Mem. Natl Inst. Polar Res., Spec. Issue, **46**, 105–112, 1987

^{40}Ar-^{39}Ar ANALYSES OF LUNAR ANORTHOSITIC BRECCIA, YAMATO-82192, FROM ANTARCTICA

Ichiro KANEOKA[1] and Nobuo TAKAOKA[2]

[1]*Geophysical Institute, Faculty of Science, University of Tokyo, 11–16, Yayoi 2-chome, Bunkyo-ku, Tokyo 113*
[2]*Department of Earth Sciences, Faculty of Science, Yamagata University, 4–12, Koshirakawacho 1-chome, Yamagata 990*

Abstract: Lunar anorthositic breccia, Yamato-82192 (Y-82192), collected at the Minami-Yamato Nunataks, Antarctica, was analysed by the ^{40}Ar-^{39}Ar method in order to reveal its chronology.

Sample Y-82192,63D shows rather peculiar degassing patterns in that most Ar was degassed only in the highest temperature fraction (1600°C). Such patterns of Ar are observed in strongly shocked lunar samples, as observed in the glassy matrix of Y-791197 and some other lunar samples. Hence, the possibility of inherited Ar cannot be excluded. Thus, the apparent ^{40}Ar-^{39}Ar age of 4237± 165 Ma (1σ) observed in the 1600°C fraction indicates the upper limit for the degassing event in the lunar highland area. On the basis of the amounts of trapped and cosmogenic Ar observed in the present sample, it is inferred that Y-82192 was not exposed on the lunar surface directly but was shielded from both heavy dose of solar wind and galactic cosmic-ray irradiations after the degassing event such as a shock impact.

1. Introduction

Since the discovery of an anorthositic breccia meteorite ALHA81005, from Antarctica (MASON, 1982), the one regarded to be of lunar origin according to the petrological, mineralogical and chemical data including isotope studies, four Antarctic meteorites have been classified as lunar meteorites (YANAI *et al.*, 1986).

Yamato-82192 (Y-82192) together with Yamato-82193 (Y-82193) have been characterized as anorthositic regolith breccias, being classified as lunar meteorites (YANAI and KOJIMA, 1985; YANAI *et al.*, 1986). Among the lunar meteorites so far reported, radiometric ages have been determined for Yamato-791197 (Y-791197) by the ^{40}Ar-^{39}Ar method (KANEOKA and TAKAOKA, 1986), and the Rb-Sr and Pb-Pb methods (NAKAMURA *et al.*, 1985; TAKAHASHI *et al.*, 1985). For Y-82192, a preliminary Rb-Sr age was reported (TAKAHASHI *et al.*, 1986). Since the age information is essential to reveal the thermal history of a sample, we have tried to date Y-82192 by the ^{40}Ar-^{39}Ar method as part of a consortium study.

2. Samples

Y-82192 was collected on the southern bare ice of the Minami-Yamato Nunataks,

* Present address: Earthquake Research Institute, University of Tokyo, 1–1, Yayoi 1-chome, Bunkyo-ku, Tokyo 113.

Antarctica by the Japanese Antarctic Research Expedition Team in the 1982–1983 field season. It is reported that this sample contains numerous clasts of melted lithic fragments, crystalline fragments and brecciated lithic fragments in matrix (YANAI and KOJIMA, 1985). Clasts are reported to be composed mostly of plagioclase, some amount of pyroxene and minor olivine, showing the sign of shock.

Y-82192,63D was taken from a mostly glassy clast portion which resulted from an impact shock, and the portion was neighboured to Y-82192,63C for which noble gas analyses were made by TAKAOKA (1986) (YANAI, private communication, 1986).

Although we tried to separate non-glassy clast from the chips of Y-82192,63D, we found it difficult to do so, because the size of each clast in this portion was relatively small, mostly less than 1 mm, and the clasts were closely surrounded by the glassy matrix. Hence, the sample was prepared as a bulk sample (clast+matrix) in the form of small chips (1–4 mm in size; total weight, 0.0556 g).

3. Experimental

The experimental procedures were almost the same as those described in KANEOKA and TAKAOKA (1986). The sample chips were cleaned with acetone, wrapped in aluminum foil, and stacked together with age standard samples MMhb-I (hornblende, K-Ar age: 519.5±2.5 Ma) (ALEXANDER *et al.*, 1978) in a vacuum-sealed quartz vial.

The samples were irradiated in the JMTR of Tohoku University, with a total fast neutron flux of about 2×10^{17} nvt/cm^2. Ar gas was extracted at the Isotope Center, 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.

System blanks were in the range of $(5\sim6)\times10^{-9}$ cm^3 STP ^{40}Ar for the fractions below 1300°C, but increased up to 1.7×10^{-8} cm^3 STP ^{40}Ar in the 1600°C fraction for 45 min. Blanks and the effects of interfering Ar isotopes produced from Ca and K were corrected to calculate an ^{40}Ar-^{39}Ar age, using the correction factors determined before (KANEOKA, 1983). The following values are assumed to calculate an ^{40}Ar-^{39}Ar age: for the trapped Ar, ^{40}Ar/^{36}Ar=1.0, ^{38}Ar/^{36}Ar=0.187, and for the cosmogentc Ar, ^{40}Ar/^{38}Ar=0.15, ^{38}Ar/^{36}Ar=1.5.

The amounts of ^{40}Ar were estimated by the peak height method using the calibrated air standard and about 20% uncertainty is assigned including that of the recovery of Ar gas for each temperature fraction.

4. Results and Discussion

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

Unfortunately, the 600°C fraction was lost due to a crack on the Ar collecting glass tube for the fraction before Ar analysis. As revealed in the gas release patterns for Y-82192,63D (Fig. 2), however, the degassing rate in this fraction can be estimated to be very small compared with higher temperature fractions. Furthermore, the lowest

Table 1. Ar isotopes in a neutron-irradiated meteorite from Antarctica.
Y-82192,63D 0.0556 g $J=0.001714\pm0.000009$

T (°C)	[^{40}Ar] ($\times10^{-8}$ cm^3 STP/g)	$^{36}Ar/^{40}Ar$ ($\times10^{-3}$)	$^{37}Ar/^{40}Ar$ ($\times10^{-3}$)	$^{38}Ar/^{40}Ar$ ($\times10^{-3}$)	$^{39}Ar/^{40}Ar$ ($\times10^{-4}$)	$^{40}Ar^*/^{39}Ar^*$	Age (Ma)
600	—	Lost before Ar analysis				—	—
700	58.7	3.850 ±0.039	5.019 ±0.199	2.186 ±0.037	0.2448 ±0.0213	53170 ±7920	8160 ±266
800	31.7	3.898 ±0.064	6.043 ±0.231	0.9433 ±0.0239	0.6424 ±0.0543	17420 ±2750	6187 ±276
900	10.9	1.258 ±0.120	10.23 ±0.23	1.244 ±0.005	1.117 ±0.028	10000 ±1990	5231 ±340
1000	4.7	5.694 ±0.141	12.01 ±0.86	1.767 ±0.082	1.709 ±0.118	6357 ±2755	4467 ±716
1100	8.9	5.657 ±0.124	16.98 ±1.30	1.489 ±0.055	0.8536 ±0.0776	10200 ±4540	5262 ±758
1200	14.8	5.796 ±0.175	38.47 ±2.07	1.812 ±0.061	0.8618 ±0.0223	7691 ±2450	4784 ±534
1300	40.1	5.415 ±0.050	36.88 ±0.77	1.459 ±0.046	0.3018 ±0.0076	9444 ±6621	5131 ±1191
1600	661.3	22.92 ±0.05	82.75 ±0.31	7.033 ±0.023	2.717 ±0.021	5527 ±557	4237 ±165
Total	831.1	20.21	68.83	6.211	1.635	5656	4275

N.B. 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) $^{40}Ar^*/^{39}Ar^*$ 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 for Ca- and K-derived interference Ar isotopes were used (KANEOKA, 1983).
$(^{39}Ar/^{37}Ar)_{Ca}=(11.3\pm0.4)\times10^{-4}$, $(^{38}Ar/^{37}Ar)_{Ca}=(2.06\pm0.03)\times10^{-3}$, $(^{36}Ar/^{37}Ar)_{Ca}=(3.72\pm0.06)\times10^{-4}$, $(^{40}Ar/^{39}Ar)_K=(19.6\pm0.4)\times10^{-2}$, $(^{38}Ar/^{39}Ar)_K=(3.47\pm0.04)\times10^{-2}$.
4) Uncertainties in the measured ratio represent those of the mass spectrometric analyses. For $^{40}Ar^*/^{39}Ar^*$ ratios and calculated ages, however, 20% of blank correction and other uncertainties are included.

temperature fraction is more or less contaminated in general cases by the terrestrial atmospheric Ar. Hence, no serious effect would occur due to the loss of this fraction for the present sample.

As shown in Figs. 1 and 2, it is noteworthy that about 80% or more of Ar was degassed at the highest temperature (1600°C). Apparently, ^{40}Ar was also degassed in the lower temperature fractions, which might cause abnormally high ^{40}Ar-^{39}Ar ages in these fractions. Since ^{40}Ar-^{39}Ar ages observed in fractions of less than 1300°C often exceed the age of 4600 Ma, these ages were probably due to the redistribution of Ar by the shock effect and/or incorporation of terrestrial Ar. Hence the ^{40}Ar-^{39}Ar age shown in the highest temperature fraction would only show some significance from the viewpoint of chronology.

In the 1600°C fraction the ^{40}Ar-^{39}Ar age of 4237 ± 165 (1σ) is obtained, which is not much different from the total ^{40}Ar-^{39}Ar age of 4275 Ma, reflecting degassing of most Ar in this fraction. The total ^{40}Ar-^{39}Ar age itself should be comparable to the K-Ar age in principle. A K-Ar age is generally regarded to show a lower limit to the

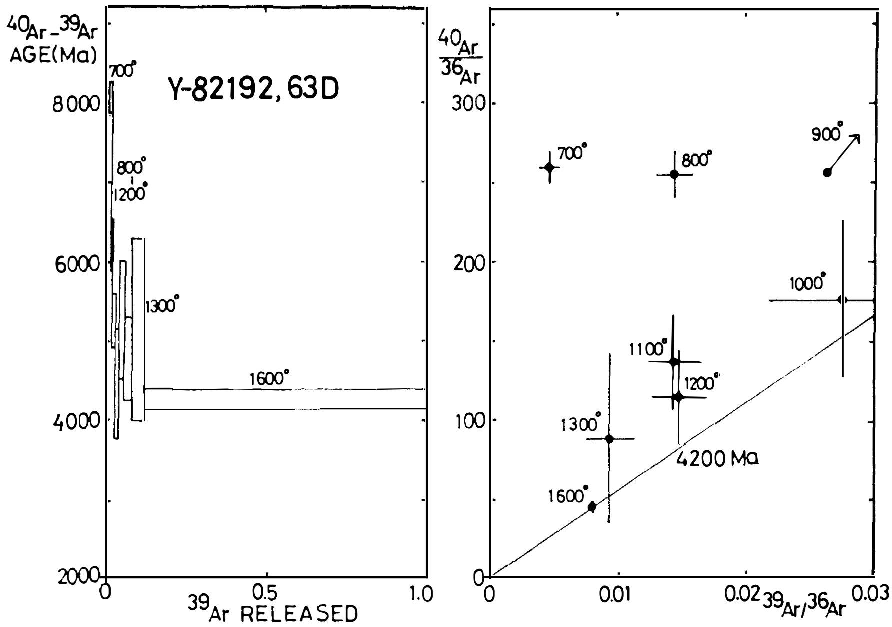

Fig. 1. The ^{40}Ar-^{39}Ar age diagram and the $^{40}Ar/^{36}Ar$-$^{39}Ar/^{36}Ar$ plot for the sample Y-82192,63D (clast+matrix). The number at each column indicates the degassing temperature in degree Celsius. The uncertainty is indicated by 1σ. In the $^{40}Ar/^{36}Ar$-$^{39}Ar/^{36}Ar$ plot, a reference isochron of 4200 Ma is shown.

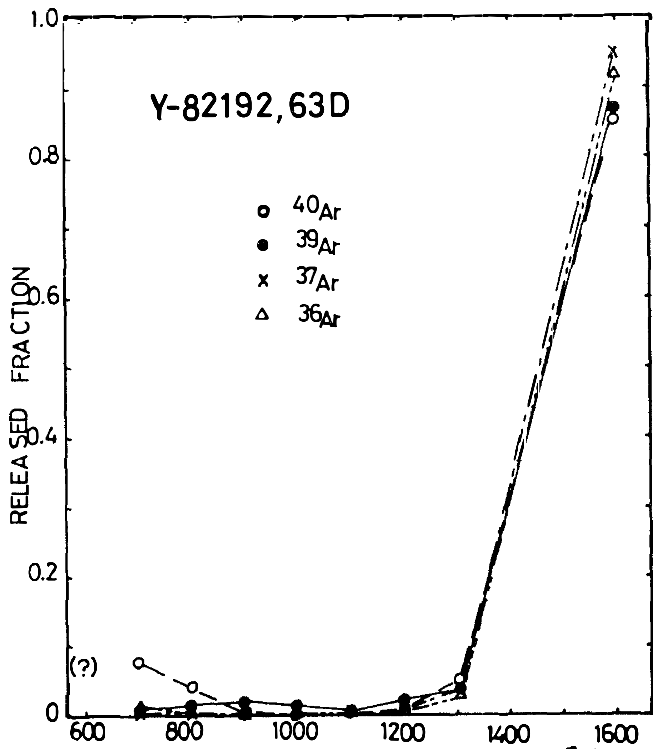

Fig. 2. The release patterns of Ar isotopes for Y-82192,63D. Note that most Ar is degassed in the highest temperature fraction.

age of an event, since Ar loss is observed much more commonly than excess Ar in extraterrestrial samples such as meteorites. If it is, the ^{40}Ar-^{39}Ar age observed in the 1600°C fraction might also indicate a younger limit for some event which occurred on the parent body of the sample. As revealed clearly in Fig. 1, however, the apparent ^{40}Ar-^{39}Ar ages are much higher than that of the highest temperature fraction and most of them exceed 4600 Ma. Furthermore, most Ar is degassed in the highest temperature fraction. Such release patterns are sometimes observed in strongly shocked lunar samples. For example, the release patterns of Ar are similar to those observed in the matrix of Y-791197 (anorthositic breccia of probable lunar origin) (KANEOKA and TAKAOKA, 1986), which shows a sign of shock impact. Abnormally high ^{40}Ar-^{39}Ar ages together with disturbed ^{40}Ar-^{39}Ar age spectra are similar to those observed in the Apollo 14 lunar fine sample 14303,13, R5,22 (KIRSTEN *et al.*, 1972), which also shows a sign of shock impact. It is almost certain that the present sample Y-82192 was also rather seriously shocked (YANAI and KOJIMA, 1985). If a sample was shocked, the previously contained gas would be largely degassed, but not always completely. As a result, some inherited Ar might be retained, which is not always trapped in the original site due to the change of the texture caused by the shock. To explain the age spectrum together with the release patterns of Ar as shown in Figs. 1 and 2, the occurrence of such a phase is required, which is originally a K-bearing phase such as plagioclase and/or glass and transformed into a structure to retain Ar more tightly. Unfortunately, we cannot specify the phase with the present information alone. However, at least we could conclude that it is the shock effect which causes anomalous release patterns of Ar.

In the case of the sample Y-82192, the ^{40}Ar-^{39}Ar age in the highest fraction would approximate the age of the shock event, if no inherited Ar occurred in this sample. However, we have no guarantee that any inherited Ar did not remain in this sample. Based on the release patterns of Ar, we might say that the secondary Ar loss after the shock event would be quite low at least for the 1600°C fraction. Thus, although we may say that the apparent ^{40}Ar-^{39}Ar age for the 1600°C fraction would represent that of the shock event which occurred for the sample, it is conservative to conclude that the age would probably indicate the upper limit for the age of the shock event that affected the sample, and the real age might be younger than 4200 Ma. The present result is not incompatible with the inference that the sample Y-82192 is an anorthositic regolith breccia of lunar origin. The age results on such regolith breccias are summarized in Table 2. Further, in Fig. 3 the histogram of radiometric ages for lunar samples is shown, where the results for Y-82192 and Y-791197 are also plotted. As discussed above, the result for Y-82192 should be interpreted to be older than the real age of the shock event for this sample. So far as the present sample is concerned, we have no result against a conjecture of the lunar highland origin for Y-82192. This sample might have been seriously reset less than 4200 Ma by some shock event such as a collision of a meteoritic material on the lunar highland.

Although the release patterns of Ar are similar between the present sample and the matrix of Y-791197, the amount of trapped Ar of solar wind composition for the present sample (trapped ^{36}Ar: 1.5×10^{-7} cm^3 STP/g) is much less than that in the matrix of Y-791197 (trapped ^{36}Ar: 3.3×10^{-4} cm^3 STP/g). Since both samples contain some

Table 2. Summary of radiometric ages for lunar meteorite.

Sample	Material	Age (Ga)*	Method	Reference**
ALHA81005	Whole rock	—	K-Ar	(1)
Y-791197	Clast	4.07±0.18	^{40}Ar-^{39}Ar	(2)
	Matrix	—	do	(2)
	Mineral separates	4.25	Pb-Pb	(3)
	do	3.9 ±0.5	Rb-Sr	(3)
	do	3.89±0.36	do	(4)
Y-82192	Clast+matrix	≤4.24±0.34	^{40}Ar-^{39}Ar	(5)
	Mineral separates	3.93±0.28	Rb-Sr	(6)

* The uncertainty in the age is 2σ.
The ages for ALHA81005 (whole rock) and Y-791197 (matrix) could not be obtained due to the large interference effect from the trapped solar wind components in these samples.

** (1) BOGARD and JOHNSON (1983), (2) KANEOKA and TAKAOKA (1986), (3) NAKAMURA *et al.* (1985), (4) TAKAHASHI *et al.* (1985), (5) this study, (6) TAKAHASHI *et al.* (1986).

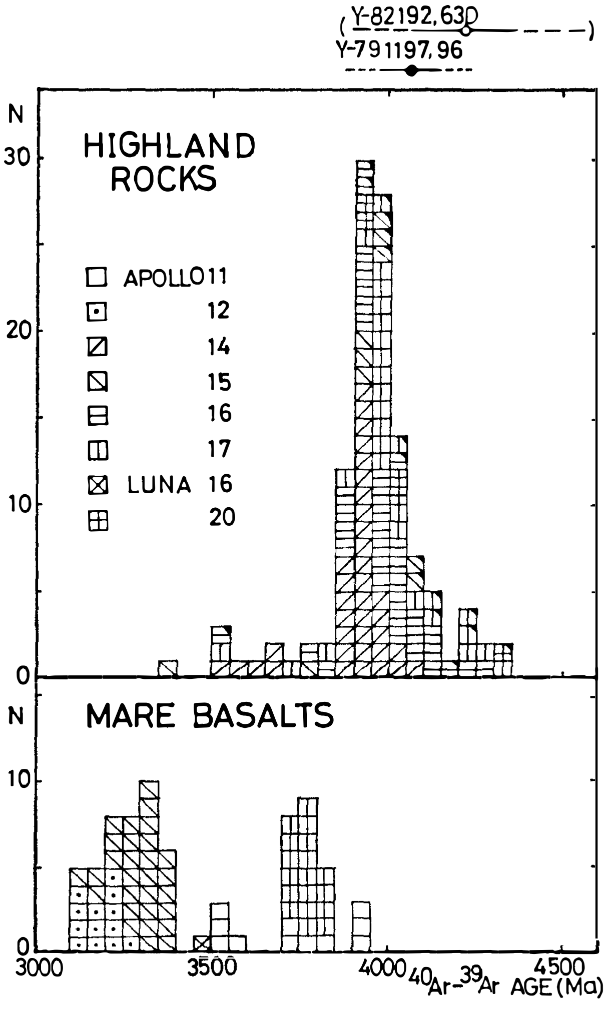

Fig. 3. Histogram of the ^{40}Ar-^{39}Ar ages observed for lunar samples. The results for samples Y-82192,63D and Y-791197,96 are also shown for comparison. As discussed in the text, the apparent ^{40}Ar-^{39}Ar age for the sample Y-82192,63D should be regarded to represent the upper limit for the age of the sample. The uncertainties in both samples are indicated with lines (1σ) and dotted lines (2σ). The data for lunar samples are referred to TURNER (1977).

amounts of glassy parts, such a difference might have been originated from the difference in the depth of burial, at least partly. After a shock event in the probably lunar highland area, the present sample would have been shielded from the heavy doses of solar wind and galactic cosmic-ray irradiations, which means that it might have been buried at some depth. (The amount of cosmogenic ^{38}Ar is calculated to be about 2.3×10^{-8} cm^3 STP/g in this sample.) Such an interpretation is also supported by other noble gas data such as Ne and He for different portions of the present sample (TAKAOKA, 1986). Based on the noble gas data, cosmic-ray exposure ages are calculated to range from about 8 to 26 Ma depending on different nuclides and assumptions (TAKAOKA, 1986).

In summary, the sample Y-82192 would have received a serious shock effect less than 4200 Ma in probably a lunar highland area and had been buried at some depth until the next cratering effect ejected it from the moon's surface.

Acknowledgments

We are grateful to Prof. T. MATSUDA and Dr. K. YANAI of the National Institute of Polar Research for providing us the sample used in this study. The manuscript has been much improved by the comments of the two anonymous reviewers.

This study is financially supported in part by the Grant-in-Aid for Cooperative Research (No. 5939007) from the Ministry of Education, Science and Culture, Japan.

References

ALEXANDER, E. C., Jr., MICKELSON, G. M. and LANPHERE, M. A. (1978): MMhb-1; A new ^{40}Ar-^{39}Ar dating standard. U.S. Geol. Surv. Open-File Rep., **78–701**, 6–9.

BOGARD, D. D. and JOHNSON, P. (1983): Trapped noble gases indicate lunar origin for Antarctic meteorite. Geophys. Res. Lett., **10**, 801–803.

KANEOKA, I. (1983): Investigation of the weathering effect on the ^{40}Ar-^{39}Ar ages of Antarctic meteorites. Mem. Natl Inst. Polar Res., Spec. Issue, **29**, 259–274.

KANEOKA, I. and TAKAOKA, N. (1986): ^{40}Ar-^{39}Ar analyses of an Antarctic meteorite Yamato-791197 of probably lunar origin. Mem. Natl Inst. Polar Res., Spec. Issue, **41**, 116–123.

KIRSTEN, T., DEUBNER, J., HORN, P., KANEOKA, I., KIKO, J., SCHAEFFER, O. A. and THIO, S. K. (1972): The rare gas record of Apollo 14 and 15 samples. Proc. Lunar Sci. Conf., 3rd, 1865–1889.

MASON, B. (1982): ALHA81005; Examination of polished thin section. Antarct. Meteorite Newsl., **5**(4).

NAKAMURA, N., UNRUH, D. M. and TATSUMOTO, M. (1985): REE, Rb-Sr and U-Pb systematics of "lunar" meteorite Yamato-791197. Papers presented to the Tenth Symposium on Antarctic Meteorites, 25–27 March 1985. Tokyo, Natl Inst. Polar Res., 103–105.

TAKAHASHI, K., SHIMIZU, H. and MASUDA, A. (1985): REE abundances in the Yamato-791197,108. Papers presented to the Tenth Symposium on Antarctic Meteorites, 25–27 March 1985. Tokyo, Natl Inst. Polar Res., 106.

TAKAHASHI, K., SHIMIZU, H. and MASUDA, A. (1986): Cosmochronological studies and REE abundances of lunar meteorite. Papers presented to the Eleventh Symposium on Antarctic Meteorite, 25–27 March 1986. Tokyo, Natl Inst. Polar Res., 43–44.

TAKAOKA, N. (1976): A low-blank metal system for rare-gas analysis. Mass Spectr., **24**, 73–86.

TAKAOKA, N. (1986): Noble gas study of Yamato-82192 lunar meteorite (preprint).

TURNER, G. (1977): Potassium-argon chronology of the Moon. Phys. Chem. Earth, **10**, 145–195.

YANAI, K. and KOJIMA, H. (1985): Lunar meteorites; recovery, curation and distribution. Papers presented to the Tenth Symposium on Antactic Meteorite, 25–27 March 1985. Tokyo, Natl Inst. Polar Res., 87–89.

YANAI, K., KOJIMA, H. and IKADAI, S. (1986): Four lunar meteorites including new specimen of Yamato-82193, preliminary examination, curation and allocation for consortium studies. Papers presented to the Eleventh Symposium on Antarctic Meteorites, 25–27 March 1986. Tokyo, Natl Inst. Polar Res., 25–27.

(*Received July 25, 1986; Revised manuscript received October 6, 1986*)