Proc. NIPR Symp. Antarct. Meteorites, **5**, 23–35, 1992

SOLAR WIND AND COSMIC RAY EXPOSURE HISTORY OF LUNAR METEORITE YAMATO-793274

O. EUGSTER, Th. MICHEL and S. NIEDERMANN

Physikalisches Institut, University of Bern, Sidlerstrasse 5, 3012 Bern, Switzerland

Abstract: We measured the isotopic abundances of the noble gases in bulk samples and grain-size separates of lunar meteorite Yamato-793274. The presence of relatively high contents of trapped solar wind gases and stable cosmic-ray produced nuclei indicates that Y-793274 consists of submature lunar regolith material, that is, Y-793274 is not quite as rich in solar wind gases as mature lunar soil. The K-^{40}Ar gas retention age is 2800±400 Ma. Breccia formation occurred 500–1000 Ma ago as estimated from a trapped ratio ^{40}Ar/^{36}Ar$=2.36\pm0.10$. The average shielding depth of 35±15 g/cm^2 during the total exposure to cosmic rays was derived from the depth sensitive cosmogenic ratio ^{131}Xe/^{126}Xe$=4.1\pm0.7$. The total exposure to cosmic rays in the lunar regolith lasted for 700±200 Ma and most of this exposure occurred before breccia formation. The concentration of ^{81}Kr is far below the 4π-saturation concentration in space; we calculate an upper limit of 0.12 Ma for the duration of the Moon–Earth transfer. The history of exposure to cosmic rays and solar wind particles for Y-793274 is very similar to that for another lunar meteorite, ALHA81005. Because the recovery sites in Antarctica lie 3000 km apart, pairing is not possible. However, the two meteorites may originate from the same ejection event on the Moon although they are mineralogically different and an inhomogeneous ejection site would have to be assumed.

1. Introduction

Yamato-793274 was found on the bare ice near the Minami-Yamato Nunataks of the Yamato Mountains, Antarctica on January 3, 1980 by the meteorite search party of the 20th Japanese Antarctic Research Expedition (JARE-20), 1979–1980 (YANAI and KOJIMA, 1991). Y-793274 (8.66 g) is a basaltic-anorthositic breccia containing a regolith component and numerous mafic mineral fragments and glasses. It is a mixture of about two thirds mare material and one third highland component (FUKUOKA, 1990; KURAT *et al.*, 1990; LINDSTROM and MARTINEZ, 1990; TAKEDA *et al.*, 1990; WARREN, 1990).

The chemical composition of Y-793274 is similar to that of lunar meteorite EET87521 (KOEBERL *et al.*, 1991; LINDSTROM *et al.*, 1991). Y-793274 contains 65–75% of magnesian VLT basalt, like Apollo-17 basalts (LINDSTROM *et al.*, 1991) whereas the highland component is compositionally similar to Apollo-16 regolith (WARREN and KALLEMEYN, 1991).

U-Pb data indicate a formation age of ~4400 Ma and a disturbance to the system ~4000 Ma ago (TATSUMOTO and PREMO, 1991). NISHIIZUMI *et al.* (1991b) measured the activities of ^{41}Ca, ^{36}Cl, and ^{26}Al. Based on ^{41}Ca these authors conclude that the maximum transition time from Moon to Earth was 0.04±0.01 Ma.

First noble gas results on samples from Y-793274 were reported by EUGSTER (1990), TAKAOKA and YOSHIDA (1990), EUGSTER *et al.* (1991a, b). In all these investigations relatively large quantities of trapped solar wind and cosmic-ray produced gases were observed, indicating that Y-793274 contains quite mature material that was exposed to cosmic particles for several hundred Ma.

In the framework of a consortium study described by TAKEDA *et al.* (1991) we obtained an interior sample of 0.048 g for the determination of the noble gas isotope abundances and exposure age studies. This paper presents the final data obtained from our analyses.

2. Experimental Procedure and Results

From chip Y-793274,66 that we obtained from the National Institute of Polar Research in Tokyo, we removed two splits (1.09 and 3.29 mg) for a first characterization of the noble gas contents (Table 1). We realized that the solar wind component far exceeds the *in situ* produced cosmogenic and radiogenic components. Thus, we decided to prepare grain size separates and to perform temperature step analyses in order to better resolve the different noble gas components.

The analyses were carried out with two gas extraction and mass spectrometer systems: system A with two glass-tube mass spectrometers and system B with two metal-tube mass spectrometers. The details of the experimental procedure and blank values are the same as those given by EUGSTER *et al.* (1991b). Blank corrections for He, Ne, Ar, and Kr were always <1% and those for Xe <3%. About 40 mg of material was crushed in a stainless steel mortar to a grain size <500 μm. One bulk sample of 1.48 mg was analyzed for He, Ne, and Ar (system B) and another one of 2.84 mg for He, Ne, Ar, Kr, and Xe (system A). The remaining mass was separated by sedimentation in acetone into three grain-size fractions of 8.2, 17.6, and 79.2 μm, respectively. Both the 8.2 and 17.6 μm fractions were analyzed twice, one sample from each fraction for He, Ne, and Ar (system B) and another one for all five noble gases (system A). The 79.2 μm fraction was analyzed twice in system B for He, Ne and Ar, and twice in system A for He-Xe. In one of the latter two analyses, the noble gases were extracted in four temperature steps.

Considering the fact that the analyzed samples were extremely small, we cannot expect the samples to be homogeneous in terms of noble gas contents. Nevertheless, the reproducibility of the replicate analyses is quite good. Generally, the individual analyses differ from the average values by not more than about 10%. The experimental data are given in Tables 1–3.

Our noble gas results can be compared with those obtained by TAKAOKA and YOSHIDA (1990) for a glass sample separated from Y-793274. The bulk samples analyzed by us contain 3–13 times more noble gases than the glasses.

Table 1. Results of He, Ne, and Ar measurements of Y-793274,66.

Sample (MS system A/B)	Weight (mg)	Temp. °C	^{4}He	^{20}Ne	^{40}Ar	^{4}He	^{20}Ne	^{22}Ne	^{36}Ar	^{40}Ar
			10^{-8}cm^{3} STP/g			^{3}He	^{22}Ne	^{21}Ne	^{38}Ar	^{36}Ar
Bulk	1.09	1700	96400	28900	32100	1930	12.32	21.2	5.25	2.37
(B)			±5000	±1700	±1500	±30	±0.20	±0.3	±0.03	±0.03
Bulk	1.48	1700	124600	32900	39100	2070	12.45	21.5	5.23	2.41
(B)			±7700	±2000	±1900	±35	±0.10	±0.1	±0.02	±0.02
Bulk	2.84	1700	98600	25500	38300	1820	12.06	20.3	5.18	2.47
(A)			±5400	±1300	±2600	±180	±0.30	±0.5	±0.05	±0.05
Bulk	3.29	1700	97700	27400	28100	1810	12.40	20.6	5.20	2.54
(B)			±5000	±1400	±1400	±20	±0.20	±0.3	±0.03	±0.03
Bulk average			104300	28700	34400	1910	12.31	20.9	5.22	2.45
			±5000	±1300	±1400	±20	±0.10	±0.2	±0.03	±0.03
79.2 µm	0.98	1700	137900	35600	41900	2240	12.51	22.0	5.21	2.40
(B)			±10100	±2600	±2200	±35	±0.17	±0.3	±0.02	±0.02
79.2 µm	1.06	1700	119600	33700	38400	1990	12.42	20.7	5.18	2.46
(B)			±8400	±2400	±1900	±35	±0.06	±0.2	±0.03	±0.02
79.2 µm	3.13	1700	123600	30500	42000	2050	12.17	22.5	5.18	2.48
(A)			±6200	±1500	±3100	±200	±0.13	±0.6	±0.05	±0.03
79.2 µm	19.7	600	15180	7200	440	1316	12.30	26.0	5.22	5.07
(A)			±600	±200	±40	±30	±0.20	±0.3	±0.03	±0.30
		900	88300	18000	3460	2135	12.00	24.4	5.17	2.81
			±6000	±1000	±300	±50	±0.20	±0.5	±0.04	±0.03
		1200	1)	1)	19620	1)	1)	1)	5.12	2.40
					±600				±0.03	±0.03
		1700	400	226	12310	67	10.6	8.5	5.12	2.40
			±140	±7	±400.	±20	±0.2	±0.8	±0.03	±0.03
		total	–	–	35800	–	–	–	5.12	2.45
					±1000				±0.03	±0.03
79.2 µm	average		127000	33300	39500	2090	12.37	21.7	5.17	2.45
			±6000	±1500	±2000	±40	±0.10	±0.2	±0.03	±0.03
17.6 µm	0.98	1700	95500	18700	25600	1810	12.31	19.9	5.19	2.47
(B)			±7100	±1370	±1300	±25	±0.10	±0.2	±0.03	±0.03
17.6 µm	2.72	1700	114000	18200	32400	1900	11.78	18.2	5.16	2.53
(A)			±5800	±900	±2800	±320	±0.13	±0.8	±0.04	±0.03
17.6 µm	average		104800	18400	29000	1855	12.04	19.0	5.18	2.50
			±6000	±900	±1500	±30	±0.10	±0.2	±0.03	±0.03
8.2 µm	0.60	1700	48400	8400	16200	1360	12.09	16.6	5.25	2.53
(B)			±4800	±860	±1100	±20	±0.09	±0.5	±0.06	±0.03
8.2 µm	2.17	1700	51400	8660	21900	1440	11.96	19.4	5.09	2.58
(A)			±3400	±440	±1700	±480	±0.15	±0.8	±0.05	±0.03
8.2 µm	average		49900	8530	19000	1400	12.02	18.0	5.17	2.55
			±3000	±500	±1100	±20	±0.10	±0.5	±0.05	±0.03

1) Sample lost.

Table 2. Results of Kr measurements of Y-793274,66.

Sample	Weight (mg)	Temp. °C	^{86}Kr 10^{-8}cm^3 STP/g	^{78}Kr/^{86}Kr	^{80}Kr/^{86}Kr	^{81}Kr/^{86}Kr	^{82}Kr/^{86}Kr	^{83}Kr/^{86}Kr	^{84}Kr/^{86}Kr
				×100					
Bulk	2.84	1700	2.15	2.23	14.0	0.003	68.9	68.6	330.4
			±0.40	±0.10	±0.3	–	±0.8	±0.7	±1.7
79.2 μm	3.13	1700	2.49	2.29	13.8	<0.001	68.1	67.5	329.0
			±0.50	±0.10	±0.3	–	±0.8	±1.3	±3.6
79.2 μm	19.7	600	0.0046	2.38	16.0	–	66.1	68.2	333.9
			±0.0011	±0.80	±2.7	–	±5.8	±0.6	±11.3
		900	0.0461	2.59	16.0	<0.013	70.9	69.6	332.7
			±0.0090	±0.24	±0.8	–	±2.8	±1.4	±8.0
		1200	1.11	2.36	14.2	<0.002	68.2	68.1	330.2
			±0.22	±0.08	±0.1	–	±0.3	±0.3	±1.8
		1700	0.824	2.32	14.2	<0.003	68.5	68.2	332.0
			±0.160	±0.04	±0.2	–	±0.5	±0.4	±2.1
		total	1.98	2.35	14.24	<0.002	68.4	68.2	331.0
			±0.28	±0.05	±0.09	–	±0.3	±0.2	±1.4
79.2 μm weighted average			2.20	2.34	14.2	<0.001	68.4	68.2	330.0
			±0.40	±0.05	±0.1	–	±0.3	±0.2	±1.4
17.6 μm	2.72	1700	1.84	2.30	14.4	<0.0004	68.8	68.2	328.9
			±0.37	±0.07	±0.4	–	±0.8	±0.8	±2.2
8.2 μm	2.17	1700	1.24	2.37	14.8	<0.008	68.8	68.5	328.5
			±0.25	±0.07	±0.3	–	±1.0	±1.1	±2.6

Table 3. Results of Xe measurements of Y-793274,66.

Sample	Weight (mg)	Temp. (°C)	^{132}Xe 10^{-8}cm^3 STP/g	^{124}Xe/^{132}Xe	^{126}Xe/^{132}Xe	^{128}Xe/^{132}Xe	^{129}Xe/^{132}Xe	^{130}Xe/^{132}Xe	^{131}Xe/^{132}Xe	^{134}Xe/^{132}Xe	^{136}Xe/^{132}Xe
				×100							
Bulk	2.84	1700	0.75	0.741	0.926	9.46	105.9	17.1	84.0	36.3	29.0
			±0.15	±0.028	±0.038	±0.17	±1.7	±0.7	±1.2	±0.7	±0.5
79.2 μm	3.13	1700	0.85	0.763	0.916	9.29	105.4	16.6	85.4	36.6	29.1
			±0.17	±0.034	±0.032	±0.28	±1.6	±0.3	±1.3	±0.8	±0.5
79.2 μm	19.7	600	0.0016	0.76	0.79	8.7	104.5	17.1	85.9	38.3	31.8
			±0.0008	±0.20	±0.35	±1.4	±9.0	±2.7	±5.3	±2.2	±1.4
		900	0.0046	1.46	2.13	10.2	100.0	17.3	92.0	37.0	28.6
			±0.0013	±0.21	±0.28	±0.5	±3.4	±1.8	±3.6	±1.2	±2.7
		1200	0.327	0.784	1.02	9.38	106.0	17.2	84.6	36.9	29.5
			±0.066	±0.050	±0.04	±0.23	±0.6	±0.4	±0.4	±0.3	±0.3
		1700	0.279	0.690	0.844	9.10	104.9	17.0	84.3	36.7	29.4
			±0.056	±0.021	±0.011	±0.21	±0.8	±0.2	±0.5	±0.3	±0.4
		total	0.61	0.746	0.948	9.26	105.5	17.1	84.5	36.8	29.5
			±0.09	±0.030	±0.025	±0.16	±0.5	±0.2	±0.3	±0.2	±0.2
79.2 μm weighted average			0.69	0.754	0.932	9.27	105.5	16.9	84.5	36.8	29.4
			±0.10	±0.030	±0.030	±0.16	±0.5	±0.2	±0.3	±0.2	±0.2
17.6 μm	2.72	1700	0.605	0.761	0.996	9.22	105.4	17.0	84.1	36.3	29.0
			±0.130	±0.023	±0.071	±0.22	±0.9	±0.7	±4.2	±0.3	±0.8
8.2 μm	2.17	1700	0.394	0.911	1.200	9.98	106.5	17.2	86.3	36.3	28.5
			±0.080	±0.064	±0.045	±0.58	±2.5	±0.5	±2.4	±0.8	±1.0

3. Partitioning of the Noble Gas Components

The isotopic ratios $(^{20}Ne/^{22}Ne)_{tr}$ and $(^{40}Ar/^{36}Ar)_{tr}$ were derived by means of a $^{20}Ne/^{22}Ne$ *versus* $^{21}Ne/^{22}Ne$ and a $^{40}Ar/^{36}Ar$ *versus* $1/^{36}Ar$ correlation plot, respectively. We obtained $(^{20}Ne/^{22}Ne)_{tr}=12.7\pm0.2$ assuming $(^{21}Ne/^{22}Ne)_{tr}=0.033$, and $(^{40}Ar/^{36}Ar)_{tr}=2.36\pm0.10$ (Fig. 1). The slope of the $^{40}Ar/^{36}Ar$ *versus* $1/^{36}Ar$ correlation line corresponds to a concentration of $(1440\pm150)\times10^{-8}$ cm^3 STP/g radiogenic ^{40}Ar; using a K concentration of 550 ppm (Koeberl *et al.*, 1991) we calculate a K-^{40}Ar gas retention age of 2800 Ma. If we adopt an average K concentration for bulk and matrix samples of Y-793274 of 712 ppm as calculated from the data given by Fukuoka (1990), Warren and Kallemeyn (1991), and

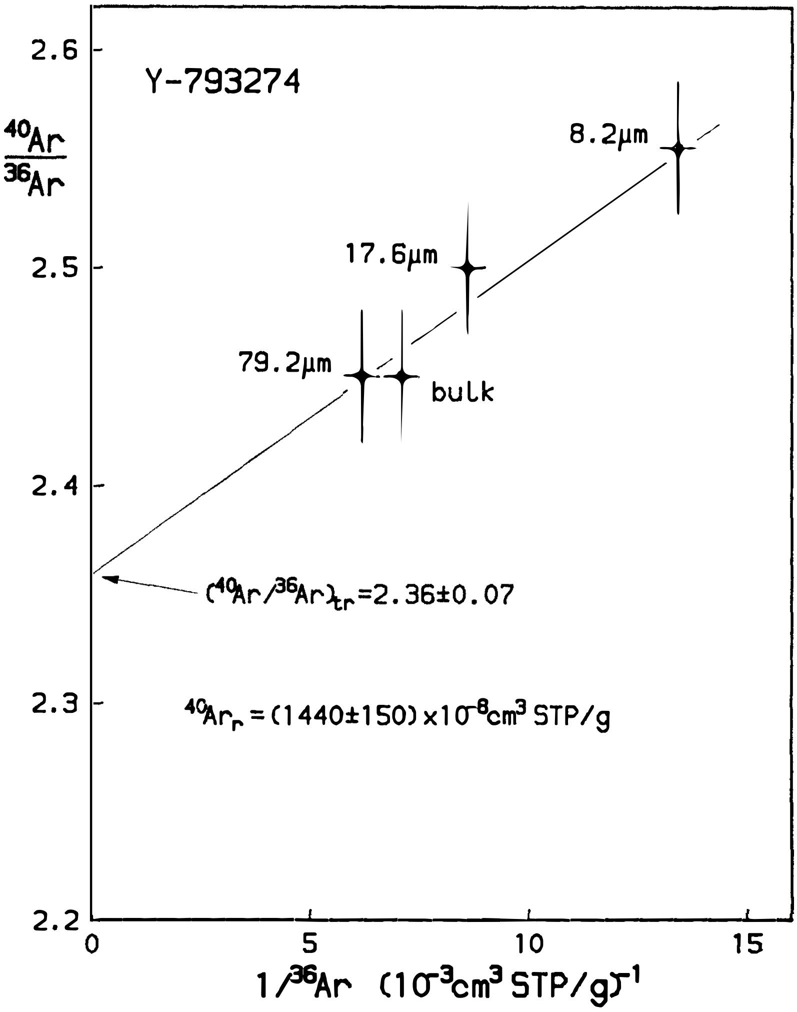

Fig. 1. $^{40}Ar/^{36}Ar$ ratios versus $1/^{36}Ar$ for the average values for bulk and the grain-size fractions of Y-793274. The ordinate intercept value gives the trapped ratio $^{40}Ar/^{36}Ar$. The slope of the correlation line corresponds to the concentration of radiogenic $^{40}Ar=(1440\pm150)\times10^{-8}$ cm^3 STP/g. Adopting 550 ppm K (Koeberl et al., 1991) a gas retention age of 2800 Ma is calculated. For 712 ppm K (see text) the K-Ar age is 2500 Ma.

YANAI and KOJIMA (1991) the gas retention age is 2500 Ma.

To partition into the trapped(tr), cosmogenic(c), and radiogenic(r) noble gas components, the following assumptions were made: $^4\mathrm{He}_{tr} = {}^4\mathrm{He} - {}^4\mathrm{He}_r - {}^4\mathrm{He}_c$, where $^4\mathrm{He}_r$ was calculated from 0.26 ppm U, 1.05 ppm Th (KOEBERL *et al.*, 1991) and 2800 Ma gas retention age; $(^4\mathrm{He}/^3\mathrm{He})_{tr} = 3000$; $(^4\mathrm{He}/^3\mathrm{He})_c = 5$; $(^{20}\mathrm{Ne}/^{21}\mathrm{Ne})_c = 0.9$; $(^{36}\mathrm{Ar}/^{38}\mathrm{Ar})_{tr} = 5.32$; $(^{36}\mathrm{Ar}/^{38}\mathrm{Ar})_c = 0.65$; $(^{40}\mathrm{Ar}/^{38}\mathrm{Ar})_c = 0.2$; $(^{40}\mathrm{Ar}/^{36}\mathrm{Ar})_{tr} = 2.36$; trapped Kr and Xe = BEOC12001 (EBERHARDT *et al.*, 1972); $(^{86}\mathrm{Kr}/^{83}\mathrm{Kr})_c = 0.015$; $(^{132}\mathrm{Xe}/^{136}\mathrm{Xe})_c = 0.5$; $(^{134}\mathrm{Xe}/^{126}\mathrm{Xe})_c = 0.05$; and $(^{136}\mathrm{Xe}/^{126}\mathrm{Xe})_c = 0.015$.

Table 4 gives the cosmogenic and Table 5 the trapped components. The 8.2 μm grain-size fraction shows, with exception of $^3\mathrm{He}_c$, systematically the lowest concentrations of cosmogenic and trapped gases. The same trend had been observed for other lunar meteorites, such as MacAlpine Hills88104 and 88105 (EUGSTER *et al.*, 1991b). The reason for this behavior is not clear. Diffusion loss during sample preparation or preheating would mainly affect He; ^{3}He, however, is about

Table 4. Cosmogenic noble gases in Y-793274.

Sample	^{3}He	^{21}Ne	^{38}Ar	^{81}Kr	^{83}Kr	^{126}Xe	^{78}Kr/^{83}Kr	^{80}Kr/^{83}Kr	^{124}Xe/^{126}Xe	^{128}Xe/^{126}Xe	^{131}Xe/^{126}Xe
	10^{-8}cm^3 STP/g			10^{-12}cm^3 STP/g							
Bulk	27.5	39.3	57.6	<0.65	590	38	0.103	0.46	0.53	2.3	3.9
	±4.7	±2.3	±18.0		±180	±8	±0.045	±0.17	±0.07	±0.4	±2.4
79.2 μm	26.1	40.2	100.2	<0.25	520	35	0.167	0.62	0.55	1.9	4.8
	±5.0	±2.4	±21.0		±100	±5	±0.025	±0.07	±0.07	±0.3	±0.7
17.6 μm	29.2	34.2	67.1	<0.07	430	34	0.150	0.70	0.50	1.6	3.6
	±5.8	±2.0	±15.2		±170	±9	±0.060	±0.30	±0.07	±0.4	±7.4
8.2 μm	26.6	18.0	46.3	<0.99	330	31	0.160	0.77	0.56	2.2	6.2
	±5.7	±1.6	±16.1		±150	±6	±0.070	±0.35	±0.09	±0.8	±3.1
Average[1)]	27.6	37.9	75.0	–	510	36	0.140	0.59	0.53	1.9	4.1
	±5.0	±2.0	±25.0		±100	±5	±0.030	±0.07	±0.03	±0.4	±0.7

1) Without 8.2 μm fraction (see text).

Table 5. Trapped noble gases in Y-793274.

Sample	^{4}He	^{20}Ne	^{36}Ar	^{84}Kr	^{132}Xe	^{20}Ne/^{22}Ne	^{40}Ar/^{36}Ar
		10^{-8}cm^3 STP/g					
Bulk	93000	28700	14000	7.0	0.75	–	–
	±11000	±1300	±600	±1.3	±0.15		
79.2 μm	116000	33300	16100	7.2	0.69	–	–
	±11000	±1500	±800	±1.3	±0.10		
17.6 μm	93000	18400	11600	6.0	0.60	–	–
	±11000	±900	±600	±1.2	±0.13		
8.2 μm	39000	8500	7400	4.1	0.39	–	–
	±11000	±500	±400	±0.8	±0.08		
From ordinate intercept						12.7	2.36
						±0.2	±0.10

the same in all fractions. It could be due to larger diffusion loss of gases from the smaller grains compared to the larger ones and, for the cosmogenic gases, lower concentrations of the target elements for ^{21}Ne, ^{38}Ar, ^{83}Kr and ^{126}Xe production. Therefore, the results of the 8.2 μm fraction were not taken into account for the calculation of the average cosmogenic concentrations (Table 4). The isotopic ratios of cosmogenic Kr and Xe are typical for lunar regolith material (*cf.* MARTI *et al.*, 1970).

4. Cosmic-ray Exposure Ages

From stable cosmogenic isotopes the total duration of exposure to cosmic rays can be calculated. The concentration of the radionuclide ^{81}Kr, on the other hand, allows us to derive an upper limit of the Moon–Earth transfer time, T_{transfer}, for Y-793274 with the following assumptions. (1) The terrestrial age $T_{\mathrm{terr}} \leqq 0.02$ Ma (NISHIIZUMI *et al.*, 1991a). (2) The saturation concentration of ^{81}Kr, $P_{4\pi}$ (sat), for the Y-793274 material in 4π-geometry, *i.e.*, during the Moon–Earth transfer, is calculated from $P_{4\pi}$ (sat) for Y-82192 of 0.221×10^{-12} cm^3 STP/g, adjusted for the chemical composition of Y-793274; we obtain $P_{4\pi}$ (sat) $= 0.243 \times 10^{-12}$ cm^3 STP/g. (3) The concentration of ^{81}Kr is assumed to be zero at ejection. This assumption is probably not correct, but assumption of any ^{81}Kr concentration inherited from exposure on the Moon will lower the given upper limit of T_{transfer}. With these assumptions and $<0.07 \times 10^{-12}$ cm^3 STP/g ^{81}Kr, as observed for the 17.6 μm fraction (Table 4), we obtain $T_{\mathrm{transfer}} < 0.12$ Ma. This value replaces an earlier result that was based on a preliminary data set (EUGSTER, 1991). Based on the ^{41}Ca concentration NISHIZUMI *et al.* (1991b) calculated $T_{\mathrm{transfer}} < 0.04 \pm 0.01$ Ma.

The large concentrations of the stable cosmogenic nuclides (Table 4) indicate that most of the cosmic-ray exposure occurred on the Moon. In order to calculate the total duration of lunar regolith exposure, we first have to derive the average shielding depth.

We would like to emphasize that two different types of "shielding depth" can be derived. The average shielding depth during the total exposure to cosmic rays is obtained from the depth sensitive ratio of two stable noble gas isotopes, such as ^{131}Xe and ^{126}Xe. The radionuclides, such as ^{41}Ca, ^{36}Cl, and ^{26}Al, however, allow us to derive the shielding depth valid only during the last period of exposure for which these radionuclides are sensitive (a few Ma). Using the theoretical depth profile for cosmogenic ^{131}Xe/^{126}Xe (HOHENBERG *et al.*, 1978) the observed value of 4.1 ± 0.7 corresponds to an average shielding depth during the total exposure on the Moon of 35 ± 15 g/cm^2. From the radionuclide activities NISHIIZUMI *et al.* (1991b) conclude that the shielding for a few Ma before ejection of the Y-793274 material was 150–190 g/cm^2.

We, thus, calculated the 2π-production rates for a shielding depth of 35 g/cm^2 and adopting the chemical abundances given by KOEBERL *et al.* (1991). For Ne, Ar and Xe we used the formulas given by HOHENBERG *et al.* (1978) and the following production rates were derived: $P_{21} = 0.112 \times 10^{-8}$ cm^3 STP/g Ma, $P_{38} = 0.102 \times 10^{-8}$ cm^3 STP/g Ma, and $P_{126} = 0.076 \times 10^{-12}$ cm^3 STP/g Ma. For the calculation of

Table 6. Duration of exposure to cosmic rays in the lunar regolith (cosmic-ray exposure age), average shielding to cosmic rays on the moon, time of breccia formation, and ^{40}Ar gas retention age of lunar meteorite Y-793274.

Cosmic-ray exposure age (Ma)[1]					Av. shielding[2] during cosmic-ray exp. age (gcm^{-2})	Breccia formation model age[3] (Ma)	^{40}Ar gas retention age[4] (Ma)
T_{21}	T_{38}	T_{83}	T_{126}	T_{av}			
(340)	740	890	470	700±200	35±15	500–1000	2800±400

1) Adopted production rates: $P_{21}=0.112\times10^{-8}$, $P_{38}=0.102\times10^{-8}$, $P_{83}=0.57\times10^{-12}$, $P_{126}=0.076\times10^{-12}$cm^3 STP/g Ma. 2) Calculated from $(^{131}Xe/^{126}Xe)_c$ in Table 4 and data given by HOHENBERG *et al.* (1978). 3) Derived from Fig. 2. 4) See Fig. 1.

P_{83} we used the formula P_{83} (10^{-12} cm^3 STP/g Ma) $= 0.006[Rb] + 0.0028[Sr] + 0.0036[Y] + 0.0026[Zr]$, where [X] is the concentration in ppm; this formula was derived from achondrites (MICHEL *et al.*, 1991) and adjusted to 2π-exposure geometry. We obtain $P_{83} = 0.57 \times 10^{-12}$ cm^3 STP/g Ma.

The resulting exposure ages are given in Table 6. The low ratio $^3He_c/^{21}Ne_c = 0.73$ indicates that most ^3He_c and probably some $^{21}Ne_c$ were lost. Therefore, exposure ages based on these isotopes were not considered for the calculation of the average exposure $T_{av} = 700\pm200$ Ma.

5. History of Y-793274 and Comparison with ALHA81005

As mentioned before, the K-^{40}Ar gas retention age is 2800 Ma with an uncertainty of about 400 Ma (Fig. 1 and Table 6). The K-^{40}Ar age is consistent with the gas retention ages usually observed for lunar basalts (BASALTIC VOLCANISM STUDY PROJECT, 1981). The time when the Y-793274 breccia was compacted can be estimated to have been 500–1000 Ma ago based on the time dependency of the trapped ratio $^{40}Ar/^{36}Ar$ (Fig. 2). As shown by EUGSTER *et al.* (1983) $(^{40}Ar/^{36}Ar)_{tr}$ is an antiquity indicator for lunar soil. For Y-793274 we obtain $(^{40}Ar/^{36}Ar)_{tr} = 2.36\pm0.10$ (Table 5). This value is considerably lower than the ratio of 5.7±1.0 observed for MAC88104/5 or 12.1±3.0 for Y-86032 (EUGSTER *et al.*, 1991b). The latter two lunar meteorites must, therefore, contain regolith material that was exposed at an earlier time to solar wind particles than the Y-793274 material.

In Fig. 3 cosmogenic ^{21}Ne and trapped ^{36}Ar in different lunar meteorites are compared. It is evident that the duration of exposure to solar wind particles is approximately proportional to that to cosmic rays. This proves that the main fraction of the stable cosmogenic nuclei in the strongly irradiated lunar meteorites was produced before they were compacted to coherent breccia material. We conclude that an exposure of Y-793274 at relatively shallow depth earlier than 500–1000 Ma ago is responsible for the production of the stable cosmogenic nuclei and trapping of solar wind particles. After breccia formation this exposure was followed by a residence in the lunar regolith at deeper depth consistent with higher shielding (150–190 g/cm^2) as indicated by the radionuclides (NISHIIZUMI *et al.*, 1991b).

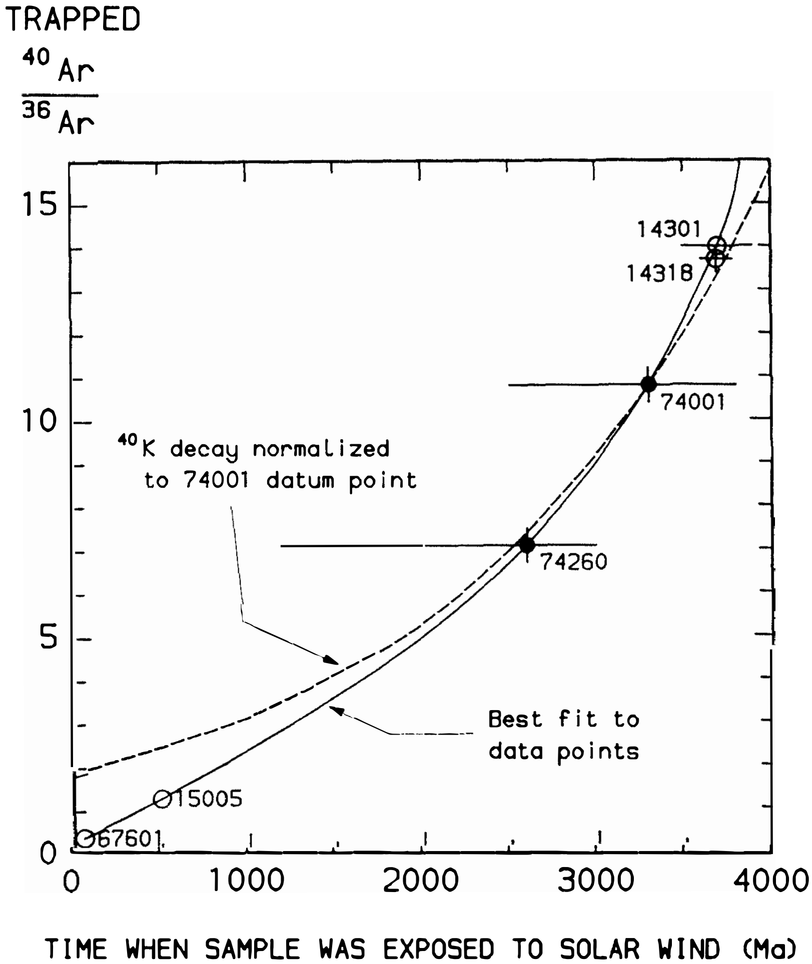

Fig. 2. Trapped $^{40}Ar/^{36}Ar$ ratios versus time when the sample was exposed to solar wind. ^{40}Ar originates from retrapping of radiogenic ^{40}Ar that was degassed from the lunar crust. ^{36}Ar is from solar wind implantation. For a ratio $(^{40}Ar/^{36}Ar)_{tr} = 2.36$ a trapping time of 500–1000 Ma is derived. Data for 14301 and 14318 from Megrue *(1973) and* Reynolds *et al. (1974), for 74001 and 74260 from* Eugster *et al. (1983), for 15005 from* Pepin *et al. (1974), and for 67601 from* Kirsten *et al. (1973).*

Both, Y-793274 and ALHA81005 show an intermediate maturity, not quite as high as mature lunar soil, such as Luna-16 soil, or as lunar meteorite Y-791197.

Inspection of the data given in Table 7 indicates that Y-793274 and ALHA81005 are similar in many respects; a similarity was already observed in our preliminary work (Eugster, 1990) and confirmed by Nishiizumi *et al.* (1991b) for the radionuclides. The exposure histories to cosmic ray and solar wind particles are essentially the same. These data allow for a common ejection event for these two meteorites, although they represent different fall events on Earth. Considering the distance of about 3000 km between the collection sites of the Yamato and Allan Hills meteorites, pairing is very improbable. The two meteorites differ quite strongly in their mineralogical composition, ALHA81005 being mainly anorthositic,

Table 7. Comparison of Y-793274 with ALHA81005.

	Cosmic-ray exp. age T_{av} (Ma)	Av. shielding d_{av} (g cm^{-2})		$^{36}Ar_{tr}$	$^{84}Kr_{tr}$	$^{132}Xe_{tr}$	Terrestrial age T_{terr} (Ma)	Moon-Earth transfer time $T_{transfer}$ (Ma)	Ejection time from Moon T_{ej} (Ma)
		during c. -r. exp. age[1]	during late exposure[2]	10^{-8}cm^3 STP/g					
Y-793274	700±200[3]	35±15[3]	150–190[6]	14000[3]	7.0[3]	0.75[3]	<0.02[4]	<0.12[3]/<0.02[4]	0.04±0.01[6]
ALHA81005	580±180[5]	~40[5]	150–175[4]	19500[5]	9.9[5]	1.15[5]	0.04–0.09[4]	<0.05[4]	0.04–0.14[4]

1) Average shielding depth during the total exposure to cosmic rays (T_{av}) on the moon.
2) Shielding during the past few million years, *i.e.*, the time for which the radionuclides ^{10}Be, ^{26}Al, ^{36}Cl, and ^{41}Ca are sensitive.
3) This work.
4) NISHIIZUMI *et al.* (1991a).
5) EUGSTER *et al.* (1986).
6) NISHIIZUMI *et al.* (1991b).

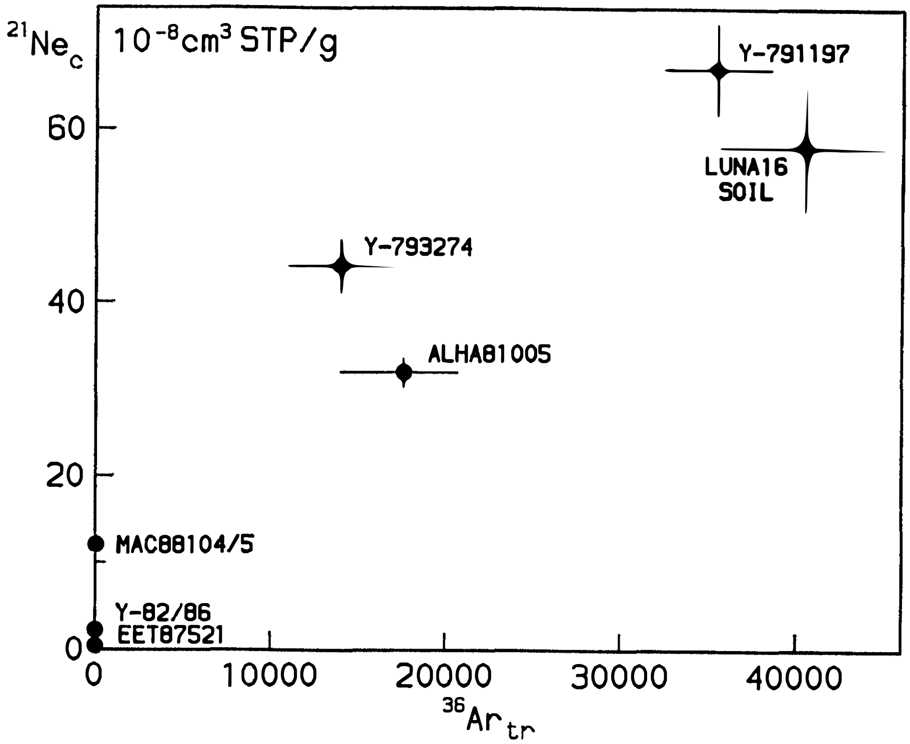

Fig. 3. *Cosmogenic ^{21}Ne versus trapped ^{36}Ar in lunar meteorites and Luna 16 soil.*

whereas Y-793274 contains only one third anorthositic material. If they really originate from the same ejection event on the Moon, the ejection site must have been quite inhomogeneous.

Acknowledgments

We are grateful to K. Yanai and H. Kojima (NIPR Tokyo) for providing the Yamato-793274 sample to us, and to H. Takeda for organizing the consortium study. We thank P. Guggisberg, D. Mermod, A. Schaller and M. Zuber for assistance at various stages of this investigation. This work was supported by the Swiss National Science Foundation.

References

Basaltic Volcanism Study Project (1981): Basaltic Volcanism on the Terrestrial Planets. New York, Pergamon Press, 1286 p.

Eberhardt, P., Geiss, J., Graf, H., Grögler, N., Mendia, M.D., Mörgeli, M., Schwaller, H., Stettler, A., Krähenbühl, U. and von Gunten, H.R. (1972): Trapped solar wind noble gases in Apollo 12 lunar fines 12001 and Apollo 11 breccia 10046. Proc. Lunar Sci. Conf., 3rd, 1821–1856.

Eugster, O. (1990): Lunar meteorite Yamato-793274: Cosmic-ray produced and solar wind noble gases. Relation with Allan Hills A81005? Papers Presented to the 15th NIPR Symposium on Antarctic Meteorites, May 30–June 1, 1990. Tokyo, Natl Inst. Polar Res., 188–190.

Eugster, O. (1991): From how many ejection sites on the moon do the lunar meteorites originate? Papers Presented to the 16th Symposium on Antarctic Meteorites, June 5–7, 1991. Tokyo, Natl Inst. Polar Res., 111–113.

EUGSTER, O., GEISS, J. and GRÖGLER, N. (1983): Dating of early regolith exposure and the evolution of trapped ^{40}Ar/^{39}Ar with time. Lunar and Planetary Science XIV. Houston, Lunar Planet. Inst., 177–178.

EUGSTER, O., GEISS, J., KRÄHENBÜHL, U. and NIEDERMANN, S. (1986): Noble gas isotopic composition, cosmic-ray exposure history, and terrestrial age of the meteorite Allan Hills A81005 from the moon. Earth Planet. Sci. Lett., **78**, 139–147.

EUGSTER, O., MICHEL, T. and NIEDERMANN, S. (1991a): Regolith history of lunar meteorites EET87521 and Yamato-793274. Lunar and Planetary Science XXII. Houston, Lunar Planet. Inst., 357–358.

EUGSTER, O., BEER, J., BURGER, M., FINKEL, R. C., HOFMANN, H. J., KRÄHENBÜHL, U., MICHEL, T., SYNAL, H. A. and WÖLFLI, W. (1991b): History of paired lunar meteorites MAC88104 and MAC88105 derived from noble gas isotopes, radionuclides, and some chemical abundances. Geochim. Cosmochim. Acta, **55**, 3139–3148.

FUKUOKA, T. (1990): Chemistry of Yamato-793274 lunar meteorite. Papers Presented to the 15th NIPR Symposium on Antarctic Meteorites, May 30–June 1, 1990. Tokyo, Natl Inst. Polar Res., 122–123.

HOHENBERG, C. M., MARTI, K., PODOSEK, F. A., REEDY, R. C. and SHIRCK, J. R. (1978): Comparisons between observed and predicted cosmogenic noble gases in lunar samples. Proc. Lunar Planet. Sci. Conf., 9th, 2311–2344.

KIRSTEN, T., HORN, P. and KIKO, J. (1973): ^{39}Ar–^{40}Ar dating and rare gas analysis of Apollo 16 rocks and soils. Proc. Lunar Sci. Conf., 4th, 1757–1784 (Geochim. Cosmochim. Acta, Suppl. 4).

KOEBERL, C., KURAT, G. and BRANDSTÄTTER, F. (1991): Lunar meteorite Yamato-793274: Mixture of mare and highland components, and barringerite from the moon. Proc. NIPR Symp. Antarct. Meteorites, **4**, 33–55.

KURAT, G., BRANDSTÄTTER, F. and KOEBERL, C. (1990): Lunar meteorite Yamato-793274: A lunar highland sample possibly rich in mare minerals. Papers Presented to the 15th NIPR Symposium on Antarctic Meteorites, May 30–June 1, 1990. Tokyo, Natl Inst. Polar Res., 193–195.

LINDSTROM, M. M. and MARTINEZ, R. R. (1990): Lunar meteorite Y793274: A second basaltic breccia. Papers Presented to the 15th NIPR Symposium on Antarctic Meteorites, May 30–June 1, 1990. Tokyo, Natl Inst. Polar Res., 114–115.

LINDSTROM, M. M., MITTLEFEHLDT, D. W., MARTINEZ, R. R., LIPSCHUTZ, M. E. and WANG, M. S. (1991): Geochemistry of Yamato-82192, -86032 and -793274 lunar meteorites. Proc. NIPR Symp. Antarct. Meteorites, **4**, 12–32.

MARTI, K., LUGMAIR, G. W. and UREY, H. C. (1970): Solar wind gases, cosmic-ray spallation products and the irradiation history of Apollo 11 samples. Proc. Apollo 11 Lunar Sci. Conf., 1357–1367.

MEGRUE, G. H. (1973): Spatial distribution of ^{40}Ar/^{39}Ar ages in lunar breccia 14301. J. Geophys. Res., **78**, 3216–3221.

MICHEL, T., EUGSTER, O. and NIEDERMANN, S. (1991): Determination of the ^{81}Kr saturation activity and Kr production rates for various meteorite classes; application to exposure ages and terrestrial ages. Meteoritics, in press.

NISHIIZUMI, K., ARNOLD, J. R., SHARMA, P., KUBIK, P. W., KLEIN, J. and MIDDLETON, R. (1991a): Cosmic ray exposure history of lunar meteorite EET87521. Lunar and Planetary Science XXII. Houston, Lunar Planet. Inst., 977–978.

NISHIIZUMI, K., ARNOLD, J. R., KLEIN, J., FINK, D., MIDDLETON, R., SHARMA, P. and KUBIK, P. W. (1991b): Cosmic ray exposure history of lunar meteorite Yamato 793274. Papers Presented to the 16th NIPR Symposium on Antarctic Meteorites, June 5–7, 1991. Tokyo, Natl Inst. Polar Res., 188–190.

PEPIN, R. O., BASFORD, J. R., DRAGON, J. C., COSCIO, M. R., JR. and MURTHY, V. R. (1974): Rare gases and trace elements in Apollo 15 drill core fines: Depositional chronologies and K-Ar ages, and production rates of spallation-produced ^{3}He, ^{21}Ne, and ^{38}Ar *versus* depth. Proc. Lunar Sci. Conf., 5th, 2149–2184.

REYNOLDS, J.H., ALEXANDER, E.C., JR., DAVIS, P.K. and SRINIVASAN, B. (1974): Studies of K-Ar dating and xenon from extinct radioactivities in breccia 14318: Implications for early lunar history. Geochim. Cosmochim. Acta, **38**, 401–417.

TAKAOKA, N. and YOSHIDA, Y. (1990): Noble gases in lunar meteorites. Papers Presented to the 15th NIPR Symposium on Antarctic Meteorites, May 30–June 1, 1990. Tokyo, Natl Inst. Polar Res., 126–128.

TAKEDA, H., SAITO, J. and MORI, H. (1990): Consortium reports of lunar meteorites Y-793274 and Y-86032. Papers Presented to the 15th NIPR Symposium on Antarctic Meteorites, May 30–June 1, 1990. Tokyo, Natl Inst. Polar Res., 110–112.

TAKEDA, H., SAITO, J., YANAI, K. and KOJIMA, H. (1991): Consortium reports of lunar meteorite Yamato-793274. Proc. NIPR Symp. Antarct. Meteorites, **4**, 3–11.

TATSUMOTO, M. and PREMO, W.R. (1991): U-Pb isotopic characteristics of lunar meteorites Yamato-793274 and Yamato-86032. Proc. NIPR Symp. Antarct. Meteorites, **4**, 56–69.

WARREN, P.H. (1990): Lunar meteorites: A survey of the first eight distinct moon rocks from Antarctica. Papers Presented to the 15th NIPR Symposium on Antarctic Meteorites, May 30–June 1, 1990. Tokyo, Natl Inst. Polar Res., 131–133.

WARREN, P.H. and KALLEMEYN, G.W. (1991): Geochemical investigation of five lunar meteorites: Implications for the composition, origin and evolution of the lunar crust. Proc. NIPR Symp. Antarct. Meteorites, **4**, 91–117.

YANAI, K. and KOJIMA, H. (1991): Varieties of lunar meteorites recovered from Antarctica. Proc. NIPR Symp. Antarct. Meteorites, **4**, 70–90.

(Received September 2, 1991; Revised manuscript received November 1, 1991)