^{40}Ar-^{39}Ar ANALYSES OF AN ANTARCTIC METEORITE YAMATO-791197 OF PROBABLE LUNAR ORIGIN

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Abstract: ^{40}Ar-^{39}Ar analyses have been applied to an Antarctic meteorite Yamato-791197 (Y-791197), an anorthositic regolith breccia of probable lunar origin (YANAI and KOJIMA, Mem. Natl Inst. Polar Res., Spec. Issue, **35**, 18, 1984).

The clast sample (Y-791197,96) shows a plateau ^{40}Ar-^{39}Ar age of 4065 ± 93 Ma at higher temperatures, which corresponds to typical age groups obtained for lunar rocks of highland origin. The matrix sample (Y-791197,97) contains a large amount of trapped Ar (^{40}Ar: $\sim 9 \times 10^{-4}$ cm^3 STP/g) with the $^{40}Ar/^{36}Ar$ ratio of about 2.5 at higher temperatures, which implies that the trapped Ar is mostly of solar wind origin. This makes it difficult to estimate a reasonable ^{40}Ar-^{39}Ar age for this portion.

The present result supports a presumption that Y-791197 originated from the moon's surface as a lunar highland breccia.

1. Introduction

Yamato-791197 (Y-791197) is a new unique meteorite found in Antarctica and has been classified as an anorthositic breccia of possibly lunar origin (YANAI and KOJIMA, 1984). Among a large number of meteorites so far collected from Antarctica, only three meteorites including the present one have been identified to have come from the Moon.

ALHA81005 was the first meteorite to have been classified as an anorthositic breccia and it includes white clasts of mainly Ca-rich plagioclase (MASON, 1982). The clasts resemble the anorthositic clast of lunar rocks brought back by the Apollo and Luna missions. The presumption that ALHA81005 originated from the moon's surface has been strongly supported by subsequent detailed studies from many aspects (Collected papers in Geophys. Res. Lett., **10**, 773–840, 1983).

Another anorthositic regolith breccia (Y-82192) has been suggested as the third lunar meteorite and its preliminary description is given in YANAI and KOJIMA (1984).

Although many studies have been undertaken on these meteorites, no definite radiometric ages have been obtained. It is significant to get information on their ages to reveal the characteristics of the lunar meteorite. This study aims to get age information for Y-791197 by the ^{40}Ar-^{39}Ar method as part of a consortium study of this sample.

2. Samples

Two portions of the sample Y-791197 were prepared for ^{40}Ar-^{39}Ar analyses. One of them is the clast sample (Y-791197,96), which includes a large clast ($\sim$4 mm in diameter). Although the allocated clast sample consists mostly of clast chips, some specks of the groundmass still remain around the fringe of clasts. Such specks were carefully removed from each clast chip by hand-picking, because even a small remainder of the groundmass might seriously affect the result for the clast sample due to the large difference in the amount of trapped Ar as expected from the result for ALHA81005 (BOGARD and JOHNSON, 1983). As a result of such treatment, the analysed specimen (0.0622 g) was reduced to a half of the original amount allocated (0.112 g). Such clasts are regarded to be composed of mostly anorthositic plagioclase with minor amounts of pyroxene and olivine (YANAI and KOJIMA, 1984).

The matrix sample (Y-791197) was analysed to compare the result with that of the clast sample. The allocated sample was used for analysis without any further pretreatment.

3. Experimental

The prepared specimens were cleaned with acetone. They were wrapped in aluminium foil and stacked together with age standard samples MMhb-1 (hornblende, K-Ar age: 519.5$\pm$2.5 Ma) (ALEXANDER *et al.*, 1978) in a vacuum-sealed quartz vial.

Samples were irradiated in the JMTR of Tohoku University receiving the total fast neutron flux of about 5×10^{17} nvt/cm^2. Ar gas was extracted and purified at the Isotope Center, University of Tokyo and analysed on a Nier-type mass spectrometer with a multiplier at Yamagata University. The mass spectrometer is operated with a resolving power of about 600 and can separate hydrocarbon peaks from each Ar isotope (TAKAOKA, 1976). Extraction and purification procedures are the same as reported before (KANEOKA, 1981). System blanks range from $\sim4\times10^{-8}$ cm^3 STP ^{40}Ar below 1300°C to (8–9)$\times10^{-8}$ cm^3 STP ^{40}Ar at 1600°C for 45 min. Such blanks and the effects of interfering isotopes produced from Ca and K were corrected to calculate an ^{40}Ar-^{39}Ar age, using the correction factors as determined before (KANEOKA, 1983).

Since the main Ar component in the matrix has been revealed to be the trapped one, the composition of trapped Ar in the clast sample has been estimated from the result for the higher temperature fractions for Y-791197,97. To calculate a ^{40}Ar-^{39}Ar age for the clast sample Y-791197,96, the following values are assumed for the trapped Ar: $^{40}Ar/^{36}Ar=2.50$, $^{38}Ar/^{36}Ar=0.187$, and for the cosmogenic Ar: $^{40}Ar/^{38}Ar=0.15$, $^{38}Ar/^{36}Ar=1.5$.

The amounts of Ar isotopes were estimated by the peak height method by using the calibrated air standard. The uncertainty in the estimated amount is assigned to be about 10% in this study.

4. Results and Discussion

The observed Ar isotopic ratios and the amount of ^{40}Ar for each temperature fraction are shown in Table 1. The age spectra of the clast sample Y-791197,96 are shown in Fig. 1 together with the $^{40}Ar/^{36}Ar$–$^{39}Ar/^{36}Ar$ plot.

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

Y-791197,96 (clast) 0.0622 g, $J=0.003716\pm0.000035$

T(°C)	$[^{40}Ar]$ $\times10^{-8}$ cm^3 STP/g	$^{36}Ar/^{40}Ar$	$^{37}Ar/^{40}Ar$	$^{38}Ar/^{40}Ar$	$^{39}Ar/^{40}Ar$	$^{40}Ar^*/^{39}Ar^*$	Age (Ma)
		($\times10^{-3}$)					
600	69.1	5.839 ±0.025	87.28 ±0.52	5.708 ±0.042	1.120 ±0.009	964.5 ±136.0	2747±199
700	72.1	18.17 ±0.03	225.7 ±1.1	30.05 ±0.19	4.501 ±0.032	224.7 ±31.4	1095±115
800	158	15.02 ±0.19	79.28 ±1.10	22.20 ±0.24	1.613 ±0.014	631.3 ±40.1	2179± 81
900	190	16.08 ±0.17	60.77 ±0.41	21.05 ±0.19	0.5144 ±0.0072	2153 ±117	3964± 88
1000	197	17.22 ±0.11	59.13 ±0.34	20.34 ±0.20	0.4944 ±0.0058	2239 ±117	4027± 86
1100	113	19.05 ±0.11	61.01 ±0.30	20.65 ±0.18	0.4815 ±0.0025	2308 ±205	4076±144
1200	136	25.26 ±0.08	66.32 ±0.35	23.54 ±0.12	0.4820 ±0.0016	2302 ±174	4072±123
1300	325	22.83 ±0.06	75.13 ±0.17	25.83 ±0.06	0.4744 ±0.0030	2421 ±77	4153± 54
1600	132	44.79 ±0.12	110.6 ±0.4	43.01 ±0.14	0.5106 ±0.0016	2303 ±189	4073±133
Total	1392.2	21.12	81.05	24.17	0.8570	1236	3106

Y-791197,97 (matrix) 0.0952 g

T(°C)	$[^{40}Ar]$ $\times10^{-8}$ cm^3 STP/g	$^{36}Ar/^{40}Ar$	$^{37}Ar/^{40}Ar$	$^{38}Ar/^{40}Ar$	$^{39}Ar/^{40}Ar$
		($\times10^{-3}$)			
600	143	75.80±1.47	23.90 ±0.57	14.79±0.36	0.3016±0.0515
700	218	132.6 ±1.5	22.63 ±0.37	27.46±0.33	0.2289±0.0342
800	562	225.9 ±1.3	8.241±0.127	44.71±0.16	0.1625±0.0118
900	1570	268.1 ±0.1	4.066±0.065	52.26±0.14	0.0547±0.0152
1000	1290	402.2 ±1.3	4.651±0.068	78.28±0.36	0.0550±0.0177
1100	702	412.6 ±2.0	6.717±0.075	82.53±0.05	0.1413±0.0123
1200	1710	397.3 ±2.0	4.340±0.035	77.43±0.33	0.0507±0.0044
1300	15700	389.7 ±0.9	1.379±0.015	72.91±0.09	0.0367±0.0026
1600	64900	389.8 ±1.2	1.185±0.034	73.30±0.39	0.0238±0.0014
Total	86795	385.9	1.568	72.70	0.0305

1) All tabulated data have been corrected for the blanks and radioactive decay of ^{37}Ar between irradiation and analysis, but do not include other corrections.
2) Uncertainties in the measured ratio represent those of the mass spectrometric analyses. For $^{40}Ar^*/^{39}Ar^*$ ratios and calculated ages, 20% of blank correction and other uncertainties are included.
3) In the calculation of $^{40}Ar^*/^{39}Ar^*$ ratios for Y-791197,96 (clast) sample, $(^{40}Ar/^{36}Ar)=2.50$ is assumed for the trapped component on the basis of the $^{40}Ar/^{36}Ar$ ratios observed at higher temperatures in Y-791197,97 (matrix).
4) For Y-791197,97 (matrix), the trapped components are so abundant that no reliable values could be obtained for $^{40}Ar^*/^{39}Ar^*$ ratios and the ratios are not included in the table.

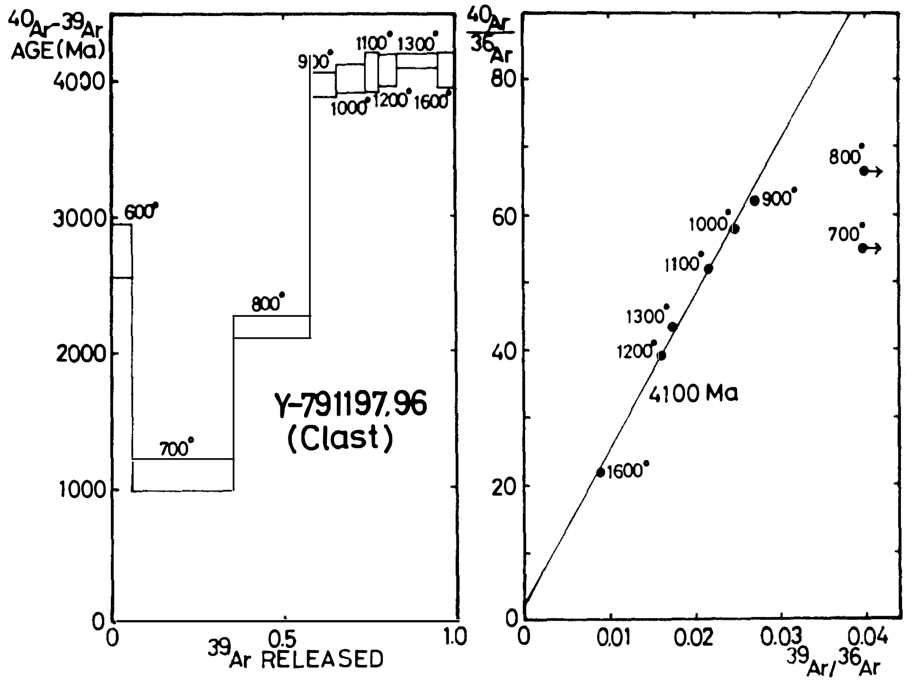

Fig. 1. The ^{40}Ar-^{39}Ar age diagram and the $^{40}Ar/^{36}Ar$-$^{39}Ar/^{36}Ar$ plot for the clast sample Y-791197, 96. The numerical figures at each column indicate the degassing temperature in °C. The uncertainties are indicated by 1σ. In the $^{40}Ar/^{36}Ar$-$^{39}Ar/^{36}Ar$ plot, a reference isochron of 4100 Ma is drawn.

As shown in Fig. 1, the clast sample Y-791197,96 indicates rather young ^{40}Ar-^{39}Ar ages in the lower temperature fractions (600–800°C), but a plateau ^{40}Ar-^{39}Ar age of 4065 ± 93 Ma at higher temperatures (900–1600°C). The observed plateau age corresponds to about 42% of the released ^{39}Ar. Since no older ^{40}Ar-^{39}Ar age is observed in the highest temperature fraction, the observed plateau ^{40}Ar-^{39}Ar age would represent either a formation age of K-bearing mineral(s) in the anorthositic breccia or an age of a seriously strong shock event which reset all the previous records on Ar isotopes in this sample. To settle this point, we need further information including ages which are determined by the different dating methods. Based on the total amounts of K-derived ^{39}Ar and Ca-derived ^{37}Ar, we can estimate the approximate K and Ca contents in this sample, which becomes 370 ppm for K and about 9.5% for Ca. The estimated K content is higher and the Ca content is lower than the reported values analysed by the neutron activation method for clast samples (*e.g.*, FUKUOKA *et al.*, 1985; LINDSTROM *et al.*, 1985). This may partly reflect the heterogeneity of each sample. Furthermore, we cannot preclude a possibility of secondary contamination for K in this sample. As shown in Fig. 2, the release patterns of Ar isotopes for the clast sample Y-791197,96 suggest that the behaviour of K-derived ^{39}Ar is different from the other Ar isotopes at lower temperatures. This implies that the trapping sites of some K are different from those which are regarded to have retained radiogenic ^{40}Ar without significant loss. We cannot designate where such contamination might have occurred.

On the other hand, the matrix sample Y-791197,97 contains very large amounts of Ar isotopes. The total ^{40}Ar content is about 8.7×10^{-4} cm^3 STP/g. When we prepared this sample for neutron irradiation, we had not known such properties. While

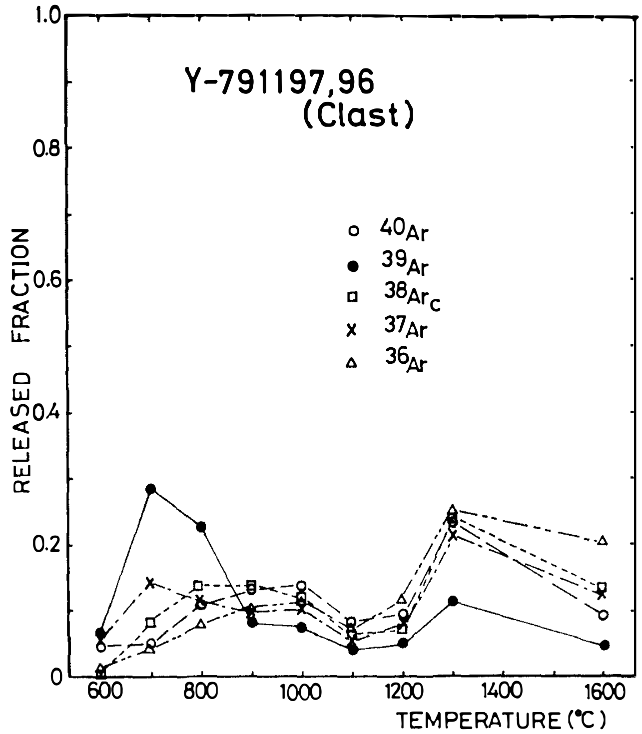

Fig. 2. The release patterns of Ar isotopes for Y-791197,96 (clast). Note that some ^{39}Ar degasses at lower temperatures without correlating with the other Ar isotopes. $^{38}Ar_C$: cosmogenic ^{38}Ar.

the sample was irradiated with neutron flux and cooled down, different portions of this sample were measured for noble gas isotope analysis independently and it revealed high noble gas contents in it (TAKAOKA, 1985). Hence, the amount of melted sample (0.0952 g) was too large to measure degassed Ar isotopes. In the Ar analyses, each measurement was undertaken by reducing the amount of Ar by about one-hundredth to that of the degassed one. The measurements of ^{37}Ar and ^{39}Ar include larger uncertainties in this sample and should be regarded to show only rough estimates for these components. Since the estimated amount of radiogenic ^{40}Ar is less than 2×10^{-5} cm^3 STP/g, which is much less than that of the total ^{40}Ar, it is difficult to get meaningful ^{40}Ar-^{39}Ar ages for the matrix sample. Hence no ^{40}Ar-^{39}Ar ages are shown for this sample in Table 1.

In Fig. 3, the apparent change in the measured $^{40}Ar/^{36}Ar$ and $^{38}Ar/^{36}Ar$ ratios is shown against the degassed temperature. The $^{40}Ar/^{36}Ar$ ratio decreases rapidly with increasing degassing temperature. In the temperature fractions higher than 1000°C, the $^{40}Ar/^{36}Ar$ ratio becomes almost constant at about 2.5, whereas the $^{38}Ar/^{36}Ar$ ratio approaches to a value of 0.187 at relatively high temperatures (1300°C, 1600°C). The apparent variation in the $^{40}Ar/^{36}Ar$ ratio might be affected by the addition of atmospheric components at least partly in the lower temperature fraction. On the other hand, the $^{38}Ar/^{36}Ar$ ratio would be affected by both the cosmogenic components and the atmospheric components together with the effect by ^{38}Ar produced from chlorine in the reactor. As shown in Fig. 4, most Ar gases were degassed in the highest temperature fractions for the matrix sample Y-791197,97. The degassed temperature seeems

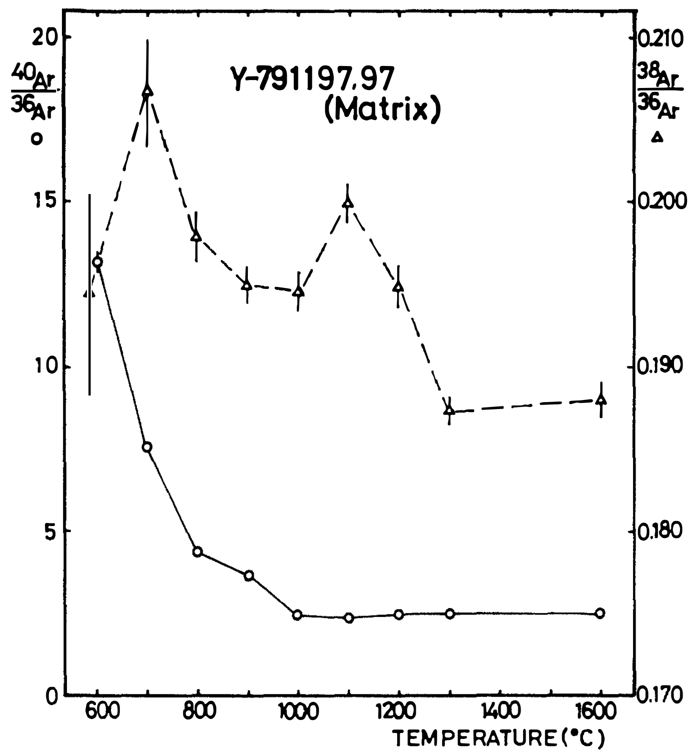

Fig. 3. The variation of the observed $^{40}Ar/^{36}Ar$ and $^{38}Ar/^{36}Ar$ ratios against the degassing temperatures for the matrix sample Y-791197,97. The high temperature fractions (1300°C, 1600°C) indicate Ar isotopic ratios similar to those observed in lunar fines (e.g., KIRSTEN et al., 1972).

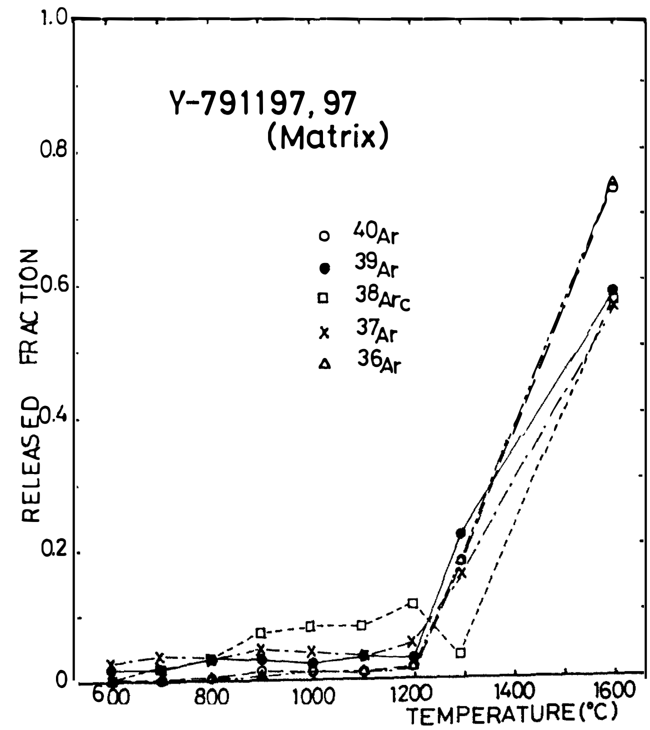

Fig. 4. The release patterns of Ar isotopes for Y-791197,97 (matrix).

too high, considering its composition. The degassing temperature was estimated with pyrometer for the Mo crucible. Hence the real degassing temperature for a sample might be lower than the estimated one. However, the relative release patterns of Ar isotopes would keep their intrinsic characteristics. Thus, the high temperature fractions (1300°C, 1600°C) would almost represent Ar isotopes of trapped components. The $^{40}Ar/^{36}Ar$ ratio is about 2.5, which is similar to those found in lunar fines and regoliths (*e.g.*, KIRSTEN *et al.*, 1972). The large enrichment of noble gases in such samples has been explained as owing to the trapping of solar wind gases in these materials. The $^{38}Ar/^{36}Ar$ ratios observed in the high temperature fractions of the matrix sample Y-791197,97 are also compatible with such an implication. Furthermore, the $^{40}Ar/^{36}Ar$ ratio observed in the matrix sample is higher than that of the solar wind-implanted Ar in any other meteorites and the matrix sample of Y-791197 contains about sixty times the radiogenic ^{40}Ar of the clast. No known meteorite with trapped solar wind gases shows an obvious excess of ^{40}Ar except for lunar regolith. These evidences favour the lunar origin of this sample. Such argument was made firstly by BOGARD and JOHNSON (1983) for the Allan Hills lunar meteorite.

Thus, both the ^{40}Ar-^{39}Ar age of the clast sample and the Ar isotopic ratios, together with large amounts of Ar isotopes in the matrix sample, for the Antarctic meteorite Y-791197 support the presumption that the meteorite originated from the moon's

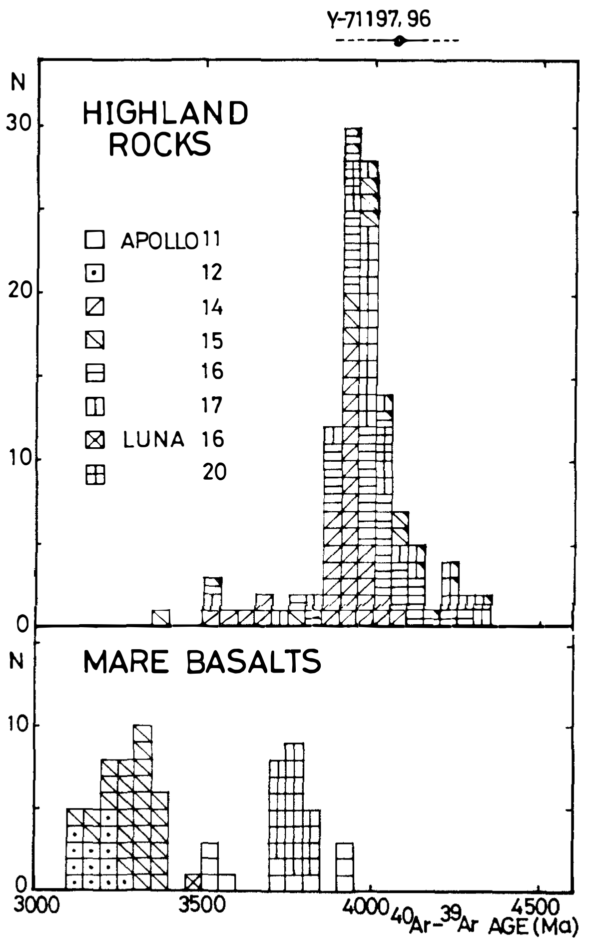

Fig. 5. Histogram of the ^{40}Ar-^{39}Ar ages observed for lunar samples. The result for Y-791197,96 is shown for comparison. The uncertainty in the ^{40}Ar-^{39}Ar age for Y-791197,96 is indicated with lines (1σ) and dotted lines (2σ). The data for lunar samples are summarized in TURNER (1977).

surface. In Fig. 5, the ^{40}Ar-^{39}Ar ages determined for lunar samples are summarized. As indicated in this figure, the ^{40}Ar-^{39}Ar age obtained for the clast sample Y-791197,96 corresponds to a typical value for the lunar highland rocks. No mare basalts show, however, such an old ^{40}Ar-^{39}Ar age. The texture and mineralogy of the meteorite Y-791197 are also similar to the lunar highland rocks (YANAI and KOJIMA, 1984).

Hence, it is concluded that the Antarctic meteorite Y-791197 would have probably originated from the lunar highland and it contains clasts with an age of 4065 ± 93 Ma. The matrix contains large amounts of Ar isotopes of probably solar wind origin.

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