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^{40}Ar–^{39}Ar ANALYSES OF A LUNAR METEORITE (YAMATO-86032) AND A FEW LL3 AND LL4 CHONDRITES FROM ANTARCTICA

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Abstract: ^{40}Ar–^{39}Ar analyses were performed for a lunar meteorite (Yamato-86032), two LL3 (Y-790448, Allan Hills-764) and one LL4 (Y-74442) chondrites from Antarctica.

The lunar meteorite Y-86032 shows a scattered ^{40}Ar–^{39}Ar age spectrum with anomalously high ages in the higher temperature fractions, indicating a shock effect on the analyzed sample.

Among the three LL chondrites analyzed, the sample Y-790448 indicates a plateau ^{40}Ar–^{39}Ar age of 4521 ± 28 Ma in the lower temperature fractions (600–800°C). The other two LL chondrites show inverse staircase spectra in the higher temperature fractions. In the LL chondrite group, un-equilibrated chondrites seem to show older ^{40}Ar–^{39}Ar ages compared with equilibrated ones, which may be related to the differences in the thermal history of each portion of their parent body.

1. Introduction

In order to clarify the thermal history of meteorites, ^{40}Ar–^{39}Ar analyses are effective, since Ar systematics are more sensitive to thermal effects compared with solid elements.

Among many meteorites recovered from Antarctica, some meteorites are regarded to have originated from the moon (*e.g.*, YANAI and KOJIMA, 1987). Yamato-86032 is an anorthositic breccia and has been described as a lunar meteorite (*e.g.*, TAKEDA *et al.*, 1989). For this meteorite, the results of consortium studies, including noble gas isotope studies, have been reported (*e.g.*, EUGSTER *et al.*, 1989; TAKAOKA and YOSHIDA, 1992). As part of the consortium studies, ^{40}Ar–^{39}Ar analyses were made on this meteorite and we report the results here.

It has been suggested that there may be a correlation between ^{40}Ar–^{39}Ar plateau ages and petrologic types of some ordinary chondrites (*e.g.*, KANEOKA, 1980; PELLAS *et al.*, 1990). To test the occurrence of such a possibility further, ^{40}Ar–^{39}Ar analyses were performed for two LL3 (Y-790448, Allan Hills-764) and one LL4 (Y-74442) chondrites.

2. Samples

Y-86032 is an anorthositic regolith breccia similar to Y-82192 and -82193 lunar meteorites in its petrological and mineralogical composition (TAKEDA *et al.*, 1989). These three meteorites were recovered from the same area and EUGSTER *et al.* (1989) have reported that they are from the same fall. Y-86032,92 is a fragment of a light clast of feldspathic fragmental breccia. This specimen was prepared from the same fragment from which the specimen Y-86032,108, used for noble gas analyses (TAKEDA *et al.*, 1989), was obtained.

Y-790448 and ALH-764 are LL3 chondrites and were selected because they are not much weathered (YANAI and KOJIMA, 1987). Y-790448 contains abundant chondrules up to 3 mm across. ALH-764 is a brecciated chondrite consisting of chondrules and chondrule fragments, numerous clasts of different lithology and glassy clasts (YANAI and KOJIMA, 1987). Y-790448,83 and ALH-764,80 are fragments of these meteorites. Y-74442,100 is a portion of LL4 chondrite Y-74442 and it has been reported that weathering is minor (YANAI and KOJIMA, 1987). This sample was selected for study in order to compare its age spectrum with those of LL3 chondrites.

3. Experimental

Sample chips with grain sizes of 1–5 mm were wrapped in aluminium foil and stacked together with the hornblende standard sample MMhb-1 (K-Ar age: 519.5 ± 2.5 Ma) (ALEXANDER *et al.*, 1978), as well as remelted CaF_2 and K_2SO_4, in a vacuum-sealed quartz vial.

Y-86032,92 was irradiated in the JMTR of Tohoku University with a total fast neutron flux of about 6×10^{17} nvt/cm^2. Y-790448,83, ALH-764,80 and Y-74442,100 were irradiated in the same reactor but under different conditions and at different times and they received a total fast neutron flux of about 1×10^{19} nvt/cm^2. Ar gas was extracted and purified at the Radioisotope Center, University of Tokyo. The Ar isotopes were measured with a VG-5400 mass spectrometer, which has a Daly photomultiplier and a resolving power of about 700, at the Institute for Study of the Earth's Interior, Okayama University (NAGAO *et al.*, 1991). Because of the high resolution of the mass spectrometer each Ar peak could be separated from hydrocarbon peaks.

Blanks and the effects of interfering Ar isotopes produced from neutron-irradiated K were corrected to calculate an ^{40}Ar–^{39}Ar age, by using correction factors determined on the basis of the measurements of Ar isotopes for neutron irradiated K_2SO_4. No correction for Ca-derived interference isotopes was done in the present study, because the Ar analyses could not be performed until more than two years after the irradiation and most of ^{37}Ar ($T_{1/2}=35.1$ days) had already decayed. However, its effect has been estimated to be less than 1% for each temperature fraction except for higher temperature fractions for an L chondrite (KANEOKA *et al.*, 1988). Hence, in the case of LL chondrites the effects of no correction for Ca-derived Ar isotopes on the calculated ages should be rather small for lower and intermediate temperature fractions. To calculate an ^{40}Ar–^{39}Ar age for Y-86032,92, the following values were assumed: for the trapped Ar, $^{40}\mathrm{Ar}/^{36}\mathrm{Ar}=2.50$, $^{38}\mathrm{Ar}/^{36}\mathrm{Ar}=0.187$, and for the cosmogenic Ar, $^{40}\mathrm{Ar}/^{38}\mathrm{Ar}=0.15$, $^{38}\mathrm{Ar}/^{36}\mathrm{Ar}=1.5$ (KANEOKA and TAKAOKA, 1986). To calculate an ^{40}Ar–^{39}Ar age for LL chondrites, the following values were assuemd:for the trapped Ar, $^{40}\mathrm{Ar}/^{36}\mathrm{Ar}=0.5$, $^{38}\mathrm{Ar}/^{36}\mathrm{Ar}=0.187$, and for the cosmogenic Ar, $^{40}\mathrm{Ar}/^{38}\mathrm{Ar}=0.15$, $^{38}\mathrm{Ar}/^{36}\mathrm{Ar}=1.5$

(PODOSEK and HUNEKE, 1973). For the trapped ^{40}Ar/^{36}Ar ratio, EUGSTER *et al.* (1989) have reported a value of 12.1 ± 0.3. If we use the value, the calculated age is reduced by about 100 Ma for each temperature fraction. However, the uncertainty in the present result is too large to discuss the significance of the difference. The amounts of ^{40}Ar were estimated by comparing the peak heights with a calibrated air standard. Based on the reproducibility of the sensitivity of the mass spectrometer, about 20% uncertainty is assigned. However, larger uncertainty might be introduced from the blank correction for some temperature fractions. Since no monitor was included to measure the production rate of ^{38}Ar from ^{37}Cl by the neutron irradiation, no corrections have been applied to this effect.

4. Results and Discussion

4.1. *Lunar meteorite Y-86032,92*

The observed Ar isotopic ratios and the amount of ^{40}Ar for Y-86032,92 are summarized in Table 1 together with the calculated ^{40}Ar–^{39}Ar ages for each temperature fraction. The ^{40}Ar–^{39}Ar age spectrum is shown in Fig. 1 and the release patterns of each Ar isotope for this meteorite are shown in Fig. 2.

The result indicates a rather scattered ^{40}Ar–^{39}Ar age spectrum with no plateau

Table 1. Ar isotopes in neutron-irradiated meteorites from Antarctica.

T (°C)	[^{40}Ar] ($\times 10^{-6}$ cm^3 STP/g)	^{36}Ar/^{40}Ar ($\times 10^{-3}$)	^{38}Ar/^{40}Ar ($\times 10^{-3}$)	^{39}Ar/^{40}Ar ($\times 10^{-4}$)	^{40}Ar*/^{39}Ar*	Age (Ma)
Y-86032,92 (Clast), 0.0906 g; *J* = 0.003443 ± 0.000017						
600	0.673	3.827 ± 0.604	0.8350 ± 0.1319	0.01953 ± 0.00308	50710 ± 8098	9323 ± 287
700	0.272	6.070 ± 0.594	4.551 ± 0.098	0.4990 ± 0.0488	1974 ± 211	3705 ± 168
800	0.131	9.447 ± 0.837	11.46 ± 1.02	1.496 ± 0.133	652.8 ± 60.7	2125 ± 116
900	0.694	5.822 ± 0.097	4.472 ± 0.075	0.5475 ± 0.0091	1800 ± 38	3561 ± 34
1000	0.123	9.161 ± 0.727	8.786 ± 0.697	1.017 ± 0.056	960.9 ± 80.6	2635 ± 116
1100	0.238	4.571 ± 0.510	2.602 ± 0.290	0.3778 ± 0.0422	2616 ± 324	4155 ± 201
1200	0.646	5.042 ± 0.414	3.033 ± 0.249	3.348 ± 0.275	2949 ± 259	4351 ± 144
1300	1.99	4.128 ± 0.552	1.231 ± 0.165	1.330 ± 0.178	7442 ± 1086	5920 ± 947
1400	1.04	4.224 ± 1.074	1.353 ± 0.344	0.9520 ± 0.2420	10392 ± 2766	6503 ± 467
1600	1.11	11.04 ± 2.64	3.598 ± 0.861	5.499 ± 1.316	1768 ± 431	3533 ± 378
Total	6.917	5.760	2.589	5.760	3200	4485
Y-790448,83(LL3) 0.5809 g; *J* = 0.1407 ± 0.0010						
600	8.04	0.5794 ± 0.0093	2.098 ± 0.034	1.275 ± 0.020	78.54 ± 1.25	4490 ± 30
700	9.55	0.4801 ± 0.0069	2.533 ± 0.034	1.240 ± 0.017	80.46 ± 1.08	4530 ± 25
800	4.67	0.8309 ± 0.0156	1.618 ± 0.030	1.222 ± 0.023	81.65 ± 1.53	4555 ± 35
900	1.75	3.390 ± 0.068	2.921 ± 0.058	1.363 ± 0.027	73.08 ± 1.46	4372 ± 35
1000	0.891	60.20 ± 2.36	8.790 ± 0.344	2.534 ± 0.099	38.13 ± 1.49	3339 ± 60
1100	0.181	780.4 ± 150.6	45.90 ± 8.86	12.03 ± 2.32	4.926 ± 0.950	949.8 ± 142.5
1200	0.221	630.5 ± 115.5	22.61 ± 4.14	11.43 ± 2.09	5.845 ± 1.070	1083 ± 149
1300	0.130	751.7 ± 232.9	26.35 ± 8.16	15.31 ± 4.74	3.933 ± 1.218	794.6 ± 199.1
1600	0.607	673.2 ± 38.5	42.47 ± 2.43	4.129 ± 0.236	15.92 ± 0.91	2121 ± 72
Total	26.04	33.07	4.000	1.599	61.34	4086

Table 1. (Continued).

T (°C)	[^{40}Ar] ($\times 10^{-6}$ cm^3 STP/g)	^{36}Ar/^{40}Ar ($\times 10^{-3}$)	^{38}Ar/^{40}Ar ($\times 10^{-3}$)	^{39}Ar/^{40}Ar ($\times 10^{-3}$)	^{40}Ar*/^{39}Ar*	Age (Ma)
ALH-764,80(LL3) 0.8028 g; J=0.1222±0.0010						
600	3.87	2.162±0.008	54.39±0.19	22.16±0.08	44.93±0.20	3374±14
700	6.10	1.172±0.004	24.75±0.05	13.55±0.03	73.63±0.21	4153±14
800	5.58	1.480±0.005	19.27±0.04	9.682±0.002	103.1±0.3	4708±15
900	5.96	3.513±0.009	25.83±0.06	8.903±0.0202	112.0±0.3	4847±14
1000	2.28	8.317±0.047	35.82±0.20	10.94±0.06	90.90±0.59	4499±17
1100	1.70	23.43±0.17	481.1±3.6	18.81±0.14	52.38±0.45	3611±19
1200	4.14	35.32±0.17	445.4±2.2	17.67±0.69	55.44±0.30	3700±15
1300	0.995	77.00±1.56	655.0±13.3	32.96±0.67	29.03±0.61	2732±32
1600	0.773	48.62±2.19	631.0±28.4	53.99±2.43	17.93±0.82	2093±58
Total	31.358	11.55	143.0	15.24	65.08	3954
Y-74442,100(LL4) 0.6395 g; J=0.1127±0.0010						
600	17.2	0.3066±0.0009	3.391±0.012	8.064±0.023	123.9±0.4	4881±16
700	19.5	1.720±0.034	2.553±0.007	8.780±0.018	113.8±0.3	4738±15
800	9.72	0.7872±0.0146	2.689±0.012	9.131±0.036	109.5±0.6	4674±17
900	6.04	0.4369±0.0050	4.465±0.027	9.748±0.059	102.6±0.7	4565±19
1000	4.30	9.937±0.078	10.85±0.07	11.64±0.08	85.93±0.64	4273±19
1100	2.27	86.46±1.10	32.48±0.41	31.25±0.39	31.98±0.42	2755±22
1200	1.73	255.4±4.2	37.72±0.62	53.06±0.87	18.82±0.32	2053±24
1300	0.801	375.6±13.4	56.44±2.00	42.64±1.51	23.41±0.84	2330±48
1600	0.684	1181±68	100.3±5.8	55.83±3.23	17.81±1.06	1986±72
Total	62.245	29.52	7.397	11.93	83.83	4233

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 $^{39}K(n, p)^{39}Ar(^{39}Ar^*)$.
3) To calculate an age, the following correction factors were used for K-derived interference Ar isotopes. Due to the decay out of ^{37}Ar, however, no corrections were applied for Ca-derived interference Ar isotopes.
For Y-86032,92
$(^{40}\mathrm{Ar}/^{39}\mathrm{Ar})_K = (6.82 \pm 0.01) \times 10^{-2}$,
$(^{38}\mathrm{Ar}/^{39}\mathrm{Ar})_K = (6.96 \pm 0.01) \times 10^{-2}$
For Y-790448,83, ALH-764,80 and Y-74442,100
$(^{40}\mathrm{Ar}/^{39}\mathrm{Ar})_K = (1.44 \pm 0.02) \times 10^{-1}$,
$(^{38}\mathrm{Ar}/^{39}\mathrm{Ar})_K = (2.48 \pm 0.01) \times 10^{-2}$.
4) $J = (\exp(\lambda t_S) - 1)/(^{40}Ar^*/^{39}Ar^*)_S$;
t_S: K-Ar age of a standard sample,
subscript "s" refers to a standard sample:
$\lambda = 5.543 \times 10^{-10}$/y.
5) Uncertainties in the measured ratio represent those of the mass spectrometric analyses and include 30% of blank correction.

age. Since this sample is an anorthositic breccia and its Ca/K ratio has been reported to be aroud 700 (KOEBERL *et al.*, 1989), the Ca-derived Ar isotopes might affect calculated ages, especially in the higher temperature fractions. However, the lack of this correction decreases the apparent ages due to the non-separation of K-derived ^{39}Ar from the Ca-derived ^{39}Ar. Hence, if this effect was corrected, the ^{40}Ar–^{39}Ar ages would be older

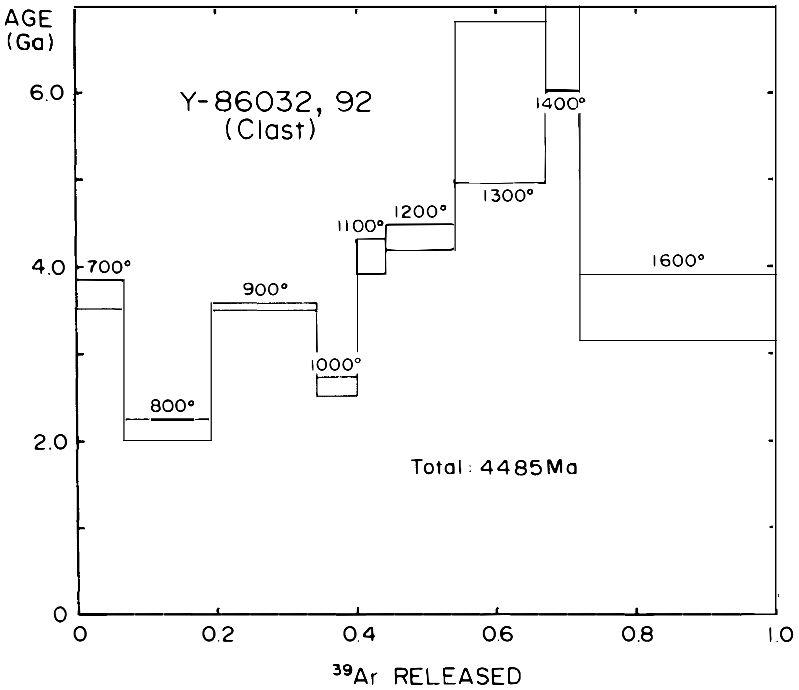

Fig. 1. ^{40}Ar–^{39}Ar *age spectrum for lunar meteorite Y-86032,92. The number at each increment indicates the degassing temperature in degree Celsius. The uncertainty is indicated by* 1σ. *"Total" represents a total* ^{40}Ar–^{39}Ar *age.*

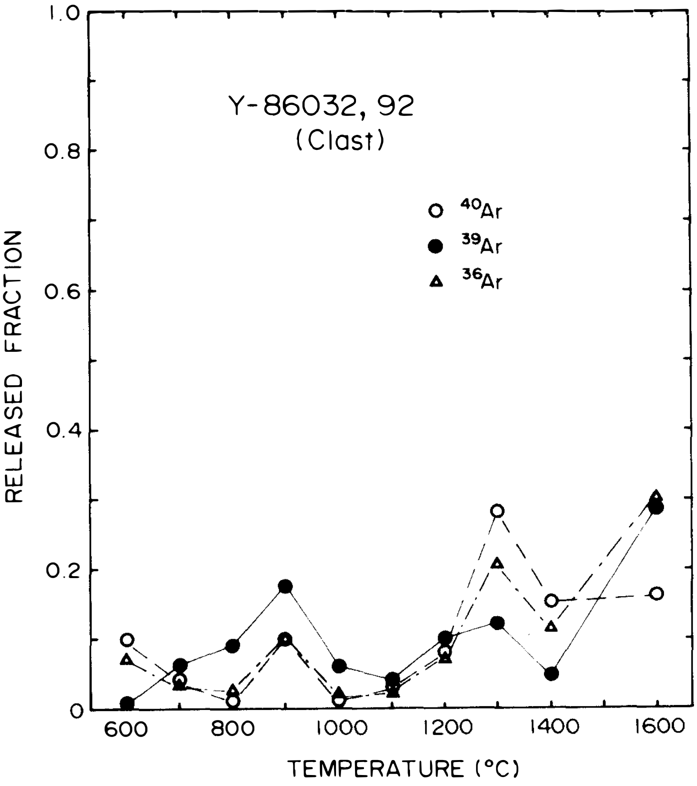

Fig. 2. Release patterns of Ar isotopes for Y-86032,92.

than those shown in Fig. 1 and Table 1. The 1300° and 1400°C temperature fractions indicate anomalously high values, which cannnot be regarded to represent any meaningful ages. A scattered age spectrum with anomalously high ^{40}Ar–^{39}Ar ages in the higher temperature fractions has been observed in lunar samples which were affected by shock (*e.g.*, KIRSTEN *et al.*, 1972). TAKEDA *et al.* (1989) have reported that a clast-laden impact melt vein penetrates the breccia. Hence, the scattered age spectrum might be the impact that ejected the meteorite from the lunar surface.

The total ^{40}Ar–^{39}Ar age for Y-86032,92 is 4485 Ma. As mentioned before, since Ca-derived Ar isotopes could not be corrected, this value should be regarded as a minimum. This age is older than the reported K-Ar ages (3700–4000 Ma) reported for this sample (EUGSTER *et al.*, 1989; TAKAOKA and YOSHIDA, 1992). For Y-86032,108, which was prepared from the same parent fragment, TAKAOKA and YOSHIDA (1992) reported the amount of ^{36}Ar as 2.85×10^{-8} cm^3 STP/g with an ^{40}Ar/^{36}Ar ratio of 121.5, whereas EUGSTER *et al.* (1989) reported the amount of ^{36}Ar for Y-86032,89 as 5.87×10^{-8} cm^3 STP/g with an ^{40}Ar/^{36}Ar ratio of 132.2. The total amount of ^{40}Ar for the present sample Y-86032,92 is 6.92×10^{-6} cm^3 STP/g with an ^{40}Ar/^{36}Ar ratio of 173.6, which corresponds to an ^{36}Ar content of 3.98×10^{-8} cm^3 STP/g. Thus, the amount of ^{36}Ar estimated for Y-86032,92 is intermediate among the reported values for Y-86032. If we assume that the ^{40}Ar–^{39}Ar age corresponds to a K-Ar age, we can estimate a K-content for Y-86032,92 based on the amount of radiogenic ^{40}Ar and the age. The value is about 90 ppm as a maximum. This value seems to be a little lower than those reported for Y-86032, which range from 108 to 209 ppm (KOEBERL *et al.*, 1989). However, reported K-contents were obtained for bulk samples whereas the present sample is an anorthositic clast. Hence, it is reasonable that the present sample has a lower K-content than a bulk sample. Heterogeneity within a sample is another factor that controls the K-content, which is largely dependent on the mineralogical composition of a sample. Furthermore, a shocked lunar microbreccia with a low K-content showed a total ^{40}Ar–^{39}Ar age of about 5700 Ma, indicating the occurrence of excess ^{40}Ar (KIRSTEN *et al.*, 1972). Hence, in the case of the sample Y-86032,92, we cannot exclude the possibility of excess ^{40}Ar.

4.2. *LL chondrites(Y-790448,83; ALH-754,80; Y-74442,100)*

The Ar isotopic ratios and the amount of ^{40}Ar for three LL chondrites are also summarized in Table 1. The ^{40}Ar–^{39}Ar age spectra for these meteorites are shown in Figs. 3–5 and the release patterns of Ar isotopes in Figs. 6–8.

Among three LL chondrites analysed, only Y-790448,83 has a relatively good plateau with an ^{40}Ar–^{39}Ar age of 4521 ± 28 Ma in the lower temperature fractions (600–800°C) covering about 67% of the integrated ^{39}Ar. For this meteorite, the higher temperature fractions (1100–1600°C) show rather young ^{40}Ar–^{39}Ar ages of less than 2000 Ma, at least partly due to the lack of a correction for the Ca-derived Ar isotopes. However, for the lower temperature fractions this effect should be quite small, less than 1% in the case of an L chondrite (KANEOKA, 1980). This should also be true for LL chondrites and therefore, we think that the plateau age obtained for Y-790448,83 is meaningful.

Samples ALH-764,80 and Y-74442,100, show no ^{40}Ar–^{39}Ar plateaus. The age

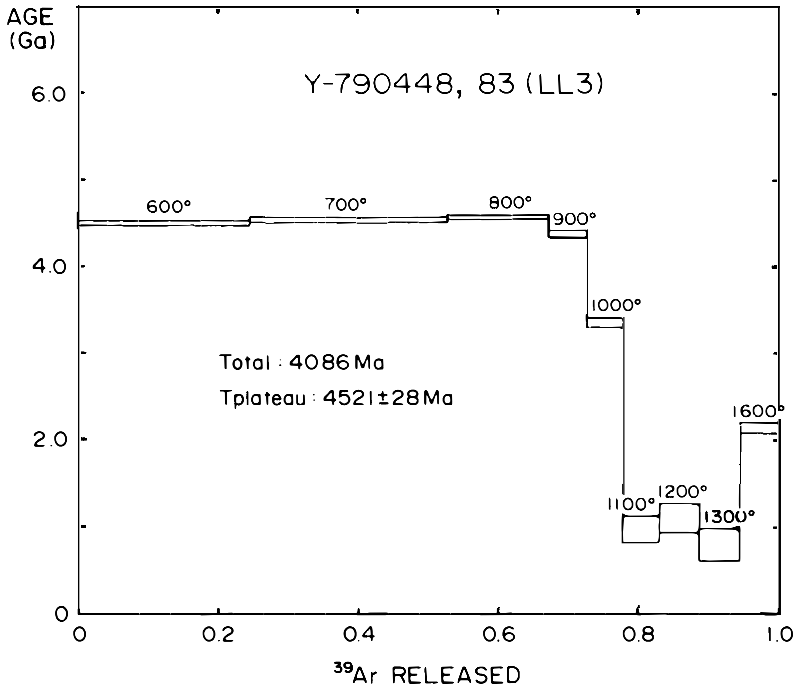

Fig. 3. *^{40}Ar–^{39}Ar age spectrum for Y-790448,83 (LL3). "Plateau" indicates a plateau age. The uncertainty is expressed as 1σ.*

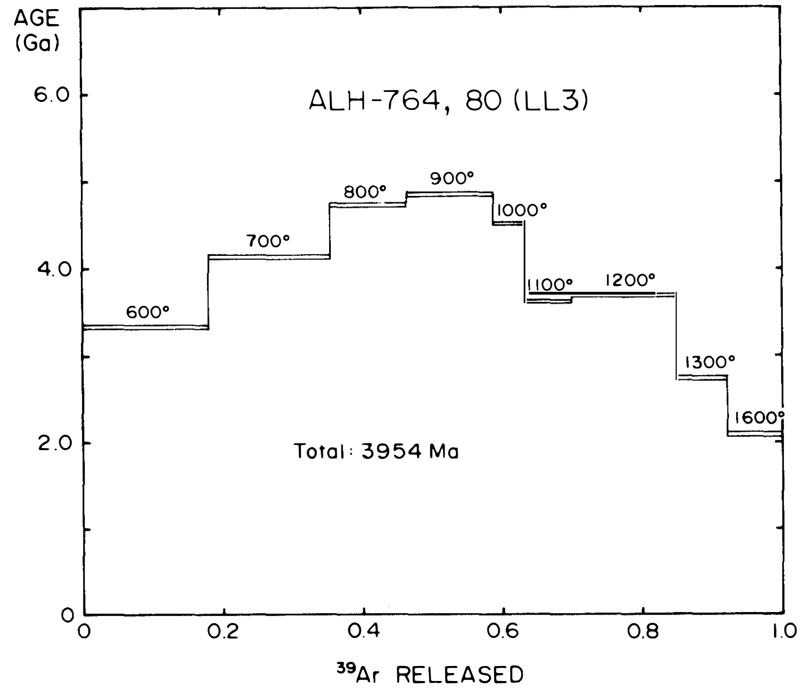

Fig. 4. *^{40}Ar–^{39}Ar age diagram for ALH-764,80 (LL3).*

spectra for both samples show a decreasing trend in the ages of the higher temperature fractions. This may reflect the effect of Ca-derived Ar isotopes to some extent. Since ALH-764,80 indicates an ^{40}Ar–^{39}Ar age spectrum where the apparent age is younger

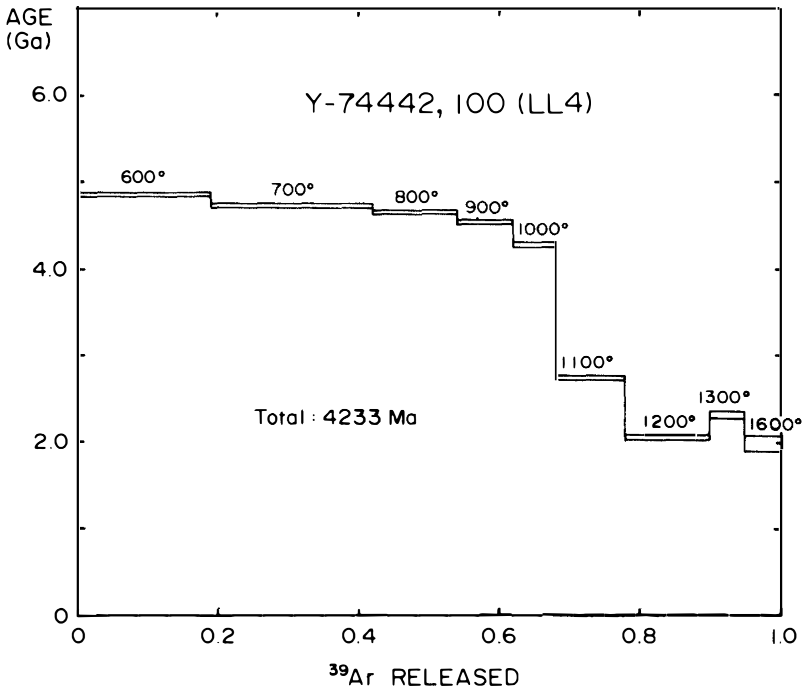

Fig. 5. ^{40}Ar–^{39}Ar age diagram for Y-74442,100 (LL4).

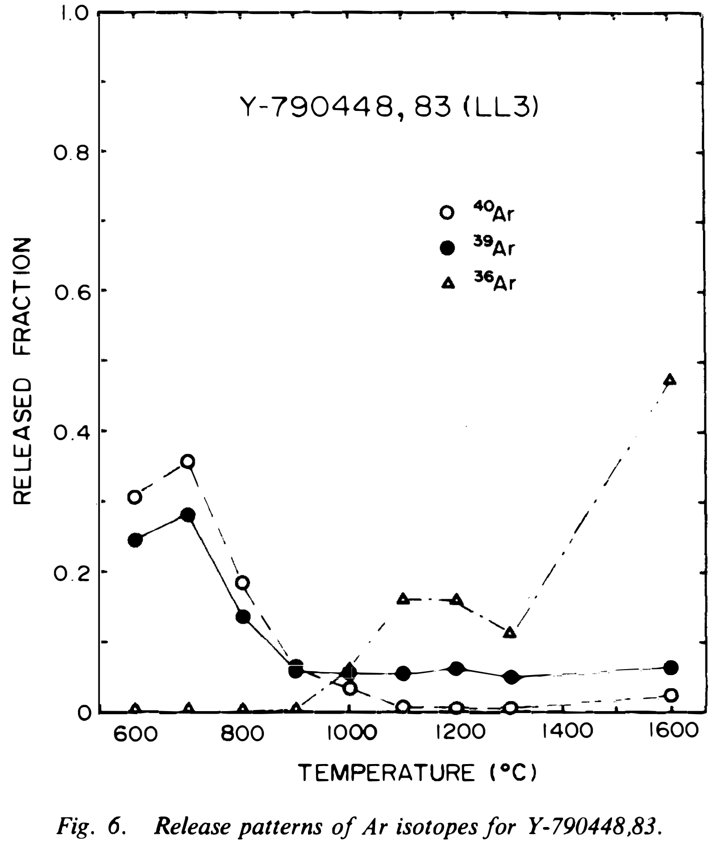

Fig. 6. Release patterns of Ar isotopes for Y-790448,83.

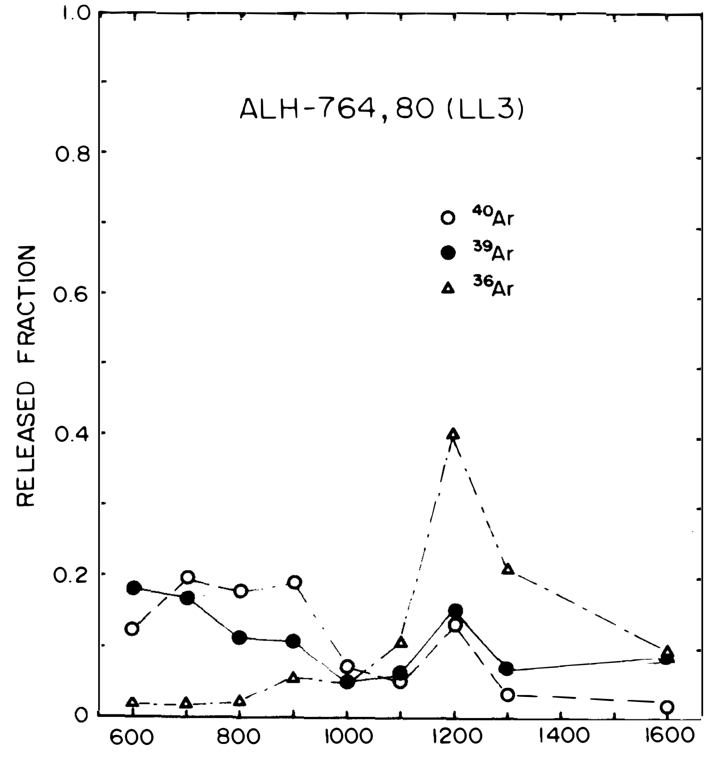

Fig. 7. Release patterns of Ar isotopes for ALH-764,80.

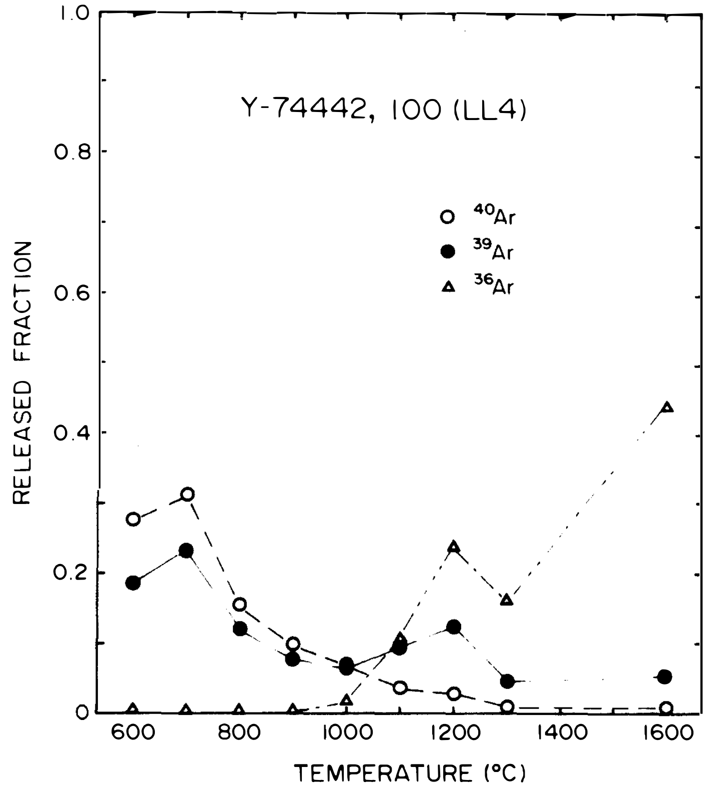

Fig. 8. Release patterns of Ar isotopes for Y-74442,100.

in the lower temperature fractions (Fig. 4), there is a possibility of some Ar loss from this sample. On the other hand, the 800°C and 900°C fractions for this sample show ^{40}Ar–^{39}Ar ages greater than 4600 Ma. To explain such a trend, it has been suggested that atmospheric Ar might have been introduced into magnetite which formed from decomposed goethite during neutron irradiation in the vacuum-sealed quartz vial (KANEOKA, 1983). Although the degassing rate of ^{36}Ar in the 800°C and 900°C fractions seems to be not so large as those of the higher temperature fractions (Fig. 7), this does not preclude the contribution of atmospheric Ar, because this sample is an LL3 chondrite and contains relatively large amounts of trapped ^{36}Ar in the higher temperature fractions. Hence, we cannot exclude the possibility that sample ALH-764,80 might have been affected by weathering to some extent.

In the case of Y-74442,100, the ^{40}Ar–^{39}Ar age spectrum indicates an inverse staircase pattern, indicating very old ^{40}Ar–^{39}Ar ages which exceed 4600 Ma in the lower temperature fractions. The total ^{40}Ar–^{39}Ar age for this sample is 4233 Ma and redistribution of Ar is quite likely due to the recoil effect during neutron irradiation for this sample. The Ca-derived Ar isotopes would affect the apparent ages in the highest temperature fractions to some extent, but their effect would be small for lower temperature fractions (KANEOKA, 1980). The release patterns for this sample (Fig. 8) indicate more degassing of ^{36}Ar in the higher temperature fractions than in the lower temperature fractions, indicating the contribution of trapped components together with some contribution from Ca-derived ^{36}Ar. The redistribution of Ar isotopes for this sample may reflect the texture of this sample such as the occurrence of interbedded fine parts among minerals, but details are unknown.

4.3. *Relationship between the ^{40}Ar–^{39}Ar ages of LL chondrites and their petrologic type*

It has been suggested that there might be a relationship between the ^{40}Ar–^{39}Ar plateau age and the petrologic type of a chondrite (*e.g.*, KANEOKA, 1980; PELLAS *et al.*, 1990). Based on the ^{40}Ar–^{39}Ar plateau ages together with ^{244}Pu chronometry, PELLAS *et al.* (1990) argued that the LL-body was a rather large asteroid (250–300 km in diameter) that required 200–300 Ma to cool to the Ar retention temperature in its innermost layers. LL chondrites of petrologic type 6 show ^{40}Ar–^{39}Ar ages which range from 4320 to 4420 Ma (*e.g.*, CADOGAN and TURNER, 1975; KANEOKA, 1981; TRIELOFF, 1990). An LL7 chondrite (ALH84027) showed an ^{40}Ar–^{39}Ar age of 4350 ± 20 Ma (TRIELOFF, 1990). On the other hand, ^{40}Ar–^{39}Ar ages of LL3 chondrites range from 4490 to 4503 Ma (*e.g.*, CADOGAN and TURNER, 1975; KANEOKA, 1980). Our result for Y-790448 (LL3) adds another example of a relatively old age for an LL3 chondrite. Three LL5 chondrites have ages with a relatively wide range (4390–4510 Ma) (TRIELOFF, 1990; TURNER *et al.*, 1978). So far, we have no reliable age data for LL4 chondrites. Thus, LL3 chondrites seem to show systematically older ^{40}Ar–^{39}Ar ages than do LL6 and LL7 chondrites. However, we do not yet have sufficient age data for LL chondrites to discuss the thermal history of the parent body in more detail. Further, since these samples are selected because they show no apparent shock effect, we should find a reason why some un-equilibrated meteorites commonly have scattered ages. These problems remain for future studies.

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