

Martian mantle signatures in Yamato nakhlites

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Abstract: We report nitrogen and heavy noble gas isotopic abundances in the Yamato nakhlites Y000593 and Y000749 and infer isotopic signatures for the magma source region in Mars. The nitrogen signature $\delta^{15}\text{N} = 13 \pm 1\%$ appears in broad plateau releases of both nakhlites and also has previously been observed in Nakhla and in Chassigny. This signature differs from the primitive indigenous nitrogen signature ($\delta^{15}\text{N} = -30\%$) and, strikingly, from nitrogen in the modern Martian atmosphere. It demonstrates that exchanges between the solid planet and its modern atmosphere have been very limited. The xenon isotopic records support this conclusion. In nakhlite Y000749 radiogenic ^{129}Xe is observed in one temperature fraction, while a five times larger component is observed in several steps of Y000593. The lack of an association with fission Xe or with indigenous Xe from the mantle source region suggests a crustal source. A crustal storage of the extinct ^{129}I was previously invoked to account for radiogenic ^{129}Xe in the Martian atmosphere. Fission Xe components due to extinct ^{244}Pu were identified in both nakhlites. These records show that the magma source region had assimilated and retained fission gas since the early differentiation of Mars. The measured concentrations of ^{40}Ar exceed the amounts produced from the decay of ^{40}K in 1.3 Ga and document that the magma inherited some radiogenic ^{40}Ar , together with fission gas. CRE ages based on spallation $^{15}\text{N}_e$ and ^{38}Ar are consistent with a reported ^{81}Kr - ^{83}Kr age and CRE ages for other nakhlites, confirming identical ejection ages for all nakhlites.

key words: Mars, nakhlites, fission xenon, radiogenic xenon, nitrogen signatures

1. Introduction

Chronologies based on extinct radionuclides in SNC meteorites (*e.g.* Halliday *et al.*, 2001) show that Mars accreted on time scales of several Ma. Constraints on the early evolution of Martian volatiles were obtained from fission xenon records in Chassigny and ALH84001 (Mathew and Marti, 2001) and in nakhlites (Mathew and Marti, 2002; Marty and Marti, 2002; Mathew *et al.*, 2003). The identification of mantle reservoirs is based on Chassigny data, which Mathew and Marti (2001) characterized as primitive component “Chass-S”, with a solar-type isotopic signature of Xe and a light nitrogen signature ($\delta^{15}\text{N} = -30\%$). This component was enriched in an olivine separate of Chassigny, lacking radiogenic ^{129}Xe and fission Xe. These properties can either be due to a late incorporation, after decay of ^{129}I and ^{244}Pu , or it may represent an interior

reservoir with substantial Xe concentrations, which could mask *in-situ* produced components.

Mathew and Marti (2001) noted that a second xenon component, Chass-E (Evolved), is related to Chass-S by the addition of fission Xe due to extinct ^{244}Pu . This Chass-E xenon signature implied that fission Xe was mixed with Chass-S Xe at the time of, or prior to, its incorporation. The fission gas is not due to *in-situ* decay of ^{244}Pu in Chassigny. Both Chass-S and Chass-E xenon components apparently represent indigenous reservoirs that are characterized by low $^{129}\text{Xe}/^{132}\text{Xe}$ (< 1.07) ratios. In those Chassigny samples Mathew and Marti (2001) also found light N ($\delta^{15}\text{N} \leq -21\%$) isotopic signatures (in the $\leq 300^\circ\text{C}$ extractions), while the heaviest observed signature in the low-temperature range was $\delta^{15}\text{N} = +15\%$ at 400°C . Light N ($\delta^{15}\text{N} = -30\%$) was interpreted to represent a primitive indigenous nitrogen signature.

The nakhlites from Yamato Mountains (Y000593 and Y000749) offer new opportunities to probe the Martian mantle. The research is carried out in consortium mode and permits petrographic, chemical and isotopic investigations on the same material (Misawa *et al.*, 2003). Marty and Marti (2002) argued that the presence of ^{244}Pu -derived fission Xe presents evidence for closed system evolution of the mantle, which indicates quite different geodynamic regimes for planets Earth and Mars. Records from these nakhlites may provide further insights into mantle characteristics, as well as data regarding the question of survival of extinct radionuclide signatures in events capable of resetting the ^{40}K - ^{40}Ar , ^{87}Rb - ^{87}Sr and ^{147}Sm - ^{143}Nd clocks recorded in the 1.3 Ga ages of nakhlites (*e.g.* Nyquist *et al.*, 2001). If exchanges with atmospheric gases did occur, also information on paleoatmospheres may be secured.

The Xe signatures observed in ALH84001 were interpreted to represent those of an ancient Martian atmosphere (Gilmour *et al.*, 1998; Mathew and Marti, 2001), while a more recent atmospheric signature, consistent with that of the modern atmosphere, was identified in a few temperature fractions of Nakhla (Mathew and Marti, 2002). The component with Chass-S xenon composition shows strong elemental fractionation in the heavy noble gas abundances: $^{36}\text{Ar}/^{132}\text{Xe}$ and $^{84}\text{Kr}/^{132}\text{Xe}$ ratios were constrained to be < 5 and < 1.1 , respectively (Mathew and Marti, 2001), and may be compared with estimated solar ratios $^{36}\text{Ar}/^{132}\text{Xe}$ and $^{84}\text{Kr}/^{132}\text{Xe}$ of 67000 and 20, respectively (Anders and Grevesse, 1989). If representative of the mantle, this evidence for noble gas fractionation may help to characterize differentiation processes during the formation of Mars. For example, an origin due to adsorption by carbon-rich matter during accretion of the Martian protoplanetesimals would favor heavy noble gases, and carbon sub-micron grains are efficient noble gas trappers (Niemeyer and Marti, 1981). These authors showed that trapped noble gases are loosely bound and elementally strongly fractionated, while no isotopic fractionations were detected. Their results also suggest, that if carbon-rich phases were in fact carriers of noble gases from early solar system reservoirs, the observed similarities in elemental fractionations for the atmospheres of planets Earth and Mars could be understood, even for fairly different trapping conditions. An identification of paleoatmospheric components could provide information for an assessment of isotopic evolutions during the period of heavy bombardment (Mathew *et al.*, 1998).

2. Mass spectrometry

Several fragments of both nakhlites Y000593 and Y000749 were wrapped in Au foils and loaded into the gas extraction and purification system. The meteorites were step-heated by an external resistance heater up to 1040°C in a double walled quartz system within a separately pumped vacuum jacket. Samples were then transferred *in vacuo* into a Mo crucible, mounted in a double walled quartz system with cooling water, for step-heating by radio frequency up to the melting temperature. Extraction blanks were measured at the same temperatures between sample measurements. The extraction blanks for N were 0.1–0.4 ng for the $\leq 1400^\circ\text{C}$ steps and was of atmospheric composition ($\delta^{15}\text{N}=0\pm 3\%$). Typical blanks for ^{36}Ar and ^{132}Xe (of atmospheric composition) were $1-3 \times 10^{-12} \text{ cm}^3\text{STP/g}$ and $1-2 \times 10^{-14} \text{ cm}^3\text{STP/g}$, respectively. Details of the analyzing procedure were described previously (Mathew and Marti, 2002). The propagated uncertainties in the isotope ratios include statistical errors and uncertainties in the discrimination and in blank corrections.

3. Fission Xe in nakhlites

A remarkable feature of the 1.3 Ga old NC meteorites, Chassigny as well as the nakhlites Nakhla and NWA817, is that they contain fission Xe components produced mostly by the decay of extinct ^{244}Pu . The Xe gas was released at temperatures above 900°C and was well mixed with indigenous (Chass-S) Xe. A model calculation of the initial ^{244}Pu content of Mars (Marty and Marti, 2002) suggests that it was consistent with the chondritic abundance. Since nakhlites are considered to represent cumulates of magmas derived from mantle reservoirs, Mathew *et al.* (2003) used Nd and U as adequate geochemical proxies for Pu to trace the behavior of Pu during fractionation processes. In a study of Xe isotopes in the Yamato nakhlites Okazaki *et al.* (2003) noted excesses in ^{136}Xe and suggested that fission xenon may be present.

We now discuss the Yamato nakhlite Xe data (Table 1) which show correlated excesses on all heavy Xe isotopes, and the relative yields identify the source as fission Xe from extinct ^{244}Pu , as was observed for other nakhlites (Mathew and Marti, 2002; Mathew *et al.*, 2003). We take the approach used by these authors to disentangle the various Xe components. In a first step, the spallation Xe component has to be evaluated and subtracted from the measured data. The Y000593 Xe data in the 800° and 900°C steps (Table 1) show only very small spallation components. For the higher temperature steps the subtraction method is used for fractions with constant fission to indigenous xenon ratios, but variable spallation components. The evaluated spallation Xe spectra show minor differences in the relative spallation yields, especially for the early releases. A slightly steeper spectrum and a very low relative ^{131}Xe yield may signal spallation yields from fractionated LREE in phosphates and glassy mesostasis (Wadhwa and Crozaz, 2003). Therefore, we adopt inferred spallation spectra as given in Appendix A, which reports the spallation-corrected Xe data. We see from the isotopic correlation of spallation-corrected ratios (Fig. 1) that all data plot close to the tie-line of Chass-S Xe and fission Xe. We further note in this figure that, although well-mixed components were reported in nakhlites (Mathew and Marti, 2002; Mathew

Table 1. Measured Xe isotopic abundances in Yamato nakhlites.

Temp. (°C)	¹³² Xe 10 ⁻¹² cm ³ /g	¹³² Xe = 1.00							
		¹²⁴ Xe	¹²⁶ Xe	¹²⁸ Xe	¹²⁹ Xe	¹³⁶ Xe	¹³¹ Xe	¹³⁴ Xe	¹³⁶ Xe
Yamato Nakhlite Y000749,51 (381 mg)									
800	0.859	0.0044 ±7	0.0040 9	0.0827 27	1.024 13	0.1570 25	0.7980 130	0.3880 30	0.3270 23
1000	4.217	0.0089 ±3	0.0138 3	0.0975 9	1.020 7	0.1660 15	0.8450 110	0.3840 20	0.3260 11
1200	7.678	0.0077 ±3	0.0087 2	0.0897 6	1.026 4	0.1634 8	0.7980 45	0.3880 25	0.3290 15
1400	3.941	0.0312 ±10	0.0483 15	0.1406 15	1.160 4	0.1902 13	0.9160 25	0.3974 12	0.3300 10
1550	2.370	0.0116 ±6	0.0147 7	0.0945 16	1.035 6	0.1620 15	0.8240 35	0.3910 20	0.3320 16
Yamato Nakhlite Y000593,85 (484 mg)									
600	0.643	0.0037 ±8	0.0036 7	0.0796 18	1.096 10	0.1530 15	0.8090 100	0.3870 52	0.3319 43
800	0.815	0.0042 ±7	0.0033 7	0.0813 13	1.174 9	0.1560 14	0.8150 95	0.3852 48	0.3284 41
900	0.786	0.0044 ±8	0.0038 7	0.0822 14	1.203 10	0.1573 14	0.8180 96	0.3861 45	0.3281 39
1000	1.928	0.0258 ±10	0.0422 11	0.1376 12	1.278 9	0.1840 11	0.8570 74	0.3880 37	0.3300 30
1200	1.080	0.0078 ±6	0.0105 7	0.0889 11	1.047 8	0.1580 12	0.8220 85	0.3908 38	0.3371 32
1400	5.130	0.0166 ±8	0.0256 9	0.1082 9	1.253 7	0.1680 10	0.8410 76	0.3946 33	0.3365 29
1550	4.676	0.0565 ±10	0.0916 13	0.2019 10	1.329 7	0.2290 10	0.9450 80	0.3923 31	0.3183 27
1650	0.458	0.0546 ±12	0.0904 14	0.1992 13	1.319 11	0.2241 13	0.9510 91	0.3918 38	0.3207 33

The ¹³²Xe concentrations are in units (10⁻¹² cm³STP/g); only data for temperature steps ≥ 800°C are given (low temperature extractions were consistent with terrestrial Xe). Uncertainties included are those in the least significant figures of the isotopic ratios (95% confidence levels).

et al., 2003), some variability is present in the Yamato nakhlites. Some temperature fractions plot halfway between data of Chass-E and the other Yamato temperature fractions and reveal fission Xe/Chass-S Xe mixing ratios which are smaller. These systematics indicate that although fission gas has generally been well assimilated in the nakhlite magma, complete mixing with indigenous Chass-S Xe was not achieved. The isotope ratios shown in Fig. 2 permit the identification of the fission source. First, we note a confirmation of varying mixing ratios fission Xe/indigenous Xe and a trend line which documents that the fission component is dominated by Xe from extinct ²⁴⁴Pu, but minor contributions from ²³⁸U can not be excluded. However, *in situ*-produced fission Xe from ²³⁸U during 1.3 Ga, based on the measured U abundance of 55 ppb (Dreibus *et al.*, 2003) can only account for ~5% of the observed fission Xe (Table 1). Figures 1

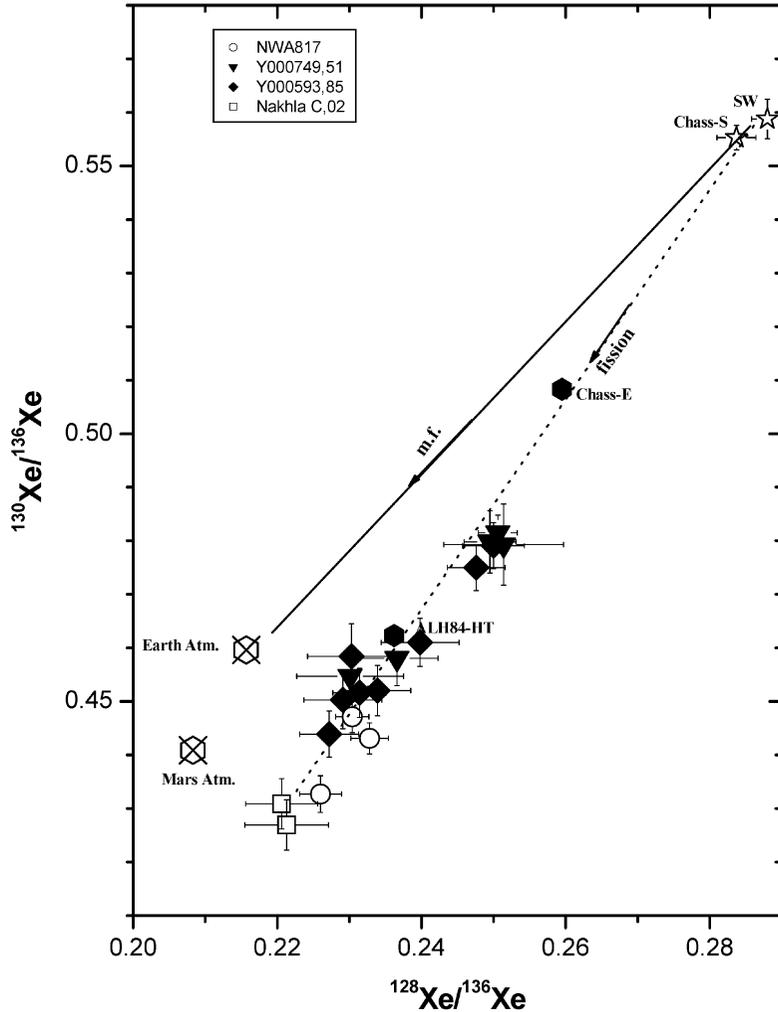


Fig. 1. Spallation-corrected $^{130}\text{Xe}/^{136}\text{Xe}$ vs. $^{128}\text{Xe}/^{136}\text{Xe}$ ratios (Appendix A) in Y000749, Y000593 and other nakhlites. Isotopic shifts due to the addition of fission Xe components to Chass-S Xe are not uniform, but the observed shifts exceed those due to fission of ^{238}U in 1.3 Ga. NWA 817 data are from Mathew *et al.* (2003), Nakhla data are from Mathew and Marti (2002) and Chass-S and Chass-E data are from Mathew and Marti (2001).

and 2 further illustrate that Y000749 Xe data cannot be explained as mixtures of modern Martian atmospheric Xe components with fission gas. We return to this issue again when we discuss ^{129}Xe data.

4. Radiogenic ^{129}Xe on Mars

There has been controversy in the literature (Drake *et al.*, 1994; Okazaki *et al.*, 2003) regarding the origin of the ^{129}Xe excesses in nakhlites, since the data do not fit a

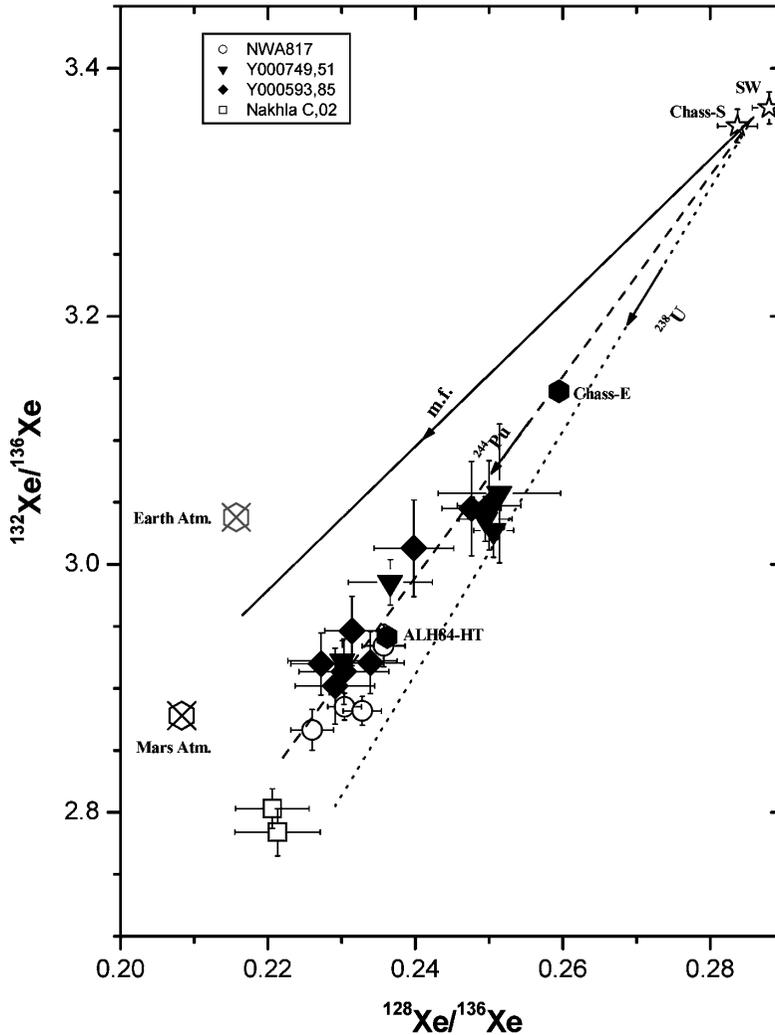


Fig. 2. Xe isotopic ratios (Appendix A) $^{132}\text{Xe}/^{136}\text{Xe}$ vs. $^{128}\text{Xe}/^{136}\text{Xe}$ in Y000749, Y000593 and other nakhlites. The shifts due to a fission Xe component identify extinct ^{244}Pu as the major contributor. NWA817, Nakhla and Chassigny data are from the same sources as Fig. 1.

tie-line of Chassigny-S (Mars mantle) and Mars atmosphere (Fig. 3), as observed in shergottite glasses. Therefore, the suggestion was made that nakhlite xenon data are affected by iddingsite with a low ratio $^{84}\text{Kr}/^{132}\text{Xe}=6$, which might suggest elemental fractionation in the iddingsite formation process on Mars. On the other hand, Mathew and Marti (2002) in their study of Nakhla showed that Xe data in the temperature steps 800° to 1000°C fit such a tie-line and probably represent a modern atmospheric component. However, the $>1000^\circ\text{C}$ data of Nakhla show indigenous Xe with the Chassigny-S isotopic composition, and are inconsistent with isotopic signatures of modern atmospheric gases. A different source for radiogenic ^{129}Xe excesses is required, as

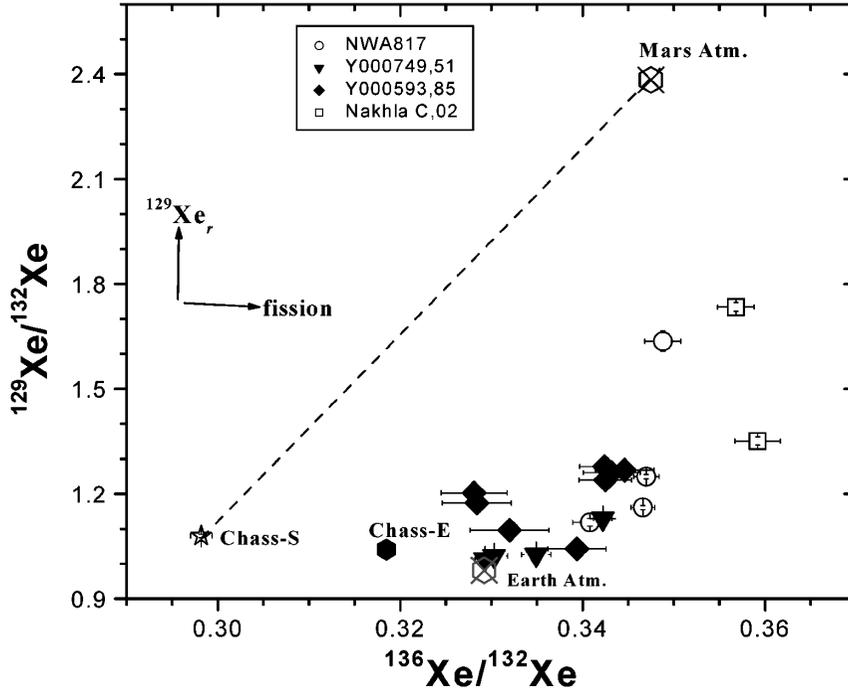


Fig. 3. Plot of the spallation-corrected $^{129}\text{Xe}/^{132}\text{Xe}$ vs. $^{136}\text{Xe}/^{132}\text{Xe}$ ratios (Appendix A) in Y000749, Y000593 and other nakhlites. Mixtures of Chass-S Xe with Martian atmospheric Xe cannot explain the observed trends. Figure also shows that radiogenic ^{129}Xe excesses and fission excesses are decoupled.

mantle (Chass-S) Xe does not carry such excesses. Mathew *et al.* (2003) confirmed variable excesses of radiogenic $^{129}\text{Xe}_r$ in recently discovered SNC meteorites which are not related to the modern Martian atmosphere. The observed excesses of radiogenic ^{129}Xe in nakhlites indicate a source inside the solid planet.

More information on the source of radiogenic ^{129}Xe can be found by analyzing the associations with interior components. We discussed the fission component in the Yamato nakhlites and can use the data in Appendix A to assess a correlation of $^{129}\text{Xe}_r$ with fission gas. ^{129}I ($t_{1/2} = 16$ Ma) and ^{244}Pu are now extinct, but radiogenic and fission Xe components recorded decay processes in the early history of Mars. If the observed radiogenic $^{129}\text{Xe}_r$ component was cycled through the mantle, it should be well mixed with the fission component which in turn was rather well mixed with indigenous mantle Xe, as discussed earlier. In Fig. 3 (see also Table 1) we observe variable ratios $^{129}\text{Xe}/^{132}\text{Xe}$, which are decoupled from those of fission Xe and indigenous mantle gas. While in nakhlite Y000749 only the 1400°C step shows a radiogenic component, the Y000593 data show only one temperature step (1200°C) lacking a radiogenic component. Radiogenic ^{129}Xe (3.0×10^{-12} cm³STP/g) is about 5 × larger than in Y000749, and ratios $^{129}\text{Xe}_r/^{136}\text{Xe}_f$ are 4.4 and 0.7, respectively. This record shows that although radiogenic ^{129}Xe was not stored and mixed in the nakhlite magma source, it represents a radiogenic

component from extinct ^{129}I and must have been stored in the solid planet. In their study of xenon isotope correlations in nakhlites Y000593, Y000749 and Y000802, Okazaki *et al.* (2003) noted that there is no simple correlation between excesses of fission ^{136}Xe and radiogenic ^{129}Xe , and they suggest that the excess could come from the Mars atmosphere. However, this interpretation has to be rejected, since indigenous Xe in the nakhlites has the isotopic signature of Chass-S xenon and differs from atmospheric Xe.

Martian crustal storage and assimilation into the ascending magma is an option. The ^{129}I storage in the crust during the early differentiation of Mars, and a release of radiogenic ^{129}Xe , after its decay were suggested by Dreibus and Wänke (1987) and by Musselwhite and Drake (2000) to account for the high ratio $^{129}\text{Xe}/^{132}\text{Xe}$ in the present atmosphere. Dreibus and Wänke (1987) noted that iodine is an incompatible and highly volatile element which could have been extracted from hot rock in the interior, in the presence of water, and incorporated into crustal rock. Musselwhite and Drake (2000) determined the solubility of iodine in a range of synthetic basaltic liquids and found values which exceed the solubility of Xe by a few orders of magnitude. They suggest that in a second stage of outgassing the atmospheric $^{129}\text{Xe}/^{132}\text{Xe}$ can be explained, if it follows a stage of an efficient removal of atmospheric gases by hydrodynamic escape and impact erosion. In these models assimilation of crustal radiogenic xenon into the lava (probably by means of a crustal carrier) may account for variable amounts in the two paired nakhlites, as well as the observed lack of correlation between radiogenic and fission components. Depletion of iodine in the mantle during the early large-scale differentiation event (*e.g.* Halliday *et al.*, 2001; Blichert-Toft *et al.*, 1999), is supported by the near absence of radiogenic ^{129}Xe , in Chass-S xenon. Since an assimilation of crustal material in lavas is here implied, are there other records which support such an origin? The heavy nitrogen signature in the modern Martian atmosphere contrasts with light ancient nitrogen ($\delta^{15}\text{N} \sim -30\%$) as observed in ALH84001 (Marti and Mathew, 2000), but nitrogen signatures in the Martian crust have not been studied.

5. Nitrogen in nakhlites

Nitrogen concentrations in Yamato nakhlites (Table 2) are similar to those in Nakhla, but smaller than in NWA 817 (Mathew *et al.*, 2003). The isotopic signatures observed in stepwise pyrolysis of the Yamato nakhlites are reported in Table 2 and are shown in Fig. 4. The low-temperature data ($<300^\circ\text{C}$) are afflicted by terrestrial contaminants; the temperature fractions in Y000749 show a small component of light nitrogen. In Y000749 a broad release plateau (500° to 1040°C) with signature $\delta^{15}\text{N} = +13\%$ was observed. A high-resolution investigation of this component was carried out in nakhlite Y000593. The broad plateau with $\delta^{15}\text{N} = +13\%$ was confirmed in a total of 13 steps over an intermediate temperature range from 350° to 1040°C , before a spallation $^{15}\text{N}_c$ component appears in steps above this temperature. This nitrogen component is not only observed in the Yamato nakhlites, but also in the plateau-release of Nakhla (Mathew and Marti, 2002), in Chassigny (Mathew and Marti, 2001), and apparently also in high-temperature steps of NWA817 (Mathew *et al.*, 2003). These

Table 2. N concentrations and isotopic signatures in the Yamato nakhlites Y000749,51 and Y000593,85.

Sample	T (°C)	N (ppm)	$\delta^{15}\text{N}$ (‰)	Sample	T (°C)	N (ppm)	$\delta^{15}\text{N}$ (‰)
Nakhlite	180	0.005	-3.4 ±3.9	Nakhlite	120	0.007	3.9 ±4.4
Y000749,51 (381 mg)	250	0.12	-2.4 ±3.7	Y000593,85 (484 mg)	200	0.032	0.1 ±1.7
	300	0.06	-3.4 ±2.4		250	0.038	1.0 ±2.2
	400	0.01	6.0 ±3.1		300	0.082	3.3 ±1.4
	500	0.04	6.1 ±2.0		350	0.102	6.7 ±1.8
	600	0.17	10.8 ±1.2		400	0.072	13.9 ±1.6
	700	0.14	12.4 ±3.2		450	0.061	13.7 ±2.4
450C	0.10	2.0 ±0.8		500	0.052	13.3 ±3.5	
800	0.061	12.0 ±0.5		550	0.074	13.8 ±1.2	
900	0.017	13.1 ±4.7		600	0.081	13.2 ±1.5	
1040	0.026	12.8 ±3.0		650	0.089	13.7 ±1.4	
1200	0.116	60.3 ±2.2		700	0.119	13.2 ±1.6	
1400	0.191	114.0 ±2.8		750	0.126	13.0 ±0.8	
1650	0.054	95.3 ±4.9		800	0.076	13.2 ±0.9	
Total		1.11		850	0.087	13.8 ±1.4	
				900	0.091	12.9 ±1.0	
				950	0.030	13.5 ±1.3	
				1040	0.031	13.1 ±1.8	
				1200	0.084	59.1 ±2.5	
				1400	0.162	68.2 ±2.0	
				1550	0.176	109.0 ±2.2	
				1650	0.019	65.6 ±4.2	
				Total		1.691	

data show the presence of nitrogen with this signature in nakhlite magma sources in the Martian mantle.

From the observed excesses in $\delta^{15}\text{N}$ (relative to the +13‰ signature) in steps above 1040°C we calculate spallation concentrations $^{15}\text{N}_c = 134$ and 118 pg in Y000593 and Y000749, respectively. This yields an average CRE age of 11 ± 1 Ma, if a production rate $P_{15} = 11.6 \text{ pgMa}^{-1}$ for $^{15}\text{N}_c$ (Mathew *et al.*, 2003) is used. The $^{15}\text{N}_c$ -derived CRE age is consistent with reported CRE ages of other nakhlites (Nyquist *et al.*, 2001;

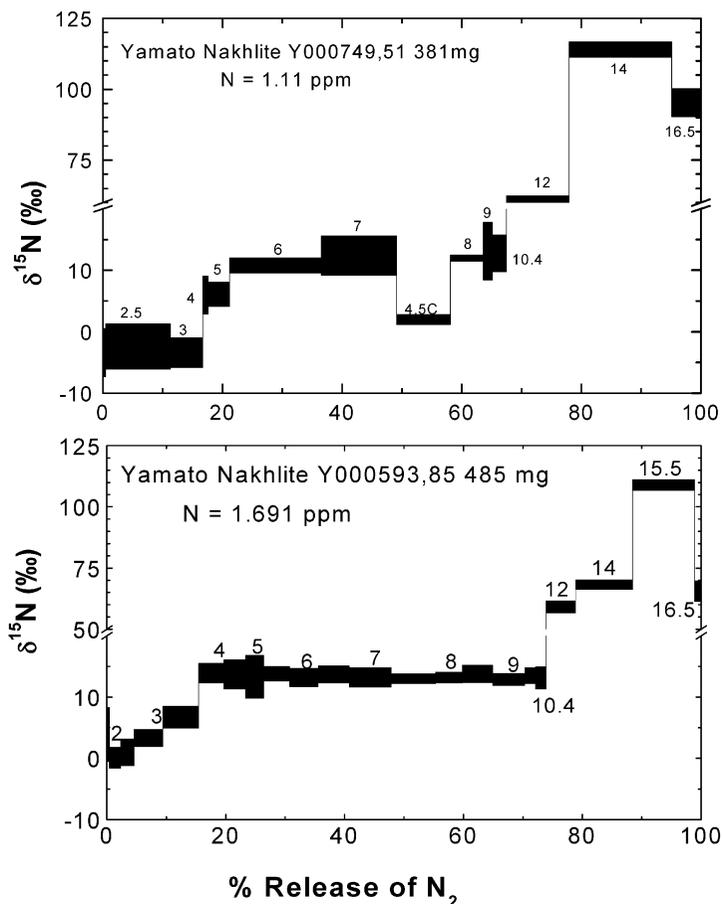


Fig. 4. Release systematics of nitrogen in the nakhlites Y000749 and Y000593. The plateau release in the $<1040^\circ\text{C}$ steps show the indigenous N signature and the excursions to heavy N in the high temperature steps signal spallation $^{15}\text{N}_c$. The cosmic ray exposure age calculated from these spallation $^{15}\text{N}_c$ excesses is consistent with the other CRE ages of nakhlites. Extraction temperatures (in hundreds of degrees) are marked close to the data bars. For Y000749 a combustion step in oxygen (at 450°C , marked 4.5C in upper panel) was sequentially added after the 700°C pyrolysis step and is not considered part of the plateau.

Mathew *et al.*, 2003; Okazaki *et al.*, 2003). This supports the implicit assumption that indigenous N in the high-temperature steps and in the plateau steps are the same component.

6. K-Ar ages and ejection times from Mars

The time of ejection from Mars is calculated as the sum of the CRE and the terrestrial age. Okazaki *et al.* (2003) determined a ^{81}Kr - ^{83}Kr age of 11.8 ± 1.0 Ma for Y000593 and give a limit for the terrestrial age <0.04 Ma. These authors use produc-

Table 3. Measured heavy noble gas concentrations and Ar isotopic ratios (95% confidence limits).

Sample	T (°C)	^{36}Ar	$^{40}\text{Ar}/^{36}\text{Ar}$	$^{36}\text{Ar}/^{38}\text{Ar}$	$^{38}\text{Ar}_c$	^{132}Xe	$^{129}\text{Xe}/^{132}\text{Xe}$	$^{36}\text{Ar}/^{132}\text{Xe}$	$^{84}\text{Kr}/^{132}\text{Xe}$
Nakhlite	180	0.118	303 ±26	5.30 ±0.15		0.1	0.98	118	3.8
Y000749,51	250	0.452	316 ±21	5.30 ±0.09		0.31	0.98	145	3.2
(381 mg)	350	0.754	358 ±16	4.58 ±0.05	0.03	0.93	0.98	79	3.6
	450	3.50	525 ±10	4.28 ±0.04	0.18	4.12	0.98	82	3.8
	550	2.10	4160 ±8	3.80 ±0.03	0.18	1.40	0.98	142	4.0
	700	1.73	8660 ±19	2.10 ±0.02	0.57	1.59	0.98	85	4.1
	800	4.02	10280 ±32	1.15 ±0.02	3.12	0.86	1.024	232	4.1
	1000	3.54	9980 ±15	1.32 ±0.03	2.30	4.22	1.02	49	3.8
	1200	7.03	1355 ±8	1.36 ±0.02	4.38	7.68	1.026	54	3.8
	1400	98.8	28 ±1.3	0.683 ±0.004	144.4	3.94	1.16	126	4.1
	1550	30.3	48 ±1.4	0.708 ±0.005	42.1	2.37	1.035	123	4.1
	>550	145			197	20.7			
Nakhlite	200	0.120	298 ±21	5.20 ±0.20		0.10	0.98	120	3.8
Y000593,85	300	0.351	305 ±12	5.20 ±0.15		0.31	0.98	113	3.6
(484 mg)	400	0.364	420 ±11	4.2 ±0.20	0.02	0.40	0.98	88	3.4
	500	3.11	528 ±6	4.28 ±0.08	0.16	4.12	0.98	73	3.8
	600	0.830	4860 ±6	1.40 ±0.03	0.50	0.64	1.096	79	3.9
	800	1.50	8860 ±9	0.841 ±0.008	1.72	0.82	1.174	48	4.0
	900	3.65	10800 ±9	0.859 ±0.005	4.06	0.79	1.203	129	3.6
	1000	4.66	6880 ±8	0.823 ±0.005	5.48	1.93	1.278	57	3.6
	1200	4.13	3870 ±5	0.734 ±0.004	5.56	1.08	1.047	50	3.7
	1400	17.2	640 ±4	0.720 ±0.003	23.5	5.13	1.253	37	3.7
	1550	74.50	45 ±1.3	0.682 ±0.003	108.9	4.68	1.329	85	3.7
	1650	24.64	42 ±1.4	0.664 ±0.003	37.25	0.46	1.319	129	3.8
	>500	131			186.3	15.5			

The data are corrected for blanks and mass discrimination. The ^{36}Ar and $^{38}\text{Ar}_c$ abundances are in units $10^{-10}\text{cm}^3\text{STP/g}$ and a spallation ratio $^{36}\text{Ar}/^{38}\text{Ar}=0.65$ is adopted, the ^{132}Xe abundances are in $10^{-12}\text{cm}^3\text{STP/g}$.

tion rates according to Eugster and Michel (1995) for the ^{21}Ne —ages of 11.9 Ma for both Y000593 and Y000749, consistent with the ^{81}Kr – ^{83}Kr age and with CRE ages obtained for other nakhlites (Nyquist *et al.*, 2001; Mathew *et al.*, 2003). This also confirms the identical ejection ages for all nakhlites.

The spallation $^{38}\text{Ar}_c$ component is released as early as 350°C and peaks at 1400° to 1550°C. The $^{38}\text{Ar}_c$ concentrations (Table 3) are 18.6×10^{-9} and $19.7 \times 10^{-9}\text{cm}^3\text{STP/g}$

for Y000593 and Y000749 are both consistent with the reported CRE age.

Okazaki *et al.* (2003), assuming a negligible contribution from Martian atmospheric ^{40}Ar , reported K- ^{40}Ar age of 1.24 ± 0.22 Ga. This assumption appears appropriate, since nitrogen and xenon records do not show an atmospheric component. A non-radiogenic $^{40}\text{Ar}/^{36}\text{Ar}$ ratio similar to the indigenous ratio $^{40}\text{Ar}/^{36}\text{Ar} = 207$ ratio (Mathew and Marti, 2001) is inferred from the data (Table 3), a ratio which does not affect the budget. From measured ^{40}Ar concentrations (Table 3) and concentration of K (Dreibus *et al.*, 2003; Oura *et al.*, 2003) we calculate crystallization ages in excess of the reported 1.3 Ga age for nakhlites (Nyquist *et al.*, 2001), ~ 1.6 Ga for Y000593 and ~ 1.5 Ga for Y000749. These excesses suggest that radiogenic ^{40}Ar was inherited by the magma.

7. Magmatic fractionation

Two scenarios were considered by Mathew *et al.* (2003) for the presence of ^{244}Pu -derived fission Xe in nakhlites. In the first option Xe components, consisting of fission Xe gas mixed with indigenous mantle Xe, were either added in variable proportions to nakhlite parent magmas, or fractionated to variable extents. A magmatic fractionation is implied by the composition of nakhlites, which could have taken place at any time after ^{244}Pu decay. A second option was mentioned suggesting that ^{244}Pu was still alive during magmatic episodes, an option consistent with the apparent trend that fission Xe is enriched in nakhlites together with U and the REE. In both scenarios the Xe components were enriched in the liquid during the course of magma generation. We may model the evolution of the fission component in the mantle during the period from the early differentiation to the recorded 1.3 Ga event, assuming a U abundance of 12 ppb. The size of this fission component is $^{136}\text{Xe}_f = 26 \times 10^{-15} \text{ cm}^3\text{STP/g}$. The component produced after differentiation (during the past 1.3 Ga) using a U concentration of 55 ppb (Dreibus *et al.*, 2003), would add $42 \times 10^{-15} \text{ cm}^3\text{STP/g}$, but the total fission component would only amount to $\sim 8\%$ of the observed average fission component ($0.8 \times 10^{-12} \text{ cm}^3\text{STP/g}$). An inferred shift due to a calculated ^{238}U -fission component would be difficult to observe in Fig. 2. Yamashita *et al.* (2003) report Pb isotopic systematics in Y000593 which indicate that no isotopic equilibration was achieved, but they suggest that the source material was subjected to two differentiation events. The first event represents the initial differentiation as recorded in the products of extinct ^{244}Pu , ^{146}Sm and ^{182}Hf . Closed-system behavior of noble gases in the mantle requires sufficient pressure and, therefore, depth for the evolving liquids, of quantities which are not well known for Mars. Since LREE, as proxies for ^{244}Pu , are strongly enriched in the mesostasis and in phosphates (Wadhwa and Crozaz, 2003), the observed trend of an enrichment of fission Xe in NWA817 (Mathew *et al.*, 2003) simply may reflect variable mesostasis abundance (Imae *et al.*, 2003; Mikouchi *et al.*, 2003).

8. Conclusions

1) Isotopic abundances of nitrogen and of heavy noble gases in nakhlites Y000593 and Y000749 were studied for signatures of the magma source region. A nitrogen

component with $\delta^{15}\text{N}=13\pm 1\%$ is observed in plateau releases of both Yamato nakhlites; it has previously been observed in Nakhla and also in Chassigny.

2) In nakhlite Y000749 radiogenic ^{129}Xe is observed in one temperature fraction, while a much larger component is observed in several steps of Y000593. The lack of an association with fission Xe as well as with indigenous Xe from the mantle source region indicates a crustal source.

3) Fission Xe components due to extinct ^{244}Pu are identified in both nakhlites. The records show that the magma source region had assimilated and retained fission gas since the early differentiation of Mars.

4) The measured concentrations of ^{40}Ar exceed the amounts produced from the decay of ^{40}K in 1.3 Ga and suggest that the magma inherited some radiogenic ^{40}Ar .

5) CRE ages based on spallation $^{15}\text{N}_c$ and ^{38}Ar are consistent with the ^{81}Kr - ^{83}Kr age (Okazaki *et al.*, 2003) and CRE ages for other nakhlites (Nyquist *et al.*, 2001; Mathew *et al.*, 2003), confirming identical ejection ages for all nakhlites.

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Appendix A. Spallation-corrected Xe isotopic ratios in Y000749,51 and Y000593,85.

Temp. (°C)	¹³² Xe 10 ⁻¹² cm ³ /g	¹³⁶ Xe = 1.00							
		¹²⁴ Xe	¹²⁶ Xe	¹²⁸ Xe	¹²⁹ Xe	¹³⁰ Xe	¹³¹ Xe	¹³² Xe	¹³⁴ Xe
Yamato Nakhlite Y000749,51									
800*	0.858	0.0130 ±21	0.0113 28	0.2514 83	3.1299 397	0.4793 76	2.4386 397	3.0572 560	1.1863 214
1000*	4.181	0.0103 ±27	0.0113 9	0.2495 36	3.0762 227	0.4798 58	2.5332 358	3.0365 181	1.1686 63
1200#	7.645	0.0146 ±18	0.0112 6	0.2506 27	3.0942 132	0.4815 33	2.3936 148	3.0274 217	1.1748 85
1400#	3.792	0.0162 ±41	0.0112 44	0.2301 74	3.2989 126	0.4547 53	2.4919 103	2.9222 161	1.1637 64
1550#	2.348	0.0157 ±33	0.0111 21	0.2366 57	3.0645 174	0.4581 51	2.4123 116	2.9855 183	1.1678 71
Yamato Nakhlite Y000593,85									
600	0.643	0.0111 ±24	0.0108 21	0.2398 54	3.3022 301	0.4610 45	2.4375 301	3.0130 390	1.1660 157
800	0.815	0.0128 ±21	0.0100 21	0.2476 40	3.5749 286	0.4750 43	2.4817 289	3.0451 380	1.1730 146
900	0.786	0.0132 ±24	0.0113 21	0.2500 43	3.6660 305	0.4791 43	2.4926 293	3.0475 362	1.1767 137
1000*	1.918	0.0140 ±41	0.0112 33	0.2303 61	3.6744 277	0.4584 61	2.3753 244	2.9136 242	1.1408 126
1200*	1.079	0.0120 ±26	0.0110 21	0.2314 37	3.0716 248	0.4516 46	2.4001 261	2.9463 269	1.1532 119
1400#	5.114	0.0116 ±34	0.0110 27	0.2272 41	3.6195 207	0.4439 43	2.3626 238	2.9197 263	1.1531 108
1550#	4.637	0.0173 ±43	0.0116 41	0.2339 46	3.7335 232	0.4520 47	2.3890 254	2.9208 251	1.1496 113
1650#	0.458	0.0135 ±39	0.0115 44	0.2291 54	3.6803 354	0.4503 46	2.3977 261	2.9019 306	1.1406 123

The ¹³²Xe data are corrected for spallation adopting a spallation spectrum obtained by the subtraction method.

* Adopted spallation spectrum of ¹²⁴Xe: ¹²⁶Xe: ¹²⁸Xe: ¹²⁹Xe: ¹³⁰Xe: ¹³¹Xe: ¹³²Xe: ¹³⁴Xe ≡ 0.55 ± 0.10: = 1.00: 1.60 ± 0.10: 1.70 ± 0.20: 0.95 ± 0.10: 1.90 ± 0.30: 1.0 ± 0.3: 0.3 ± 0.1.

Adopted spallation spectrum of ¹²⁴Xe: ¹²⁶Xe: ¹²⁸Xe: ¹²⁹Xe: ¹³⁰Xe: ¹³¹Xe: ¹³²Xe: ¹³⁴Xe ≡ 0.58 ± 0.10: = 1.00: 1.45 ± 0.05: 1.60 ± 0.15: 0.85 ± 0.06: 2.1 ± 0.3: 0.8 ± 0.2: 0.3 ± 0.1.

Uncertainties listed are those in the least significant figures of the isotopic ratios (95% confidence levels). The uncertainties in the isotopic ratios include variations by assuming lower (and upper) limits of the spallation spectrum.