°C, which probably correspond to different minerals. On the other hand, the release pattern of ^{37}Ar is quite different from those of ^{40}Ar and ^{39}Ar. ^{37}Ar is hardly degassed below 1200°C and most ^{37}Ar is degassed at the highest temperature. This means that Ca is mostly distributed in the high temperature mineral, whereas K is distributed in a few kinds of minerals, especially in the low temperature mineral. The release patterns of spallogenic ^{38}Ar and ^{36}Ar are quite similar each other, which implys that most ^{36}Ar is of spallogenic origin. Furthermore, these release patterns are different from that of ^{37}Ar below 1200°C. Hence, the target elements for spallogenic Ar at lower temperatures may be mainly Fe and Ti, whereas those at higher temperatures are probably dominated by Ca. No observable trapped component was identified in this sample.

Another example is shown in Fig. 7, where the release patterns of each Ar

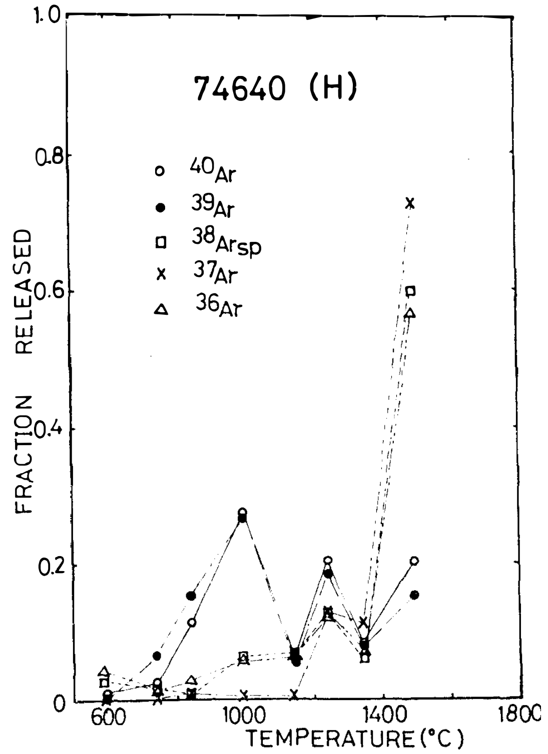

Fig. 6. The release patterns of Ar isotopes for Yamato-74640. Note that ^{40}Ar has a similar release pattern to that of ^{39}Ar, which seems to have three peaks at 1000, 1200 and 1500°C, respectively, reflecting different minerals from which K-derived ^{39}Ar and radiogenic ^{40}Ar were outgassed. The release pattern of ^{36}Ar resembles that of spallogenic ^{38}Ar, suggesting that most ^{36}Ar is of spallogenic origin for this meteorite.

isotope for Yamato-74159 (Eucrite) are shown. The release patterns of ^{40}Ar and ^{39}Ar are quite similar each other. Furthermore, the release pattern of spallogenic ^{38}Ar is similar to those of ^{36}Ar and Ca-derived ^{37}Ar. In this sample, trapped ^{38}Ar can be identified. However, its release pattern is different from others, particularly at lower temperature fractions. Hence, even if the trapped component is included in each fraction, its contribution is very small compared to spallogenic Ar for this sample. Furthermore, the similarity of release patterns between spallogenic ^{38}Ar and Ca-derived ^{37}Ar suggest that the target elements for spallogenic Ar in this sample were mostly Ca through whole temperature fractions. Since the main peaks for the release patterns of ^{39}Ar and ^{37}Ar appear at the same temperatures, the distribution of K and Ca are not so different in this sample. This may reflect a character for rather simple mineral compositions in this sample.

Although the figure is not shown here, the release patterns of Ar isotopes for Yamato-74190 (L) indicate the intermediate character between the two examples as described here. Yamato-74097 (Diogenite) shows more complex release pat-

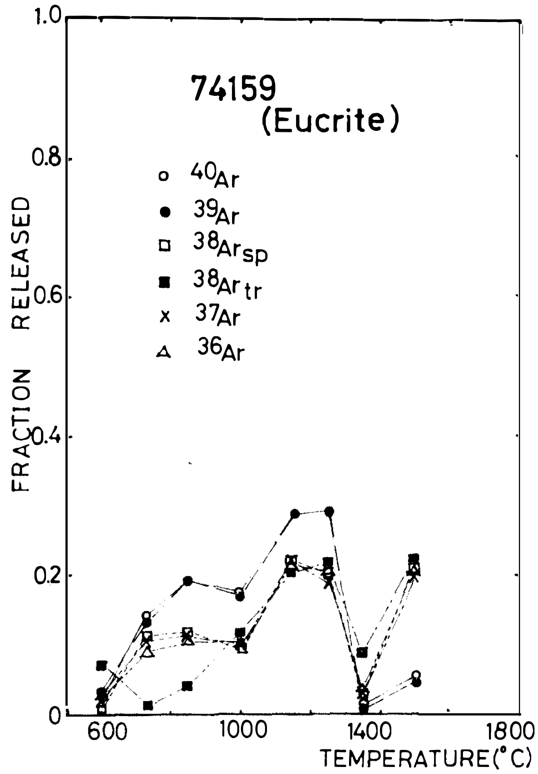

Fig. 7. The release patterns of Ar isotopes for Yamato-74159. The release patterns of ^{36}Ar and spallogenic ^{38}Ar are quite similar to that of Ca-derived ^{37}Ar, indicating that the main target element for spallogenic components in this sample is Ca. Note that trapped ^{38}Ar has a different release pattern from those of the other isotopes.

terns including larger uncertainties, though Ca-derived ^{37}Ar was mostly degassed at higher temperatures.

5.3. *K and Ca concentration*

K and Ca concentration in the sample can be estimated by comparing the total amounts of K-derived ^{39}Ar and Ca-derived ^{37}Ar between the sample and the standard sample. Present standard sample LP-6 (biotite) contains 8.37% K and 0.15% Ca by weight. Since the Ca-content in the standard sample is so low that the obtained value of Ca-content has probably more uncertainty than that of K-content.

In the present study, we have got the following conversion ratio for the ^{39}K (n, p) ^{39}Ar reaction.

$$^{39}\text{Ar}^*/\text{K}=(4.8\pm0.7)\times10^{-5}\ \text{cc STP/g K}.$$

Furthermore, the relation of production ratio between K-derived ^{39}Ar and Ca-derived ^{37}Ar has been estimated to be as follows by using the four standard samples

Table 2. Summary of ^{40}Ar-^{39}Ar ages of Yamato-74 meteorites.

Sample	[K] (%)*	[Ca] (%)*	Total	^{40}Ar-^{39}Ar age (m.y.)**			Plateau range
				Minimum	Maximum	Plateau	
Yamato-74640 (H5-6)	0.080	1.0	4317	2626 ±383	4790 ±328	4407 ± 71	1000-1350°C (61 % of released ^{39}Ar)
Yamato-74190 (L6)	0.081	0.69	443.2	338.4 ± 35.5	1329 ±103	357.4 ± 32.4	600-880°C (46 % of released ^{39}Ar)
Yamato-74159 (eucrite)	0.050	6.7	4043	2876 ± 98	4398 ±423	4075 ± 49	850-1250°C (75 % of released ^{39}Ar)
Yamato-74097 (diogenite)	0.0048	0.51	1190	1090 ± 87	~1270	1100 ± 62	1200-1500°C (55 % of released ^{39}Ar)

* K- and Ca-contents were estimated from the total amounts of ^{39}Ar and ^{37}Ar of samples by comparing those of the standard sample LP-6. About 20 % uncertainty is included in each value.

** ^{40}Ar-^{39}Ar age was calculated by using the following constants for ^{40}K.
$\lambda_e = 0.581 \times 10^{-10} y^{-1}$, $\lambda_\beta = 4.962 \times 10^{-10} y^{-1}$, $^{40}K/K = 1.167 \times 10^{-4}$ (Steiger and Jäger, 1977).
Uncertainties in the ages represent 1 σ.

in total,

$$K/Ca=(0.54\pm0.11)\ ^{39}Ar^{*}/^{37}Ar.$$

The relatively large uncertainty reflects those of reproducibility including the separated procedures of Ar extraction and purification and Ar analyses.

By using these relations, K- and Ca-contents have been obtained for present samples, whose results are summarized in Table 2.

As shown in Table 2, the estimated K-contents for Yamato-74640 and Yamato-74190 are of the order of 800 ppm, which almost agree with the averaged K-contents for H- and L-chondrites (MASON, 1971). Although the obtained Ca-content for Yamato-74640 is in the range of averaged H-chondrites within the experimental error, the value of Ca-content for Yamato-74190 is distinctly lower than that of the averaged L-chondrites. Hence, there remains a possibility that the high temperature Ca minerals might not have been completely melted in this sample. Since the estimated K-content in this sample is reasonable, the effect of incomplete melting would not affect the obtained age significantly.

Yamato-74159 has been chemically analyzed by H. HARAMURA (TAKEDA *et al.*, 1978), which indicates the values of 0.058% K and 6.78% Ca. Present results are in good agreement with these values within the experimental uncertainties, indicating the reliability both for concentrations and the complete degassing of Ar from this sample.

Although the results for Yamato-74097 show relatively low K-content of only 48 ppm and about 0.5% of Ca, these values are less reliable than those for the other samples. The published results on K-contents of diogenites are much variable (0.7–90 (?) ppm, MASON, 1971), covering the present result. The pyroxene compositions of Yamato-74097 have shown the Ca-content of 0.71–0.75% (TAKEDA *et al.*, 1978). Since the meteorite is reported to consist almost entirely of pyroxene, present result on the Ca-content may be a little underestimated. If this is the case, the possibility of incomplete degassing from this sample cannot be denied. Even if Ca-derived ^{37}Ar was not completely degassed, radiogenic ^{40}Ar would probably have been almost entirely degassed as revealed from the total K-content and the release pattern of ^{39}Ar. Hence, it does not affect the discussion on the obtained ^{40}Ar–^{39}Ar age for this sample.

6. Discussion

In the present study, we have determined the ^{40}Ar–^{39}Ar ages of four Yamato-74 meteorites, whose results are different one another reflecting their different history.

The age spectrum of Yamato-74640 is typically seen in some meteorites. For example, St. Severin meteorite (LL6) shows a quite similar age spectrum to this sample, where a little younger ^{40}Ar–^{39}Ar age is observed below about 20% of cumulative released ^{39}Ar, followed by a plateau age (PODOSEK, 1971). Although PODOSEK assumed 4600 m.y. for the plateau age of St. Severin in 1971, he corrected it to 4500 m.y. in a later paper (PODOSEK and HUNEKE, 1973). Furthermore, if the new decay constants for ^{40}K are used in the calculation of the age, it decreases to the value of 4400 m.y. which is in good agreement with the result of Yamato-74640. So far, more than 10 chondrites have been reported which have given well-defined plateaus in the range of 4400–4600 m.y. (WETHERILL, 1975). These ^{40}Ar–^{39}Ar ages should be reduced by about 100 m.y. after the new decay constants for ^{40}K. These ages are commonly interpreted as either a formation time, or the time of a very thorough metamorphic outgassing event. In effect, these meteorites are more or less altered, though the values of the ^{40}Ar–^{39}Ar ages do not correlate with the degree of metamorphism.

These ^{40}Ar–^{39}Ar ages generally agree with the Rb–Sr internal isochron ages of ordinary chondrites even after the new decay constants for ^{40}K and ^{87}Rb (KIRSTEN, 1978), since the change of the decay constant of ^{87}Rb from $1.39\times10^{-11}\,y^{-1}$ to $1.42\times10^{-11}\,y^{-1}$ also reduces the calculated Rb–Sr age by 100 m.y. around the age of 4500 m.y. However, they seem to be a little younger than Pb–Pb and/or Sm–Nd ages of meteorites which are still in the range of 4500–4600 m.y. even after the new decay constants are used. Since Pb–Pb and Sm–Nd ages are likely to be less disturbed by a later event than ^{40}Ar–^{39}Ar and Rb–Sr internal isochron ages, the ages obtained by different methods probably reflect different events. However it does not necessarily mean that the ^{40}Ar–^{39}Ar age (and/or Rb–Sr age) indicates the time of secondary metamorphism because the Pb–Pb and/or Sm–Nd ages may reflect the time of a more primitive differentiation of large scale for the parent body and the ^{40}Ar–^{39}Ar and/or Rb–Sr ages the later differentiation of minor scale. Furthermore, if a metamorphism is presumed for the event indicated by a ^{40}Ar–^{39}Ar age, we must assume a very thorough metamorphism which caused a complete degassing of high temperature minerals. The results of Rb–Sr systems also suggest complete redistribution of Rb and Sr among the various minerals. This requires a relatively long and high temperature regime for meteorites, just below the melting point of each mineral.

Hence, the ^{40}Ar–^{39}Ar age of Yamato-74640 may represent either the formation time of the meteorite corresponding to the differentiation of the minor scale or the time of intense metamorphism, though the meaning of the age has some ambiguity in the latter case.

In the case of Yamato-74190, the age spectrum clearly indicates a later event for this meteorite. It is well known that many L-chondrites have relatively young gas retention ages which have a peak around 300–500 m.y. especially when concordant K–Ar and U–He ages are taken (HEYMANN, 1967; TAYLOR and HEYMANN, 1969). This problem has been attacked in more detail by using the ^{40}Ar–^{39}Ar method, from which we can designate the time of event more definitely from the age spectrum (TURNER, 1969; BOGARD *et al.*, 1976). The results indicate that most L-chondrites show quite similar age spectra as observed in Yamato-74190. They show mostly the youngest ^{40}Ar–^{39}Ar age at the lowest or relatively lower degassing temperature around 300–600 m.y. The apparent ^{40}Ar–^{39}Ar age then increases gradually at higher temperatures, but never reaches a plateau. Because of the characteristic release pattern of Ar and the age distribution of meteorites, it is generally interpreted that the youngest ^{40}Ar–^{39}Ar ages indicate the time of episodic heating such as the times of major collisional events among meteorite parent objects (TURNER, 1969; BOGARD *et al.*, 1976). Since Yamato-74190 has been classified as an L6 chondrite (KIMURA *et al.*, 1978) and shows a quite similar ^{40}Ar–^{39}Ar age spectrum to some other L-chondrites, we can interprete the ^{40}Ar–^{39}Ar age of about 350 m.y. as the time of a major collision for the parent object of this meteorite. Although the present result does not seem to agree with the reported K–Ar age (KAMAGUCHI and OKANO, 1978), we have no proper explanation for this at present.

Yamato-74159 seems to show an intermediate age of 4075 m.y., which is definitely younger than Yamato-74640. It is known that ^{40}Ar–^{39}Ar ages of most achondrites are less than 4400 m.y., and sometimes there is no definite plateau age suggesting later degassing events (PODOSEK and HUNEKE, 1973; KIRSTEN and HORN, 1975, RAJAN *et al.*, 1975). It is noteworthy that the ^{40}Ar–^{39}Ar age spectrum of Pasamonte (eucrite) (PODOSEK and HUNEKE, 1973) is quite similar to that of Yamato-74159; Pasamonte also shows a plateau-like age of about 4050 m.y. (after the new decay constants for ^{40}K) at the intermediate temperatures which cover more than 70% of released ^{39}Ar. The apparent ^{40}Ar–^{39}Ar age increases up to 4400 m.y. at the highest temperature, which is also seen in the age spectrum of Yamato-74159 (see Fig. 4). Thus, the plateau-like ages observed at the intermediate temperatures for Yamato-74159 agree well with that for Pasamonte within the experimental uncertainty, including their release patterns. Furthermore, TAKEDA *et al.* (1978) have reported that Yamato-74159 is a eucritic polymict breccia which has a texture and pyroxene chemical trend similar to those of Pasamonte. Hence, there is a possibility that Yamato-74159 may be composed of some components which have an origin and thermal history in common with Pasamonte.

Eucrites have often shown relatively younger Rb–Sr or ^{40}Ar–^{39}Ar ages of less than 4400 m.y. For example, Bereba and Sioux County show the Rb–Sr internal isochron ages of about 4080 and 4100 m.y., respectively, whereas the Rb–Sr whole rock isochron age including these eucrites show an older age of 4470±130 m.y. (BIRCK and ALLÈGRE, 1978, recalculated with the new decay constant for ^{87}Rb). Furthermore, Pasamonte shows definitely older Sm–Nd and Pb–Pb ages of about 4500 m.y., though its Rb–Sr systematics seem to have been disturbed (UNRUH *et al.*, 1977). Hence, the age of about 4100 m.y. observed in Yamato-74159 and some other eucrites may represent the outgassing event on the achondrite parent body.

The Sm–Nd and Pb–Pb systematics do not seem to have been disturbed at this time for Pasamonte. If these eucrites have a common origin and thermal history with Pasamonte, we may further conjecture that the impact of meteoroids on the achondrite parent body would be one of the likely processes to produce disturbed ages.

Yamato-74097 is one of the diogenites which show the same chemistry and textures as those of the Yamato-692 diogenite (TAKEDA *et al.*, 1975), whose texture is unlike that of the other diogenites known to date. It has been reported to be unbrecciated and texturally the pyroxene seems to have recrystallized to a granoblastic texture (TAKEDA *et al.*, 1978). These stones have no fusion crust and consist almost entirely of pyroxene. They have a cosmic-ray exposure age of about 35 m.y., which also resembles that of Yamato-692 diogenite but differs from other diogenites known to date (NAGAO and TAKAOKA, 1979). These results suggest that the Yamato diogenites may have a common parent body different from the other diogenites.

Concerning the age of the diogenite, very little has been known so far, since they are K-poor meteorites composed mostly of pyroxene. Only a Rb–Sr internal isochron age of about 4500 m.y. has been reported for Tatahouine (BIRCK *et al.*, 1975). As discussed above, however, Yamato diogenites have quite different characteristics from the other diogenites known to date. In this respect, an apparent young plateau-like ^{40}Ar–^{39}Ar age of about 1100 m.y. for Yamato-74097 is very interesting, even if the uncertainty in the obtained age is relatively large. Such young plateau-like ^{40}Ar–^{39}Ar ages have only been known for two nakhlites (a kind of achondrite), Nakhla and Lafayette both of which show a plateau ^{40}Ar–^{39}Ar age of about 1300 m.y. As shown in Fig. 5, Yamato-74097 shows a completely different age spectrum from the other meteorites examined in this study. It shows rather higher ^{40}Ar–^{39}Ar ages at the lower temperature fractions and a little lower but similar ^{40}Ar–^{39}Ar ages at the higher temperature fractions. Since the K-content in this sample is so low, we cannot give much weight in the apparent difference in the obtained ^{40}Ar–^{39}Ar ages due to relatively large uncertainty. To produce such an age spectrum, we must assume a complete Ar resetting about 1100 m.y. ago for this sample. The recrystallization of pyroxene in this sample might have been associated with this event. Generally it is not easy to cause a complete Ar redistribution without melting the sample. However, a very intense metamorphism may be able to do this. In the case of Nakhla, the Rb–Sr internal isochron age also shows the same value as the ^{40}Ar–^{39}Ar age (PAPANASTASSIOU and WASSERBURG, 1974; GALE *et al.*, 1975). GALE *et al.* (1975) have suggested that the age of the Nakhla achondrite represents the time of an igneous crystallization event on the parent body of Nakhla on the ground that a well-defined Rb–Sr internal isochron means the occurrence of a very thorough Sr isotopic equilibration at this time and its texture indicates Nakhla to be a cumulate. Nakhla is also an unbrecciated achondrite. If this is the case, it means the occurrence of relatively young igneous activity on the parent body of some meteorites, which gives an important key to disclose the evolution of the solar system. Although we have no additional data for Yamato-74097 diogenite, it may also suggest a relatively young event for this meteoritic parent body. Since the other Yamato diogenites seem to have a common origin with this diogenite, they are also expected to show similar ^{40}Ar–^{39}Ar ages. At present, we cannot designate whether the apparent young event for these diogenites corresponds to an igneous crystallization as Nakhla or a very intense metamorphism on the parent body of these diogenites. In this respect, it is urgently desired that the diogenite is examined by the other dating methods, too. Then, we may be able to specify the characteristics of the event more clearly.

Acknowledgments

The authors express their thanks to Prof. T. NAGATA and Dr. K. YANAI of the National Institute of Polar Research for providing them with the samples used in this study. They also appreciate Drs. H. TAKEDA of the University of Tokyo and N. TAKAOKA of Osaka University for their useful information on samples.

They are grateful to Dr. R. HUTCHISON of the British Museum (Natural History) who reviewed the manuscript and improved the English.

This study was financially supported by the Ministry of Education under the grant No. 234024. One of them (I.K.) thanks the Ito Science Foundation for its financial support in part in this study.

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(*Received August 25, 1978*)