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NOBLE GASES AND MINERALOGY OF PRIMARY IGNEOUS MATERIALS OF THE YAMATO-793605 SHERGOTTITE

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Abstract: Mineralogical and petrologic study on the Y-793605 lherzolitic shergottite using an optical microscope and an electron microprobe shows that this meteorite is a primary cumulate rock with close affinity to ALH77005 (and possibly to LEW88516), and is different from Shergotty. Strong shock effects, 30–50 GPa, are observed as finely fractured texture of pyroxene, maskelynite and brownish color olivine.

Noble gas analyses by total melt and stepwise heating were performed on 17.86 and 50.99 mg primary igneous materials from Y-793605, 10, respectively. Xe isotopic ratios show weak isotope signature for shergottite, which is different from those of nakhlites, Chassigny and ALH84001. Cosmic-ray exposure ages calculated from cosmogenic ^{3}He and ^{21}Ne are 5.1–5.8 Ma, which is slightly longer than the ages, 3.3–4.0 Ma, reported for other two lherzolitic shergottites ALH77005 and LEW88516. Multistage exposure to cosmic-rays would be responsible for the difference. Apparent K-Ar age of 1430–1860 Ma is calculated, which is concordant with the young crystallization ages for martian meteorites, though the age is still ambiguous.

1. Introduction

Among twelve martian meteorites Yamato-793605 is only one which has not been systematically studied until recently. Based on mineralogical study, Y-793605 is a lherzolitic shergottite, having strong affinity to the lherzolitic shergottites ALH77005 and LEW88516 (MIKOUCHI and MIYAMOTO, 1996a, b). A consortium study on this small meteorite (16 g of recovered mass) has been organized by KOJIMA *et al.* in 1996 (KOJIMA *et al.*, 1997). Y-793605,10 and Y-793605,73 meteorite samples with 212 mg total mass were allocated to us from National Institute of Polar Research, *via* P. H. WARREN for investigation of noble gas isotopic compositions and mineralogy (KOJIMA *et al.*, 1997). According to KOJIMA *et al.* (1997), lumps of 152 mg is approximately representative materials from Y-793605,10, and grains of 60 mg, Y-793605,73, are glass-rich material. In this paper, we present mineralogical characteristics and noble

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gas data obtained on non-glassy part separated from the Y-793605,10 sample, and discuss on the genetic relationship with other martian meteorites. Detailed study on remaining sample and on the glassy materials (Y-793605,73) is in progress.

EUGSTER *et al.* (1997) have summarized that five or six ejection events on Mars are responsible for eleven martian meteorites; *i.e.*, 0.87 Ma (basaltic shergottite EET79001), 2.8 Ma (basaltic shergottites QUE94201, Shergotty, and Zagami), 3.8 Ma (lherzolitic shergottites LEW88516 and ALH77005), 11.0 Ma (nakhlites Nakhla, Governador Valadares, and Lafayette), 11.6 Ma or in the nakhlite group (chassignite Chassigny), and 14.4 Ma (orthopyroxenite ALH84001). Hence, it is interesting to clarify whether the Y-793605 lherzolite belongs to the lherzolitic shergottite group ejected 3.8 Ma ago.

2. Sample and Experimental Methods

This study is planned to analyze lithic materials, primary igneous rock, so we have carefully excluded the black glass materials from the Y-793605, 10 sample for analyses. The black glass material contained in the large lithic fragment was cut away using an ultra accurate cutting machine (Accutom 5). One thin section and some chips were prepared from the large lithic fragment rich in primary igneous materials for mineralogical study and noble gas analysis. The black glass materials taken from the Y-793605,10 sample were not analyzed in this study.

The thin section was studied using an optical microscope to identify minerals and to see shock effects on this meteorite. Detailed mineralogical study was performed using an electron probe microanalyzer (JEOL 733 superprobe), operated at 15 kV and 10 nA for analyses of silicate and oxide minerals, and at 20 kV and 10 nA for sulfide mineral. Quantitative analytical data were obtained through a ZAF correction method. Nine appropriate minerals were used as standards for quantitative analyses of silicate and sulfide. Plagioclase and chromite standards were used for plagioclase and chromite analyses.

Noble gases were analyzed for two chips, 17.86 and 50.99 mg, by total melt and stepwise heating gas extraction, respectively, on a modified-VG5400 noble gas mass spectrometer (*e.g.*, NAGAO *et al.*, 1995; MIURA *et al.*, 1995). Bruderheim (L6) standard sample prepared by Prof. J. H. REYNOLDS at the University of California, Berkeley also has been measured to evaluate the noble gas data of this martian meteorite obtained in our laboratory. The meteorite samples were loaded in a glass sample holder connected to a noble gas extraction and purification system and preheated at about 150°C overnight. The extraction temperature was 1750°C for total melt, and those for stepwise heating were 700, 1000, 1300, 1750 and 1800°C. Evolved noble gases were purified by exposing on two hot Ti-Zr getters and on a SORB-AC getter, and then separated into four fractions, He-Ne, Ar, Kr, and Xe using two charcoal traps cooled at temperatures of liquid nitrogen, −70°C, and −7°C, respectively. He, Ne and Ar were measured by Daly-multiplier collector, and Kr and Xe by ion counting collector system. Sensitivities and mass discrimination correction factors were determined by measuring known amounts of terrestrial atmospheric noble gases and a helium standard gas with $^{3}He/^{4}He = 1.71 \times 10^{-4}$ prepared in our laboratory by mixing ^{3}He and ^{4}He gases.

Blank levels during the analyses were $^4He=(4.0–5.3)\times10^{-10}$, $^{20}Ne=(1.16–1.71)\times10^{-12}$, $^{40}Ar=(1.1–-5.4)\times10^{-10}$, $^{84}Kr=(1.8–8.7)\times10^{-14}$ and $^{132}Xe=(0.59–1.9)\times10^{-14}$ cm^3 STP. Blank correction has been applied for the concentrations and isotopic ratios presented in Tables 2 and 3. Errors for isotopic ratios are 1σ, and uncertainties for noble gas concentrations are about 10%.

3. Results and Discussion

3.1. Mineralogy

Petrographic observation of the thin section indicates that Y-793605 is a cumulate achondrite consisting of olivine, low-Ca and high-Ca pyroxene, maskelynite (diaplectic glass converted from plagioclase by impacts), chromite, and minor amounts of ilmenite, pyrrhotite, and whitlockite (Fig. 1). Representative compositions of these minerals are tabulated in Table 1. Poikilitic texture is commonly observed: subrounded olivine grains ~1 mm in diameter are enclosed in large low-Ca pyroxenes with ~2 mm in diameter. High-Ca pyroxene occurs in contact with low-Ca pyroxene and olivine, and maskelynite mostly occurs in contact with high-Ca pyroxene. These mineral occurrence suggests a crystallization sequence of Y-793605 to be (1) accumulation of olivine with intercumulus liquid, (2) formation of low-Ca pyroxene by reaction between olivine and liquid, and (3) crystallization of high-Ca pyroxene and plagioclase. Figure 2 shows that Fe# of low-Ca pyroxene shows a liner relationship to that of poikilitically enclosed olivine. This indicates that olivine cumulates locally reacted and equilibrated with surrounded intercumulus low-Ca pyroxene, being consistent with an interpretation from petrological observation described above (2). However, major element compositions of olivine are variable between grains from Fo 67 to 74, suggesting that post accumulational equilibration has been achieved only between olivine and adjacent low-Ca pyroxene, but not achieved between olivine grains beyond intercumulus phases.

Three types of pyroxene were detected in Y-793605 (Fig. 3). Low-Ca pyroxene has two compositionally distinct groups, magnesian and ferroan types. The compositional trend of pyroxenes can be explained by closed-system crystallization from a melt: the magnesian pyroxene has been crystallized first, and then the ferroan low-Ca and the high-Ca pyroxene have been co-crystallized. This interpretation is confirmed by the occurrence of pyroxenes that the ferroan low-Ca pyroxene often occurs in contact with the high-Ca pyroxene. Both magnesian and ferroan types of low Ca-pyroxene commonly show a weak Ca zoning, *e.g.*, Ca concentration of the magnesian low-Ca pyroxene increases from 1.5 wt% core to 1.9 wt% rim. Small amounts of MnO (0.3–0.7 wt%) and Cr_2O_3 (0.3–1.0 wt%) are contained in all types of pyroxene, which is in contrast to the case of olivine that contains MnO (0.5–0.7 wt%) but no detectable Cr_2O_3. Maskelynite (Fig. 4) shows a wide range of compositions from An 52 to 62 (Fig. 5). Compositions are variable even in a single maskelynite grain, *e.g.*, from An 53 to 62, but no systematic compositional signatures such as zoning were observed in maskelynite. Maskelynite contains 0.2–0.4 wt% K and other minerals contains undetectable amounts of K. Thus, maskelynite must be a major host phase of *in situ* produced radiogenic ^{40}Ar in Y-793605 meteorite.

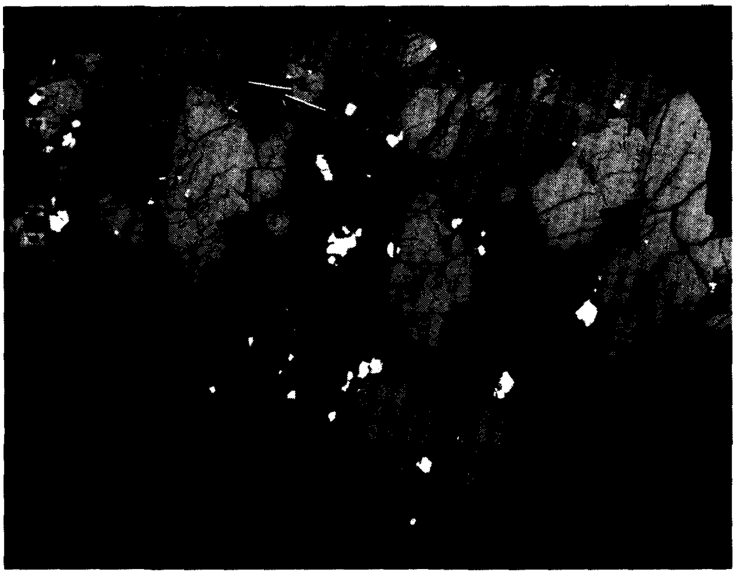

Fig. 1. A back-scattered electron (BSE) image of the thin section of Y-793605 shergottite. This whole view shows that olivine (light gray) and pyroxene (gray) are predominant and olivine grains are poikilitically enclosed by low-Ca pyroxene. Dark gray portions are maskelynite indicated by an arrow. Bright grains are mostly chromite.

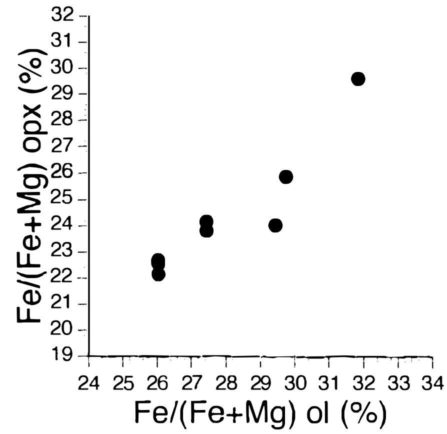

Fig. 2. A diagram showing a linear relationship between Fe# (=Fe/(Fe+Mg)) in low-Ca pyroxene and olivine. Each point is plotted from a set of compositions of low-Ca pyroxene and poikilitically enclosed olivine. Compositions of minerals were taken from electron-microprobe analyses of portions close to a contact plane of the two minerals.

Chromite occurs as subhedral grains with diameters from 30 to 200 μm in low-Ca pyroxene and olivine. Presence of chromite in olivine suggests that chromite is also cumulus phase in Y-793605, as well as olivine crystals. Some chromite grains in pyroxene are Ti-rich, but most chromite is Ti-bearing chromite (Table 1 and Fig. 6). Other than major-phase minerals described above, three accessory minerals were observed in Y-793605. Pyrrhotite with diameters from 100 to 300 μm rarely occurs in high-Ca pyroxene. 1–25 wt% Ni is detected in the pyrrhotite analyses (Table 1), indicating that Ni-rich phases are included in pyrrhotite grains. Back-scattered imaging with high contrast confirms the presence of small Ni-rich phases in pyrrhotite (Fig. 7). Ilmenite and whitlockite are observed only in maskelynite. In Fig. 4, an ilmenite crystal coexists with a whitlockite, suggestive of co-crystallization of both minerals from the intercumulus feldspasic liquid.

Like other SNC meteorites, Y-793605 had been a subject to strong impacts, possibly when it was ejected from Mars. Olivine and low- and high-Ca pyroxene are finely fractured and show mosaic extinction. Plagioclase is converted to maskelynite. Some chromite grains show planar fractures. Based on the shock classification scheme of olivine, pyroxenes, and spinel (*e.g.*, STÖFFLER *et al.*, 1988), these shock-induced

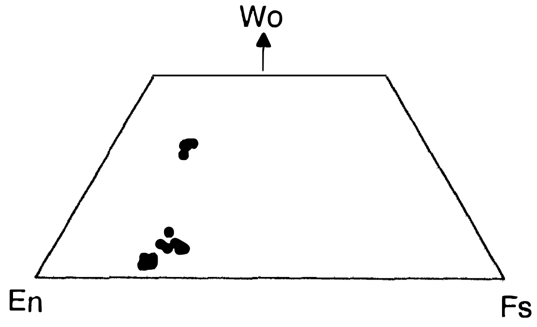

Fig. 3. Pyroxene composition (mol%). Low-Ca pyroxene has two distinct compositional groups, magnesian and ferroan types.

Fig. 4. A BSE image of maskelynite containing ilmenite (I) and whitlockite (W).

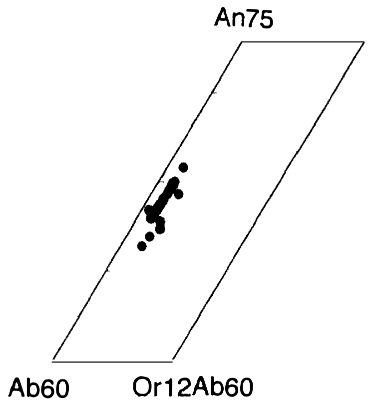

Fig. 5. Maskelynite composition plotted in a anorthite (An)-albite(Ab)-orthoclase (Or) diagram in terms of atomic ratio.

mineralogical features in Y-793605 are consistent with the shock effects by pressures more than 30 GPa and probably less than 50 GPa, being correspond to impact velocities from 3 km/s to 4.5 km/s provided hugoniot of Y-793605 is similar to that of basalt (AHRENS and WATT, 1980). In addition to the normal cataclastic shock effects, olivine grains in Y-793605 exhibit brownish color when observed in transmitted light. The brown olivine was also observed in ALHA77005 shergottite and the oxidation reaction from Fe^{2+} to Fe^{3+} in olivine crystals could be responsible for the brown color (OSTERTAG *et al.*, 1984).

Mineralogical investigation in this study clearly indicates that the Y-793605 shergottite is a cumulate origin that is characterized by poikilitic textures. Cumulus phases are olivine and chromite, indicating that Y-793605 is a primary cumulate rock and differs from Shergotty meteorite whose cumulus phase is low-Ca pyroxene. Comparison of Y-793605 with ALHA77005 shergottite whose petrology described in ISHII *et al.* (1979), MCSWEEN *et al.* (1979), MCSWEEN and STÖFFLER (1980), LUNDBERG *et al.* (1990), and IKEDA (1994) yields similarities in many respects; (1) cumulate texture dominated by olivine and low-Ca pyroxene, (2) species of constituent minerals, *i.e.*, olivine, low- and high-Ca pyroxene, maskelynite, chromite, pyrrhotite, ilmenite, and whitlockite, (3) major and minor element compositions of all minerals, (4) diameters of minerals in both cumulus and intercumulus phases, (5) records of strong shock impacts, and (6) brownish color of olivine crystals. LUNDBERG *et al.* (1990) reported that ALHA77005 consists of materials with two textural types, light-colored poikilitic mass and darker interstitial materials. The former type is nearly identical to the texture of the Y-793605 thin section investigated in this study. All these evidence listed above suggests that Y-793605 and ALHA77005 might have been originated from a single parental magma through similar crystallization history.

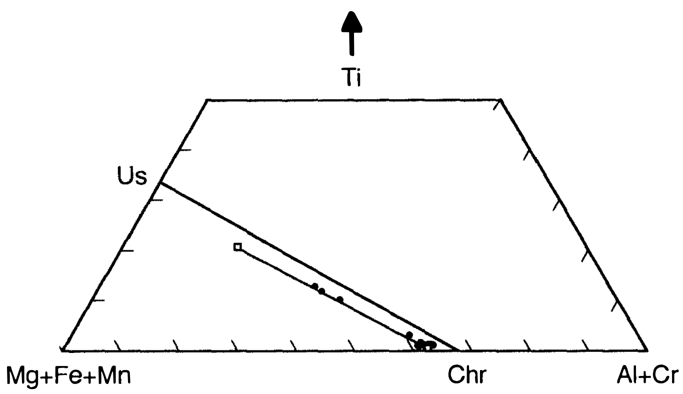

Fig. 6. Chromite composition plotted in a Ti−(Mg+Fe+Mn)−(Al+Cr) diagram in terms of atomic ratio. A tie line is connected between ulvospinel (Us) and chromite (Chr). A dark gray line connecting open squares shows composition of chromite in ALHA77005 from IKEDA (1994).

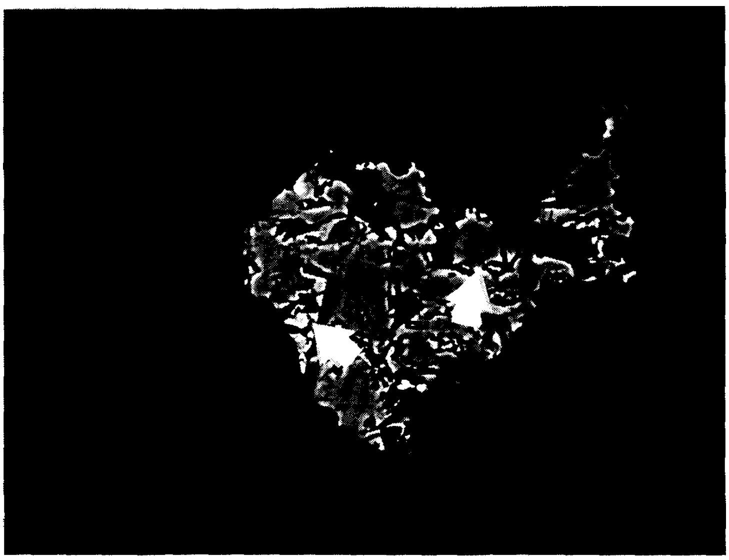

Fig. 7. A BSE image of a pyrrhotite grain. Brighter portions (indicated by arrows) are seen within gray host pyrrhotite, where Ni concentration is fairly high up to 25 wt%.

Table 1. Representative chemical compositions of olivine, pyroxenes, maskelynite, chromite, ilmenite, whitlockite, and pyrrhotite determined by electron microprobe analyses.

	Olivine	low-Ca Pyroxene		high-Ca Pyroxene	Maskelynite
wt%		magnesian	ferroan		
SiO_2	37.02	55.04	52.69	52.74	56.54
TiO_2	0.01	0.09	0.35	0.23	0.07
Al_2O_3	0.03	0.31	0.86	0.99	27.41
FeO	27.03	14.06	18.33	9.62	0.32
MnO	0.44	0.55	0.57	0.48	0.00
MgO	35.86	27.87	23.25	18.25	0.10
CaO	0.14	1.55	3.51	16.09	10.61
Na_2O	0.00	0.06	0.09	0.24	4.99
K_2O	0.00	0.00	0.00	0.00	0.29
Cr_2O_3	0.06	0.49	0.36	1.06	0.04
NiO	0.03	0.03	0.03	0.02	0.00
SO_3	0.08	0.00	0.05	0.00	0.01
P_2O_5					
Total	100.69	100.05	100.10	99.71	100.38

	Chromite		Ilmenite	Whitlockite	Pyrrhotite
	high-Ti	low-Ti			
SiO_2	0.05	0.07	0.00	0.14	Fe 60.43
TiO_2	13.78	1.00	55.12	0.05	S 37.29
Al_2O_3	5.53	6.74	0.08	0.04	Co 0.15
FeO	42.69	27.32	38.86	0.93	Ni 2.03
MnO	0.70	0.58	0.77	0.01	Cr 0.06
MgO	3.44	6.71	4.53	3.37	
CaO	0.05	0.00	0.00	47.19	
Na_2O	0.01	0.00	0.00	1.35	
K_2O	0.00	0.00	0.00	0.05	
Cr_2O_3	30.05	56.50	0.66	0.00	
NiO	0.00	0.02	0.07	0.03	
SO_3	0.00	0.00	0.00	0.06	
P_2O_5				46.50	
Total	96.30	98.94	100.09	99.72	99.96

3.2. Noble gases

Noble gas isotopic ratios and concentrations obtained by total melt analysis on 17.86 mg sample and by stepwise heating on 50.99 mg are presented in Tables 2 and 3 along with those for the Bruderheim standard sample of 32.5 mg measured in a series of the Y-793605 analyses. Comparison of the data for the Bruderheim standard with reported ones by other laboratories shows generally good agreements. Stepwise heating of Y-793605 indicates that He is released mostly (>80% of total) at low temperatures of 700 and 1000°C with cosmogenic $^3He/^4He$ ratio (>0.2). Radiogenic ^4He concentrations could not be determined owing to low concentration of radiogenic ^4He and overwhelming cosmogenic He as inferred from the high $^3He/^4He$ ratios obtained by stepwise heating as well as total melt experiments. Radiogenic ^4He likely has lost recently by impact shock. In contrast to this meteorite, $^3He/^4He$ of Bruderheim

Table 2. Isotopic ratios of He, Ne and Ar, and noble gas concentrations in the Y-793605 shergottite and the Bruderheim standard sample.

	^{3}He	^{4}He	$^{3}He/^{4}He$	^{20}Ne	^{21}Ne	^{22}Ne	$^{20}Ne/^{22}Ne$	$^{21}Ne/^{22}Ne$	^{36}Ar	^{38}Ar	^{40}Ar	$^{38}Ar/^{36}Ar$	$^{40}Ar/^{36}Ar$	^{84}Kr	^{132}Xe
Y-793605, 10															
Total melt	89.1	391	0.2279	14.4	12.6	15.5	0.9317	0.8136	3.32	2.46	2580	0.7408	776.3	82.5	15.8
(17.86mg)			±.0026				±.0083	±.0062				±.0069	± 2.1		
Stepwise heating (50.99mg)															
700℃	37.8	159	0.2377	0.998	0.381	0.533	1.8725	0.7151	0.189	0.0509	81.5	0.2686	430.27	32.2	11.6
			±.0013				±.0056	±.0031				±.0046	± .80		
1000℃	30.5	140	0.2177	0.661	0.657	0.815	0.8115	0.8070	0.152	0.0786	136	0.5168	893.8	5.42	1.75
			±.0036				±.0028	±.0047				±.0071	± 3.5		
1300℃	13.8	62.2	0.2225	5.46	5.33	6.51	0.8391	0.8197	0.957	0.793	689	0.8287	719.82	22.0	6.29
			±.0025				±.0030	±.0017				±.0076	± .93		
1750℃	1.37	7.18	0.191	4.89	4.78	5.88	0.8323	0.8141	1.25	1.09	810	0.8744	649.47	23.9	4.56
			±.016				±.0080	±.0063				±.0080	± .93		
1800℃	--	--	--	0.045	0.0026	0.0062	7.26	0.42	0.0393	0.0107	11.8	0.271	300.2	0.68	0.16
							±.97	±.13				±.022	± 1.5		
Total	83.5	368	0.227	12.1	11.2	13.7	0.883	0.818	2.59	2.02	1730	0.780	668	84.2	24.4
Bruderheim	550	5450	0.10093	105	116	127	0.8261	0.9090	12.4	13.7	11800	1.107	952.4	69.7	106
Std. (32.5mg)			±.00050				±.0012	±.0015				±.011	± 3.3		
	500[1]	5340[1]	0.0936[1]	93.7[1]	101.1[1]	110.5[1]	0.848[1]	0.915[1]	14.9[1]	15.1[1]	12400[1]	1.01[1]	832[1]	80[2]	114[2]
	±31	±45	±.0059	±5.4	± 5.4	±5.8	±.066	±.069	±2.1	±.8	±1010	±.15	±135	83[3]	114[3]

Concentrations of He, Ne and Ar are in the unit of 10^{-8} cm^3STP/g, and those of ^{84}Kr and ^{132}Xe in 10^{-12} cm^3STP/g.
[1] Averaged values of the data in compilation by Schultz and Kruse (1989); [2] Eugster *et al.* (1981); [3] Freundel *et al.* (1986)

Table 3. Concentrations and isotopic ratios of Kr and Xe in the Y-793605 shergottite and the Bruderheim standard sample.

	^{84}Kr	^{78}Kr	^{80}Kr	^{81}Kr	^{82}Kr	^{83}Kr	^{86}Kr	^{132}Xe	^{124}Xe	^{126}Xe	^{128}Xe	^{129}Xe	^{130}Xe	^{131}Xe	^{134}Xe	^{136}Xe
		$^{84}Kr=100$							$^{132}Xe=100$							
Y-793605, 10																
Total melt	82.5	0.679	4.37	0.022	20.95	20.65	30.46	15.8	0.426	0.420	7.13	113.3	15.23	77.7	39.2	33.0
(17.86mg)		±.062	±.15	±.009	± .54	± .35	± .41		±.074	±.122	±.26	±2.2	± .52	±1.8	±1.4	±1.1
Stepwise heating (50.99mg)																
700℃	32.2	0.595	4.05	0.015	20.56	20.24	30.85	11.6	0.462	0.351	7.12	98.4	15.01	79.52	38.60	33.21
		±.039	±.14	±.011	± .22	± .41	± .47		±.066	±.018	±.16	±1.4	± .30	± .79	± .77	± .49
1000℃	5.42	0.769	4.58	0.059	21.39	21.00	30.50	1.75	1.063	0.382	6.75	106.4	15.64	80.93	39.23	34.46
		±.092	±.23	±.024	± .64	± .92	± .76		±.126	±.170	±.59	±5.1	± .76	±3.55	±2.02	±1.42
1300℃	22.0	0.701	4.48	0.0280	20.98	20.48	30.44	6.29	0.559	0.380	7.09	110.5	15.26	78.01	38.96	32.87
		±.031	±.12	±.0089	± .37	± .41	± .61		±.089	±.049	±.32	±2.4	± .77	±1.99	±1.17	± .82
1750℃	23.9	0.720	4.51	0.0287	20.98	20.69	30.40	4.56	0.528	0.375	7.43	126.3	15.58	81.11	39.97	33.67
		±.042	±.12	±.0057	± .35	± .37	± .55		±.094	±.100	±.30	±3.5	± .56	±1.67	± .45	±1.13
1800℃	0.68	0.68	4.27	0.192	21.7	19.6	31.6	0.16	0.418	0.356	7.21	99.4	15.20	79.28	38.83	32.87
		±.26	±.34	±.045	±1.3	±1.4	±1.3		±.030	±.022	±.10	± .7	± .26	± .51	± .57	± .44
Bruderheim	69.7	1.567	8.15	0.0345	24.41	26.08	29.78	106	0.569	0.663	8.49	128.1	16.11	82.16	38.44	32.16
Std. (32.5mg)		±.066	±.15	±.0079	± .30	± .28	± .33		±.033	±.027	±.16	± .9	± .22	± .98	± .19	± .27

Concentrations of ^{84}Kr and ^{132}Xe are in the unit of $10^{-12} cm^3 STP/g$.

(0.1009±0.0005) is about half of cosmogenic $^{3}He/^{4}He$ ratio, suggesting that about half of total ^{4}He would be radiogenic produced by U and Th decay. Ne, Ar, Kr and Xe are released dominantly at relatively high temperatures of 1300 and 1750°C. In case of Kr and Xe, a release peak at the lowest extraction temperature (700°C) is probably due to desorption of atmospheric contamination, which is supported by the isotopic compositions similar to the atmospheric ones as will be discussed later. Ne is dominated by cosmogenic components except for the lowest and the highest extraction temperatures for which release of a small amount of trapped Ne is observed, which may be an atmospheric contamination on the sample or from a crucible. Cosmogenic $^{22}Ne/^{21}Ne$ ratio (1.2117±0.0092) for the total melt analysis presented in Table 4 was corrected for the small contribution of trapped Ne assuming that trapped Ne is atmospheric and $(^{20}Ne/^{22}Ne)_{cosm}=0.8$ (EUGSTER *et al.*, 1993).

3.2.1. Cosmic-ray exposure age of Y-793605

As described before, cosmic-ray exposure age will give crucial information concerning the origin of Y-793605, *i.e.*, whether this meteorite was ejected from the Mars with other known martian meteorites. $^{21}Ne/^{22}Ne$ ratios for total melt and for 1000, 1300 and 1750°C of stepwise heating are higher than 0.8. This indicates negligible contribution of solar cosmic-ray produced Ne in this meteorite (GARRISON *et al.*, 1995), which is consistent with the observation of cosmic-ray produced radionuclides (NISHIIZUMI and CAFFEE, 1997). ^{3}He, ^{21}Ne, ^{38}Ar and ^{81}Kr concentrations are presented in Table 4. The high ratios of cosmogenic $^{22}Ne/^{21}Ne$ (=1.212) and $^{3}He/^{21}Ne$ (7.07 and

Table 4. Cosmogenic noble gases, production rates, cosmic-ray exposure ages, and K-Ar ages of the Y-793605 and the Bruderheim Std.

Sample	^{3}He	^{21}Ne	^{38}Ar	^{81}Kr	^{22}Ne	P_3	P_{21}	P_{38}
	$10^{-9}cm^3$ STP/g			$10^{-12}cm^3$ STP/g	^{21}Ne	$10^{-9}cm^3$ STP/g/Ma		
Y-793605,10								
Total melt (17.86 mg)	89.1	12.6	2.09	0.0182	1.2117 ±.0092	16.1[1]	2.18[1]	0.729[1]
Stepwise heating (50.99 mg)								
Total	83.5	11.2	1.76	0.0224	–	16.1[1]	2.18[1]	0.729[1]
Bruderheim Std. (32.5 mg)	550	116	13.0	0.0240	1.1001 ±.0018	16.2[4]	3.48[4]	0.433[5]

Sample	T_3	T_{21}	T_{38}	T_{av}	^{81}Kr-Kr[3]	K-Ar[6]
	Ma					Ma
Y-793605,10						
Total melt (17.86 mg)	5.53	5.78	2.87	5.4[2] ±.3	–	1860 ±160
Stepwise heating (50.99 mg)						
Total	5.19	5.14	2.41		–	1430 ±140
Bruderheim Std. (32.5 mg)	34.0	33.3	30.0	32 ±2	33±8	

[1] Production rates calculated using the formulas by EUGSTER and MICHEL (1995); [2] Average of T_3 and T_{21} for total melt and stepwise heating; [3] ^{81}Kr-Kr exposure age based on cosmogenic $^{78}Kr/^{83}Kr$ ratio; [4] Production rates using the formulas by EUGSTER (1988); [5] Production rate using the formula by SCHULTZ *et al.* (1991); [6] K concentration of 204 ppm was adopted (WARREN and KALLEMEYN, 1997).

7.49) indicate a small preatmospheric body for this meteorite, which is consistent with the small recovered mass (16 g). Concentration of ^{81}Kr ($1.8–2.2\times10^{-14}$cm^3 STP/g) of this meteorite, which must be a lower limit due to a radioactive decay after fall on the Earth, is in the range for chondrites (*e.g.*, EUGSTER, 1988; EUGSTER *et al.*, 1993). Concentrations of target elements for ^{81}Kr production, Sr, Rb, Zr, Y etc., should be similar or higher than those in chondrites. We failed to obtain a terrestrial age of this meteorite based on the cosmogenic Kr stable isotopes and ^{81}Kr due to large uncertainties in determination of cosmogenic ^{78}Kr/^{83}Kr, ^{80}Kr/^{83}Kr and ^{82}Kr/^{83}Kr ratios.

Production rates of ^{3}He, ^{21}Ne and ^{38}Ar for Y-793605 are calculated by the formulas proposed by EUGSTER and MICHEL (1995) for HED meteorites and the chemical compositions of Y-793605 reported by WARREN and KALLEMEYN (1997). Since the mineral assemblage of Y-793605 lherzolitic shergottite is similar to those of diogenites, we adopted the formulas for diogenites. Calculated exposure age based on the cosmogenic ^{3}He and ^{21}Ne concentrations are 5.1–5.8 Ma. Whereas exposure age of 2.4–2.9 Ma, about half of the ^{3}He and ^{21}Ne ages, is obtained by the cosmogenic ^{38}Ar concentrations and the production rates P_{38} (Table 4). Accuracy of concentrations of cosmogenic noble gases measured in this work are supported by the concordant cosmic-ray exposure ages, 30–34 Ma, obtained by the cosmogenic ^{3}He, ^{21}Ne, ^{38}Ar concentrations in the Bruderheim (L6) standard sample. ^{81}Kr-Kr exposure age of 33 ± 8 Ma for this meteorite agrees well to the ages. Main target element for ^{38}Ar production is Ca. As described above and shown in Table 1, main Ca-bearing minerals of the Y-793605 are high-Ca pyroxene, maskelynite and whitlockite. Hence most probable reason for the short exposure age, T_{38}, is a low concentration of Ca compared to the bulk chemical composition owing to a deficiency of these minerals in our small samples used for noble gas analyses.

Because only three martian meteorites are categorized as lherzolitic shergottites (MIKOUCHI and MIYAMOTO, 1996a, b) until now, it is very interesting to know whether Y-793605 was ejected by a common impact event which produced the ALH77005 and LEW88516 meteorites. If we adopt an average value of 5.4 ± 0.3 Ma (ranging 5.1–5.8 Ma) based on the ^{3}He and ^{21}Ne concentrations, Y-793605 seems to have longer exposure age compared to the other lherzolites, ALH77005 ($3.32\pm$ 0.53 Ma) and LEW88516 (3.98 ± 0.58 Ma) (EUGSTER *et al.*, 1997). ^{10}Be exposure age, $\geqq4.0$ Ma, is also longer than those of ALH77005 and LEW88516 (NISHIIZUMI and CAFFEE, 1997), which is consistent with our observation. Ejection ages, *i.e.*, exposure age plus terrestrial age, for ALH77005 and LEW88516 are proposed as 3.52 ± 0.60 Ma and $4.00\pm$ 0.60 Ma, respectively (EUGSTER *et al.*, 1997). The ejection age of Y-793605 is approximately same as the exposure age owing to the short ^{36}Cl terrestrial age, 35 ± 35 ky (<70 ky) (NISHIIZUMI and CAFFEE, 1997). If the exposure and ejection ages of Y-793605 are really different from those of ALH77005 and LEW88516, Y-793605 should have originated by an additional ejection event. However, close genetic relationship among these lherzolites as described above seems to require a common ejection event on Mars. If this is a case, the disagreement of exposure and ejection ages among them might have been caused by multistage irradiation process. In this scenario Y-793605 had been irradiated by cosmic-rays at a shallower depth in their parent body, Mars or a block ejected from Mars, before the final breakup which produced these lherzolitic meteorites. We expect to obtain information concerning the discordant ages from noble gas data on remaining glassy materials of Y-793605, 10 and Y-793605,73.

3.2.2. K-Ar age

Measured $^{40}Ar/^{36}Ar$ ratios are much lower than the high value (>2000) observed in martian atmosphere by the Viking lander (OWEN *et al.*, 1977). K-Ar age is calculated to be 1860±160 and 1430±140 Ma for total melt and stepwise heating samples, respectively, on the following assumptions; 1) K concentration of 204 ppm (WARREN and KALLEMEYN, 1997) with 10% uncertainty, 2) no trapped martian atmospheric Ar with high $^{40}Ar/^{36}Ar$ ratio (>2000), 3) measured ^{40}Ar concentrations are *in situ* produced radiogenic, and 4) experimental uncertainty in Ar concentrations is 10%. The K-Ar ages calculated based on the above assumptions are consistent with the young crystallization ages determined for martian meteorites (*e.g.*, MCSWEEN, 1994) except for the old one of ALH84001 orthopyroxenite (>3400 Ma; MIURA *et al.*, 1995; EUGSTER *et al.*, 1997; GOSWAMI *et al.*, 1997).

However, the K-Ar age for Y-793605 calculated above may not represent a real gas retention age. As described above, K presents only in maskelynite (0.2–0.4 wt%) and is undetectable in other minerals. Abundance of the maskelynite phase in our samples was estimated to be 5–10 % under microscopic observation, which is consistent with the reported K concentration of 204 ppm in bulk sample (WARREN and KALLEMEYN, 1997). As plagioclase (maskelynite) is surrounded by Ca-rich pyroxene, *in situ* produced radiogenic ^{40}Ar will be released at the eutectic melting temperature lower than 1270°C (BOWEN, 1956). Hence most of radiogenic ^{40}Ar is expected to be released from the K bearing mineral, maskelynite, at the temperatures of 700, 1000 and 1300°C during the stepwise heating experiment. However, $^{40}Ar/^{36}Ar$ ratios corrected for cosmogenic ^{36}Ar are almost constant in the 1000, 1300 and 1750°C fractions (Table 5), where 95% of total ^{40}Ar was released without any sharp release peaks. This may indicate that radiogenic ^{40}Ar might have been redistributed at the shock heating because this meteorite is heavily shocked (see mineralogy section). If radiogenic ^{40}Ar was lost partly at the shock heating, the calculated age would be a lower limit. Negligible abundance of radiogenic ^{4}He in this meteorite can be also explained by the shock degassing. On the other hand, we can consider another possibility that the high $^{40}Ar/^{36}Ar$ ratio at the high temperature, 1750°C, is due to martian crustal or atmospheric Ar trapped in Mg-rich pyroxene or olivine at their crystallization. Because the trapped martian atmospheric or crustal Ar with high $^{40}Ar/^{36}Ar$ if any in this meteorite will increase apparent K-Ar age, the calculated age must be an upper limit. Hence meaning of the calculated K-Ar age, 1430–1860 Ma, for Y-793605 is still ambiguous. ^{39}Ar-^{40}Ar experiment may clarify the K-Ar system of this meteorite.

3.2.3. Trapped noble gases

Concentrations of trapped light noble gases, He and Ne are negligibly small in our samples. Trapped ^{36}Ar, ^{84}Kr and ^{132}Xe concentrations are listed in Table 5. Trapped ^{36}Ar concentrations are calculated assuming $^{38}Ar/^{36}Ar$ ratios of 0.188 and 1.55 for trapped and cosmogenic Ar, respectively. All ^{84}Kr and ^{132}Xe are assumed to be trapped. Kr isotopic ratios are similar to those of terrestrial atmospheric values except for a small contribution of cosmogenic isotopes to the light Kr isotopes. Xe isotopic ratios as well as elemental compositions of trapped ^{36}Ar, ^{84}Kr and ^{132}Xe are examined in Figs.

Table 5. Trapped heavy noble gas composition and $^{40}Ar/^{36}Ar$ ratios corrected for cosmogenic Ar.

Sample	^{36}Ar	^{84}Kr	^{132}Xe	$^{36}Ar/^{132}Xe$	$^{84}Kr/^{132}Xe$	$^{40}Ar/^{36}Ar$ [1]
	$10^{-12}cm^3$ STP/g					
Y-793605,10						
Total melt (17.86 mg)	1970	82.5	15.8	125	5.22	1310
Stepwise heating (50.99 mg)						
700°C	178	32.2	11.6	15.3	2.78	458
1000°C	115	5.42	1.75	65.7	3.10	1180
1300°C	506	22.0	6.29	80.4	3.50	1360
1750°C	619	23.9	4.56	136	5.24	1310
1800°C	36.9	0.68	0.16	230	4.3	320
Total	1450	84.2	24.4	59.4	3.45	1190
Bruderheim Std. (32.5 mg)	550	116	13.0	37.7	0.658	2950

[1] Corrected for cosmogenic ^{36}Ar.

8–10. We could not obtain information to constrain martian $^{38}Ar/^{36}Ar$ ratio, though distinctly high ratio, 0.244±0.012, compared with those for Earth and meteorites are reported (*e.g.*, WIENS *et al.*, 1986; PEPIN, 1991).

In Fig. 8, trapped $^{36}Ar/^{132}Xe$ *vs.* $^{84}Kr/^{132}Xe$ ratios for Y-793605 are plotted on the trend for many martian meteorites and martian atmosphere. Terrestrial atmosphere is also on the extension of this trend as noted previously (OTT, 1988). Plotted elemental compositions for the lowest and the highest temperature fractions of Y-793605 are off from the trend. Released Kr and Xe abundances in these fractions are 39 and 48% of total Kr and Xe, respectively. Because isotopic ratios of Xe in the fractions are close to those of terrestrial atmosphere (Fig. 10), they are presumably terrestrial atmospheric contamination elementally fractionated by some contamination mechanisms and/or fractional release during the stepwise heating. On the other hand, the data points for middle temperatures, 1000, 1300 and 1750°C, which comprise more than 50% of total Kr and Xe, are plotted on the trend, which is different from the trend for chondrites (see datum point of Bruderheim chondrite). The datum point for total melt also plotted close to that of 1750°C fraction. Most achondrites such as HEDs and silicate phase of pallasites also belong to this trend (NAGAO, 1994), though the meaning of this trend is not clear yet. Some adsorption and/or sorption mechanisms to trap ambient noble gases with negligible fractionation effect on isotopic ratios would be responsible for the trend as reported by YANG *et al.* (1982).

The Y-793605 shows weak isotopic signature for shergottites in the plot of $^{129}Xe/^{132}Xe$ *vs.* $^{84}Kr/^{132}Xe$ (Fig. 9), where data points at the high temperature fractions 1000, 1300 and 1750°C lie roughly along the line connecting Chassigny and EETA79001 shergottite lithology C (glassy part). The ratios of Y-793605 differ from those of nakhlites and orthopyroxenite ALH84001, which have different trends as presented in the figure for comparison. Noble gases in Chassigny and EETA79001 lithology C may represent gases in martian mantle and in martian atmosphere, respective-

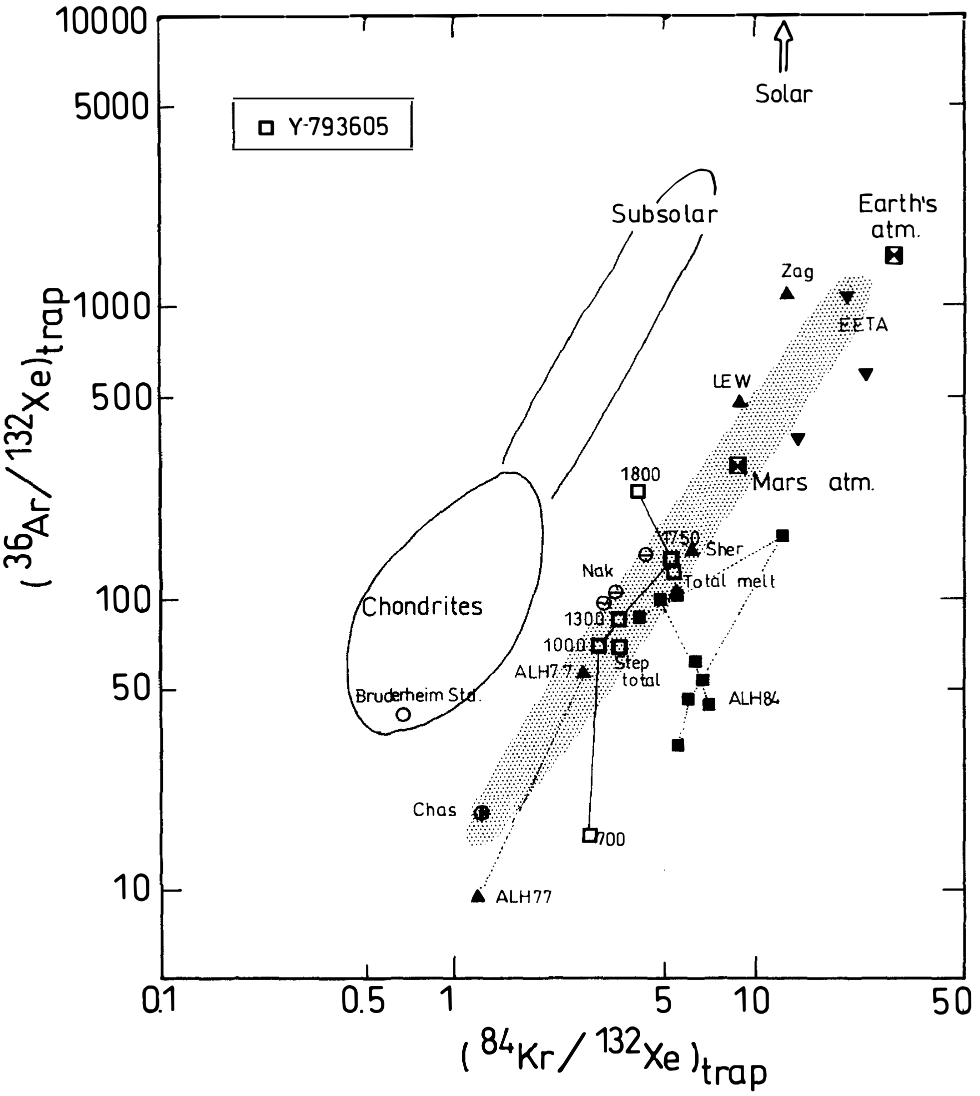

Fig. 8. Plot of trapped $^{36}Ar/^{132}Xe$ vs. $^{84}Kr/^{132}Xe$ ratios of Y-793605 martian meteorite and Bruderheim (L6). "Subsolar" is a component enriched in Ar observed in E-chondrites (CRABB and ANDERS, 1981). Data for martian atmosphere and meteorites are plotted for comparison (POLLACK and BLACK, 1982; BECKER and PEPIN, 1984; BOGARD et al., 1984; SWINDLE et al., 1986; OTT, 1988; OTT and LÖHR, 1992, MIURA et al., 1995). Zag–Zagami; EETA–EETA79001; LEW–LEW88516; Sher–Shergotty; Nak–Nakhla; ALH84–ALH84001; ALH77–ALH77005; Chas–Chassigny.

ly (SWINDLE *et al.*, 1986; BECKER and PEPIN, 1984; WIENS *et al.*, 1986). The datum point for 1750°C fraction is close to LEW88516, and both are along the trend for shergottites. Accordingly, noble gas compositions show that Y-793605 and LEW88516 are related to shergottites. Though the lowest (700°C) and the highest (1800°C) temperature fractions of Y-793605 and some data points for ALH77005 are plotted near the datum point of Chassigny, they likely represent elementally fractionated terrestrial atmosphere as demonstrated by atmospheric Xe isotopic ratios in Fig. 10 (For ALH77005, see MIURA *et al.*, 1995).

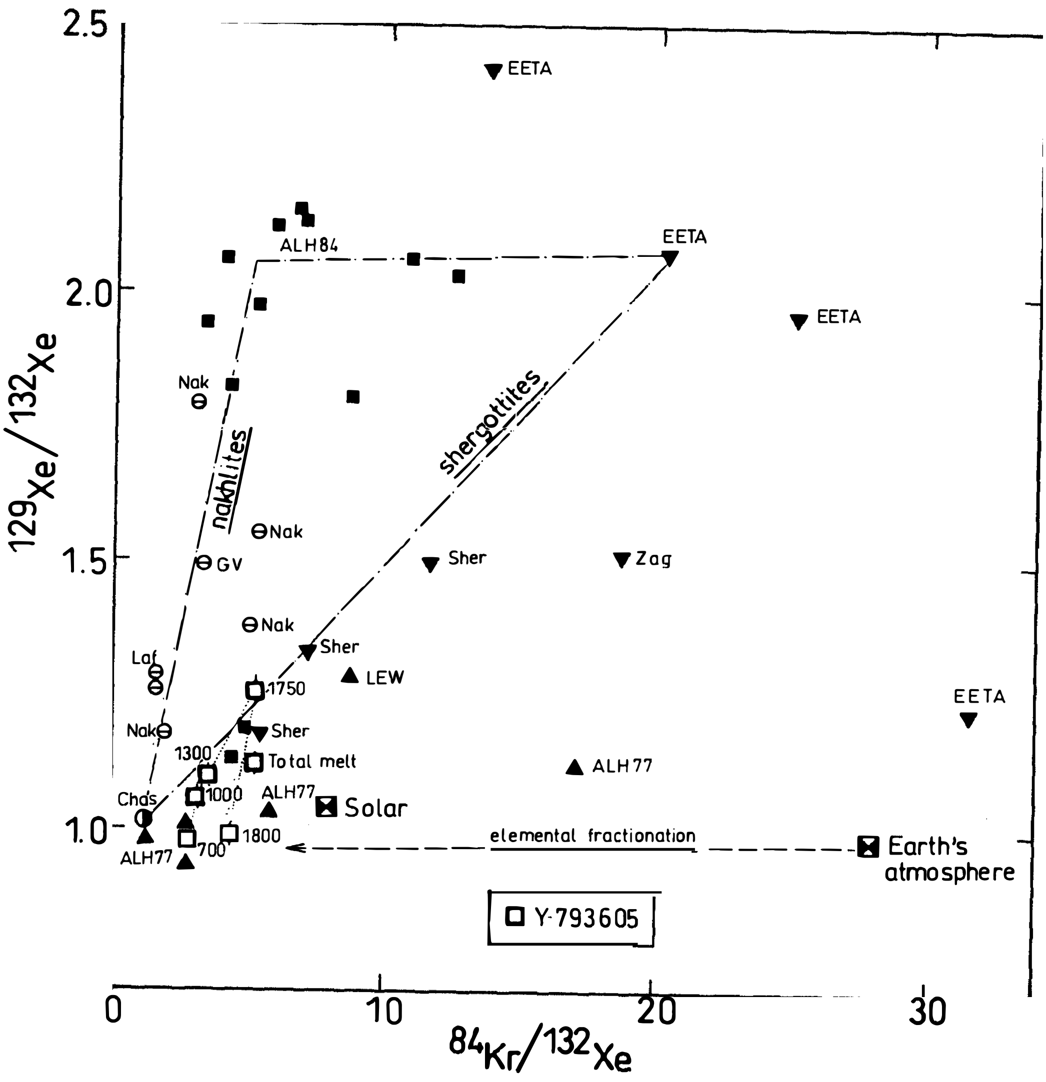

Fig. 9. Plot of $^{129}Xe/^{132}Xe$ vs. $^{84}Kr/^{132}Xe$ ratios for Y-793605. Data for other martian meteorites are from DRAKE *et al. (1994),* SWINDLE *et al. (1995) and* MIURA *et al. (1995). Laf–Lafayette; GV–Governador Valadares; for others see caption of Fig. 8.*

Figure 10 is a plot of ^{136}Xe/^{132}Xe *vs.* ^{129}Xe/^{132}Xe ratios. The ratios for 700 and 1800°C of Y-793605 are identical with the terrestrial atmospheric ones, and are clearly different from those of Chassigny. This indicates a possible contamination of terrestrial atmospheric Xe for the Y-793605 studied in this work. The high ^{136}Xe/^{132}Xe ratio in 1000°C fraction presumably indicates a release of fissiogenic ^{136}Xe or H-Xe along with the shergottite parent body (SPB) xenon (SWINDLE *et al.*, 1986). Mixture of terrestrial atmospheric Xe and SPB-Xe can explain the Xe isotopic ratios of 1300 and 1750°C fractions.

Xe isotopic ratios of Y-793605 show only a weak affinity to shergottites with SPB-Xe isotope signature. This may partly due to relatively large contamination of terrestrial atmospheric Xe owing to a low concentration of trapped martian Xe. The low concentrations of trapped heavy noble gas component would be due to the cumu-

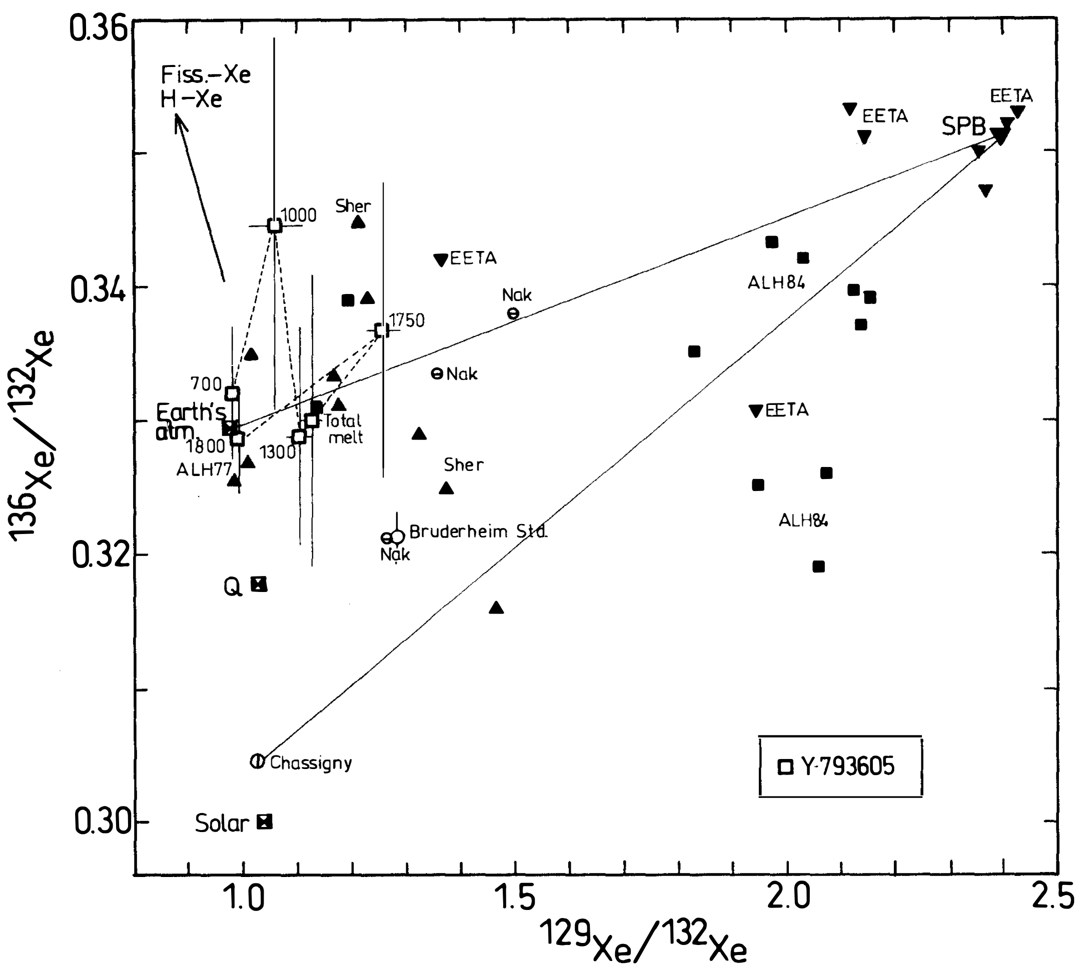

Fig. 10. Plot of $^{136}Xe/^{132}Xe$ vs. $^{129}Xe/^{132}Xe$ ratios of Y-793605 and Bruderheim (L6). Data for SPB (Shergottite Parent Body)-Xe and EETA79001 (SWINDLE et al., 1986), Solar (EBERHALDT et al., 1972), Q (WIELER et al., 1992) and SNCs (OTT, 1988) are shown for comparison.

late origin of this meteorite.

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