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Noble gases of Yamato 980459 shergottite

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Abstract: Isotopic ratios and concentrations of noble gases were determined for the Yamato (Y) 980459 olivine-phyric shergottite with a stepped heating extraction method. Trapped noble gas concentrations are low, and especially He and Ne are dominated by cosmogenic nuclides. Heavy noble gases, Ar, Kr and Xe, in the high temperature fractions (1000–1750℃) show the martian atmospheric signatures: $^{40}Ar/^{36}Ar$ and $^{129}Xe/^{132}Xe$ ratios corrected for cosmogenic gases are >1000 and >1.4, respectively, and the data points plot along the mixing line between the Mars atmosphere and Chassigny in the system of $^{129}Xe/^{132}Xe$ *vs*. $^{84}Kr/^{132}Xe$. Contribution of elementally fractionated Earth's atmospheric noble gases is significant in the low temperature fractions (400–800℃), which has been frequently reported for meteorites from hot deserts. Cosmic-ray exposure ages calculated based on cosmogenic ^{3}He, ^{21}Ne and ^{38}Ar are 1.6, 2.5 and 2.1 Ma, respectively. Considering partial loss of He from the meteorite, the exposure age of Y980459 would be around 2.1–2.5 Ma. Though the terrestrial age of this meteorite has not been reported so far, the ages reported for Antarctic SNCs are ≤ 0.29 Ma. Hence, the ejection age for Y980459 could be in the range of 2.1–2.8 Ma, which is comparable to those of some basaltic shergottites, but different from other olivine-phyric shergottites ranging mostly 0.7–1.2 Ma. Isotopic ratios of Kr show excesses in ^{80}Kr and ^{82}Kr, with $^{82}Kr/^{80}Kr$ of 0.375, which results from epithermal neutron captures on ^{79}Br and ^{81}Br. The minimum pre-atmospheric size of Y980459 was calculated as 27 cm in radius, based on the ^{21}Ne exposure age and the n-capture ^{80}Kr and Br concentrations of 3.0×10^{-13} cm^{3}STP/g and 0.205 ppm, respectively. The calculated K-Ar age is 0.99 Ga from the total ^{40}Ar and reported K concentration of 157 ppm. The age, however, gives an upper limit for the crystallization age of this meteorite, because of possible contribution of martian atmospheric Ar, as well as the terrestrial atmosphere.

key words: Martian meteorite, noble gases, cosmic ray exposure, shergottite, Y980459

1. Introduction

Yamato (Y) 980459 shergottite was discovered as a small single stone weighing 82.46 g at the bare ice field around the Yamato Mountains (Kojima and Imae, 2002; Misawa, 2003) located at the 350 km south of Syowa Station (Kojima *et al*., 2000). In this area, the most meteorites have been collected (*e.g*., Kojima *et al*., 2000). The meteorite shows basaltic texture and is mainly composed of olivine, clinopyroxene and glass (Kojima and Imae, 2002). Most of the olivine in Y980459 is phenocryst and the textural and petrographic features resemble those of olivine-phyric shergottites, such as EETA 79001 lithology A, DaG 476, Dho 019, NWA 1068, NWA 1195, and SaU 005 (Misawa, 2003, 2004). Absence of plagioclase and maskelynite is a unique feature of this meteorite (*e.g.*, Misawa, 2003; Mikouchi *et al.*, 2004; Greshake *et al.*, 2003).

As a part of the consortium study on the Y980459 shergottite (Misawa, 2003, 2004), we present noble gas isotopic compositions to confirm its martian origin, estimate cosmic-ray exposure (CRE), K-Ar ages and the pre-atmospheric size, and compare with other martian meteorites previously reported.

2. Experimental procedure

A Y980459 bulk sample, weighing 146.6 mg, for noble gas measurement was cut from a block to reserve the rest of the provided sample. The sample wrapped with 10 μm thick Al-foil was put in a side arm of the sample holder, which is connected to an extraction furnace. The sample holder and purification line were heated overnight at 150 and 300°C, respectively, under ultrahigh vacuum condition to remove atmospheric contamination in advance of the measurement. Noble gases were extracted by heating the sample in a Mo crucible of the extraction furnace stepwise at the temperatures of 400, 600, 800, 1000, 1300 and 1750°C. The heating durations are 30 and 20 min for the 400–1000 and 1300–1750°C fractions, respectively. Evolved gases were purified with two Ti-Zr getters and two SAES getters. Helium and Ne were separated from other heavier noble gases by adsorbing Ar, Kr and Xe on a charcoal trap kept at the liquid nitrogen temperature (77 K), and introduced into a noble gas mass spectrometer (modified VG5400/MS-II) for isotope analyses. After the He and Ne measurements, Ar, Kr and Xe were released from the charcoal trap by heating it. Krypton and Xe were trapped on a cryogenically cooled sintered stainless steel trap at the temperature of 105 K, and then Ar was measured. Isotope abundances of Kr and Xe were measured separately by releasing them from the steel trap at the temperatures of 150 and 220 K, respectively.

Sensitivities and mass discrimination correction factors were determined by measuring known amount of the atmosphere (*ca.* 5×10^{-4} cm^{3}STP) and a ^{3}He and ^{4}He mixture with ^{3}He/^{4}He$=1.71\times10^{-4}$. Prior to the sample measurements, blank gases were measured at 1000 and 1750°C following the same procedure as for the sample. Gas amounts of the two blank measurements were within the narrow range of 8–9 $\times10^{-10}$ (^{4}He), 2.5×10^{-12} (^{20}Ne), 6–8$\times10^{-10}$ (^{40}Ar), 2×10^{-14} (^{84}Kr) and 4×10^{-15} (^{132}Xe) in the unit of cm^{3}STP. The blank gases contribute less than 8%, except for ^{4}He (400, 600, 1000, 1300 and 1750°C fractions) and ^{40}Ar (600°C fraction).

3. Results and discussion

Isotopic ratios of noble gases and concentrations of representative isotopes are presented in Tables 1, 2 and 3. The data have been corrected for the blanks noted above. Presented errors for isotopic ratios are statistical 1σ, and uncertainties for the

Table 1. He, Ne and Ar isotopic ratios and noble gas concentrations of Y980459 shergottite.

Temp.	$^{4}He^{\#}$	$^{3}He/^{4}He$	$^{22}Ne^{\#}$	$^{20}Ne/^{22}Ne$	$^{21}Ne/^{22}Ne$	$^{36}Ar^{\#}$	$^{38}Ar/^{36}Ar$	$^{40}Ar/^{36}Ar$
400 ºC	23.4	0.210 ± 0.016	0.144	3.107 ± 0.049	0.5420 ± 0.0075	0.369	0.19325 ± 0.00053	303.35 ± 0.52
600 ºC	41.8	0.1622 ± 0.0069	0.210	0.903 ± 0.025	0.7003 ± 0.0043	0.0333	0.279 ± 0.015	393 ± 18
800 ºC	121	0.1187 ± 0.0018	2.11	0.8058 ± 0.0056	0.801 ± 0.013	0.351	0.6010 ± 0.0069	632.6 ± 5.8
1000 ºC	7.25	0.131 ± 0.032	3.24	0.8233 ± 0.0026	0.8155 ± 0.0054	0.317	0.914 ± 0.013	509.8 ± 4.2
1300 ºC		ND	1.19	0.8557 ± 0.0056	0.8247 ± 0.0021	0.287	1.206 ± 0.018	258.41 ± 0.63
1750 ºC		ND	2.13	0.8695 ± 0.0046	0.8256 ± 0.0027	1.13	1.2775 ± 0.0050	191.98 ± 0.50
	193	0.1397	9.03	0.8726	0.8087	2.48	0.9525	322

He, Ne, and Ar concentrations in 10^{-9} cm^{3}STP/g.

Table 2. Kr isotope ratios of Y980459 shergottite.

Temp.	$^{84}Kr^{\#}$	$^{78}Kr/^{84}Kr$	$^{80}Kr/^{84}Kr$	$^{82}Kr/^{84}Kr$	$^{83}Kr/^{84}Kr$	$^{86}Kr/^{84}Kr$
400 ºC	38.6	0.00598 ± 0.00029	0.03958 ± 0.00078	0.2005 ± 0.0011	0.2018 ± 0.0020	0.3062 ± 0.0024
600 ºC	3.94	0.00555 ± 0.00074	0.0404 ± 0.0029	0.2010 ± 0.0058	0.1972 ± 0.0081	0.3040 ± 0.0087
800 ºC	3.24	0.00704 ± 0.00096	0.0561 ± 0.0016	0.2176 ± 0.0096	0.2101 ± 0.0062	0.3049 ± 0.0095
1000 ºC	2.62	0.01012 ± 0.00088	0.0810 ± 0.0022	0.2284 ± 0.0089	0.2264 ± 0.0037	0.298 ± 0.010
1300 ºC	2.14	0.0117 ± 0.0018	0.0789 ± 0.0059	0.2339 ± 0.0097	0.2370 ± 0.0087	0.296 ± 0.012
1750 ºC	7.72	0.01303 ± 0.00082	0.0841 ± 0.0016	0.2400 ± 0.0048	0.2389 ± 0.0041	0.2951 ± 0.0062
total	58.3	0.00734	0.0498	0.2092	0.2093	0.3038

Concentration in 10^{-12} cm^{3}STP/g.

Table 3. Xe isotope ratios of Y980459 shergottite.

Temp.	$^{132}Xe^{\#}$	$^{124}Xe/^{132}Xe$	$^{126}Xe/^{132}Xe$	$^{128}Xe/^{132}Xe$	$^{129}Xe/^{132}Xe$	$^{130}Xe/^{132}Xe$	$^{131}Xe/^{132}Xe$	$^{134}Xe/^{132}Xe$	$^{136}Xe/^{132}Xe$
400 ºC	10.2	0.00349 ± 0.00044	0.00345 ± 0.00032	0.0711 ± 0.0020	0.9774 ± 0.0085	0.1501 ± 0.0022	0.7891 ± 0.0058	0.3882 ± 0.0073	0.3269 ± 0.0030
600 ºC	3.27	0.0041 ± 0.0015	0.00305 ± 0.00020	0.0693 ± 0.0036	0.990 ± 0.018	0.1519 ± 0.0028	0.787 ± 0.011	0.388 ± 0.010	0.3286 ± 0.0043
800 ºC	2.15	0.0045 ± 0.0024	0.00331 ± 0.00046	0.0721 ± 0.0035	1.017 ± 0.041	0.1476 ± 0.0071	0.795 ± 0.019	0.3917 ± 0.0089	0.334 ± 0.013
1000 ºC	0.366	ND	0.0053 ± 0.0024	0.077 ± 0.010	1.474 ± 0.069	0.152 ± 0.018	0.787 ± 0.064	0.383 ± 0.048	0.331 ± 0.020
1300 ºC	0.293	0.026 ± 0.012	0.0074 ± 0.0032	0.0744 ± 0.0059	1.471 ± 0.083	0.159 ± 0.019	0.828 ± 0.046	0.386 ± 0.037	0.334 ± 0.025
1750 ºC	0.984	0.0143 ± 0.0040	0.0104 ± 0.0010	0.0842 ± 0.0080	1.390 ± 0.030	0.160 ± 0.014	0.806 ± 0.029	0.395 ± 0.020	0.335 ± 0.016
total	17.2	0.0048	0.0039	0.0718	1.027	0.1509	0.791	0.3888	0.3287

Concentration in 10^{-12} cm^{3}STP/g.

noble gas concentrations are estimated as $\leq 10\%$ based on the reproducibility of the measured sensitivities. Concentrations of cosmogenic (c) and trapped (t) noble gases in Tables 4 and 5, respectively, were calculated using the following isotope ratios for the end members: terrestrial atmospheric $(^{21}Ne/^{22}Ne)_t = 0.029$; $(^{38}Ar/^{36}Ar)_t = 0.188$; $(^{126}Xe/^{130}Xe)_t = 0.0218$ (Ozima and Podosek, 2002), $(^{21}Ne/^{22}Ne)_c = 0.70$ (600°C fraction: Table 1), $(^{38}Ar/^{36}Ar)_c = 1.5$ (typical value: *e.g.*, Smith *et al.*, 1977), and cosmogenic Xe isotopes of the Stannern Eucrite (Marti *et al.*, 1966). In the calculation, the ^{21}Ne released at 800–1750°C and all of the measured ^{3}He were considered cosmogenic. The terrestrial atmosphere values were assumed for $(^{38}Ar/^{36}Ar)_t$ and $(^{126}Xe/^{130}Xe)_t$, because at 400 and 600°C terrestrial atmosphere contribution was observed. The assumed $(^{38}Ar/^{36}Ar)_t$ of 0.188 is lower than that for the martian atmosphere (0.244: Pepin, 1991) and could result in overestimate of $[^{38}Ar]_c$. The difference in the $^{126}Xe/^{130}Xe$ ratio between the terrestrial and Mars atmospheres (0.0212; Pepin, 1991) is not critical for calculating the trapped Xe isotopic ratios. Trapped noble gas concentrations are generally low, and cosmogenic nuclides are dominant especially in He and Ne. In the following, we will discuss the ejection age, the heavy trapped noble gas compositions, and the K-Ar age of Y980459. The pre-atmospheric size of Y980459 is also estimated based on excesses in ^{80}Kr and ^{82}Kr, which are produced by neutron captures on ^{79}Br and ^{81}Br, respectively.

3.1. *Cosmogenic ^{3}He, ^{21}Ne and ^{38}Ar concentrations and the ejection age*

Neon isotopic ratios plotted in Fig. 1 show atmospheric contamination in the lowest temperature (400°C) fraction. The low $(^{21}Ne/^{22}Ne)_c$ ratio (*ca.* 0.7) observed at 600 °C would be released from in Na-rich phases (Smith and Huneke, 1975) as reported in Antarctic nakhlites (Okazaki *et al.*, 2003). Unlike the Antarctic nakhlites and other shergottites, Y980459 does not contain any plagioclase (Greshake *et al.*, 2003; Mikouchi *et al.*, 2004), but about 2 wt% Na_2O in mesostasis glass (25% modal abundance) has been reported (Mikouchi *et al.*, 2004; Ikeda, 2004). Hence, a Na-rich phase in Y980459 could be the glassy mesostasis. Higher solar cosmic ray (SCR) contribution relative to galactic cosmic ray (GCR) is unlikely as a reason for the low $^{21}Ne/^{22}Ne$, because SCR effects can be confined to the outer few cm (Caffee *et al.*, 1988) that would be ablated during the entry to the Earth atmosphere in a case for a typical-sized (*ca.* 50 cm in diameter) meteoroid (ReVelle, 1979). The GCR spallation under low shielding conditions probably demands a complex exposure history for Y980459, because excesses at $^{80,82}Kr$ were observed (see Section 3.2), which is explained by neutron capture effects under relatively high shielding condition. Measurements for short-lived nuclides in this meteorite are necessary to reveal the exposure history. In the following discussion, we don't consider the case of complex exposures.

In contrast to the lower temperature fractions, the elevated $^{21}Ne/^{22}Ne$ ratios (0.80–0.83) were observed in the higher temperatures (≥ 800°C), which are plausibly derived from olivine and pyroxene. Indigenous trapped Ne could not be identified in this meteorite. Accordingly, this suggests that trapped component of He is scarce or absent.

Concentrations and production rates of cosmogenic ^{3}He, ^{21}Ne and ^{38}Ar, and calculated CRE ages are listed in Table 4. The production rates were calculated using

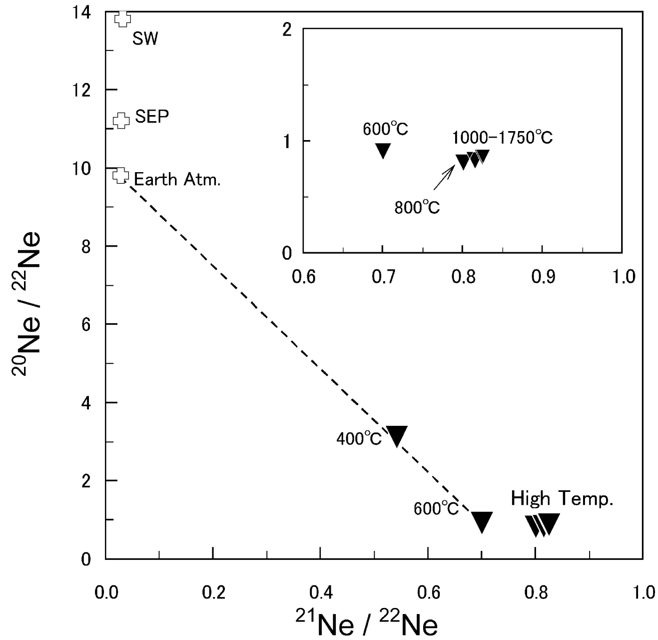


Fig. 1. Three isotope plot of Ne. Isotopes are dominated by cosmogenic Ne except for the lowest temperature of 400℃, where adsorbed terrestrial atmospheric Ne was released. In the fraction of 600℃, $^{21}Ne/^{22}Ne$ ratio is low compared with those of higher temperature fractions. Data for solar wind (SW) and solar energetic particles (SEPs) are from Benkert et al. (1993), while the Earth's atmosphere Ne is from Ozima and Podosek (2002).

Table 4. Cosmogenic ^{3}He, ^{21}Ne and ^{38}Ar concentrations and cosmic-ray exposure ages.

$^{3}He_c$	$^{21}Ne_c$	$^{38}Ar_c$	P_3^*	P_{21}^*	P_{38}^*	T_3	T_{21}	T_{38}
(10^{-10} cm^3/g)			(10^{-10} cm^3/g/Ma)			(Ma)		
270	72.9	21.7	166	28.9	10.1	1.6	2.5	2.1

* Production rates have been corrected for target element compositions and shielding condition.

the formula for eucrites by Eugster and Michel (1995) and the bulk chemical compositions presented in Misawa (2003, 2004). For the correction of the shielding condition, we applied $(^{21}Ne/^{22}Ne)_c = 0.826$ (the 1750℃ fraction: Table 1). The CRE ages calculated based on the cosmogenic ^{3}He, ^{21}Ne and ^{38}Ar are 1.6, 2.5 and 2.1 Ma, respectively. Considering potential partial loss of He from the meteorite, the CRE age of Y980459 would be around 2.1–2.5 Ma. Though the actual terrestrial age of this meteorite has not been determined, the ages for Antarctic SNCs reported so far range 0.007–0.29 Ma (Eugster *et al.*, 2002). From the calculated CRE age and expected terrestrial age, the ejection age for Y980459 would be in the range of 2.1–2.8 Ma.

As shown in Fig. 2, the ejection age of Y980459 is not in agreement with any other olivine-phyric shergottites; *i.e.*, EET 79001, SaU 005/094 and DaG 476/489/670/735/

876 show distinctly young ejection ages (0.7–1.2 Ma: Eugster *et al.*, 2002; Marty *et al.*, 2001; Nyquist *et al.*, 2001) and Dho 019 has the oldest one among the martian meteorites (20 Ma: Shukolyukov *et al.*, 2002). In contrast, the ejection age of Y980459 is comparable to those for basaltic shergottites, Shergotty (3.0±0.3 Ma: Eugster *et al.*, 2002), Zagami (3.0±0.3 Ma: Eugster *et al.*, 2002), NWA 480 (2.4±0.3 Ma: Marty *et al.*, 2001), Los Angeles (3.0±0.3 Ma: Eugster *et al.*, 2002) and QUE 94201 (2.8±0.3 Ma: Eugster *et al.*, 2002).

Source crater pairing has been discussed based on the concordance between ejection and crystallization ages (Nyquist *et al.*, 2001). Crystallization ages for olivine-phyric shergottites are diverse: 172±18 Ma (Rb-Sr) for EETA79001 lithology A (Nyquist *et al.*, 1986), 474±11 Ma (Sm-Nd) for DaG 476 (Borg *et al.*, 2000), 575±7 Ma (Sm-Nd) for Dho 019 (Borg *et al.*, 2001). Basaltic shergottites are in a relatively small range around 170 Ma (Nyquist *et al.*, 2001), except for QUE 94201 (327 Ma: Borg *et al.*, 1997). Hence, the relation between petrographic classification and ejection and crystallization ages suggests that each olivine-phyric shergottite might have originated from different source craters.

It is expected that Y980459 was ejected by an impact event, which was different from the event(s) ejected basaltic shergottites occurred within a short period. Alternatively, a large-scale impact might have excavated the Y980459 olivine-phyric shergottite along with basaltic shergottites. According to the model calculation on the

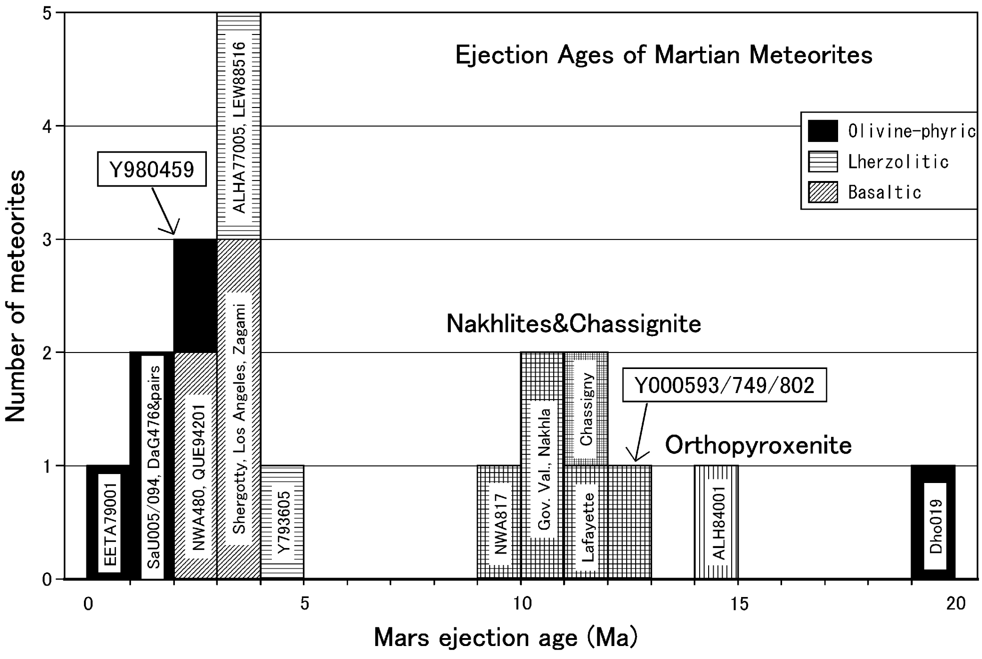


Fig. 2. Histogram of ejection ages for martian meteorites. The Y980459 is in the group of basaltic shergottites with ejection ages of 2–3 Ma, not in the olivine-phyric shergottite range (mostly 0.7–1.2 Ma). Data sources: Eugster et al. (2002); Marty et al. (2001); Nyquist et al. (2001); Okazaki et al. (2003); Shukolyukov et al. (2002).

mean sizes and ejecta frequencies (Mileikowsky *et al.*, 2000), 2 and 1 ejection events producing fragments of 15 and 30 cm mean radius, respectively, are expected within 3 Ma (the basaltic shergottite CRE duration). Thus, the pre-atmospheric size of 27 cm calculated for Y980459 (see below) seems to be preferable to the latter case of a single impact event ejecting Y980459.

3.2. *Neutron-capture effect and pre-atmospheric size*

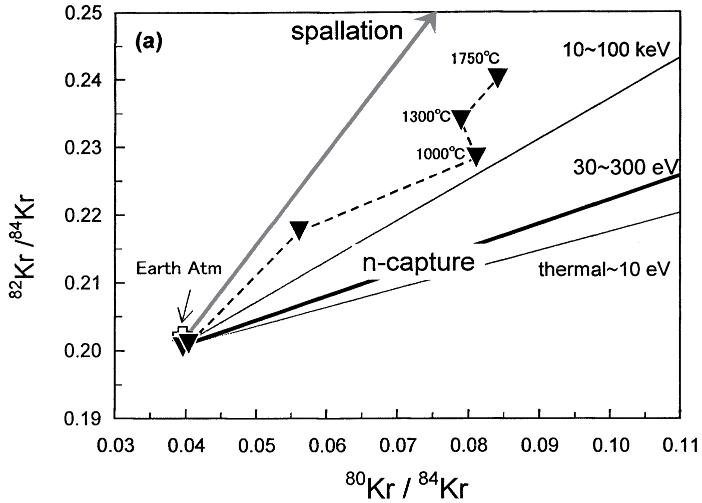
As shown in Fig. 3a, Y980459 has excesses in ^{80}Kr and ^{82}Kr, which can be explained by neutron capture (shown in subscript "n") on Br. We calculated the concentration of $[^{80}\mathrm{Kr}]_n$ and $(^{82}\mathrm{Kr}/^{80}\mathrm{Kr})_n$ ratio as 3.0×10^{-13} cm^{3}STP/g and 0.375, respectively, by subtracting spallogenic and trapped ^{80}Kr and ^{82}Kr from the measured values. In the calculation, spallogenic ^{78}Kr/^{83}Kr was estimated as 0.151 from the regression line (Fig. 3b) for $(^{86}\mathrm{Kr}/^{83}\mathrm{Kr})_s=0.0152$ (Marti and Lugmair, 1971), while $(^{78}\mathrm{Kr}/^{83}\mathrm{Kr})_t$ of 0.0281 (determined in the 600°C fraction) was assumed. We also assumed isotopic ratios for trapped (t) and spallogenic (s) components: $(^{80}\mathrm{Kr}/^{82}\mathrm{Kr}/^{83}\mathrm{Kr})_t=0.1967/1.004/1$ (Earth's atmosphere), $(^{80}\mathrm{Kr}/^{82}\mathrm{Kr}/^{83}\mathrm{Kr})_s=0.495/0.765/1$ (Marti *et al.*, 1966). The calculated $(^{82}\mathrm{Kr}/^{80}\mathrm{Kr})_n$ of 0.375 is close to the theoretical production ratio for epithermal neutron captures on Br of 0.38 (Marti *et al.*, 1966). According to the calculation method of Eugster *et al.* (2002), we estimated the minimum radius for the Y980459 meteoroid to be 27 cm. In the calculation, we assumed that the excess $^{80,\,82}$Kr result from exposures to cosmic rays during the Mars-Earth transfer. The ^{21}Ne exposure age of 2.5 Ma and Br concentration of 0.205 ppm (Dreibus *et al.*, 2003) were applied. The minimum radius of 27 cm corresponds to 270 kg using the density of 3.25 g/cm^3 for Y980459 estimated from the mineral modal abundance and mineral chemistry (Mikouchi *et al.*, 2004). The pre-atmospheric size for Y980459 is the largest so far among shergottites (22–25 cm corresponding to 150–220 kg: Eugster *et al.*, 2002).

3.3. *Trapped noble gases*

Concentrations of trapped heavy noble gases ^{36}Ar, ^{84}Kr and ^{132}Xe, and isotopic ratios of ^{40}Ar/^{36}Ar, ^{129}Xe/^{132}Xe, ^{129}Xe/^{130}Xe and ^{136}Xe/^{130}Xe are presented in Table 5. Contribution of cosmogenic ^{36}Ar is corrected both in the ^{36}Ar concentration and ^{40}Ar/^{36}Ar. Corrections of cosmogenic ^{84}Kr and ^{132}Xe were not applied for ^{84}Kr and ^{132}Xe concentrations because of the negligible contribution, while the Xe isotopic ratios have been corrected for cosmogenic isotopes.

The system of $(^{36}\mathrm{Ar}/^{132}\mathrm{Xe})_t$ versus $(^{84}\mathrm{Kr}/^{132}\mathrm{Xe})_t$ (Fig. 4) shows that the data plot along the trend line through the Earth and Mars atmospheres, SNCs and HEDs, while chondrite clans show a different trend (Busemann *et al.*, 2000; Okazaki *et al.*, 2001). Though the plot scatters in a wide area, the trend observed in Y980459 is consistent with its martian origin as observed in the high temperature fractions (1000–1750°C).

The plot of $(^{129}\mathrm{Xe}/^{132}\mathrm{Xe})_t$ *versus* $(^{84}\mathrm{Kr}/^{132}\mathrm{Xe})_t$ (Fig. 5) shows that Earth's atmospheric noble gases adsorbed on this meteorite are released at the lowest temperature (400°C), which is consistent with the Ne isotopes (Fig. 1). In the high temperatures (1000, 1300 and 1750°C), the martian atmospheric noble gas signature is observed as the data points plot along the mixing line between those of Chassigny and the Martian atmosphere. This trend is one of characteristics for shergottites as pointed out in many



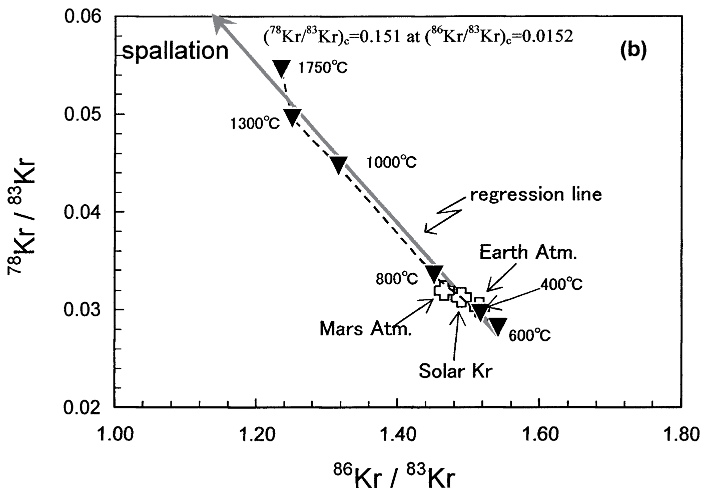


Fig. 3. Isotopic ratios of Kr for Y980459. Excesses in ^{80}Kr and ^{82}Kr relative to spallogenic Kr are pronounced in the higher temperature fractions (a), which result from neutron-capture reactions on ^{79}Br and ^{80}Br. The spallation and n-capture Kr compositions are from Marti et al. (1966). The plot of ^{86}Kr/^{83}Kr vs. ^{78}Kr/^{83}Kr shows these three isotopes can be explained by mixing between spallogenic and trapped components (b). Spallogenic ^{78}Kr/^{83}Kr ratio was calculated assuming (^{86}Kr/^{83}Kr)$_s$=0.0152 (Marti and Lugmair, 1971). Data sources: Solar Kr (Kr-1: Pepin, 1991); Mars atmosphere (Eugster et al., 2002); Earth atmosphere (Ozima and Podosek, 2002).

previous reports (*e.g.*, Ott, 1988; Bogard and Garrison, 1998; Bogard *et al.*, 2001). The shergottite line is distinct from the nakhlite line, for which noble gas compositions are plotted between Chassigny and "elementally fractionated martian atmosphere". This noble gas signature is consistent with the petrographic classification of the Y980459

Table 5. Concentrations[1], elemental ratios and isotopic ratios of trapped noble gases in Y980459 shergottite.

Temp.	$[^{36}Ar]_t$	$[^{84}Kr]_t$ [2]	$[^{132}Xe]_t$ [2]	$(^{36}Ar/^{132}Xe)_t$	$(^{84}Kr/^{132}Xe)_t$	$^{40}Ar/(^{36}Ar)_t$ [3]	$(^{129}Xe/^{132}Xe)_t$	$(^{129}Xe/^{130}Xe)_t$	$(^{136}Xe/^{130}Xe)_t$
400 °C	0.368	38.6	10.2	36.1	3.79	304.56	0.974	6.509	2.183
	± 0.037	± 3.9	± 1.0	± 5.4	± 0.57	± 0.53	± 0.021	± 0.085	± 0.038
600 °C	0.0310	3.94	3.27	9.5	1.21	423	0.985	6.50	2.158
	± 0.0031	± 0.39	± 0.33	± 1.4	± 0.18	± 20	± 0.034	± 0.17	± 0.036
800 °C	0.241	3.24	2.15	112	1.51	923	1.011	6.89	2.26
	± 0.024	± 0.32	± 0.22	± 17	± 0.23	± 11	± 0.073	± 0.32	± 0.12
1000 °C	0.141	2.62	0.366	386	7.15	1141	1.46	9.83	2.23
	± 0.015	± 0.26	± 0.037	± 58	± 1.07	± 28	± 0.22	± 0.83	± 0.26
1300 °C	0.0642	2.14	0.293	219	7.3	1154	1.46	9.51	2.18
	± 0.0075	± 0.21	± 0.029	± 33	± 1.1	± 69	± 0.23	± 0.71	± 0.21
1750 °C	0.191	7.72	0.984	194	7.8	1132	1.37	9.02	2.17
	± 0.020	± 0.77	± 0.098	± 29	± 1.2	± 25	± 0.19	± 0.65	± 0.11
total	1.04	58.3	17.2	60.2	3.39	771	1.022	6.822	2.188

1) $[^{36}Ar]_t$ in 10^{-9} cm^3 STP/g; $[^{84}Kr]_t$ and $[^{132}Xe]_t$ in 10^{-12} cm^{3}STP/g.

2) Presented are measured values because of negligible (<2%) contribution of cosmogenic component.

3) Corrected only for cosmogenic ^{36}Ar, not for radiogenic ^{40}Ar.

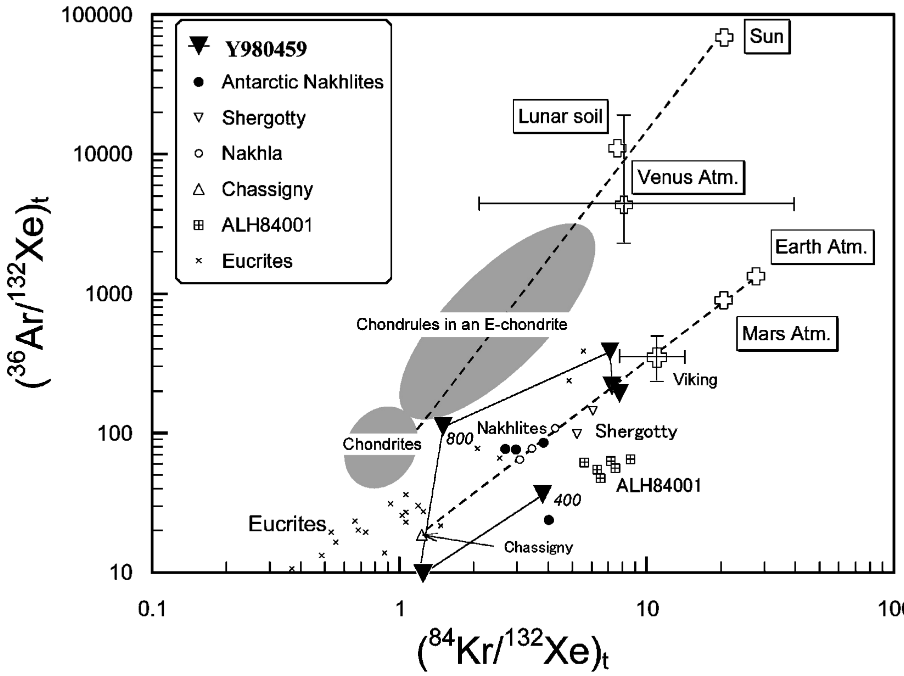


Fig. 4. Plot of trapped $^{36}Ar/^{132}Xe$ versus $^{84}Kr/^{132}Xe$ ratios. The ratios are plotted along a trend line passing the martian atmosphere and SNCs. Data points of high temperatures ($\geq$1000°C) are plotted in the area for shergottites. Data sources: Sun (Anders and Grevesse, 1989); lunar soil (Eberhardt et al., 1972); terrestrial atmosphere (Ozima and Podosek, 2002); Venusian atmosphere (estimated from Pepin (1991) assuming $^{132}Xe/^{130}Xe$=6.5); chondrules in an E-chondrite (Okazaki et al., 2001); ordinary and carbonaceous chondrites (Busemann et al., 2000); Viking probe data (Owen et al., 1977); Mars atmosphere (trapped gases in shergottite glasses; Bogard and Garrison, 1998); Shergotty, Nakhla, Chassigny (Ott, 1988); ALH 84001 (Miura et al, 1995; Bogard and Garrison, 1998); Antarctic nakhlites (Okazaki et al., 2003); eucrites (Miura et al., 1998).

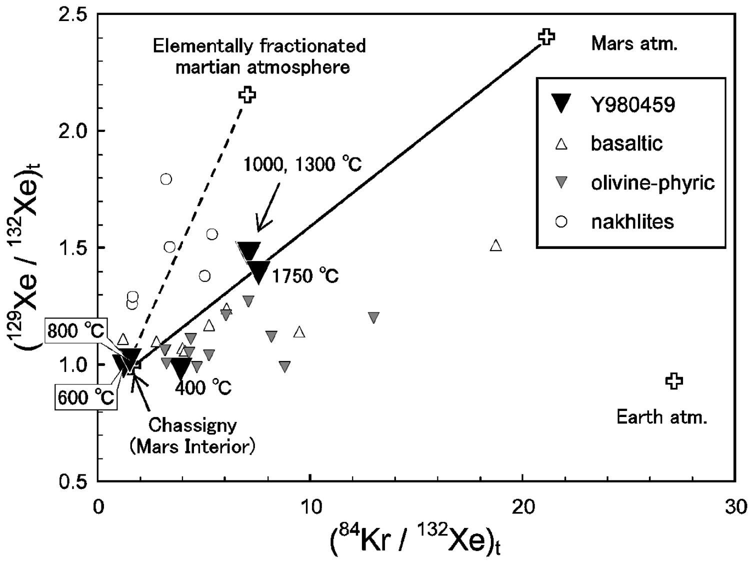


Fig. 5. Correlation diagram between $^{129}Xe/^{132}Xe$ *and* $^{84}Kr/^{132}Xe$ *ratios. Data points are plotted along the mixing line between Chassigny and the martian atmosphere, indicating presence of a martian atmospheric component. An only exception is 400°C fraction, in which terrestrial atmospheric contamination is suggested. Though 600°C and 800°C fractions are very similar to the Chassigny type, they are probably fractionated terrestrial noble gases as shown in Fig. 7. There is little difference between olivine-phyric and basaltic shergottites in the bulk compositions, in spite of variable shock degrees. Data sources: Bogard and Garrison (1998); Busemann and Eugster (2002); Folco et al. (2000); Garrison and Bogard (2000); Mathew et al. (2003); Mohapatra and Ott (2000); Ott (1988); Ott et al. (1988); Schwenzer et al. (2002b, 2004); Shukolyukov et al. (2002); Swindle et al. (1989, 1996); Zipfel et al. (2000).*

meteorite as a shergottite (Kojima and Imae, 2002). Compared to other olivine-phyric and basaltic shergottites, little difference can be seen in the plot (bulk compositions are shown in Fig. 5), although there is diversity in the shock features or abundance of impact-produced phases, such as maskelynite. The lack of clear correlation between the noble gas signature and shock features suggests that there are one or more host phases for the martian atmospheric (not interior) gas in addition to maskelynite.

Noble gases released at 600 and 800°C, as found in Fig. 5, have elemental ratios resembling those of Chassigny, which might reflect noble gases of the martian interior (Ott and Begemann, 1985; Ott, 1988; Bogard *et al.*, 2001; Mathew and Marti, 2001). However, Xe isotope ratios of Y980459 plotted in Fig. 6 indicate that the Xe released at the temperatures of 400, 600 and 800°C is similar to that of the Earth atmosphere, much different from that of Chassigny. At 1000–1750°C, the data points shift toward the martian atmosphere, and the 1300–1750°C fractions show a hint of the contribution of solar Xe (Fig. 6), although they have relatively large errors. Contamination of elementally fractionated Earth's atmospheric noble gas has often been observed in meteorites discovered in hot deserts (Mohapatra *et al.*, 2002; Schwenzer *et al.*, 2002a). The fractionated Earth atmosphere with the lowest $^{84}Kr/^{132}Xe$ of about 1 and the Earth

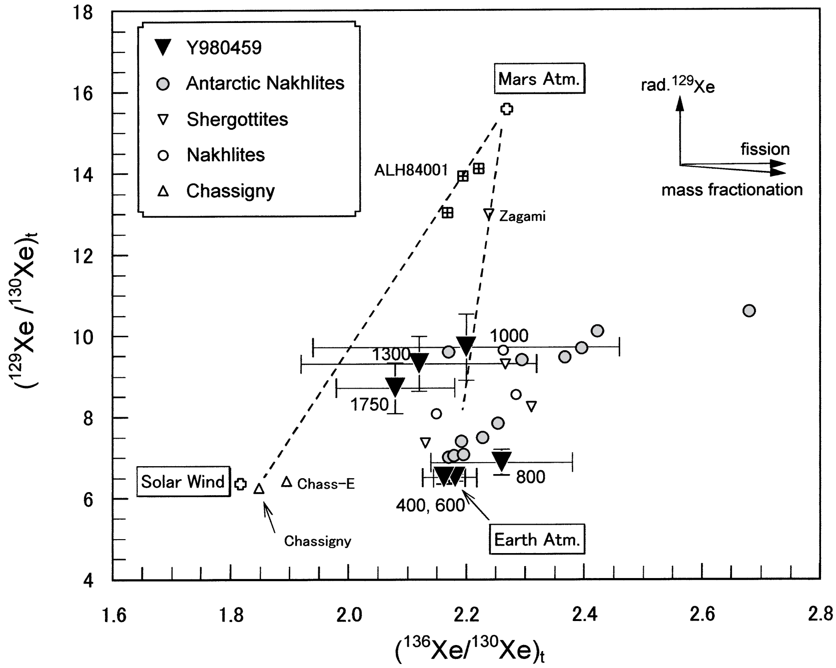


Fig. 6. Plot of $^{129}Xe/^{130}Xe$ versus $^{136}Xe/^{130}Xe$ ratios. The Xe isotopic ratios show that the low temperature fractions are mainly composed of the terrestrial atmosphere. High temperature fractions show a martian atmospheric signature. Data sources: Mathew et al. (1998); Miura et al. (1995); Okazaki et al. (2003); Ott (1988).

atmospheric ^{129}Xe/^{132}Xe has been reported for SaU 005 (Mohapatra *et al.*, 2002). Possible host phases of the heavily fractionated Earth atmosphere could be carbonate and/or other weathering products in the meteorites (*e.g.*, Zipfel *et al.*, 2000; Crozaz and Wadhwa, 2001). This hypothesis is supported by removal of fractionated noble gases from the Dho 378 shergottite with diluted HNO_3 treatment (Park and Nagao, 2003).

The plot of ^{40}Ar/(^{36}Ar)$_t$ *versus* (^{129}Xe/^{132}Xe)$_t$ (Fig. 7) also shows that the Earth's atmospheric noble gases are released at the lowest temperature of 400°C. In addition to the contamination of the Earth's atmospheric gas, the upward shift of ^{40}Ar/(^{36}Ar)$_t$ in the 400–800°C fractions could result from *in situ* produced radiogenic ^{40}Ar from K, which is consistent with that the mesostasis glass enriched in K (Ikeda, 2004) would release noble gases at those temperatures. In contrast, the high ^{40}Ar/^{36}Ar ratios at the temperatures higher than 1000°C are accompanied by high ^{129}Xe/^{132}Xe ($>$1.4), suggesting the presence of the martian atmosphere. In Fig. 7, we presented three curves representing the mixtures between the Earth and Mars atmospheres, the elementally fractionated (^{36}Ar/^{132}Xe$=$250) Earth atmosphere and the Mars atmosphere, and Chassigny and the Mars atmosphere. Although ^{40}Ar/^{36}Ar and ^{129}Xe/^{132}Xe ratios of the Earth's atmosphere (296 and 0.9833, respectively) are not significantly different from those for Chassigny (^{40}Ar/^{36}Ar $<$212: Marty and Marti, 2002; ^{129}Xe/^{132}Xe$=$1.08: Mathew and Marti, 2001), the Chassigny ^{36}Ar/^{132}Xe of 15.1 (Ott, 1988) cannot produce

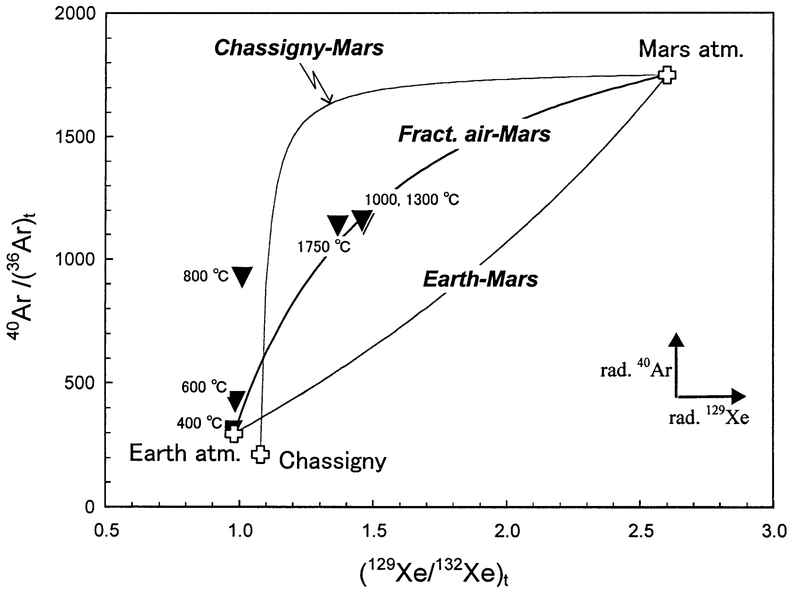


Fig. 7. Plot of $^{40}Ar/^{36}Ar$ versus $^{129}Xe/^{132}Xe$ ratios. A martian atmospheric signature is observed in the high temperature fractions ($\geq$800℃). The curves are mixing lines between the terrestrial and martian atmospheres, elementally fractionated ($^{36}Ar/^{132}Xe=250$) terrestrial atmosphere and the martian atmosphere, and Chassigny and the Mars atmosphere. Used data for calculating the mixing lines are $^{40}Ar/^{36}Ar=1750$, $^{129}Xe/^{132}Xe=2.60$ and $^{36}Ar/^{132}Xe=900$ for the Mars atmosphere (Bogard and Garrison, 1998, 1999), $^{40}Ar/^{36}Ar=296$, $^{129}Xe/^{132}Xe=0.98$ and $^{36}Ar/^{132}Xe=1343$ for the Earth atmosphere (compiled in Ozima and Podosek, 2002), $^{40}Ar/^{36}Ar=212$, $^{129}Xe/^{132}Xe=1.08$ and $^{36}Ar/^{132}Xe=15.1$ for Chassigny (Mathew and Marti, 2001; Ott, 1988; Marty and Marti, 2002).

the line through the high temperature data for Y980459. Thus, the most plausible explanation for the data in Fig. 7 is mixing between the elementally fractionated Earth atmosphere, the Mars atmosphere, and *in situ* produced radiogenic ^{40}Ar, although small contribution from solar Xe, as mentioned above (Fig. 6), cannot be ruled out.

3.4. K-Ar gas retention age and indigenous $^{40}Ar/^{36}Ar$ of Y980459

We calculated K-Ar gas retention age of 990±140 Ma for Y980459 using the measured ^{40}Ar concentration of 7.99×10^{-7} cm^{3}STP/g and the average K concentration of 157±24 ppm (166 ppm: Greshake *et al.*, 2003; 175 ppm: Dreibus *et al.*, 2003; 130 ppm: Shirai and Ebihara, 2004). The error for the age is estimated by assuming 10% uncertainties for ^{40}Ar concentration and the range for K concentration. The calculated age of 990 Ma is much younger than K-Ar ages for most chondrites (typically 4.5 Ga; *e.g.*, Turner, 1988), which indicates a recent resetting event on its parent body such as volcanic event or impact shock and supports the Mars origin of this meteorite. However, in the case of martian meteorites, *in situ* produced radiogenic ^{40}Ar is difficult to separate from the ^{40}Ar of the martian atmosphere, in which ^{40}Ar/^{36}Ar ratio is 1750 (Bogard and Garrison, 1998), and hence the K-Ar age calculated using the observed concentration of ^{40}Ar gives an upper limit. Shih *et al*. (2003) reported Rb-Sr age of 0.304 Ga using acid-washed whole rock and mineral separate data. Assuming that the true K-Ar age is same as the Rb-Sr age, we can calculate the trapped $^{40}Ar/^{36}Ar$ ratio of Y980459 as 563 using the trapped ^{36}Ar concentration in Table 5. The calculated $(^{40}Ar/^{36}Ar)_t$ is clearly lower than those of basaltic shergottites (ranging from 1175 to 2055; compiled in Garrison and Bogard, 1998), and close to the upper limit computed for Nakhla (Terribilini *et al*., 1998). The $^{40}Ar/^{36}Ar$ ratio of Y980459 was probably affected and decreased by terrestrial atmospheric contamination as previously described for heavy noble gases. If we assume that the 400–800°C released Ar are terrestrial contamination with $^{40}Ar/^{36}Ar = 296$, the original Mars atmospheric $^{40}Ar/^{36}Ar$ ratio preserved in Y980459 becomes 1265.

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References

Anders, E. and Grevesse, N. (1989): Abundances of the elements: Meteoritic and solar. Geochim. Cosmochim. Acta, **53**, 197–214.

Benkert, J.-P., Baur, H., Signer, P. and Wieler, R. (1993): He, Ne, and Ar from the solar wind and solar energetic particles in lunar ilmenites and pyroxenes. J. Geophys. Res., **98** (E7), 13147–13162.

Bogard, D.D. and Garrison, D.H. (1998): Relative abundances of argon, krypton, and xenon in the Martian atmosphere as measured in Martian meteorites. Geochim. Cosmochim. Acta, **62**, 1829–1835.

Bogard, D.D. and Garrison, D.H. (1999): Argon-39-argon-40 "ages" and trapped argon in martian shergottites, Chassigny, and Allan Hills 84001. Meteorit. Planet. Sci., **34**, 451–473.

Bogard, D.D., Clayton, R.N., Marti, K., Owen, T. and Turner, G. (2001): Martian volatiles: Isotopic composition, origin, and evolution. Space Sci. Rev., **96**, 425–458.

Borg, L.E., Nyquist, L.E., Taylor, L.A., Wiesmann, H. and Shih, C.-Y. (1997): Constraints on Martian differentiation processes from Rb-Sr and Sm-Nd isotopic analyses of the basaltic shergottite QUE 94201. Geochim. Cosmochim. Acta, **61**, 4915–4931.

Borg, L.E., Nyquist, L.E., Wiesmann, H., Reese, Y. and Papike, J.J. (2000): Sr-Nd isotopic systematics of martian meteorite DaG476. Lunar and Planetary Science XXXI. Houston, Lunar Planet. Inst., Abstract #1036 (CD-ROM).

Borg, L.E., Nyquist, L.E., Reese, Y., Wiesmann, H., Shih, C.-Y., Ivanova, M., Nazarov, M.A. and Taylor, L. A. (2001): The age of Dhofar 019 and its relationship to the other martian meteorites. Lunar and Planetary Science XXXII. Houston, Lunar Planet. Inst., Abstract #1144 (CD-ROM).

Busemann, H. and Eugster, O. (2002): The trapped heavy noble gases in recently found martian meteorites. Lunar and Planetary Science XXXIII. Houston, Lunar Planet. Inst., Abstract #1823 (CD-ROM).

Busemann, H., Baur, H. and Wieler, R. (2000): Primordial noble gases in "phase Q" in carbonaceous and ordinary chondrites studied by closed-system stepped etching. Meteorit. Planet. Sci., **35**, 949–973.

Caffee, M.W., Goswami, J.N., Hohenberg, C.M., Marti, K. and Reedy, R.C. (1988): Irradiation records in meteorites. Meteorites and the Early Solar System, ed. by J.F. Kerridge and M.S. Matthews. Tucson,

Univ. Arizona Press, 205–245.
Crozaz, G. and Wadhwa, M. (2001): The terrestrial alteration of Saharan Shergottites Dar al Gani 476 and 489: A case study of weathering in a hot desert environment. Geochim. Cosmochim. Acta, **65**, 971–978.
Dreibus, G., Haubold, R., Huisl, W. and Spettel, B. (2003): Composition of the chemistry of Yamato 980459 with DaG 476 and SaU 005. International Symposium—Evolution of Solar System Materials: A New Perspective from Antarctic Meteorites. Tokyo, Natl Inst. Polar Res., 19–20.
Eberhardt, P., Geiss, J., Graf, H., Grögler, N., Mendia, M.D., Mörgeli, M., Schwaller, H., Steller, 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. and Michel, Th. (1995): Common asteroid break-up events of eucrites, diogenites, and howardites and cosmic-ray production rates for noble gases in chondrites. Geochim. Cosmochim. Acta, **59**, 177–199.
Eugster, O., Busemann, H., Lorenzetti, S. and Terribilini, D. (2002): Ejection ages from krypton-81-krypton-83 dating and pre-atmospheric sizes of martian meteorites. Meteorit. Planet. Sci., **37**, 1345–1360.
Folco, L., Franchi, I.A., D'Orazio, M., Rocchi, S. and Schultz, L. (2000): A new martian meteorite from the Sahara: The shergottite Dar al Gani 489. Meteorit. Planet. Sci., **35**, 827–839.
Garrison, D.H. and Bogard, D.D. (1998): Isotopic composition of trapped and cosmogenic noble gases in several Martian meteorites. Meteorit. Planet. Sci., **33**, 721–736.
Garrison, D.H. and Bogard, D.D. (2000): Cosmogenic and trapped noble gases in the Los Angeles martian meteorite (abstract). Meteorit. Planet. Sci., **35**, A58.
Greshake, A., Fritz, J. and Stöffler, D. (2003): Petrography and shock metamorphism of the unique shergottite Yamato 980459. International Symposium—Evolution of Solar System Materials: A New Perspective from Antarctic Meteorites. Tokyo, Natl Inst. Polar Res., 29–30.
Ikeda, Y. (2004): Petrology of the Yamato 980459 shergottite. Antarct. Meteorite Res., **17**, 35–54.
Kojima, H. and Imae, N. (2002): Meteorite Newslett., **11** (1), 48.
Kojima, H., Kaiden, H. and Yada, T. (2000): Meteorite search by JARE-39 in 1998–99 season. Antarct. Meteorite Res., **13**, 1–8.
Marti, K. and Lugmair, G.W. (1971): Kr^{81}-Kr and K-Ar^{40} ages, cosmic-ray spallation products, and neutron effects in lunar samples from Oceanus Procellarum. Proc. Lunar Sci. Conf., **2nd**, 1591–1605.
Marti, K., Eberhardt, P. and Geiss, J. (1966): Spallation, fission, and neutron capture anomalies in meteoritic krypton and xenon. Z. Naturforsch., **21a**, 398–413.
Marty, B. and Marti K. (2002): Signatures of early differentiation of Mars. Earth Planet. Sci. Lett., **196**, 251–263.
Marty, B., Marti, K. and the Théodore Monod Consortium (2001): Noble gases in new SNC meteorites NWA 817 and NWA 480 (abstract). Meteorit. Planet. Sci., **36**, A122–A123.
Mathew, K. J. and Marti, K. (2001): Early evolution of Martian volatiles: Nitrogen and noble gas components in ALH84001 and Chassigny. J. Geophys. Res., **106** (E1), 1401–1422.
Mathew, K. J., Kim, J.S. and Marti, K. (1998): Martian atmospheric and indigenous components of xenon and nitrogen in the Shergotty, Nakhla, and Chassigny group meteorites. Meteorit. Planet. Sci., **33**, 655–664.
Mathew, K. J., Marty, B., Marti, K. and Zimmermann, L. (2003): Volatiles (nitrogen, noble gases) in recently discovered SNC meteorites, extinct radioactivities and evolution. Earth Planet. Sci. Lett., **214**, 27–42.
Mikouchi, T., Koizumi, E., McKay, G., Monkawa, A., Ueda, Y., Chokai, J. and Miyamoto, M. (2004): Yamato 980459: Mineralogy and petrology of a new shergottite-related rock from Antarctica. Antarct. Meteorite Res., **17**, 13–34.
Mileikowsky, C., Cucinotta, F.A., Wilson, J.W., Gladman, B., Horneck, G., Lindegren, L., Melosh, J., Rickman, H., Valtonen, M. and Zheng, J.Q. (2000): Natural transfer of viable microbes in space: 1. From Mars to Earth and Earth to Mars. Icarus, **145**, 391–427.
Misawa, K. (2003): The Yamato 980459 shergottite consortium. International Symposium—Evolution of Solar System Materials: A New Perspective from Antarctic Meteorites. Tokyo, Natl Inst. Polar Res., 84–85.
Misawa, K. (2004): The Yamato 980459 olivine-phyric shergottite consortium. Antract. Meteorite Res., **17**,

1–12.

Miura, Y.N., Nagao, K., Sugiura, N., Sagawa, H. and Matsubara, K. (1995): Orthopyroxenite ALH84001 and shergottite ALH77005: Additional evidence for a Martian origin from noble gases. Geochim. Cosmochim. Acta, **59**, 2105–2113.

Miura, Y.N., Nagao, K., Sugiura, N., Fujitani, T. and Warren, P.H. (1998): Noble gases, ^{81}Kr-Kr exposure ages and ^{244}Pu-Xe ages of six eucrites, Béréba, Binda, Camel Donga, Juvinas, Millbillillie, and Stannern. Geochim. Cosmochim. Acta, **62**, 2369–2387.

Mohapatra, R.K. and Ott, U. (2000): Trapped noble gases in Sayh al Uhaymir 005: A new martian meteorite from Oman (abstract). Meteorit. Planet. Sci., **35**, A113.

Mohapatra, R.K., Schwenzer, S.P. and Ott, U. (2002): Krypton and xenon in Martian meteorites from hot deserts—The low temperature component. Lunar and Planetary Science XXXIII. Houston, Lunar Planet. Inst., Abstract #1532 (CD-ROM).

Nyquist, L., Wiesmann, H., Shih, C.-Y. and Bansal, B. (1986): Sr isotopic systematics of EETA 79001 glass. Lunar and Planetary Science XVII. Houston, Lunar Planet. Inst., 624–625.

Nyquist, L.E., Bogard, D.D., Shih, C.-Y., Greshake, A., Stöffler, D. and Eugster, O. (2001): Ages and geologic histories of martian meteorites. Space Sci. Rev., **96**, 105–164.

Okazaki, R., Takaoka, N., Nagao, K., Sekiya, M. and Nakamura, T. (2001): Noble-gas-rich chondrules in an enstatite meteorite. Nature, **412**, 795–798.

Okazaki, R., Nagao, K., Imae, N. and Kojima, H. (2003): Noble gas signatures of Antarctic nakhlites, Yamato (Y) 000593, Y000749, and Y000802. Antarct. Meteorite Res., **16**, 58–79.

Ott, U. (1988): Noble gases in SNC meteorites: Shergotty. Nakhla, Chassigny. Geochim. Cosmochim. Acta, **52**, 1937–1948.

Ott, U. and Begemann, F. (1985): Are all the 'martian' meteorites from Mars? Nature, **317**, 509–512.

Ott, U., Löhr, H.P. and Begemann, F. (1988): New noble gas data for SNC meteorites: Zagami, Lafayette, and etched Nakhla (abstract). Meteoritics, **23**, 295–296.

Owen, T., Biemann, K., Rushneck, D.R., Biller, J.E., Howarth, D.W. and Lafleur, L.L. (1977): The composition of the atmosphere at the surface of Mars. J. Geophys. Res., **82**, 4635–4639.

Ozima, M. and Podosek, F.A. (2002): Noble Gas Geochemistry. 2nd ed. Cambridge, Cambridge Univ. Press, 286 p.

Park, J. and Nagao, K. (2003): Noble gas studies of Dhofar 378 Martian meteorite (abstract). Meteorit. Planet. Sci., **38**, A79.

Pepin, R.O. (1991): On the origin and early evolution of terrestrial planet atmospheres and meteoritic volatiles. Icarus, **92**, 2–79.

ReVelle, D.O. (1979): A quasi-simple ablation model for large meteorite entry: Theory versus observations. J. Atmos. Terr. Phys., **41**, 453–473.

Schwenzer, S.P., Mohapatra, R.K. and Ott, O. (2002a): Nitrogen and noble gases in caliche from the martian meteorite SaU 008. Geochim. Cosmochim. Acta, **66** (15A), A693.

Schwenzer, S.P., Mohapatra, R.K., Herrmann, S. and Ott, U. (2002b): Noble gas distribution in the martian meteorite Sayh al Uhaymir 005 (SaU 005). Lunar and Planetary Science XXXIII. Houston, Lunar Planet. Inst., Abstract #1624 (CD-ROM).

Schwenzer, S.P., Herrmann, S. and Ott, U. (2004): Noble gases in two samples of EETA 79001 (lith. A). Lunar and Planetary Science XXXV. Houston, Lunar Planet. Inst., Abstract #1641 (CD-ROM).

Shih, C.-Y., Nyquist, L.E. and Wiesmann, H. (2003): Isotopic studies of Antarctic olivine-phyric shergottite Y980459. International Symposium—Evolution of Solar System Materials: A New Perspective from Antarctic Meteorites. Tokyo, Natl Inst. Polar Res., 125–126.

Shirai, N. and Ebihara, M. (2004): Chemical characteristics of a Martian meteorite, Yamato 980459. Antarct. Meteorite Res., **17**, 55–67.

Shukolyukov, Yu. A., Nazarov, M.A. and Schultz, L. (2002): A new martian meteorite: the Dhofar 019 shergottite with an exposure age of 20 million years. Solar System Res., **36**, 125–135.

Smith, S.P. and Huneke, J.C. (1975): Cosmogenic neon produced from sodium in meteoritic minerals. Earth Planet. Sci. Lett., **27**, 191–199.

Smith, S.P., Huneke, J.C., Rajan, R.S. and Wasserburg, G.J. (1977): Neon and argon in the Allende meteorite. Geochim. Cosmochim. Act, **41**, 627–647.

Swindle, T.D., Nichols, R. and Olinger, C.T. (1989): Noble gases in the nakhlite Governador Valadares. Lunar and Planetary Science XX. Houston, Lunar Planet. Inst., 1097–1098.

Swindle, T.D., Li, B. and Kring, D.A. (1996): Noble gases in Martian meteorite QUE94201. Lunar and Planetary Science XXVII. Houston, Lunar Planet. Inst., 1297–1298.

Terribilini, D., Eugster, O., Burger, M., Jakob, A. and Krähenbühl, U. (1998): Noble gases and chemical composition of Shergotty mineral fractions, Chassigny, and Yamato 793605: The trapped argon-40/argon-36 ratio and ejection times of Martian meteorites. Meteorit. Planet. Sci., **33**, 677–684.

Turner, G. (1988): Dating of secondary events. Meteorites and the Early Solar System, ed. by J.F. Kerridge and M.S. Matthews. Tucson, Univ. of Arizona Press, 276–288.

Zipfel, J., Scherer, P., Spettel, B., Dreibus, G. and Schultz, L. (2000): Petrology and chemistry of the new shergottite Dar al Gani 476. Meteorit. Plenet. Sci., **35**, 95–106.