Antarct. Meteorite Res., **18**, 117–132, 2005

Mars ejection times and neutron capture effects of the nakhlites Y000593 and Y000749, the olivine-phyric shergottite Y980459, and the lherzolite NWA1950

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(Received November 14, 2004; Accepted January 25, 2005)

Abstract: We measured the concentrations and isotopic composition of the noble gases He, Ne, Ar, Kr, and Xe in the paired antarctic nakhlites Y000593 and Y000749, and in the antarctic olivine-phyric shergottite Y980459. Furthermore, we analyzed He, Ne, and Ar in lherzolite NWA1950. For the two nakhlite specimens we obtain Mars ejection times of 11.2±1.2 Ma and 12.3±1.8 Ma, respectively, in agreement with those for the four nakhlites dated before. Y980459 yields longer cosmic-ray exposure (CRE) ages based on ^{21}Ne and ^{38}Ar (2.9 and 2.5 Ma, respectively) than based on ^{3}He, ^{81}Kr-^{83}Kr, and ^{10}Be (1.5, 1.9, and 1.1 Ma, respectively).We interpret this difference to be due to an additional cosmogenic component produced by solar cosmic rays. The Mars ejection time of this meteorite is essentially its CRE age of 1.1 Ma and agrees with the ejection times of the four other olivine-phyric shergottites. The ejection time of NWA1950 is 4.1±1.4 Ma and lies within the range of the other three lherzolites. In the two nakhlites and in Y980459 we observe effects induced by the reaction ^{79}Br (n, $\gamma\beta$) ^{80}Kr. For the nakhlites this ^{80}Kr was produced in free space during Mars-Earth transfer; from its concentration we calculate a pre-atmospheric mass of >170 kg. On the other hand, a pre-atmospheric size for the Y980459 meteoroid can not be derived from our data. We interpret the occurrence of an excess of $^{80}Kr_n$ to be due to trapping of this nuclide from the martian atmosphere, as was observed by other workers for martian meteorite EETA79001. For Y980459 we also find an excess of 71×10^{-8} cm^{3}STP ^{40}Ar/g that originates from trapped martian atmospheric gases. We show that up to eight impact events in a time span of 0.73 Ma to 19.8 Ma are responsible for ejecting the martian meteorites studied until now. Each event occurred in a specific surface region characterized by the mineralogy of the meteorites blasted off by these cratering processes.

key words: martian meteorites, nakhlites, shergottites, cosmic-ray exposure ages, ejection times

1. Introduction

The meteorites whose parent body is Mars vary considerably in their mineralogical composition. In his Mars Meteorite Compendium Meyer (2003) gives the summary of the modal mineralogy in volume percent for six different types of martian meteorites.

The major minerals are olivine (ol), pyroxene (px), and plagioclase (plag), partially converted to maskelynite, the minor ones (never more than a few percent) are chromite, Ti-rich magnetite, phosphate, and sulfide. Seven types of martian meteorites have been observed; six of them are characterized *e.g.* by their ratios of olivine to pyroxene and plagioclase to pyroxene: 1) clinopyroxenites, also called nakhlites (ol/px$=$0.18, plag/px $\leq$0.05); 2) basaltic shergottites ($<$0.005, 0.5); 3) lherzolites (1.3, 0.3); 4) olivine-phyric shergottites (0.3, 0.3); 5) dunite, only member Chassigny (18, 0.4); and 6) orthopyroxenite, only member Allan Hills (ALH) 84001 (0, 0.01). A seventh type is represented by the unique meteorite Elephant Moraine (EET) A79001 that consists of three main lithologies: lithology A is similar to the olivine-phyric shergottites, lithology B is basaltic, similar to Shergotty but depleted in rare earth elements, and lithology C is an assemblage of glass pods and thin interconnecting glass veins.

The martian meteorites were ejected from the surface of Mars by asteroidal or cometary impact in a number of discrete events (Nyquist *et al.*, 2001; Meyer, 2003). These events are characterized by the time, when they occurred, the ejection time, also called ejection age (T_{ej}). The T_{ej} is the sum of the cosmic-ray exposure (CRE) age and the terrestrial age (T_{terr}), *i.e.* the time when the meteorite fell on Earth. The CRE age is identical to the Mars-Earth transfer time in case the meteoritic material was not pre-exposed to CRs on Mars and did not experience a change of its geometry in space. All references concerning T_{ej} are given in the caption of Fig. 1. The earliest ejection event is represented by Dhofar (DHO) 019, an olivine-phyric shergottite, 19.8±2.3 Ma. The only orthopyroxenite, ALH84001, has an ejection age of 14.7±0.9 Ma. It is the only meteorite from the ancient martian crust (for references see Nyquist *et al.*, 2001). The clinopyroxenites (nakhlites) have a common ejection age of 10.8±0.7 Ma. The same impact event may also be responsible for the only dunite (Chassigny) since its $T_{ej}=11.3\pm0.6$ Ma. The six basaltic shergottites yield ejection ages in the range of 2.8±0.3 Ma. They consist predominantly of the clinopyroxenes pigeonite and augite and differ from the four lherzolites that consist mainly of olivine, orthopyroxene, and chromite. Lherzolites and the olivine-phyric shergottites were ejected 4.1±0.4 Ma and 1.16±0.06 Ma ago, respectively. As mentioned above, the ejection age of another olivine-phyric shergottite, DHO 019, is 19.8±2.3 Ma. Finally, the unique meteorite EETA79001 shows an ejection age of 0.73±0.15 Ma.

Since Meyer (2003) published his compendium some additional martian meteorites were dated: For the olivine-phyric shergottite Northwest Africa (NWA) 1068 Mathew *et al.* (2003) obtained an average CRE age of 2.01 Ma. The various specific ages vary from 1.14 Ma (^{21}Ne age, T_{21}) to 2.60 Ma (^{15}N age, T_{15}). According to Marti (pers. comm.) T_{15} is less reliable than T_{21}, because partitioning of N into the trapped and cosmogenic components is difficult and because the N production rate is not as well known as that for ^{21}Ne. Thus, we consider the ^{21}Ne age to be the most reliable age for NWA1068. For the basaltic shergottite NWA856 Mathew *et al.* (2003) gave an average ^{3}He, ^{21}Ne, ^{38}Ar CRE age of 2.60 Ma, the specific ages being within 10% of this value. For NWA1195, an olivine-phyric shergottite, Nishiizumi and Hillegonds (2004) reported a CRE age of about 1.1 Ma without specifying from which nuclide this age was obtained. The olivine-phyric shergottite Yamato (Y) 980459 was studied by several authors: Okazaki and Nagao (2004) measured the cosmogenic noble gases and obtained

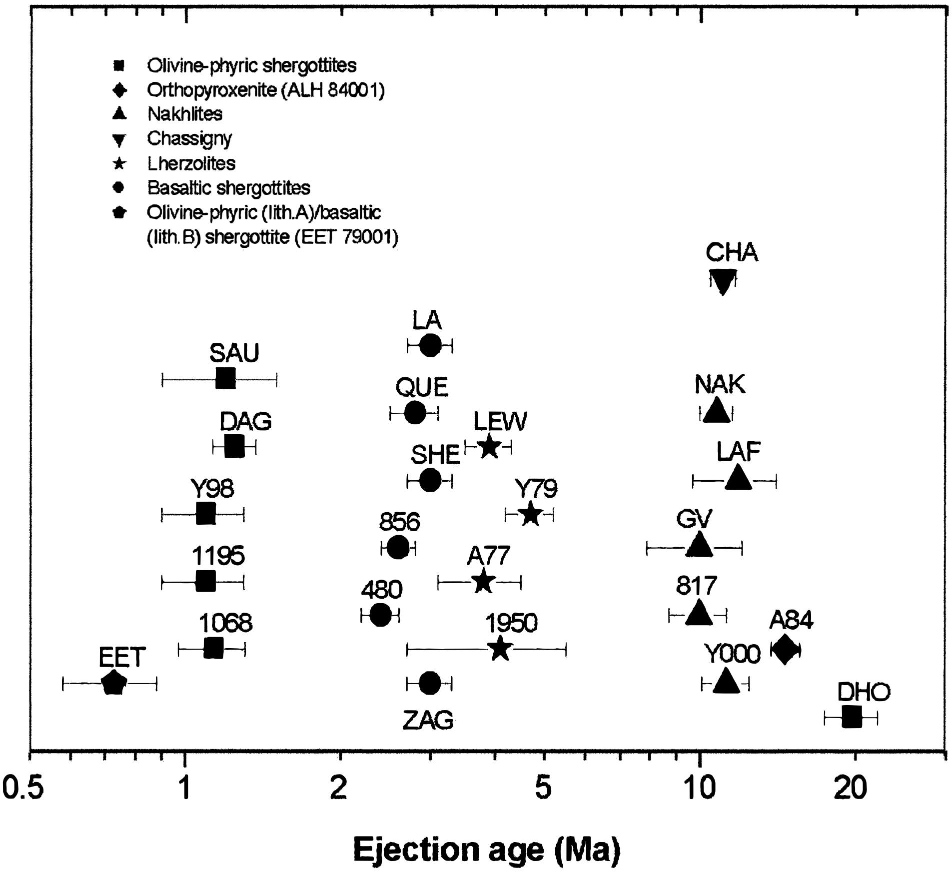

Fig. 1. Ejection ages (Ma) of the martian meteorites dated until now: EET—EETA 79001 [Ref. 1], SAU—average for all paired SaU martian meteorites [3], DAG—average for all paried DaG martian meteorites [1], Y98—Y980459 [4], 1195—NWA 1195 [4], 1068—NWA 1068 [5], LA—Los Angeles [3], QUE—QUE 94201 [3], SHE—Shergotty [3], 856—NWA 856 [2], 480—NWA 480 [2], ZAG—Zagami [3], LEW—LEW 88516 [3], Y79—Y-793605 [1], A77—ALHA77005 [3], 1950—NWA 1950 [6], CHA—Chassigny [1], NAK—Nakhla [3], LAF—Lafayette [1], GV—Governador Valadares [1], 817—NWA 817 [2], Y000—average for Y000593/749/802 [6], A84—ALH 8400 [3], DHO—DHO 019 [7].

The error bars represent the 2 sigma error of the average value for the different individual CRE age determinations of a given meteorite.

References: [1] Nyquist et al. (2001), [2] Mathew et al. (2003), [3] Eugster et al. (2002); [4] ^{10}Be age (Nishiizumi and Hillegonds, 2004), [5] ^{21}Ne age (Mathew et al., 2003), typical error of 15% adopted, [6] this work, [7] Shukolyukov et al. (2000).

a CRE age around 2.1–2.5 Ma, confirmed by Christen *et al.* (2004) who gave an average CRE age of 2.6–2.8 Ma. Nishiizumi and Hillegonds (2004), however, reported a CRE age of 1.1±0.2 Ma based on the ^{10}Be activity and concluded that the stable cosmogenic noble gases must be enhanced due to solar cosmic rays or a pre-exposure on the parent body. This discrepancy of the CRE ages obtained from the different dating methods will be discussed below. Finally, one or several of the paired nakhlites Y000593, Y000749, and Y000802 were studied by Okazaki *et al.* (2003), Murty *et al.* (2003), and Christen *et al.* (2004). The results yield the typical Mars ejection age of about 11 Ma for the nakhlites (Nyquist *et al.*, 2001).

In this work we present the final results for the nakhlites Y000593 and Y000749, and for the olivine-phyric shergottite Y980459. Preliminary data had been given in an abstract by Christen *et al.* (2004). Additional data are presented for the lherzolite NWA1950. We will discuss the CRE ages and their relation to the ages of the other meteorites of the same type. For the nakhlites and the olivine-phyric shergottite we also present results on the Kr and Xe isotopes. This allows us to determine the epithermal neutron flux based on neutron produced ^{80}Kr. As the neutron flux depends on the geometric characteristics of the meteoroid we will attempt to determine the pre-atmospheric size of the investigated meteorites. There might be a small contribution of fission Xe, but lacking precise data on the U concentration the discussion of this component is not meaningful. Furthermore, radiogenic ^{4}He, ^{40}Ar, and ^{129}Xe are not discussed. ^{4}He is usually depleted due to diffusion loss and only upper limits for the U and Th concentrations are known. ^{40}Ar and ^{129}Xe are mixtures of martian atmospheric and in situ produced radiogenic gases. Their proportions can not be derived from our data, therefore we will not calculate gas retention ages based on these nuclides.

2. Samples and experimental procedure

The nakhlites Y000593 and Y000749 were collected by the Japanese Antarctic Research Expedition in 2000 (JARE-41). These two specimens and Y000802 are paired and were distributed to numerous workers for a consortium study (Misawa *et al.*, 2003). The recovered masses of Y000593 and Y000749 are 13.713 kg and 1.283 kg, respectively. Samples of 355 mg and 419 mg, respectively, were allocated to us. The olivine-phyric shergottite Y980459 (recovered mass 82.46 g) was also studied in the framework of a consortium; a sample of 211 mg was obtained from the National Institute of Polar Research (NIPR) in Tokyo. Lherzolite NWA1950 (two stones of 414 g and 383 g) were found in 2001 in the Atlas Mountains (Morocco). We purchased a 1.5 g sample from B. Fectay (The Earth's Memory LLC, Aumont, France).

The samples for He, Ne, and Ar analyses (for sample weights see Table 1) were crushed in a stainless steel mortar to pass a 750 μm sieve. The samples for the Kr and Xe measurements (Tables 2 and 3) were loaded as uncrushed splits into the extraction system to minimize adsorption of terrestrial air. The weights of the samples loaded into the extraction system are given in Tables 1–3. The meteorite samples were heated in vacuum at 90°C for several days in the storage arm of the extraction system to remove adsorbed terrestrial atmospheric gases. He, Ne, and Ar were extracted in a single step at 1700°C. For Y980459, Y000593, and Y000749 we performed two He, Ne, and Ar analyses: one sample of each meteorite was analyzed using a radio-frequency heated crucible and our system B, consisting of two mass spectrometers equipped with secondary electron multipliers, one mass spectrometer for He and Ne, and the other one for Ar analyses. A second sample of each meteorite was analyzed using a resistance heated gas extraction crucible and our system C, consisting of a Mass Analyser Products 215–

Table 1. Results of He, Ne, and Ar measurements.

Meteorite (system, sample weight)	^{4}He	^{20}Ne	^{40}Ar	^{4}He/^{3}He	^{20}Ne/^{22}Ne	^{22}Ne/^{21}Ne	^{36}Ar/^{38}Ar	^{40}Ar/^{36}Ar
		10^{-8}cm^{3} STP/g						
Y980459,59 (B, 21.73 mg)	28.3 ±3.0	0.788 ±0.090	93.4 ±4.0	11.2 ±0.9	*	*	1.22 ±0.05	*
Y980459,59 (C, 147.02 mg)	*	0.67 ±0.07	*	11.3 ±0.4	0.849 ±0.017	1.19 ±0.05	1.00 ±0.02	298 ±6
Y980459,59 (average)	28.3 ±3.0	0.729 ±0.060	93.4 ±4.0	11.3 ±0.4	0.849 ±0.017	1.19 ±0.05	1.11 ±0.6	298 ±6
Y000593,103 (B, 20.43 mg)	952 ±30	2.40 ±0.12	1183 ±40	47.9 ±0.8	*	1.24 ±0.11	0.754 ±0.010	737 ±20
Y000593,103 (C, 292.23 mg)	*	1.81 ±0.20	*	63.5 ±2.0	0.837 ±0.010	1.22 ±0.07	*	553 ±25
Y000593,103 (average)	952 ±30	2.10 ±0.30	1183 ±40	55.7 ±8.0	0.837 ±0.020	1.23 ±0.03	0.754 ±0.010	645 ±90
Y000749,61 (B, 21.28 mg)	806 ±25	2.16 ±0.18	1280 ±40	39.7 ±0.6	* ±0.100	* ±0.23	0.742 ±0.012	870 ±20
Y000749,61 (C, 327.52 mg)	*	2.12 ±0.20	*	*	0.847 ±0.010	1.243 ±0.025	*	447 ±20
Y000749,61 (average)	806 ±25	2.14 ±0.07	1280 ±40	39.7 ±0.6	0.847 ±0.010	1.243 ±0.025	0.742 ±0.012	658 ±200
NWA 1950 (B, 30.22 mg)	31.0 ±1.0	1.11 ±0.04	142.2 ±5.0	4.65 ±0.10	0.848 ±0.020	1.258 ±0.015	1.191 ±0.030	515 ±20
NWA 1950 (B, 51.35 mg)	30.6 ±1.0	1.09 ±0.04	129.8 ±5.0	4.72 ±0.10	0.866 ±0.020	1.252 ±0.015	1.068 ±0.030	518 ±20
NWA 1950 (B, 101.51 mg)	31.1 ±1.0	1.06 ±0.04	114.3 ±5.0	4.81 ±0.10	0.839 ±0.020	1.259 ±0.015	1.044 ±0.030	476 ±20
NWA 1950 (average)	30.9 ±1.0	1.09 ±0.04	128.8 ±5.0	4.73 ±0.10	0.851 ±0.020	1.256 ±0.015	1.101 ±0.030	503 ±20

* Instability of mass spectrometer occurred; unreliable data obtained.

50 mass spectrometer with an ion counting system. For NWA1950 three He, Ne, and Ar analyses were performed with system B. Kr and Xe were extracted by resistance heating in two temperature steps (800°C and 1700°C) and then analyzed with our system C. Details of blank and background corrections and of the analytical procedure are described by Busemann and Eugster (2002) and Eugster *et al*. (1993). The results are given in Tables 1–3. The errors correspond to a 95% confidence level (2σ) and include the statistical errors of the ratio measurements, as well as the uncertainties of the concentration determination and of the blank and isotope fractionation corrections. Inspection of Table 1 shows that for some of the analyses instabilities of the mass spectrometer occurred. The respective data were too unreliable to be considered for calculating average values.

3. Partitioning of the noble gases

The noble gases in the investigated meteorites are a mixture of CR produced, c,

Table 2. Results of Kr measurements.

Meteorite (sample weight)		^{86}Kr 10^{-12}cm^{3}STP / g	$\frac{^{78}\mathrm{Kr}}{^{86}\mathrm{Kr}}$	$\frac{^{80}\mathrm{Kr}}{^{86}\mathrm{Kr}}$	$\frac{^{81}\mathrm{Kr}}{^{86}\mathrm{Kr}}$	$\frac{^{82}\mathrm{Kr}}{^{86}\mathrm{Kr}}$	$\frac{^{83}\mathrm{Kr}}{^{86}\mathrm{Kr}}$	$\frac{^{84}\mathrm{Kr}}{^{86}\mathrm{Kr}}$
Y980459,59;	800°C	28.5	0.0238	0.148	–	0.735	0.737	3.61
(147.02 mg)		±6.0	±0.0030	±0.018		±0.070	±0.080	±0.25
	1700°C	8.3	0.0374	0.228	0.0069	0.786	0.744	3.37
		±1.7	±0.0070	±0.025	±0.0025	±0.120	±0.080	±0.25
	total	36.8	0.0269	0.166	0.00156	0.747	0.739	3.56
		±7.0	±0.0030	±0.018	±0.00060	±0.070	±0.080	±0.25
Y000593,103;	800°C	30.2	0.0164	0.127	0.0003	0.655	0.630	3.20
(292.23 mg)		±6.0	±0.0012	±0.008	±0.0002	±0.045	±0.040	±0.12
	1700°C	5.9	0.192	0.590	0.0125	1.286	1.464	3.89
		±1.2	±0.015	±0.040	±0.0016	±0.080	±0.090	±0.20
	total	36.1	0.0451	0.203	0.00229	0.758	0.766	3.31
		±7.0	±0.0035	±0.014	±0.00030	±0.050	±0.050	±0.13
Y000749,61;	800°C	21.8	0.0167	0.120	0.0011	0.694	0.650	3.35
(327.52 mg)		±4.0	±0.0018	±0.012	±0.0002	±0.060	±0.030	±0.20
	1700°C	10.4	0.0899	0.319	0.0070	0.927	0.971	3.29
		±2.0	±0.0090	±0.025	±0.0008	±0.070	±0.070	±0.20
	total	32.2	0.0403	0.184	0.0030	0.769	0.754	3.33
		±6.0	±0.0040	±0.015	±0.0004	±0.060	±0.040	±0.20

(spallation and secondary neutron reactions), radiogenic, r, (^{40}K, ^{129}I, ^{235,238}U, and ^{232}Th decay), fissiogenic, f, (^{235,238}U, ^{244}Pu), and trapped, tr, components. In the following the assumptions for the partitioning of the noble gas components are given. For references see Terribilini *et al.* (1998) and Okazaki *et al.* (2003).

Helium: $^{3\,\mathrm{and}\,4}\mathrm{He}_{\mathrm{tr}}=0$ and $(^4\mathrm{He}/^3\mathrm{He})_c=6.2$.

Neon is almost entirely cosmogenic. For the correction of a small $\mathrm{Ne}_{\mathrm{tr}}$ contribution we assumed Ne of terrestrial atmospheric composition.

Argon: $(^{36}\mathrm{Ar}/^{38}\mathrm{Ar})_{\mathrm{tr}}=4.4\pm1.1$. This includes martian atmospheric and mantle Ar. Furthermore, $(^{36}\mathrm{Ar}/^{38}\mathrm{Ar})_c=0.65$.

Krypton: $\mathrm{Kr}_{\mathrm{tr}}$ was assumed to have the isotopic composition of terrestrial atmospheric Kr. E. g. for the 1700°C fractions of Y000593 and Y000749 the $^{80}\mathrm{Kr}_{\mathrm{tr}}$ component is 22% and 40%, respectively, of total ^{80}Kr. Only the 1700°C fractions of these analyses show the signature of an additional cosmogenic Kr component.

Xenon: Figure 2 shows that Xe is a mixture of cosmogenic and trapped Xe. ^{129}Xe contains an additional contribution of radiogenic ^{129}Xe from ^{129}I decay. From our data we cannot determine the isotopic composition of the trapped component. In this paper we do not focus on the Xe components but refer to the comprehensive work on nakhlites and shergottites of Mathew *et al.* (2003). All data on Kr and Xe not discussed in this

Table 3. Results of Xe measurements.

Meteorite (sample weight)		^{132}Xe $10^{-12}cm^3STP/g$	$\frac{^{124}Xe}{^{132}Xe}$	$\frac{^{126}Xe}{^{132}Xe}$	$\frac{^{128}Xe}{^{132}Xe}$	$\frac{^{129}Xe}{^{132}Xe}$	$\frac{^{130}Xe}{^{132}Xe}$	$\frac{^{131}Xe}{^{132}Xe}$	$\frac{^{134}Xe}{^{132}Xe}$	$\frac{^{136}Xe}{^{132}Xe}$
Y980459,59; (147.02 mg)	800°C	56.7 ±11.0	0.0032 ±0.0006	0.0027 ±0.0004	0.0716 ±0.0070	1.027 ±0.070	0.149 ±0.010	0.777 ±0.050	0.388 ±0.025	0.280 ±0.030
	1700°C	15.0 ±3.0	0.0051 ±0.0017	0.0048 ±0.0012	0.0810 ±0.0140	1.115 ±0.120	0.147 ±0.018	0.800 ±0.080	0.355 ±0.025	0.320 ±0.040
	total	71.7 ±14.0	0.0036 ±0.0008	0.0031 ±0.0006	0.0736 ±0.0080	1.045 ±0.080	0.149 ±0.010	0.782 ±0.060	0.381 ±0.025	0.288 ±0.040
Y000593,103; (292.23 mg)	800°C	37.7 ±8.0	0.0027 ±0.0006	0.0029 ±0.0004	0.0715 ±0.0060	1.010 ±0.035	0.155 ±0.008	0.809 ±0.030	0.396 ±0.014	0.339 ±0.025
	1700°C	24.0 ±5.0	0.0107 ±0.0045	0.0223 ±0.0060	0.101 ±0.005	1.146 ±0.040	0.173 ±0.010	0.835 ±0.035	0.376 ±0.016	0.311 ±0.030
	total	61.7 ±12.0	0.0058 ±0.0017	0.0104 ±0.0020	0.0830 ±0.0050	1.063 ±0.040	0.162 ±0.010	0.819 ±0.030	0.388 ±0.015	0.328 ±0.030
Y000749,61; (327.52 mg)	800°C	29.9 ±6.0	0.0025 ±0.0006	0.0026 ±0.0004	0.0704 ±0.0030	1.026 ±0.040	0.152 ±0.004	0.802 ±0.030	0.385 ±0.015	0.343 ±0.025
	1700°C	22.3 ±4.5	0.0117 ±0.0020	0.0215 ±0.0025	0.1124 ±0.0035	1.157 ±0.040	0.173 ±0.006	0.836 ±0.020	0.381 ±0.014	0.298 ±0.020
	total	52.2 ±10.0	0.0064 ±0.0013	0.0107 ±0.0016	0.0889 ±0.0030	1.082 ±0.040	0.161 ±0.005	0.817 ±0.020	0.383 ±0.015	0.324 ±0.020

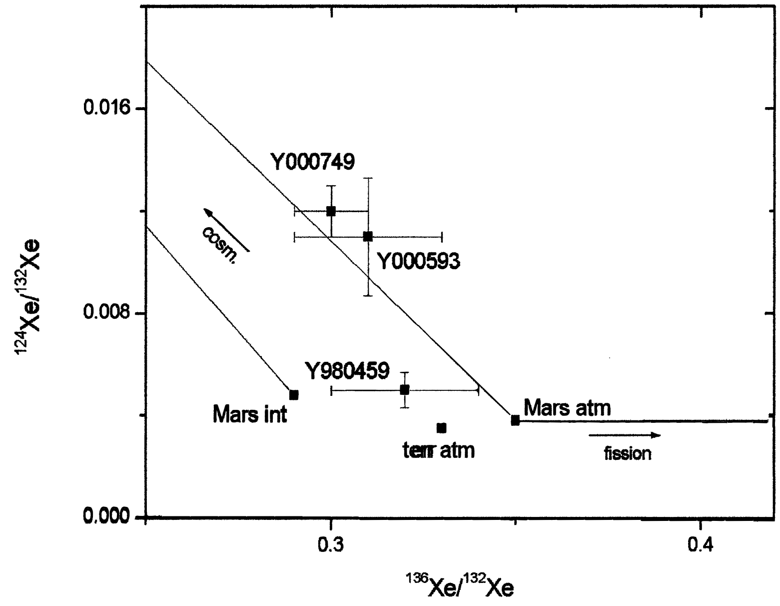

Fig. 2. $^{124}Xe/^{132}Xe$ versus $^{136}Xe/^{132}Xe$ for the investigated meteorites.

work will be presented in a forthcoming publication in the context of martian trapped noble gases.

4. Cosmogenic noble gases and CRE ages

Dating of the ejection events from Mars allows us to determine the source crater pairing of meteorites. The ejection time is calculated from the CRE age and the terrestrial age (see Introduction). The CRE age is obtained from the stable cosmogenic noble gas isotopes and, for short CRE ages, from ^{10}Be. The terrestrial age is calculated from radioactive nuclides such as ^{10}Be, ^{14}C, ^{26}Al, ^{36}Cl, ^{53}Mn, and ^{81}Kr (*cf.* Nishiizumi, 1987; Jull, 2005).

Tables 4 and 5 give the concentrations and isotopic ratios of the cosmogenic nuclides. In order to calculate a CRE age we have to determine the production rates for the specific nuclides. The production rates were calculated according to the procedure of Eugster and Michel (1995) using the chemical abundances given in Table 6. For the shielding correction of the ^{21}Ne production rate we adopted the formula for diogenites for NWA1950, that for eucrites for the two nakhlites, and that for howardites for Y980459. The resulting production rates and CRE ages are given in Table 7. For calculating the ^{81}Kr-^{83}Kr CRE age (T_{81}) the terrestrial age (T_{terr}) has to be known in order to correct for the decay of ^{81}Kr on Earth. Nishiizumi and Hillegonds (2004) reported a T_{terr} of 0.055 ± 0.020 Ma for the Y000593/000749/000802 nakhlites based on ^{14}C and ^{41}Ca concentrations. Adopting a ^{81}Kr half-life of 229000 years (Baglin, 1993) the apparent T_{81} has to be corrected by a factor of 0.846. For Y000593 we obtain $T_{81} = 10.8 \pm 2.0$ Ma, almost the same age as that reported by Okazaki *et al.* (2003) if we correct their value also by a factor of 0.846. Furthermore, these authors use the old value for the ^{81}Kr half-life of 213000 years (Eastwood *et al.*, 1964) instead of the new one of 229000 years (Baglin, 1993). With these corrections T_{81} of Okazaki *et al.* (2003) becomes 10.7 Ma. For the Y000749 specimen we obtain $T_{81} = 7.7 \pm 2.0$ Ma. We do not know why this age is considerably lower than the ages obtained by the other methods, but on unrecognized interference on mass 81 might explain a low ^{83}Kr/^{81}Kr ratio and consequently a low T_{81} value.

The olivine-phyric shergottite Y980459 yields CRE ages from the various cosmogenic nuclides that vary in the range of 1.1 to 2.9 Ma (Table 7). Ages based on ^{3}He (T_3) and ^{10}Be (T_{10}) are lower than those based on ^{21}Ne (T_{21}) and ^{38}Ar (T_{38}). Nishiizumi and Hillegonds (2004) obtained a ^{10}Be CRE age of 1.1 ± 0.2 Ma and interpreted the higher ^{21}Ne and ^{38}Ar ages to be due to (1) a pre-exposure on Mars before Y980459 was ejected or (2) an addition of solar cosmic-ray (SCR) produced nuclides. These authors observed a higher concentration of ^{26}Al in the near-surface sample indicating SCR exposure. Explanation (1) is supported by the presence of neutron produced ^{80}Kr as given in Table 8 and observed by Okazaki and Nagao (2004). ^{80}Kr$_n$ may have been produced under relatively high shielding conditions in the martian regolith, where also ^{21}Ne and ^{38}Ar were accumulated. The low ^{3}He CRE age may be explained by ^{3}He diffusion loss that, however, has not been observed for the other olivine-phyric shergottites Sayh al Uhaymir (Park *et al.*, 2001), Dar al Gani (Nyquist *et al.*, 2001), and NWA1068 (Mathew *et al.*, 2003). If such a pre-exposure on Mars

Table 4. Cosmogenic, trapped, and radiogenic He, Ne, and Ar ($10^{-8}cm^3STP/g$).

Meteorite	cosmogenic				trapped	radiogenic	
	^{3}He	^{21}Ne	^{38}Ar	^{22}Ne/^{21}Ne	^{36}Ar	^{4}He	^{40}Ar
Y980459,59	2.50 ±0.30	0.721 ±0.070	0.245 ±0.030	1.182 ±0.060	0.154 ±0.050	12.8 ±3.0	*
Y000593,103	17.1 ±0.7	2.04 ±0.30	2.36 ±0.30	1.225 ±0.030	0.30 ±0.10	846 ±30	< 1183
Y000749,61	20.3 ±0.8	2.04 ±0.10	2.55 ±0.30	1.237 ±0.030	0.29 ±0.10	680 ±25	< 128
NWA 1950	6.53 ±0.30	1.02 ±0.10	0.205 ±0.025	1.249 ±0.020	0.123 ±0.040	< 10	< 128.8

* see text.

Table 5. Cosmogenic Kr and Xe.

Meteorite	^{81}Kr	^{83}Kr	^{126}Xe	^{78}Kr/^{83}Kr	^{80}Kr/^{83}Kr	^{82}Kr/^{83}Kr	^{124}Xe/^{126}Xe	^{128}Xe/^{126}Xe
	$10^{-12}cm^3STP/g$							
Y980459,59	0.057 ±0.020	0.51 ±0.15	*	0.25 ±0.10	1.44 ±0.40	1.56 ±0.90	*	*
Y000593,103	0.074 ±0.015	4.74 ±1.0	0.46 ±0.14	0.21 ±0.03	0.57 ±0.12	0.78 ±0.40	*	1.8 ±0.6
Y000749,61	0.074 ±0.015	3.23 ±0.6	0.42 ±0.10	0.23 ±0.05	0.61 ±0.20	0.85 ±0.45	0.45 ±0.20	2.6 ±0.6

* Error > 60%.

Table 6. Chemical abundances (weight%) of elements relevant for this work.

	Ref	Na	Mg	Al	Si	K	Ca	Ti	Cr	Mn	Fe	Ni	Th ppm	U ppm
Y980459	[1, 2]	0.43	11.8	2.79	22.8	0.0175	4.38	0.32	0.51	0.39	13.8	0.0255	<0.1	<0.02
Y000593/749	[2–5]	0.48	6.45	1.03	22.4	0.133	10.2	0.268	0.186	0.42	16.6	0.01	0.225	0.056
NWA 1950	[6]	0.33	15.9	1.49	20.5	0.022	2.82	0.22	0.61	0.37	15.6	0.03	—	—

[1] Misawa (2003); [2] Dreibus *et al*. (2003); [3] Shirai *et al*. (2002); [4] Imae *et al*. (2003); [5] Oura *et al*. (2003); [6] average values for lherzolites ALHA77005, LEW 88516, and Y-793605 given by Meyer (2003).

Table 7. Production rates and CRE ages for the olivine-phyric shergottite Y980459, the paired nakhlites Y000593, Y000749, and Y000802, and the lherzolite NWA 1950.

	Production rates (10^{-8} cm^{3}STP / g, Ma)			CRE ages (Ma)						Ref.
	P_3	P_{21}	P_{38}	T_3	T_{21}	T_{38}	T_{81}	T_{10}	$T_{adopted}$	
Y980459 olivine-phyric shergottite	1.628	0.248	0.0980	1.54 ± 0.3	2.9 ± 0.4	2.5 ± 0.4	1.9 ± 0.8		–	[1]
				1.6	2.5	2.1	–		–	[2]
								1.1 ± 0.2	1.1 ± 0.2	[5]
Y000593 nakhlite	1.613	0.171	0.208	10.6 ± 1.6	12.0 ± 1.8	11.3 ± 1.7	10.8 ± 2.0		11.2 ± 1.2	[1]
				12.6	11.6	8.4	10.7		10.8	[3]
				10.3	13.5	8.8	–		10.9	[4]
Y000749 nakhlite	1.613	0.171	0.208	12.6 ± 1.9	12.0 ± 1.8	12.2 ± 1.8	(7.7) ± 2.0		12.3 ± 1.8	[1]
				12.3	11.9	8.6	–		10.9	[3]
Y000802 nakhlite				11.4	13.0	8.4	–		11.9	[3]
Average for all determinations of Y 00593/000749/000802									11.3 ± 0.4	
NWA 1950 lherzolite	1.588	0.194	0.0716	4.1 ± 0.6	5.3 ± 0.8	2.9 ± 0.4	–		4.1 ± 1.4	[1]

[1] This work; [2] Okazaki and Nagao (2004); [3] Okazaki *et al.*(2003); [4] Murty *et al.*(2003), average of two samples; [5] Nishiizumi and Hillegonds (2004).

Table 8. Neutron-induced ^{80}Kr, $^{80}Kr_n$, epithermal neutron fluxes, ϕ_n (30–300 eV), slowing down densities, q, and pre-atmospheric sizes.

Meteorite	$^{80}Kr_n$ 1) $10^{-12}cm^3STP/g$	Br 2) ppm	T_{av} 3) Ma	$P(^{80}Kr_n)$ $\frac{10^{-12}cm^3STP/g}{ppm\ Br \times Ma}$	ϕ_n(30-300eV) $ncm^{-2}s^{-1}$	q $ncm^{-3}s^{-1}$	R_{min} cm	ρ 4) gcm^{-3}	M_{min} kg
Y980459	0.48 ± 0.20	0.205	1.1	2.1 5)	5)	5)	5)	5)	5)
Y000593	0.37 ± 0.14	0.17	11.2	0.19	0.39	0.014	23	3.37	170
Y000749	0.37 ± 0.14	0.17	12.3	0.18	0.37	0.013	23	3.37	170

1) Assuming $(^{80}Kr/^{83}Kr)_{sp} = 0.495$; 2) Dreibus *et al.* (2003); 3) from Table 7; 4) for densities ρ see Eugster *et al.* (2002); 5) calculation not meaningful, see text.

occurred more than a few Ma ago ^{10}Be with its half-life of 1.6 Ma would not be affected by it and the ^{10}Be CRE age would yield a reliable Mars-Earth transfer time. Nuclides produced by SCRs (explanation 2) could have been accumulated in free space. T_{21} and T_{38} are much more sensitive to SCRs than T_3 and T_{10} (Hohenberg *et al.*, 1978; Graf *et al.*, 1990). Consequently, T_{21} and T_{38} would yield too high CRE ages. We conclude that the ^{10}Be based CRE age of 1.1±0.2 Ma (Nishiizumi and Hillegonds, 2004) is, in the case of Y980459, the most reliable age. The ^{81}Kr-^{83}Kr age (T_{81}) of 1.9±0.8 Ma given in Table 7 agrees within experimental errors with T_{10}. As the terrestrial age of Y980459 has not been determined it is possible that T_{81} is enhanced as a result of ^{81}Kr decay on Earth.

The two paired nakhlites specimens Y000593 and Y000749 studied in this work yield average CRE ages of 11.2±1.2 Ma and 12.3±1.8 Ma, respectively. Our ages are close to those obtained by other workers. We conclude that the three paired specimens of the Yamato nakhlite yield the same Mars ejection time as the previously known nakhlites Governador Valadares, 10.0±2.1 Ma, Lafayette, 11.9±2.2 Ma, and Nakhla, 10.75±0.40 Ma (Nyquist *et al.*, 2001).

For lherzolite NWA1950 we obtain an average CRE age of 4.1±1.4 Ma. This age is within the range of the CRE ages of the other dated lherzolites of 2.9 to 4.7 Ma (Nyquist *et al.*, 2001). NWA1950 is also similar to the previously analyzed lherzolites (cf. Terribilini *et al.*, 1998; Eugster *et al.*, 2002) in other characteristics: $(^{22}Ne/^{21}Ne)_c$ of 1.249 is within the range of 1.207 to 1.29 for ALHA77005, LEW88516, and Y-793605 and the $^{36}Ar_{tr}$ concentration of $0.123 \times 10^{-8} cm^3STP/g$ is similar to that of Y-793605 ($0.187 \times 10^{-8} cm^3STP/g$, Terribilini *et al.*, 1998).

5. Mars ejection times

For calculating the ejection time, T_{ej}, we have to add the terrestrial age, T_{terr}, to the CRE age. T_{terr} for Y980459 and NWA1950 is not known but generally for martian meteorites a $T_{terr} < 0.3$ Ma was observed (Eugster *et al.*, 2002). Nishiizumi and Hillegonds (2004) reported for Y000593/00749/000802 a T_{terr} of 0.055±0.020 Ma. For the meteorites studied in this work we adopt ejection times that are identical to the CRE ages ($T_{adopted}$, Table 7) and obtain for the olivine-phyric shergottite Y980459, the paired nakhlites, and the lherzolite NWA1950 average ejection ages of 1.1±0.2 Ma, 11.3 ±0.4 Ma, and 4.1±1.4 Ma, respectively.

Figure 1 demonstrates the ejection ages of the martian meteorites that were dated until now. In the figure caption we give the references for the CRE ages. We conclude that the following ejection times for the different types of martian meteorites can be distinguished. The first event occurred when DHO 019, a olivine-phyric shergottite, was ejected 19.8±2.3 Ma ago. ALH 84001, the only orthopyroxenite, was ejected 14.7±0.9 Ma ago. Chassigny (11.3±0.6 Ma) and the nakhlites (average T_{ej} = 10.8±0.7 Ma) differ strongly in their mineralogy but may have been ejected in the same event. The lherzolites (average T_{ej} = 4.1±0.4 Ma) were followed by the basaltic shergottites (average T_{ej} = 2.8±0.3 Ma). Another impact occurred 1.16±0.06 Ma into an area of olivine-phyric composition. Finally, 0.73±0.15 Ma ago the unique olivine-phyric/basaltic shergottite EETA79001 was ejected. If we take these average ejection times at face value, we conclude that the presently dated martian meteorites represent seven different source areas. If Chassigny and the mineralogically strongly differing nakhlites were produced by different events, we observe eight impact events on Mars.

Model calculations for the transfer times of rocks ejected from Mars are essentially in agreement with the observed CRE ages for material ejected slightly above escape velocity of 5 km/s. Gladman *et al.* (1996) found that 95% of all ejected rocks reach Earth within 20 Ma and only about 20% are expected to have CRE ages < 1Ma. In contrast to lunar meteorites (*cf.* Vogt *et al.*, 1991) no clear evidence for a complex exposure history has been observed for martian meteorites. If the impacts on Mars are occurring at intervals of a few Ma, as indicated by the CRE ages, the impactors are likely of the order of kilometers (Gladman, 1997). Consequently, the resulting craters must be considerably larger than kilometers in size. Thus, most ejected rocks originate from more than a few meters depth and did not experience a pre-exposure to cosmic rays on Mars. The size of the ejected rocks from such impacts is estimated to be in a range of 20–200 cm (Artemieva and Ivanov, 2002; Eugster *et al.*, 2002). The number of martian meteoroids from an impact event must be enormous and source crater pairing of specimens collected on Earth is not surprising.

6. Neutron induced ^{80}Kr

The concentrations and isotopic ratios of cosmogenic Kr are given in Table 5. Adopting a ratio $^{80}Kr/^{83}Kr = 0.495$ for spallation produced Kr (Marti *et al.*, 1966) we obtain the concentration of $^{80}K_{rn}$ that was produced by neutron capture of ^{79}Br (Table 8). The calculation of $^{82}Kr_n$ from ^{81}Br is not meaningful because the experimental error is $>100\%$. The $^{80}Kr_n$ concentration is a measure for the pre-atmospheric size of the meteoroid, if $^{80}Kr_n$ was produced in situ during the time the meteoroid was exposed to cosmic rays in free space. Other possibilities to explain an excess of $^{80}Kr_n$ are a pre-exposure to cosmic rays on Mars before ejection of the meteorite or trapping of martian atmospheric $^{80}Kr_n$. However, as Nishiizumi and Hillegonds (2004) state, a pre-exposure for martian meteorites has not yet been observed and Rao *et al.* (2002) point out that other nakhlites did not acquire $^{80}Kr_n$ via trapping of martian atmospheric Kr. Therefore, we consider the $^{80}Kr_n$ in the Y000593 and Y000749 nakhlites to be *in situ* produced during the Mars-Earth transfer. Following the procedure outlined by Eugster *et al.* (2002) we derive the pre-atmospheric size of these two samples and obtain a radius, adopting spherical shape, of >23 cm (Table 8). Nakhlites have a density of about 3.37 g/cm^3 as estimated from their mineralogical composition. Consequently their pre-atmospheric mass was >170 kg. This lower limit for their mass is in the typical range for martian meteorites.

For Y980459 we come to a different conclusion. In the discussion of the CRE ages obtained from various cosmogenic nuclides we have shown that this meteorite contains a component of cosmogenic isotopes produced by solar cosmic rays. As their penetration depth in extraterrestrial matter is of the order of a few cm (*cf.* Hohenberg *et al.*, 1978) our sample of Y980459 must originate from a small meteoroid or from a location close to the pre-atmospheric surface. However, as shown in Table 8, a relatively large production rate for $^{80}Kr_n$ would result from a CRE age of 1.1 Ma and the measured concentrations of $^{80}Kr_n$ and ^{79}Br. This would indicate that the sample originates from a location several tens of centimeters within the meteoroids. The contradiction can only be understood if we assume that the Y980459 material trapped most of its $^{80}Kr_n$ from the martian atmosphere in a similar way as observed for EETA79001 (Rao *et al.*, 2002). This conclusion is supported by the presence of ^{40}Ar from the martian atmosphere: adopting a crystallization age of 304 Ma for Y980459 (Shih *et al.*, 2003) and a K concentration of 0.0175% (Table 6) we calculate 22.5×10^{-8}cm^{3}STP/g radiogenic ^{40}Ar. As this meteorite contains 93.4×10^{-8}cm^{3}STP/g ^{40}Ar (Table 1), 71×10^{-8}cm^{3}ST/g ^{40}Ar must originate from trapped martian atmospheric gases. Thus, it is reasonable to assume that part of $^{80}Kr_n$ is also trapped gas from the martian crust and a calculation of a pre-atmospheric size for Y980459 from our data is not meaningful. In their temperature release experiment with six temperature steps Okazaki and Nagao (2004) could show that excess of $^{80}Kr_n$ and $^{82}Kr_n$ relative to spallation Kr are pronounced in the higher temperature fractions. These authors estimated the minimum radius for the Y980459 meteoroid to have been 27 cm.

7. Conclusions

The Mars ejection times for the investigated meteorites are essentially identical to the CRE ages, as the terrestrial ages are negligible compared to the CRE ages and pre-exposure on Mars was not observed. For the olivine-phyric shergottite Y980459 we consider the ^{10}Be age of 1.1 Ma to be the most reliable CRE age because the ^{21}Ne and ^{38}Ar based CRE ages appear to be enhanced due to an addition of a solar cosmic-ray produced component. This age is in agreement with the Mars ejection times of four other olivine-phyric shergottites. The paired nakhlite specimens Y000593 and Y000749 yield Mars ejection times of 11.2 Ma and 12.3 Ma, respectively, similar to those observed for four nakhlites dated earlier. NWA1950 is the fourth lherzolite dated until now. It yields a Mars ejection age of 4.1 Ma. This is within the range of 3.8–4.7 Ma obtained for the other meteorites of this type. Taking all dated martian meteorites into account we conclude that they were ejected by up to eight impact events on Mars. Each event produced one specific type of meteorite that represents the geologic characteristics of the source area. If Chassigny and the nakhlites were ejected by the same impact at a mineralogically heterogeneous area, the number of events is reduced to seven.

The olivine-phyric shergottite Y980459 contains neutron induced ^{80}Kr from the reaction ^{79}Br (n, $\gamma\beta$) ^{80}Kr. We conclude that most of $^{80}Kr_n$ was not produced in situ during Mars-Earth transfer. Most of this Kr component was acquired, along with ^{40}Ar from K decay, by the meteoritic matter on the martian surface. These gases originate from outgassing of the martian crust. On the other hand, the nakhlites Y000593 and Y000759 do not contain martian atmospheric $^{80}Kr_n$. The observed concentration of this nuclide was induced by secondary cosmic-ray produced neutron capture of ^{79}Br in free space. For the parent meteoroid of these two specimens we calculate a minimum pre-atmospheric mass of 170 kg.

Acknowledgments

We thank the National Institute of Polar Research in Tokyo for the samples of Y980459, Y000593, and Y000749. Constructive comments by the reviewers D. Bogard and R. Okazaki greatly improved the manuscript. Technical support by H. E. Jenni, A. Schaller, and H. Lüthi is gratefully acknowledged. We are indebted to A. Chaoui for her help in preparing the manuscript.

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