



**HAL**  
open science

# **A chondritic Martian mantle revealed by the heavy noble gas composition of the chassignite NWA 8694**

Sandrine Péron, Sujoy Mukhopadhyay

## ► **To cite this version:**

Sandrine Péron, Sujoy Mukhopadhyay. A chondritic Martian mantle revealed by the heavy noble gas composition of the chassignite NWA 8694. *Geochimica et Cosmochimica Acta*, 2025, 392, pp.137-147. <10.1016/j.gca.2025.01.002>. <insu-04991779>

**HAL Id: insu-04991779**

**<https://insu.hal.science/insu-04991779v1>**

Submitted on 14 Mar 2025

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

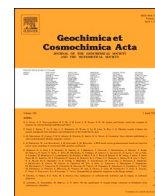


Distributed under a Creative Commons CC BY-NC-ND 4.0 - Attribution - Non-commercial use - No Derivative Works - International License





Contents lists available at ScienceDirect

# Geochimica et Cosmochimica Acta

journal homepage: [www.elsevier.com/locate/gca](http://www.elsevier.com/locate/gca)

## A chondritic Martian mantle revealed by the heavy noble gas composition of the chassignite NWA 8694

Sandrine Péron<sup>\*</sup> , Sujoy Mukhopadhyay<sup>1</sup> 

Department of Earth and Planetary Sciences, University of California, Davis, Davis, CA 95616, USA

### ARTICLE INFO

Associate editor: Yves Marrocchi

#### Keywords:

Mars  
Chassignites  
Volatile origin  
Noble gases  
Planet accretion  
Atmosphere formation

### ABSTRACT

Accretion of volatile elements is a critical step to make a planet habitable. It is often assumed that terrestrial planets initially captured solar gases from the nebula, which are partially ingassed into their interior during the magma ocean phase, and then chondritic and/or cometary volatiles are delivered during the main accretion phase or after. Recent krypton isotopic measurements of the Martian meteorite Chassigny have however shown that chondritic volatiles were acquired on Mars in the first Myr of Solar System formation before nebular capture. Yet, Martian mantle is heterogeneous, with multiple reservoirs as evidenced with the hydrogen isotopic composition of shergottites, and it is unclear if this is also the case for noble gases. In this study, we investigate the noble gas (Ne, Ar, Kr, Xe) isotopic and elemental composition of the chassignite NWA 8694, which constitutes a link between chassignites and nakhlites, via laser step-heating in order to assess potential heterogeneities of the Martian mantle. Similar to Chassigny, we found evidence for high Ar, Kr and Xe abundances, potentially at least one order of magnitude higher than in the Earth's mantle, in the NWA 8694 mantle source based on a low  $^{40}\text{Ar}/^{36}\text{Ar}$  ratio. We also found a chondritic component and a Martian atmospheric component in NWA 8694, the latter with fractionated Ar/Kr/Xe elemental ratios compared to Mars' atmosphere. This Martian atmosphere component was possibly introduced through aqueous alteration by surface fluids, as observed in MIL nakhlites. The chondritic component corresponds to the composition of the NWA 8694 mantle source and hence confirms previous observation in Chassigny. A chondritic Martian mantle is in stark contrast with the presence of solar Kr and Xe in the Martian atmosphere. This suggests that chondritic volatiles were delivered to terrestrial planets in the first Myr of Solar System formation in presence of the nebula. Solar gases in the atmosphere could have been captured from the nebula afterwards or delivered by material similar to comets. If captured from the nebula, it would require the solar gases to be trapped either in polar ice caps or the regolith so as not to be lost via hydrodynamic escape after the nebula dissipates. Alternatively, delivery of solar gases associated with comets could occur after cessation of hydrodynamic escape on Mars, but the one comet (67P/C-G) that has been measured so far does not show a pure solar-like Xe and Kr isotopic composition.

### 1. Introduction

The history of volatile elements (i.e., hydrogen, carbon, nitrogen) on terrestrial planets is critical to understanding how a planet becomes habitable (e.g., Hirschmann and Dasgupta, 2009; Peslier et al., 2017). Models of volatile accretion on terrestrial planets often assume that planets captured a primordial atmosphere from the solar nebula, that was partially ingassed into a magma ocean (Harper and Jacobsen, 1996; Mizuno et al., 1980; Pepin and Porcelli, 2002). This solar signature was subsequently modified by fractionation during gravitational escape of

the atmosphere and addition of chondritic and/or cometary volatiles during the main phase of accretion or during a late veneer phase (Harper and Jacobsen, 1996; Pepin and Porcelli, 2002). However, the sources and subsequent evolution of volatiles on terrestrial planets are highly debated (Albarède, 2009; Alexander et al., 2012; Halliday, 2013; Marty, 2012; Moreira, 2013; Péron et al., 2021; Piani et al., 2020). For instance, most volatile elements show a chondritic isotopic composition (Albarède, 2009; Alexander et al., 2012; Broadley et al., 2020; Holland et al., 2009; Marty, 2012; Péron et al., 2021; Piani et al., 2020), and so whether the interior of terrestrial planets acquired gases from the nebula

<sup>\*</sup> Corresponding author at: Institut des Sciences de la Terre d'Orléans, UMR 7327, Université d'Orléans, CNRS, BRGM, OSUC, F-45071 Orléans, France.  
E-mail address: [sandrine.peron@cnrs-orleans.fr](mailto:sandrine.peron@cnrs-orleans.fr) (S. Péron).

<sup>1</sup> Present address: School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287, USA.

<https://doi.org/10.1016/j.gca.2025.01.002>

Received 4 September 2024; Accepted 6 January 2025

Available online 11 January 2025

0016-7037/© 2025 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

remains an open question. While the neon isotopic composition of the Earth's mantle is "solar-like" (e.g., Honda et al., 1991; Moreira, 2013; Williams and Mukhopadhyay, 2018), acquisition of this solar signature has been debated between solar-wind irradiation of Earth's precursors (Moreira, 2013; Péron et al., 2018) and dissolution of solar gases into the mantle captured from the nebula (Mukhopadhyay, 2012; Williams and Mukhopadhyay, 2018), and it is debated whether other terrestrial planets have solar gases in their interiors.

Since Mars is a planetary embryo, mostly formed in the first 4 Myr of Solar System formation (Dauphas and Pourmand, 2011), the volatile composition of Mars provides an observational window into volatile accretion and evolutionary processes during the early phase of terrestrial planets formation. Being highly volatile and chemically inert, noble gases are unique tracers of volatile sources as well as of physical processes affecting volatiles during and after accretion, like mantle degassing, regassing, and atmospheric volatile loss (e.g., Avice et al., 2018b; Marty et al., 2019; Moreira, 2013; Mukhopadhyay and Parai, 2019; Parai, 2022). In particular, the isotopic ratios of two non-radiogenic noble gas isotopes record information about the volatile sources, while isotopic ratios of radiogenic isotopes provide information about timing of volatile delivery, degassing and loss (e.g., Avice et al., 2018b; Marty et al., 2019; Moreira, 2013; Mukhopadhyay and Parai, 2019; Parai, 2022).

The trapped noble gases of the Martian meteorite Chassigny are very distinct from the Martian atmospheric composition and are thought to represent the Martian interior composition (Mathew and Marti, 2001; Ott, 1988; Swindle, 2002). Based on xenon isotopic analyses of Chassigny, it was argued that the Martian interior contained solar xenon, and by inference solar krypton (Mathew and Marti, 2001; Ott, 1988), like in the Martian atmosphere (Avice et al., 2018a; Conrad et al., 2016; Mathew et al., 1998). The Martian atmosphere has solar krypton and fractionated xenon isotopes, consistent with a starting solar xenon component (Avice et al., 2018a; Conrad et al., 2016; Mathew et al., 1998). Thus, there would be no clear evidence for chondritic heavy noble gases on Mars, and it has been assumed that the presence of solar heavy noble gases in the Martian atmosphere was the result of degassing from the Martian mantle, which inherited solar gases from ingassing of a primordial captured atmosphere (Avice et al., 2018a; Mathew and Marti, 2001).

The xenon isotopic composition of Chassigny is, however, ambiguous with respect to fingerprinting a solar volatile source for the Martian interior (Moreira, 2013), and recent high-precision krypton isotopic measurements of Chassigny show a clear chondritic component with no indication for a solar component in the Martian mantle (Péron and Mukhopadhyay, 2022). Since the Martian mantle shows heterogeneities in the hydrogen isotopic composition, reflecting multiple water reservoirs (Barnes et al., 2020), whether the Martian mantle is also heterogeneous for heavy noble gases remains unclear. To address this issue, here we investigate the noble gas composition of NWA 8694, the third chassignite discovered after Chassigny and NWA 2737 (Hewins et al., 2020; Udry et al., 2020). NWA 8694 represents a direct link between chassignites and nakhlites based on mineralogy and geochemical composition (Hewins et al., 2020) as well as on heavy noble gas elemental composition (Nagao et al., 2019). Chassignites and nakhlites likely come from the same shield volcano but different magma bodies and have similar crystallisation and ejection ages (Hewins et al., 2020; McCubbin et al., 2013; Udry and Day, 2018; Udry et al., 2020). The chassignite NWA 2737 was shown to have lost its Martian mantle gases but contain Martian atmospheric noble gases (Marty et al., 2006). Therefore, NWA 8694 is an appropriate sample to investigate potential Martian mantle noble gas heterogeneities.

## 2. Material and methods

The methods used in this study are similar to that described in Péron and Mukhopadhyay (2022) and in Péron et al. (2020), with some

differences that are explained below.

### 2.1. Samples

Samples of NWA 8694 were provided by the French National Museum of Natural History (MNHN). The samples were small fragments, less than 1-cm size, and were devoid of fusion crust. Samples were cleaned in acetone and then loaded in pre-degassed tantalum capsules. One capsule was loaded with 35.9 mg and a second one with 43.6 mg.

### 2.2. Noble gas analyses

The two sample capsules, as well as an empty and pre-degassed tantalum capsule for blank analyses, were loaded in an ultra-high vacuum laser chamber with a sapphire view port. To protect the view port, a sapphire cover slip was added on top of the sample holder. The chamber was baked at  $\sim 100$  °C for 24 h in order to remove atmospheric noble gases adsorbed on the chamber and processing line. As in Péron and Mukhopadhyay (2022), noble gases were extracted by step-heating between 250 °C and 1600 °C with a 150 W Teledyn Photon Machines Fusions Diode laser (wavelength = 810 nm), which is coaxially aligned with a single-color optical pyrometer. The procedure used to calibrate the pyrometer is given in Péron and Mukhopadhyay (2022).

After extraction, gases were purified with a hot (400 °C) and then a cold NP10 SAES getter, and then trapped on a Janis stainless steel cryogenic trap at 7 K. A second cryogenic trap with activated charcoal was used to effectively separate the heavy noble gases (Ar, Kr, Xe) from each other. The procedure used for separation is very similar to protocol 2 in Péron et al. (2020) with one temperature cycle before each separation, except that one of the cryogenic traps is filled with activated charcoal instead of being a stainless steel trap.

Noble gases were analyzed sequentially with a Noblesse HR (Nu instruments) mass spectrometer fitted with two Faraday cups and six electron multipliers (2F6M). The filament voltage was kept at  $-78$  V and the trap current was at 250  $\mu$ A for all analyses. Neon isotopes,  $^{20}\text{Ne}$ ,  $^{21}\text{Ne}$  and  $^{22}\text{Ne}$ , were analyzed in multicollection on electron multipliers on the right side of the peaks, where interference between  $^{20}\text{Ne}^+$  and  $^{40}\text{Ar}^{++}$  is resolved. Signals of  $\text{HF}^+$  and  $\text{CO}_2^+$  were measured to correct  $^{20}\text{Ne}^+$  and  $^{22}\text{Ne}^+$  signals, respectively, using a  $\text{CO}_2^+/\text{CO}_2^+$  ratio that was determined to be  $0.0064 \pm 0.0003$ . Argon isotopes,  $^{36}\text{Ar}$ ,  $^{38}\text{Ar}$  and  $^{40}\text{Ar}$ , were measured in multicollection, with  $^{40}\text{Ar}$  on a Faraday cup and the non-radiogenic argon isotopes on electron multipliers. Krypton isotopes were measured in three steps, all on electron multipliers, with first  $^{78}\text{Kr}$ ,  $^{82}\text{Kr}$  and  $^{86}\text{Kr}$ , followed by  $^{80}\text{Kr}$  and  $^{84}\text{Kr}$  and finally  $^{83}\text{Kr}$ . Xenon isotopes were analyzed in two steps on electron multipliers, with  $^{124}\text{Xe}$ ,  $^{126}\text{Xe}$ ,  $^{129}\text{Xe}$ ,  $^{130}\text{Xe}$ ,  $^{132}\text{Xe}$ ,  $^{136}\text{Xe}$  measured in the first step and  $^{126}\text{Xe}$ ,  $^{128}\text{Xe}$ ,  $^{131}\text{Xe}$ ,  $^{132}\text{Xe}$  and  $^{134}\text{Xe}$  measured in the second step.

Sensitivities and mass discriminations of the mass spectrometer were assessed through repeat analyses of an air standard. Blank analyses were carried out as for the samples through heating of an empty tantalum capsule (i.e., hot blanks). Blanks were below 1 % for Ne, and so the neon data are not blank-corrected because blanks are negligible and have an atmospheric composition (Table 1). The Ar, Kr and Xe data (Tables 1, 2 and 3) are corrected for blanks, blank proportions being between 1–16 %, 5–24 % and 1.4–24 % for Ar, Kr, Xe, respectively. There was a blank problem during the 1200 °C step of capsule 2 compromising the Ar, Kr and Xe analyses, but not the Ne measurement, which is why the Ar, Kr and Xe data are not reported for this step. For the 1600 °C step of capsule 1, only the Ne measurement is reported because the sapphire cover slip used to protect the view port broke during this step heating, compromising the heavy noble gas analyses.

When sample analyses were started the 30 min long cold blanks (i.e., line blank isolated for 30 min, which is the duration of each heating step for sample and hot blank) were below  $2.7 \times 10^{-14}$  ccSTP,  $5.2 \times 10^{-13}$  ccSTP,  $1.7 \times 10^{-14}$  ccSTP,  $6.4 \times 10^{-16}$  ccSTP for  $^{22}\text{Ne}$ ,  $^{36}\text{Ar}$ ,  $^{84}\text{Kr}$  and  $^{130}\text{Xe}$ , respectively.

**Table 1**

Neon and argon abundances and isotopic compositions of NWA 8694. The  $^{40}\text{Ar}/^{36}\text{Ar}$  corrected ratio is the  $^{40}\text{Ar}/^{36}\text{Ar}$  ratio corrected for cosmogenic contribution on  $^{36}\text{Ar}$ . The values considered for the Earth's atmosphere (air standard) are reported (Eberhardt et al., 1965; Nier, 1950; Sano et al., 2013). Uncertainties are 1sigma. n.a. stands for not analyzed, due to analytical issues, Ar, Kr, Xe were not measured in the 1200 °C step of capsule 2 and in the 1600 °C step of capsule 1 (refer to text).

T (°C)	$^{22}\text{Ne}$ ( $\times 10^{-9}$ ccSTP/g)	$\sigma$	$^{20}\text{Ne}/^{22}\text{Ne}$	$\sigma$	$^{21}\text{Ne}/^{22}\text{Ne}$	$\sigma$	$^{36}\text{Ar}$ ( $\times 10^{-10}$ ccSTP/g)	$\sigma$	$^{38}\text{Ar}/^{36}\text{Ar}$	$\sigma$	$^{40}\text{Ar}/^{36}\text{Ar}$	$\sigma$	$^{40}\text{Ar}/^{36}\text{Ar}$ corrected	$\sigma$
<b>NWA 8694 (35.9 mg, capsule 1)</b>														
250	0.054	0.001	1.7617	0.0184	0.657	0.013	1.69	0.03	0.2175	0.0008	678.0	11.7	693.5	11.9
500	0.54	0.01	0.9137	0.0027	0.776	0.004	3.42	0.05	0.2788	0.0015	2272.2	32.0	2437.3	34.3
950	2.95	0.03	0.8002	0.0020	0.829	0.003	5.43	0.06	0.5629	0.0011	2719.0	10.6	3766.4	14.7
1150	6.02	0.08	0.8180	0.0009	0.825	0.004	6.27	0.07	1.2176	0.0024	314.3	0.2	1324.9	0.9
1250	4.77	0.06	0.8208	0.0009	0.820	0.004	6.80	0.08	0.9570	0.0026	307.5	0.3	714.8	0.6
1400	4.48	0.06	0.8183	0.0009	0.819	0.004	5.42	0.08	1.0531	0.0059	164.3	1.1	457.7	3.1
1500	1.93	0.03	0.8228	0.0009	0.816	0.004	7.57	0.09	1.1497	0.0025	118.9	0.5	413.5	1.9
1600	1.71	0.02	0.8220	0.0009	0.815	0.004	n.a.		n.a.		n.a.			
<b>NWA 8694 (43.6 mg, capsule 2)</b>														
250	0.042	0.001	1.8898	0.0199	0.675	0.014	1.72	0.04	0.2134	0.0015	531.9	11.2	542.4	11.4
500	0.50	0.01	0.9340	0.0024	0.798	0.004	2.08	0.05	0.3187	0.0030	2626.1	57.5	2909.0	63.7
950	7.28	0.11	0.8163	0.0010	0.825	0.003	2.27	0.03	0.6308	0.0022	3262.1	23.1	4856.8	34.4
1200	7.32	0.11	0.8115	0.0010	0.826	0.003	n.a.		n.a.		n.a.			
1250	5.13	0.05	0.8216	0.0008	0.822	0.003	7.89	0.09	1.3637	0.0023	139.2	0.3	1078.4	2.5
1400	3.04	0.04	0.8214	0.0009	0.818	0.004	4.59	0.07	1.2307	0.0055	128.7	1.1	565.7	4.8
1500	4.72	0.05	0.8214	0.0008	0.817	0.003	8.23	0.09	1.1653	0.0020	109.2	0.3	395.7	1.2
<b>Earth's atmosphere (used as standard)</b>														
			9.80		0.029				0.188		295.5			

**Table 2**

Krypton abundance and isotopic composition of NWA 8694. The values considered for the Earth's atmosphere (air standard) are reported (Basford et al., 1973). Uncertainties are 1sigma.

T (°C)	$^{84}\text{Kr}$ ( $\times 10^{-12}$ ccSTP/g)	$\sigma$	$^{78}\text{Kr}/^{84}\text{Kr}$	$\sigma$	$^{80}\text{Kr}/^{84}\text{Kr}$	$\sigma$	$^{82}\text{Kr}/^{84}\text{Kr}$	$\sigma$	$^{83}\text{Kr}/^{84}\text{Kr}$	$\sigma$	$^{86}\text{Kr}/^{84}\text{Kr}$	$\sigma$
<b>NWA 8694 (35.9 mg, capsule 1)</b>												
250	4.28	0.07	0.00633	0.00042	0.0404	0.0010	0.2056	0.0032	0.2015	0.0030	0.3098	0.0045
500	4.04	0.08	0.00715	0.00048	0.0405	0.0011	0.1997	0.0033	0.2052	0.0033	0.2994	0.0048
950	20.3	0.14	0.00976	0.00032	0.0509	0.0007	0.2161	0.0021	0.2189	0.0019	0.3014	0.0029
1150	4.54	0.08	0.01572	0.00066	0.0679	0.0020	0.2390	0.0033	0.2469	0.0034	0.3039	0.0039
1250	5.41	0.09	0.00998	0.00041	0.0510	0.0015	0.2133	0.0027	0.2188	0.0030	0.3023	0.0038
1400	4.31	0.09	0.00685	0.00039	0.0390	0.0013	0.2040	0.0025	0.2037	0.0027	0.3130	0.0039
1500	6.77	0.12	0.00720	0.00034	0.0416	0.0012	0.2031	0.0022	0.2026	0.0024	0.3100	0.0033
<b>NWA 8694 (43.6 mg, capsule 2)</b>												
250	3.48	0.06	0.00753	0.00049	0.0417	0.0010	0.2025	0.0033	0.2073	0.0034	0.3058	0.0046
500	2.53	0.06	0.00670	0.00057	0.0439	0.0014	0.2077	0.0042	0.2004	0.0038	0.3050	0.0057
950	12.7	0.10	0.00924	0.00037	0.0472	0.0007	0.2119	0.0025	0.2145	0.0022	0.3056	0.0033
1250	4.54	0.08	0.01085	0.00046	0.0516	0.0014	0.2208	0.0025	0.2173	0.0028	0.3099	0.0036
1400	2.36	0.07	0.00728	0.00051	0.0422	0.0016	0.2072	0.0029	0.2018	0.0032	0.3008	0.0045
1500	8.94	0.10	0.00651	0.00025	0.0389	0.0009	0.2013	0.0018	0.2007	0.0019	0.3110	0.0027
<b>Earth's atmosphere (used as standard)</b>												
			0.00609		0.0396		0.2022		0.2014		0.3052	

### 3. Results

#### 3.1. Neon and argon isotopic compositions

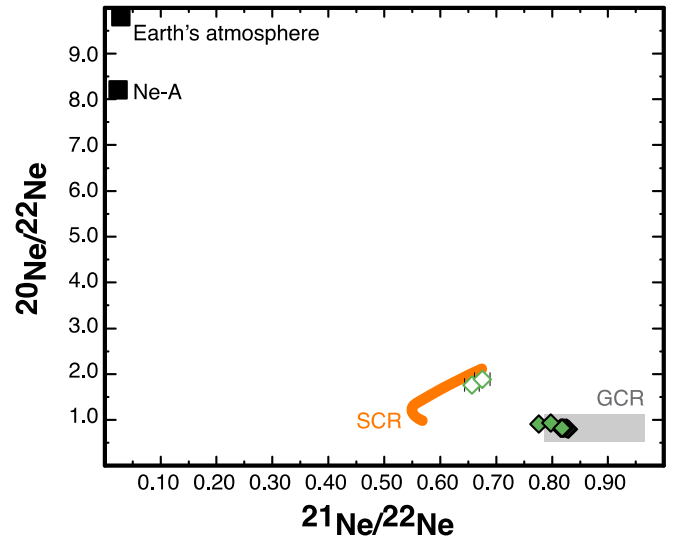
The Ne data are plotted in Fig. 1. Most of the heating steps have a Ne isotopic composition typical of cosmogenic Ne produced from Galactic Cosmic Rays or GCR (Wieler, 2002; Wieler et al., 2016). The two low temperature steps (at 250 °C) deviate from the GCR composition and have a Ne isotope composition close to cosmogenic Ne produced from Solar Cosmic Rays or SCR (Reedy, 1992; Wieler et al., 2016). The range of SCR cosmogenic Ne was calculated based on NWA 8694 composition (Hewins et al., 2020) and the production rates determined for target elements for shielding depths between 0.5 and 10 g/cm<sup>2</sup> (Reedy, 1992). Overall, all the heating steps have a Ne isotope composition intermediate between SCR and GCR Ne. SCR Ne has been commonly found in Martian meteorites (Garrison et al., 1995; Roth et al., 2017; Wieler et al.,

2016). Alternatively, the low temperature steps may represent a trapped Martian component in NWA 8694. In that case, the trapped component is interpreted to have a  $^{20}\text{Ne}/^{22}\text{Ne}$  of  $5.89 \pm 0.64$  (Fig. S1 in Supplementary Information) based on the intersection between the regression line through the measured neon data and the line joining the meteorite component Ne-A (Black and Pepin, 1969) and Earth's atmosphere.

The  $^{40}\text{Ar}/^{36}\text{Ar}$  ratio is corrected for cosmogenic contribution on  $^{36}\text{Ar}$  (Table 1), considering a cosmogenic  $^{38}\text{Ar}/^{36}\text{Ar}$  ratio of 1.538 (Wieler, 2002) and the Phase Q  $^{38}\text{Ar}/^{36}\text{Ar}$  ratio of 0.1873 (Busemann et al., 2000) for the trapped component. Phase Q is likely a carbonaceous phase carrying the majority of Kr and Xe in chondrites and sometimes the only carrier in achondrites (Busemann et al., 2000; Busemann and Eugster, 2002). While porous carbon, possibly graphene, was identified as a carrier of Q gases in meteorites (Amari et al., 2013), as along with sulfides (Marrocchi et al., 2015), the precise origin of phase Q is still debated (e.g., Marrocchi et al., 2015). Notwithstanding the origin of Q,

**Table 3**  
Xenon abundance and isotopic composition of NWA 8694. The values considered for the Earth's atmosphere (air standard) are reported (Basford et al., 1973). Uncertainties are 1sigma.

T (°C)	$^{130}\text{Xe}$ ( $\times 10^{-13}$ ccSTP/g)	$\sigma$	$^{124}\text{Xe}/^{130}\text{Xe}$	$\sigma$	$^{126}\text{Xe}/^{130}\text{Xe}$	$\sigma$	$^{128}\text{Xe}/^{130}\text{Xe}$	$\sigma$	$^{129}\text{Xe}/^{130}\text{Xe}$	$\sigma$	$^{131}\text{Xe}/^{130}\text{Xe}$	$\sigma$	$^{132}\text{Xe}/^{130}\text{Xe}$	$\sigma$	$^{134}\text{Xe}/^{130}\text{Xe}$	$\sigma$	$^{136}\text{Xe}/^{130}\text{Xe}$	$\sigma$	
<b>NWA 8694 (35.9 mg, capsule 1)</b>																			
250	4.25	0.13	0.0258	0.0017	0.0197	0.0010	0.484	0.007	6.58	0.07	5.22	0.05	6.53	0.06	2.54	0.03	2.11	0.02	
500	2.22	0.15	0.0238	0.0018	0.0137	0.0017	0.470	0.011	7.25	0.11	5.09	0.08	6.34	0.07	2.43	0.04	2.08	0.02	
950	16.4	0.27	0.0310	0.0009	0.0348	0.0011	0.491	0.003	8.33	0.04	5.15	0.03	6.50	0.03	2.53	0.02	2.16	0.01	
1150	3.32	0.11	0.0288	0.0007	0.0237	0.0009	0.478	0.003	7.98	0.11	4.64	0.06	5.31	0.06	2.05	0.03	1.73	0.02	
1250	8.33	0.20	0.0288	0.0007	0.0237	0.0009	0.478	0.003	6.56	0.06	4.92	0.05	6.05	0.06	2.31	0.03	1.95	0.02	
1400	6.64	0.17	0.0281	0.0018	0.0284	0.0011	0.489	0.006	6.65	0.06	5.21	0.05	6.58	0.06	2.54	0.03	2.13	0.02	
1500	4.72	0.12	0.0326	0.0016	0.0322	0.0028	0.493	0.009	6.62	0.07	5.12	0.05	6.32	0.05	2.46	0.03	2.05	0.01	
<b>NWA 8694 (43.6 mg, capsule 2)</b>																			
250	6.45	0.18	0.0236	0.0013	0.0235	0.0007	0.480	0.005	6.56	0.05	5.26	0.04	6.59	0.05	2.59	0.03	2.16	0.02	
500	1.04	0.07	0.0149	0.0016	0.0182	0.0034	0.486	0.019	6.84	0.14	4.88	0.10	6.02	0.09	2.26	0.06	1.89	0.02	
950	21.7	0.32	0.0261	0.0008	0.0269	0.0006	0.478	0.003	7.33	0.04	5.20	0.03	6.56	0.03	2.55	0.02	2.16	0.01	
1250	6.81	0.16	0.0641	0.0033	0.0799	0.0044	0.554	0.007	6.66	0.05	5.04	0.04	6.23	0.05	2.39	0.03	2.01	0.01	
1400	8.52	0.17	0.0269	0.0015	0.0261	0.0007	0.481	0.005	6.57	0.04	5.25	0.04	6.60	0.05	2.56	0.02	2.16	0.02	
1500	11.0	0.17	0.0247	0.0011	0.0241	0.0007	0.477	0.004	6.55	0.04	5.19	0.04	6.57	0.04	2.53	0.02	2.13	0.01	
<b>Earth's atmosphere (used as standard)</b>																			
			0.0234	0.0218	0.0471	0.0471	6.50	5.21	6.61	2.56	2.18								



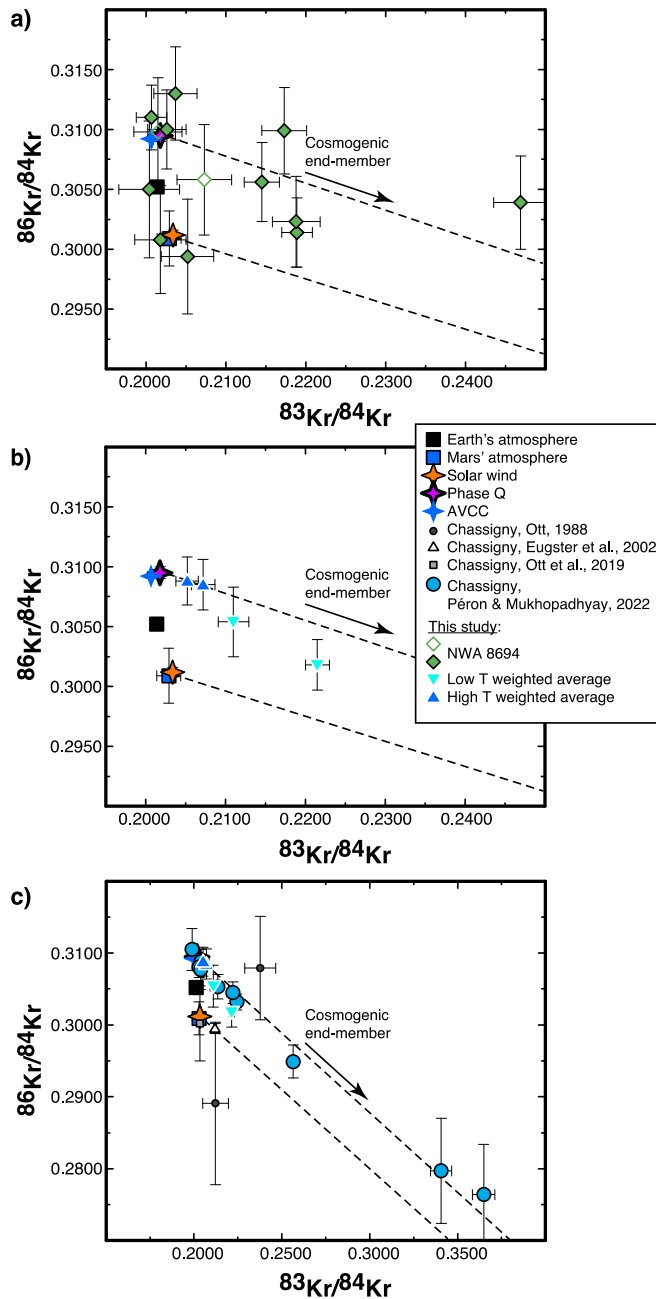
**Fig. 1.** Three neon isotope plot of NWA 8694 heating steps. Each symbol corresponds to one heating step. The two low temperature steps at 250 °C are represented with the open diamonds. As reference, compositions of Earth's atmosphere, Ne-A (Black and Pepin, 1969), cosmogenic Ne produced from Galactic Cosmic Rays or GCR (Wieler, 2002) and Solar Cosmic Rays or SCR are indicated. The range for SCR was calculated based on NWA 8694 composition (Hewins et al., 2020) and production rates from target elements (Reedy, 1992). The Ne isotope data of NWA 8694 is consistent with the presence of GCR and SCR Ne. Alternatively, extrapolation of the Ne data intersects the Ne-A and Earth's atmosphere line at  $^{20}\text{Ne}/^{22}\text{Ne} = 5.89 \pm 0.64$  (Fig. S1).

similar  $^{40}\text{Ar}/^{36}\text{Ar}$  ratios are obtained if instead of Q a solar-like  $^{38}\text{Ar}/^{36}\text{Ar}$  ratio is considered for the trapped component. The corrected  $^{40}\text{Ar}/^{36}\text{Ar}$  ratios of the high temperature steps (>1400 °C) may represent upper limits of the Martian mantle  $^{40}\text{Ar}/^{36}\text{Ar}$  ratio (Mathew and Marti, 2001). As such, the Martian mantle source of NWA 8694 would have a  $^{40}\text{Ar}/^{36}\text{Ar}$  ratio of ~400, consistent with values of ~300–400 obtained for Chassigny (Mathew and Marti, 2001; Péron and Mukhopadhyay, 2022).

Cosmic-ray exposure ages were determined based on the  $^{21}\text{Ne}$  and  $^{38}\text{Ar}$  data, and the NWA 8694 composition (Hewins et al., 2020), following methods in Eugster and Michel (1995) and Welten et al. (1997). For neon, we considered that all steps were purely cosmogenic and for argon we corrected for the trapped component as explained above. The average  $^{21}\text{Ne}$  exposure age is  $10.65 \pm 1.47$  Ma and the average  $^{38}\text{Ar}$  exposure age is  $9.06 \pm 0.68$  Ma for the two capsules. These values are in agreement with literature data for chassignites: a range between 8.3 Ma and 12.3 Ma has been determined based on  $^{21}\text{Ne}$  and  $^{38}\text{Ar}$  (Marty et al., 2006; Nagao et al., 2019; Ott, 1988).

### 3.2. Krypton and xenon isotopic compositions

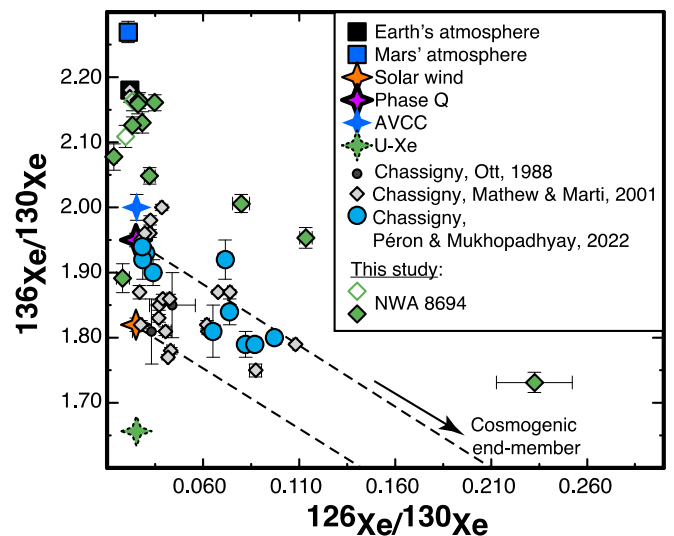
The krypton isotopic composition of NWA 8694 is represented in Fig. 2, showing the  $^{86}\text{Kr}/^{84}\text{Kr}$  and the  $^{83}\text{Kr}/^{84}\text{Kr}$  ratios. Isotope  $^{86}\text{Kr}$  is not produced in significant amount through spallation reaction (Wieler, 2002) and so the  $^{86}\text{Kr}/^{84}\text{Kr}$  ratio is ideally suited to trace the Martian trapped component, whereas  $^{83}\text{Kr}$  is the Kr isotope most affected by spallation (Wieler, 2002), making the  $^{83}\text{Kr}/^{84}\text{Kr}$  ratio ideal for deconvolving the cosmogenic contribution. Individual heating steps of NWA 8694 (Fig. 2a) have larger uncertainties than our measurements of Chassigny (Péron and Mukhopadhyay, 2022), due to lower analyzed mass. However, the NWA 8694 data plot in a triangle between chondritic (as represented by AVCC and Phase Q), solar-like (solar wind or Martian atmosphere) and a cosmogenic component. To identify trends more clearly, we computed error-weighted averages of the low (500 °C–1150 °C) and high-temperature heating steps (1250 °C–1500 °C),



**Fig. 2.** Krypton isotope composition of NWA 8694. a) Our measurements of NWA 8694 are represented with the green diamonds. Each symbol corresponds to one heating step. The two low temperature steps at 250 °C are represented with the open diamonds. b) The error-weighted averages for the low temperature steps (500 °C–1150 °C, light blue triangles) and high temperature steps (1250 °C–1500 °C, dark blue triangles) are represented for both capsules. c) The error-weighted averages for NWA 8694 are compared to literature data for Chassigny (Eugster et al., 2002; Ott, 1988; Ott et al., 2019; Péron and Mukhopadhyay, 2022). On all panels, dotted lines represent mixing lines between cosmogenic Kr and Phase Q (Busemann et al., 2000)/Solar Wind (Meshik et al., 2014). The compositions of Earth's atmosphere (Basford et al., 1973), Mars' atmosphere (Swindle et al., 1986), and Average Carbonaceous Chondrites or AVCC (Péron et al., 2021) are also reported. The high-temperature error-weighted averages (panel b) clearly point towards a trapped chondritic Kr component (i.e., for the NWA 8694 mantle source).

since the cosmogenic component is mostly released at  $\leq 1200$  °C, and steps above 1250 °C are mostly reflective of the trapped meteorite component (i.e., the Martian mantle) (Mathew and Marti, 2001; Ott, 1988; Péron and Mukhopadhyay, 2022). The error-weighted averages (Fig. 2b) of the low temperature steps are  $0.2215 \pm 0.0015$  and  $0.2110 \pm 0.0019$  for the  $^{83}\text{Kr}/^{84}\text{Kr}$  ratio, and  $0.3018 \pm 0.0021$  and  $0.3054 \pm 0.0029$  for the  $^{86}\text{Kr}/^{84}\text{Kr}$  ratio, for capsules 1 and 2, respectively. The two low-temperature steps at 250 °C are not considered here as they are more susceptible to terrestrial atmospheric contamination, but similar results would be obtained if included. The error-weighted averages of the high temperature steps are  $0.2072 \pm 0.0015$  and  $0.2052 \pm 0.0014$  for the  $^{83}\text{Kr}/^{84}\text{Kr}$  ratio, and  $0.3085 \pm 0.0021$  and  $0.3088 \pm 0.0020$  for the  $^{86}\text{Kr}/^{84}\text{Kr}$  ratio, for capsules 1 and 2, respectively. When considering these error-weighted averages, the data plot along a mixing line between a chondritic and cosmogenic end-member with the averages for the high temperature steps very close to the chondritic value ( $^{86}\text{Kr}/^{84}\text{Kr}$  of  $0.3092 \pm 0.0002$  for Average Carbonaceous Chondrites or AVCC, (Péron et al., 2021)), similar to data for Chassigny (Fig. 2c). The error-weighted averages of the low temperature steps deviate slightly from a chondritic-cosmogenic mixing line towards a solar composition, suggesting that in addition to chondritic and cosmogenic Kr, a minor solar-like component is present in NWA 8694.

The xenon isotopic data are plotted in Fig. 3, showing the  $^{136}\text{Xe}/^{130}\text{Xe}$  and  $^{126}\text{Xe}/^{130}\text{Xe}$  ratios. Isotope  $^{136}\text{Xe}$  is not produced in significant amount by spallation, whereas  $^{126}\text{Xe}$  is the most affected by spallation (Wieler, 2002). The Xe data fall into a triangle between Martian atmosphere (contribution from Martian atmosphere and terrestrial contamination cannot be distinguished in Fig. 3), a chondritic or solar component and a cosmogenic component. Fig. 4 showing the  $^{129}\text{Xe}/^{132}\text{Xe}$  and  $^{136}\text{Xe}/^{132}\text{Xe}$  ratios allows to better identify the different components in NWA 8694. The error-weighted averages (Fig. 4b) of the low temperature steps (500 °C–1150 °C) are  $1.285 \pm 0.003$  and  $1.117 \pm 0.003$  for the  $^{129}\text{Xe}/^{132}\text{Xe}$  ratio, and  $0.3293 \pm 0.0010$  and  $0.3295 \pm 0.0013$  for the  $^{136}\text{Xe}/^{132}\text{Xe}$  ratio, for capsules 1 and 2, respectively. As for Kr, including the 250 °C steps in these calculations would give similar results. Also, we note that Xe concentrations are quite low for the 500 °C step for the two separate aliquots, especially for the aliquot in capsule 2 (Table 3), and so these two steps may not be very meaningful. The error-weighted averages of the high temperature steps (1250



**Fig. 3.** Xenon isotope composition of NWA 8694. The NWA 8694 data are compared to literature data for Chassigny (Mathew and Marti, 2001; Ott, 1988; Péron and Mukhopadhyay, 2022). The composition of U-Xe is also reported (Pepin, 2000). The composition of the Martian atmosphere is from Mathew et al. (1998), AVCC from Eugster et al. (1967), and the cosmogenic component from Marti et al. (1966). Refer to caption of Fig. 2 for more details.

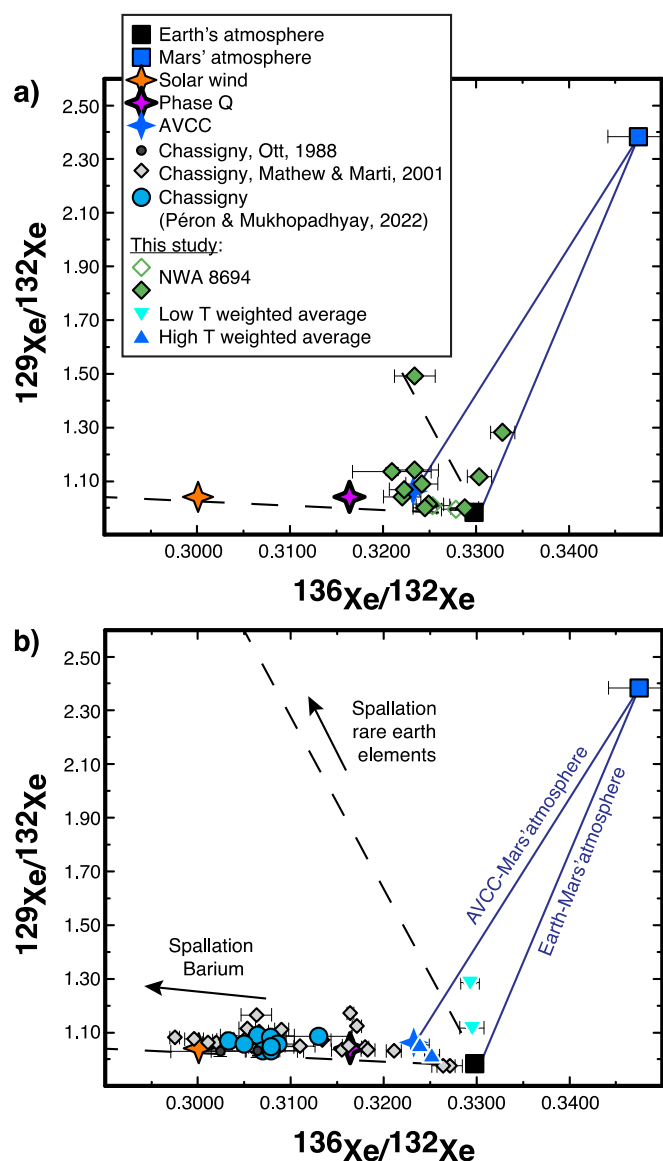


Fig. 4. Xenon isotope composition of NWA 8694. a) Individual heating steps of NWA 8694, b) the error-weighted averages for NWA 8694 and literature data for Chassigny (Mathew and Marti, 2001; Ott, 1988; Péron and Mukhopadhyay, 2022). The compositions of cosmogenic Xe from Barium and Rare Earth Elements are from Hohenberg et al. (1981) and Average Carbonaceous Chondrites (AVCC) from Pepin (2003). Refer to caption of Figs. 2 and 3 for more details.

$^{\circ}\text{C}$ – $1500^{\circ}\text{C}$ ) are  $1.052 \pm 0.002$  and  $1.014 \pm 0.002$  for the  $^{129}\text{Xe}/^{132}\text{Xe}$  ratio, and  $0.3239 \pm 0.0010$  and  $0.3252 \pm 0.0008$  for the  $^{136}\text{Xe}/^{132}\text{Xe}$  ratio, for capsules 1 and 2, respectively. Most of the individual heating steps (Fig. 4a) and the weighted averages of the low and high temperature steps fall into a triangle between a chondritic end-member, the Earth's atmosphere and the Martian atmosphere, with a little deviation towards the cosmogenic component for a few of the steps. NWA 8694 shows more terrestrial atmospheric contamination for Xe than Chassigny, which is commonly the case for desert meteorites (Wieler et al., 2016).

### 3.3. Elemental ratios

The elemental ratios  $^{36}\text{Ar}/^{132}\text{Xe}$  and  $^{84}\text{Kr}/^{132}\text{Xe}$  in Figs. 5 and 6 also show mixing between a chondritic component and a Martian atmospheric component. Some of the heating steps of NWA 8694 tend to have lower  $^{84}\text{Kr}/^{132}\text{Xe}$  ratios than expected based on mixing between a

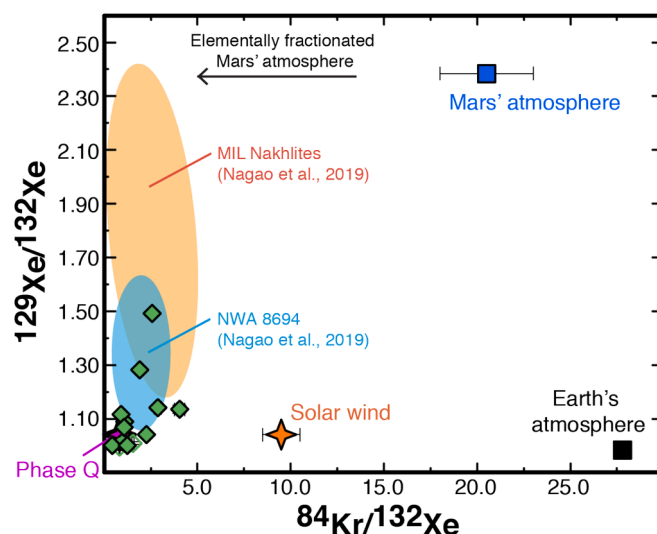


Fig. 5. Xenon and krypton isotope and elemental compositions of NWA 8694. The heating steps of NWA 8694 are represented with the green diamonds, the two low temperature steps at  $250^{\circ}\text{C}$  with the open diamonds. Our NWA 8694 data appear consistent with the results of Nagao et al. (2019). The ranges of composition of MIL nakhilites, which show mixing between a Martian interior (chassigny-like) component and an elementally fractionated Martian atmosphere component, is also reported (Nagao et al., 2019). For reference, the compositions of Mars' atmosphere (Bogard and Garrison, 1998; Mathew et al., 1998), Earth's atmosphere (Ozima and Podosek, 2002), Phase Q (Busemann et al., 2000) and Solar Wind (Heber et al., 2009) are shown. Chassigny data (Mathew and Marti, 2001; Ott, 1988; Péron and Mukhopadhyay, 2022) are not reported here as they plot on top of Phase Q in this space. NWA 8694 data show mixing between a chondritic interior component and a fractionated Martian atmospheric component.

chondritic component and a Martian atmospheric component, consistent with Nagao et al. (2019)'s results from NWA 8694. These latter steps plot in the field of MIL nakhilites, which show an elementally fractionated Martian atmospheric component (Nagao et al., 2019).

We further note that the elemental ratios need not be strictly taken at face value to represent the mantle composition due to potential elemental fractionation during noble gas extraction (Mathew and Marti, 2001). In particular, the  $^{36}\text{Ar}/^{132}\text{Xe}$  and  $^{84}\text{Kr}/^{132}\text{Xe}$  ratios that are lower than the chondritic values (as represented by Phase Q and AVCC) for Chassigny and NWA 8694 (Fig. 6) remain to be explained. Another complication for desert meteorites like NWA 8694 is the potential occurrence of elementally fractionated terrestrial air (or EFA), as observed in several Martian meteorites from hot and cold (Antarctica) deserts mostly in low temperature ( $<1000^{\circ}\text{C}$ ) heating steps showing air-like Xe isotopic ratios and low  $^{36}\text{Ar}/^{132}\text{Xe}$  and  $^{84}\text{Kr}/^{132}\text{Xe}$  ratios about 10 and 1–2, respectively (e.g., Mohapatra et al., 2009; Nagao et al., 2008; Schwenger et al., 2009). From our NWA 8694 data it seems like the Earth's atmosphere component is not severely fractionated elementally but we cannot completely exclude a fractionated air component.

Importantly, all the data points in Fig. 6 are strikingly distinct from the solar wind composition and cluster around the chondritic component with some deviation towards Mars' atmosphere for NWA 8694.

### 3.4. Cosmogenic xenon

Cosmogenic Xe is not preponderant for most of the heating steps, except for the  $1150^{\circ}\text{C}$  and  $1250^{\circ}\text{C}$  steps (Fig. 3). Hence, correction for cosmogenic Xe is not required to identify the trapped components of NWA 8694. Here we further note that correcting for cosmogenic Xe may not be straightforward, likely due to important variability of the cosmogenic Xe isotopic composition with target material composition (Hohenberg et al., 1981; Hohenberg and Rowe, 1970).

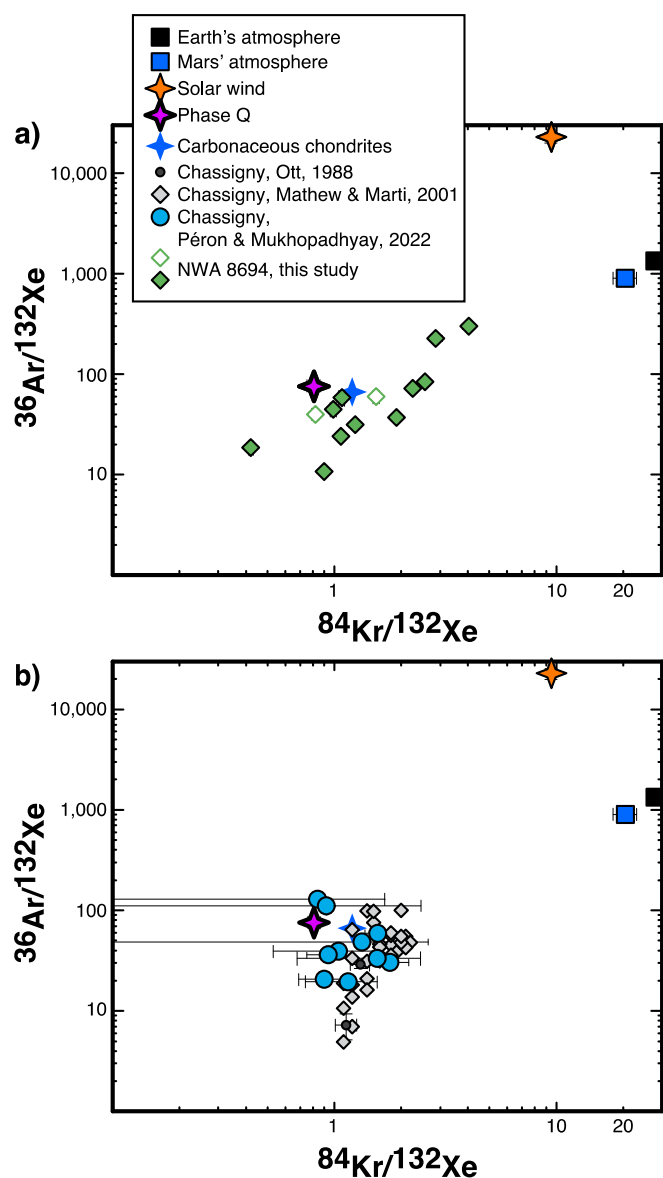


Fig. 6. Argon, krypton and xenon elemental ratios. a) Individual heating steps for NWA 8694, b) comparison with literature data for Chassigny (Mathew and Marti, 2001; Ott, 1988; Péron and Mukhopadhyay, 2022). The two low temperature steps at 250 °C are represented with the open diamonds. Abundance of  $^{36}\text{Ar}$  is corrected for cosmogenic contribution (refer to text), but not  $^{84}\text{Kr}$  and  $^{132}\text{Xe}$  as this is negligible. The compositions of Phase Q (Busemann et al., 2000), Carbonaceous chondrites (Mazor et al., 1970), Solar Wind (Heber et al., 2009), the Earth's (Ozima and Podosek, 2002) and Mars' (Bogard and Garrison, 1998) atmospheres are reported as reference. The heating steps show a composition close to the chondritic component with some mixing with a Martian atmospheric component, as in Fig. 5.

An example of cosmogenic correction is given in Fig. 7. We used the same method as presented by Cassata (2017), which does not make assumption of the exact isotopic composition of the trapped component. Similar results are obtained if assuming that the trapped component has a composition similar to Phase Q. However, results vary depending on the Xe isotopic composition considered for the cosmogenic end-member, in particular for the  $^{131}\text{Xe}/^{130}\text{Xe}$  ratio (Fig. 7). For the cosmogenic end-member, we consider the composition obtained by fitting the steps above 500 °C with the Isoplot software in a  $^{131}\text{Xe}/^{130}\text{Xe}$ – $^{136}\text{Xe}/^{130}\text{Xe}$  isotopic space, with  $^{131}\text{Xe}$  one Xe isotope as they show two-component mixing between a cosmogenic and trapped end-members (method 1 in Fig. 7). This gives a cosmogenic  $^{131}\text{Xe}/^{126}\text{Xe}$  ratio of  $2.40 \pm 0.32$ . We also

consider values obtained with equation 1 of Hohenberg et al. (1981) taking into account that the ratio  $(\text{La} + \text{Ce} + \text{Nd})/\text{Ba}$  is 0.292 for NWA 8694 based on Hewins et al. (2020)'s data (method 2 in Fig. 7), which gives a cosmogenic  $^{131}\text{Xe}/^{126}\text{Xe}$  ratio of  $3.98 \pm 0.10$ , significantly higher than the previous value obtained by fitting the measured data. Some of the corrected data considering this second method plot below AVCC or Solar wind (Fig. 7), which does not appear reasonable. Other Xe isotopic ratios for the cosmogenic end-member are similar between the two methods, except to a much lower extent for the  $^{132}\text{Xe}/^{126}\text{Xe}$  ratio, which is  $0.46 \pm 0.34$  with method 1 and  $0.92 \pm 0.03$  with method 2. The reason for an apparent lower  $^{131}\text{Xe}/^{126}\text{Xe}$  cosmogenic ratio for NWA 8694 than the predicted value given by Hohenberg et al. (1981) is unclear, but could be related to the sample composition and/or to the fact that production of cosmogenic  $^{131}\text{Xe}$  is strongly depth-dependent, with the  $^{131}\text{Xe}/^{126}\text{Xe}$  ratio increasing with depth (Burnett et al., 1975).

Overall, the Xe data corrected for cosmogenic composition plot in a triangle between Earth's air, Mars' atmosphere and the chondritic end-member (Fig. 7), which support previous observations (sections 3.2 and 3.3). However, we note that the cosmogenic correction requires assumptions and the corrected Xe data alone do not allow unambiguous identification of the trapped components of NWA 8694.

## 4. Discussion

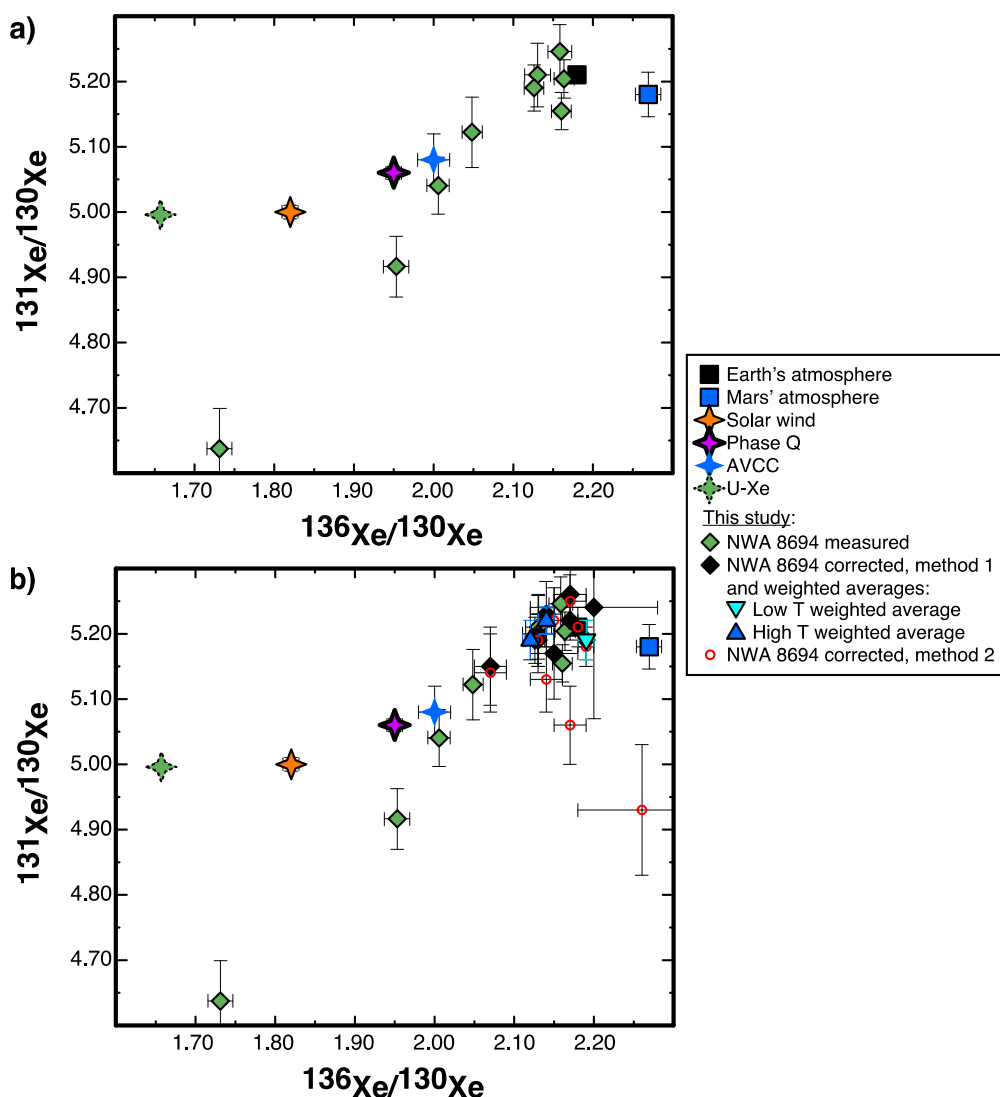
### 4.1. The trapped components in NWA 8694

The heavy noble gas (Ar, Kr, Xe) elemental and isotopic composition of the chassignite NWA 8694 (Figs. 3, 4, 5 and 6) is distinct from Chassigny, which shows a nearly pure trapped chondritic component (Péron and Mukhopadhyay, 2022). Instead, the Kr and Xe isotopic ratios and the  $^{36}\text{Ar}/^{132}\text{Xe}$  and  $^{84}\text{Kr}/^{132}\text{Xe}$  ratios of NWA 8694 consistently show mixing between a chondritic component, Earth's atmosphere, a solar-like component identified as the Martian atmosphere based on the  $^{129}\text{Xe}/^{132}\text{Xe}$  and elemental ratios, with addition of a cosmogenic component. These components are most clearly seen in the low- and high-temperature error-weighted averages of the two sample aliquots. Given the larger uncertainties of the individual steps in NWA 8694 compared to Chassigny (due to smaller sample size), we use the error-weighted averages of Kr and Xe isotopic compositions (Figs. 2 and 4), together with the elemental ratios to infer the composition of the NWA 8694 mantle source.

The presence of an Earth's atmosphere component (as seen in particular in Fig. 4) is attributable to contamination of the samples during its residence on Earth. Hence, the NWA 8694 data point to two trapped components: a component isotopically similar to the Martian atmosphere but with elementally fractionated ratios, released at low temperatures (<1150 °C) and also observed in MIL nakhlites (Nagao et al., 2019), as well as a chondritic component released at higher temperatures (>1200 °C), similar to the trapped component in Chassigny (Péron and Mukhopadhyay, 2022). Note that the third chassignite, sample NWA 2737, mostly contains a modern Martian atmosphere component with unfractionated noble gas elemental ratios (Marty et al., 2006).

Nagao et al. (2019) suggested that MIL nakhlites and NWA 8694 were aqueously altered by surface fluids to account for the presence of the elementally fractionated Martian atmosphere component, consistent with the fact that this component is released at lower temperatures. Additional evidence that the parental melt of NWA 8694 interacted with the Martian surface comes from the Ge/Si ratio that shows melt degassing (Hewins et al., 2020). Since the Kr and Xe isotopic ratios, along with the  $^{84}\text{Kr}/^{132}\text{Xe}$  ratio, suggest that the solar-like component is elementally fractionated Martian atmosphere, the solar-like component is not reflective of the NWA 8694 mantle source composition.

The chondritic component that is clearly visible in the Kr and Xe isotopic compositions of the high temperature steps in NWA 8694 (Figs. 2, 4, 5) corresponds to the composition of the NWA 8694 mantle



**Fig. 7.** Xenon isotopic ratios  $^{131}\text{Xe}/^{130}\text{Xe}$  vs.  $^{136}\text{Xe}/^{130}\text{Xe}$ . a) Individual heating steps above 500 °C for NWA 8694, b) measured data are compared with data corrected for cosmogenic contribution using either a fit to determine the cosmogenic end-member composition (method 1, black diamonds) or equation 1 of Hohenberg et al. (1981) to calculate the values of the cosmogenic end-member (method 2, red circles). Error-weighted averages for the high temperature and low temperature steps are shown for data corrected with method 1. Refer to captions of Figs. 2 and 3 for more details.

source. The Kr measurements of NWA 8694 however do not allow us to identify whether the composition is better represented by Average Carbonaceous Chondrites – AVCC (Eugster et al., 1967; Péron et al., 2021) or the composition of Phase Q (Busemann et al., 2000).

Chassigny and NWA 8694, and more globally chassignites and nakhlites, are closely related, likely coming from the same shield volcano but different magma bodies, based on mineralogy, geochemical composition (e.g., trace element abundance patterns, volatile abundances, radiogenic isotopes), similar crystallization and ejection ages (Hewins et al., 2020; McCubbin et al., 2013; Udry and Day, 2018; Udry et al., 2020). The measurements of NWA 8694 in this study confirm the identification of a chondritic mantle source for Kr and Xe for Chassigny (Péron and Mukhopadhyay, 2022). This chondritic Martian mantle component is thus likely common to at least the chassignites and possibly nakhlites.

#### 4.2. A volatile-rich Martian interior

As with Chassigny, the NWA 8694 Kr and Xe data supports high primordial gas abundances in the Martian mantle (also see Marty and Marti, 2002) and so virtually no fissiogenic Kr and Xe is observable.

Spontaneous fission of  $^{244}\text{Pu}$  (half-life of 82 Myr) produces  $^{86}\text{Kr}$  as well as  $^{131}\text{Xe}$ ,  $^{132}\text{Xe}$ ,  $^{134}\text{Xe}$  and  $^{136}\text{Xe}$ , with fission yield of 0.11 % and 5.6 % for  $^{86}\text{Kr}$  and  $^{136}\text{Xe}$ , respectively (Ozima and Podosek, 2002). Spontaneous fission of  $^{238}\text{U}$  (half-life of 4.468 Gyr) produces  $^{83}\text{Kr}$ ,  $^{84}\text{Kr}$ ,  $^{86}\text{Kr}$  as well as  $^{131}\text{Xe}$ ,  $^{132}\text{Xe}$ ,  $^{134}\text{Xe}$  and  $^{136}\text{Xe}$ , with fission yield of 0.95 % and 6.3 % for  $^{86}\text{Kr}$  and  $^{136}\text{Xe}$ , respectively (Ozima and Podosek, 2002). Maintaining a low  $^{40}\text{Ar}/^{36}\text{Ar}$  ratio ( $\sim 300$ ) for the chassignite mantle source over 4.5 Gyr of  $^{40}\text{K}$  production would require a mantle  $^{36}\text{Ar}$  concentration  $\sim 2 \times 10^{-12}$  mol/g, assuming a mantle K concentration of 170 ppm (Taylor et al., 2010). Taking the K concentration of at least 309 ppm for Bulk Silicate Mars (Dreibus and Wänke, 1987; Taylor, 2013; Wänke et al., 1994; Yoshizaki and McDonough, 2020) would give even higher estimates for Mars noble gas abundances, but the Martian crust was likely formed very early (Bouvier et al., 2018), with about 50 % of K having been extracted from the mantle to the crust (Grott et al., 2013), and so it seems more appropriate to make estimates for mantle concentrations rather than for Bulk Silicate Mars. This estimated  $^{36}\text{Ar}$  concentration for the Martian mantle is at least one order of magnitude higher than that of the bulk Earth mantle (Halliday, 2013; Marty, 2012). Given the chondritic elemental ratios Ar/Xe and Kr/Xe for Chassigny (Mathew and Marti, 2001; Péron and Mukhopadhyay, 2022) and NWA

8694 (Fig. 6), if the chassignite mantle source has about  $2 \times 10^{-12}$  mol/g of  $^{36}\text{Ar}$ , then it would also have at least  $2.1 \times 10^{-14}$  mol/g of  $^{84}\text{Kr}$  and  $2.6 \times 10^{-14}$  mol/g of  $^{132}\text{Xe}$ , assuming the values of Phase Q for the elemental ratios (Busemann et al., 2000), which is also at least one order of magnitude higher than the Earth's mantle (Halliday, 2013; Marty, 2012). Fissionogenic Kr is negligible for the Earth's mantle (Péron et al., 2021), and so with such high concentrations of primordial gas for the Martian mantle it is also expected to be negligible. This would also be the case for Xe. The latter conclusion however relies on supposedly high heavy noble gas abundances in the Martian mantle based on the low  $^{40}\text{Ar}/^{36}\text{Ar}$  ratio of Chassigny and NWA 8694. It is indeed difficult to estimate the heavy noble gas concentrations of the chassignite mantle source based on the measured abundances of Ar, Kr and Xe of Chassigny and NWA 8694 alone. In particular, for NWA 8694 there is clear evidence for melt degassing based on the Ge/Si ratio (Hewins et al., 2020) and this meteorite also shows addition of Martian atmospheric gases and cosmogenic gases. However, high abundances of heavy noble gases are consistent with other lines of evidence showing high volatile abundances (e.g., halogens, moderately volatiles) for the Martian mantle compared to the Earth's mantle (Dreibus and Wänke, 1987; Khan et al., 2022; Taylor, 2013). Therefore, Chassigny and NWA 8694 show evidence for a volatile-rich Martian mantle based on Ar, Kr and Xe isotopic and elemental compositions, with negligible fissionogenic Kr and Xe. This implies that the Martian mantle has not been strongly degassed, unlike the Earth's mantle (Allègre et al., 1986).

#### 4.3. Martian volatile sources

A chondritic Kr and Xe mantle source for chassignites is in stark contrast with solar Kr and Xe in the Martian atmosphere (Avice et al., 2018a; Conrad et al., 2016; Marty et al., 2006; Mathew et al., 1998; Swindle and Jones, 1997). The Martian atmosphere contains isotopically solar Kr, and mass-dependently fractionated solar Xe consistent with a starting solar Xe component that was progressively lost by hydrodynamic escape (Avice et al., 2018a; Cassata et al., 2022; Conrad et al., 2016; Mathew et al., 1998). This observation suggests that chondritic heavy noble gases were acquired in the Martian interior prior to solar gases in the atmosphere. Interestingly, the nitrogen isotopic composition of Chassigny also shows origin from chondritic-like material (Deligny et al., 2023). Given the rapid formation timescale of Mars, with most of its mass accreted in less than 4 Myr after the start of Solar System formation (Dauphas and Pourmand, 2011; Tang and Dauphas, 2014), it implies that chondritic volatiles were being delivered to planetary embryos from their building blocks in the first Myr after Solar System formation, in the presence of the solar nebula, which dissipated in about 4 Myr (Wang et al., 2017). Therefore, our study further supports early acquisition of chondritic volatiles by terrestrial planets in the presence of the solar nebula (Deligny et al., 2023; Péron and Mukhopadhyay, 2022).

Chondritic heavy noble gases could have been delivered by inner solar system bodies like enstatite chondrites (Piani et al., 2020), or outer solar system bodies similar to carbonaceous chondrites scattered inwards due to giant planet migrations or radial transport in the disk before the formation of Jupiter (Ciesla and Cuzzi, 2006; O'Brien et al., 2014). Based on moderately volatile elements, it was recently suggested that most of Martian volatiles were delivered by inner solar system bodies similar to enstatite chondrites and ordinary chondrites, with minor contribution of carbonaceous chondrite-like bodies (Kleine et al., 2023; Paquet et al., 2023). Heavy noble gases, as well as the N isotopic composition of Chassigny (Deligny et al., 2023) cannot currently allow us to distinguish between these different chondritic sources.

Given the Martian mantle is chondritic, the solar composition in Mars' atmosphere cannot be accounted for solely by outgassing of the Martian mantle, as generally assumed in models of atmosphere formation (Lammer et al., 2018; Pahlevan et al., 2022). Outgassing of the chondritic Martian mantle associated with hydrodynamic escape also

could not produce the solar atmosphere, as this combination of processes would enrich the atmosphere in heavier isotopes, and solar Kr is depleted in heavier Kr isotopes compared to chondritic Kr.

If solar Kr and Xe in the Martian atmosphere originate from nebular capture, then a specific process must be at play in order not to lose these solar gases due to hydrodynamic escape caused by higher solar activity after the nebula dissipated (Erkaev et al., 2014). It also implies that the magma ocean phase may have ended before dissipation of the nebula, which is consistent with rapid mantle solidification in about 4–5 Myr (Elkins-Tanton, 2008). We suggest that atmospheric solar Kr and Xe could have been trapped in the polar ice caps or the regolith (Zahnle, 1993) to prevent their loss, a scenario that would require Martian surface to have been cold, below the freezing point of water, after dissipation of the nebula. Alternatively, solar noble gases could have been delivered by comets (or planetesimals) to the Martian atmosphere after dissipation of the nebula. However, it is unclear if comets have a solar composition for Kr and Xe, and the one comet for which Kr isotopes were measured, comet 67P/C-G, seems to show a deficit in  $^{86}\text{Kr}$  relative to solar Kr (Rubin et al., 2018) as well as a deficit in  $^{134}\text{Xe}$  and  $^{136}\text{Xe}$  relative to solar (Marty et al., 2017). No planetesimal carrying significant concentrations of solar Xe and Kr gas has yet been identified. However, we note that based on nucleosynthetic anomalies (e.g., in  $^{94}\text{Mo}$ ,  $^{96}\text{Zr}$ ) there appears to have been planetesimals in the inner solar system that are not in our collection of meteorite samples (Burkhardt et al., 2021). And finally, we note that late addition of chondritic noble gases has to be negligible in order not to alter the near pure solar Kr isotopic composition of the Martian atmosphere.

#### 5. Conclusion

We investigated the noble gas (Ne, Ar, Kr, Xe) isotopic and elemental compositions of the chassignite NWA 8694 via laser step-heating in order to determine the Martian mantle composition and hence assess Martian volatile sources.

We found that the  $^{40}\text{Ar}/^{36}\text{Ar}$  ratios corrected for cosmogenic contribution on  $^{36}\text{Ar}$  of the high temperature steps is about 400, which may represent an upper limit of the NWA 8694 mantle source (Mathew and Marti, 2001), and is similar to values of about 300–400 obtained for Chassigny (Mathew and Marti, 2001; Péron and Mukhopadhyay, 2022). This low radiogenic value suggests that the Martian mantle has been only slightly degassed, and heavy noble gas (Ar, Kr, Xe) concentrations in the chassignite mantle source are likely at least one order of magnitude higher than in the Earth's mantle. Such high concentrations for heavy noble gases would be consistent with other evidence showing high abundances of halogens and moderately volatile elements in the Martian mantle (Dreibus and Wänke, 1987; Khan et al., 2022; Taylor, 2013), arguing for a volatile-rich Martian interior.

The Kr and Xe isotopic and elemental compositions of NWA 8694 show mixing of three trapped components, a chondritic component, Martian atmosphere and Earth's atmosphere, with addition of cosmogenic gases. These components are most clearly visible in the low- and high-temperature error-weighted averages of the two sample aliquots. The Earth's atmospheric component is related to shallow contamination of the meteorite on Earth. The Martian atmospheric component is released at low temperatures and is elementally fractionated, as observed in MIL nakhlites (Nagao et al., 2019), which could be attributed to aqueous alteration by surface fluids (Nagao et al., 2019). The chondritic component is mostly identified in the higher temperature steps and corresponds to the composition of the NWA 8694 mantle source, as observed for the Chassigny mantle source for heavy noble gases (Péron and Mukhopadhyay, 2022) and nitrogen (Deligny et al., 2023). Given chassignites and nakhlites are likely coming from the same shield volcano (Hewins et al., 2020; McCubbin et al., 2013; Udry and Day, 2018; Udry et al., 2020), this chondritic composition is expected to be common to chassignites and nakhlites.

A chondritic Martian mantle for Kr and Xe is in stark contrast with

solar Kr and Xe in the Martian atmosphere (Avicé et al., 2018a; Conrad et al., 2016; Mathew et al., 1998). This suggests that chondritic volatiles were acquired before solar gas in the atmosphere. Since Mars formed in a few Myr (Dauphas and Pourmand, 2011; Tang and Dauphas, 2014), it suggests that chondritic volatiles were delivered to terrestrial planets in the first Myr after Solar System formation in the presence of the nebula (Deligny et al., 2023; Péron and Mukhopadhyay, 2022). Solar gases in the atmosphere could originate from capture of the nebula or late delivery by cometary-like material. Captured nebular gases would need to have been trapped in polar ice caps or the regolith (Zahnle, 1993), after magma ocean solidification, in order not to be lost via hydrodynamic escape, a process expected to be efficient after the dissipation of the nebula (Erkaev et al., 2014).

### CRedit authorship contribution statement

**Sandrine Péron:** Writing – original draft, Methodology, Investigation, Conceptualization. **Sujoy Mukhopadhyay:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization.

### Data availability

Data are available through the Astromaterials Data Repository at <https://doi.org/10.60520/IEDA/113460>.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Acknowledgements

We thank Guillaume Avicé and an anonymous reviewer for their insightful and helpful comments that improved this contribution, as well as Yves Marrocchi for efficient editorial handling. We thank the French National Museum of Natural History (MNHN) for graciously providing the NWA 8694 samples (sending number: ar797, colhelper request: 154212).

### Appendix A. Supplementary material

The Supplementary material contains Figure S1 showing Ne isotope data. Supplementary material to this article can be found online at <http://doi.org/10.1016/j.gca.2025.01.002>.

### References

- Albarède, F., 2009. Volatile accretion history of the terrestrial planets and dynamic implications. *Nature* 461, 1227–1233.
- Alexander, C.M.O.D., Bowden, R., Fogel, M.L., Howard, K.T., Herd, C.D.K., Nittler, L.R., 2012. The provenances of asteroids, and their contributions to the volatile inventories of the Terrestrial Planets. *Science* 337, 721.
- Allègre, C.J., Staudacher, T., Sarda, P., 1986. Rare gas systematics, formation of the atmosphere, evolution and structure of the Earth's mantle. *Earth Planet. Sci. Lett.* 81, 127–150.
- Amari, S., Matsuda, J.-I., Stroud, R.M., Chisholm, M.F., 2013. Highly concentrated nebular noble gases in porous nanocarbon separates from the Saratov (L4) Meteorite. *Astrophys J* 778, 37.
- Avicé, G., Bekaert, D.V., Chennaoui Aoudjehane, H., Marty, B., 2018a. Noble gases and nitrogen in Tissint reveal the composition of the Mars atmosphere. *Geochem. Perspect. Lett.* 6, 11–16.
- Avicé, G., Marty, B., Burgess, R., Hofmann, A., Philippot, P., Zahnle, K., Zakharov, D., 2018b. Evolution of atmospheric xenon and other noble gases inferred from Archean to Paleoproterozoic rocks. *Geochim. Cosmochim. Acta*.
- Barnes, J.J., McCubbin, F.M., Santos, A.R., Day, J.M.D., Boyce, J.W., Schwenger, S.P., Ott, U., Franchi, I.A., Messenger, S., Anand, M., Agee, C.B., 2020. Multiple early-formed water reservoirs in the interior of Mars. *Nat. Geosci.* 13, 260–264.

- Basford, J.R., Dragon, J.C., Pepin, R.O., Coscio, M.R.J., Murthy, V.R., 1973. Krypton and xenon in lunar fines. In: Gose, W.A. (Ed.), *Fourth Lunar Science Conference*. Pergamon Press, Houston, Tx.
- Black, D.C., Pepin, R.O., 1969. Trapped neon in meteorites — II. *Earth Planet. Sci. Lett.* 6, 395–405.
- Bogard, D.D., 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.
- Bouvier, L.C., Costa, M.M., Connelly, J.N., Jensen, N.K., Wielandt, D., Storey, M., Nemchin, A.A., Whitehouse, M.J., Snape, J.F., Bellucci, J.J., Moynier, F., Agranier, A., Gueguen, B., Schönbacher, M., Bizzarro, M., 2018. Evidence for extremely rapid magma ocean crystallization and crust formation on Mars. *Nature* 558, 586–589.
- Broadley, M.W., Barry, P.H., Bekaert, D.V., Byrne, D.J., Caracausi, A., Ballentine, C.J., Marty, B., 2020. Identification of chondritic krypton and xenon in Yellowstone gases and the timing of terrestrial volatile accretion. *Proceedings of the National Academy of Sciences*.
- Burkhardt, C., Spitzer, F., Morbidelli, A., Budde, G., Render, J.H., Kruijjer, T.S., Kleine, T., 2021. Terrestrial planet formation from lost inner solar system material. *Sci. Adv.* 7, eabj7601.
- Burnett, D.S., Drozd, R.J., Morgan, C.J., Podosek, F.A., 1975. Exposure history of Bench Crater rocks. *Lunar and Planetary Science Conference Proceedings* 2, 2219–2240.
- Busemann, H., Baur, H., Wieler, R., 2000. Primordial noble gases in “phase Q” in carbonaceous and ordinary chondrites studied by closed-system stepped etching. *Meteor. Planet. Sci.* 35, 949–973.
- Busemann, H., Eugster, O., 2002. The trapped noble gas component in achondrites. *Meteor. Planet. Sci.* 37, 1865–1891.
- Cassata, W.S., 2017. Meteorite constraints on Martian atmospheric loss and paleoclimate. *Earth Planet. Sci. Lett.* 479, 322–329.
- Cassata, W.S., Zahnle, K.J., Samperton, K.M., Stephenson, P.C., Wimpenny, J., 2022. Xenon isotope constraints on ancient Martian atmospheric escape. *Earth Planet. Sci. Lett.* 580, 117349.
- Ciesla, F.J., Cuzzi, J.N., 2006. The evolution of the water distribution in a viscous protoplanetary disk. *Icarus* 181, 178–204.
- Conrad, P.G., Malespin, C.A., Franz, H.B., Pepin, R.O., Trainer, M.G., Schwenger, S.P., Atreya, S.K., Freissinet, C., Jones, J.H., Manning, H., Owen, T., Pavlov, A.A., Wiens, R.C., Wong, M.H., Mahaffy, P.R., 2016. In situ measurement of atmospheric krypton and xenon on Mars with Mars Science Laboratory. *Earth Planet. Sci. Lett.* 454, 1–9.
- Dauphas, N., Pourmand, A., 2011. Hf–W–Th evidence for rapid growth of Mars and its status as a planetary embryo. *Nature* 473, 489–492.
- Deligny, C., Füri, E., Deloule, E., Peslier, A.H., Faure, F., Marrocchi, Y., 2023. Origin of nitrogen on Mars: first in situ N isotope analyses of Martian meteorites. *Geochim. Cosmochim. Acta* 344, 134–145.
- Dreibus, G., Wänke, H., 1987. Volatiles on Earth and Mars: a comparison. *Icarus* 71, 225–240.
- Eberhardt, P., Eugster, E., Marti, K., 1965. A redetermination of the isotopic composition of atmospheric neon. *Z. Naturforsch.* 20a, 623–624.
- Elkins-Tanton, L.T., 2008. Linked magma ocean solidification and atmospheric growth for Earth and Mars. *Earth Planet. Sci. Lett.* 271, 181–191.
- Erkaev, N.V., Lammer, H., Elkins-Tanton, L.T., Stökl, A., Odert, P., Marq, E., Dorfi, E.A., Kislyakova, K.G., Kulikov, Y.N., Leitzinger, M., Güdel, M., 2014. Escape of the martian protoatmosphere and initial water inventory. *Planet. Space Sci.* 98, 106–119.
- Eugster, O., Eberhardt, P., Geiss, J., 1967. Krypton and xenon isotopic composition in three carbonaceous chondrites. *Earth Planet. Sci. Lett.* 3, 249–257.
- Eugster, O., Busemann, H., Lorenzetti, S., Terribilini, D., 2002. Ejection ages from krypton-81–krypton-83 dating and pre-atmospheric sizes of martian meteorites. *Meteor. and Planet. Science* 37, 1345–1360.
- Eugster, O., Michel, T., 1995. Common asteroid break-up events of eucrites, diogenites, and howardites and cosmic-ray production rates for noble gases in achondrites. *Geochim. Cosmochim. Acta* 59, 177–199.
- Garrison, D.H., Rao, M.N., Bogard, D.D., 1995. Solar-proton-produced neon in shergottite meteorites and implications for their origin. *Meteoritics* 30, 738.
- Grott, M., Baratoux, D., Hauber, E., Sautter, V., Mustard, J., Gasnault, O., Ruff, S.W., Karato, S.I., Debaille, V., Knapmeyer, M., Sohl, F., Van Hoolst, T., Breuer, D., Morschhauser, A., Toplis, M.J., 2013. Long-term evolution of the Martian Crust–Mantle System. *Space Sci. Rev.* 174, 49–111.
- Halliday, A., 2013. The origins of volatiles in the terrestrial planets. *Geochim. Cosmochim. Acta* 105, 146–171.
- Harper, C.L., Jacobsen, S.B., 1996. Noble gases and Earth's accretion. *Science* 273, 1814–1818.
- Heber, V.S., Wieler, R., Baur, H., Olinger, C., Friedmann, A., Burnett, D.S., 2009. Noble gas composition of the solar wind as collected by the Genesis mission. *Geochim. Cosmochim. Acta* 73, 7414–7432.
- Hewins, R.H., Humayun, M., Barrat, J.A., Zanda, B., Lorand, J.P., Pont, S., Assayag, N., Cartigny, P., Yang, S., Sautter, V., 2020. Northwest Africa 8694, a ferroan chassignite: Bridging the gap between nakhlites and chassignites. *Geochim. Cosmochim. Acta* 282, 201–226.
- Hirschmann, M.M., Dasgupta, R., 2009. The H/C ratios of Earth's near-surface and deep reservoirs, and consequences for deep Earth volatile cycles. *Chem. Geol.* 262, 4–16.
- Hohenberg, C.M., Hudson, B., Kennedy, B.M., Podosek, F.A., 1981. Xenon spallation systematics in Angra dos Reis. *Geochim. Cosmochim. Acta* 45, 1909–1915.
- Hohenberg, C.M., Rowe, M.W., 1970. Spallation yields of xenon from irradiation of Cs, Ce, Nd, Dy, and a rare Earth mixture with 730-Mev protons. *J. Geophys. Res.* 1896–1977 (75), 4205–4209.

- Holland, G., Cassidy, M., Ballentine, C.J., 2009. Meteorite Kr in earth's mantle suggests a late accretionary source for the atmosphere. *Science* 326, 1522–1525.
- Honda, M., McDougall, I., Patterson, D.B., Douglis, A., Clague, D., 1991. Possible solar noble-gas component in Hawaiian basalts. *Nature* 349, 149–151.
- Khan, A., Sossi, P.A., Liebske, C., Rivoldini, A., Giardini, D., 2022. Geophysical and cosmochemical evidence for a volatile-rich Mars. *Earth Planet. Sci. Lett.* 578, 117330.
- Kleine, T., Steller, T., Burkhardt, C., Nimmo, F., 2023. An inner solar system origin of volatile elements in Mars. *Icarus* 397, 115519.
- Lammer, H., Zerkle, A.L., Gebauer, S., Tosi, N., Noack, L., Scherf, M., Pilat-Lohinger, E., Güdel, M., Grenfell, J.L., Godolt, M., Nikolaou, A., 2018. Origin and evolution of the atmospheres of early Venus, Earth and Mars. *Astron. Astrophys. Rev.* 26, 2.
- Marrocchi, Y., Avicé, G., Estrade, N., 2015. Multiple carriers of Q noble gases in primitive meteorites. *Geophys. Res. Lett.* 42, 2093–2099.
- Marti, K., Eberhardt, P., Geiss, J., 1966. Spallation, Fission, and Neutron Capture Anomalies in Meteoritic Krypton and Xenon. *Zeitschrift Für Naturforschung A* 21, 398–426.
- Marty, B., 2012. The origins and concentrations of water, carbon, nitrogen and noble gases on Earth. *Earth Planet. Sci. Lett.* 313–314, 56–66.
- Marty, B., Heber, V.S., Grimberg, A., Wieler, R., Barrat, J.-A., 2006. Noble gases in the Martian meteorite Northwest Africa 2737: A new chassignite signature. *Meteorit. Planet. Sci.* 41, 739–748.
- Marty, B., Altwegg, K., Balsiger, H., Bar-Nun, A., Bekaert, D.V., Berthelier, J.J., Bieler, A., Brioso, C., Calmonte, U., Combi, M., De Keyser, J., Fiethe, B., Fuselier, S.A., Gasc, S., Gombosi, T.I., Hansen, K.C., Hässig, M., Jäckel, A., Kopp, E., Korth, A., Le Roy, L., Mall, U., Mousis, O., Owen, T., Rème, H., Rubin, M., Sémon, T., Tzou, C.-Y., Waite, J. H., Wurz, P., 2017. Xenon isotopes in 67P/Churyumov-Gerasimenko show that comets contributed to Earth's atmosphere. *Science* 356, 1069–1072.
- Marty, B., Bekaert, D.V., Broadley, M.W., Jaupart, C., 2019. Geochemical evidence for high volatile fluxes from the mantle at the end of the Archaean. *Nature* 575, 485–488.
- Marty, B., Marti, K., 2002. Signatures of early differentiation of Mars. *Earth Planet. Sci. Lett.* 196, 251–263.
- Mathew, K.J., Kim, J.S., Marti, K., 1998. Martian atmospheric and indigenous components of xenon and nitrogen in the Shergotty, Nakhla, and Chassigny group meteorites. *Meteor. and Planet. Science* 33, 655–664.
- Mathew, K.J., Marti, K., 2001. Early evolution of martian volatiles: nitrogen and noble gas components in ALH84001 and Chassigny. *J. Geophys. Res.* 106, 1401–1422.
- Mazor, E., Heymann, D., Anders, E., 1970. Noble gases in carbonaceous chondrites. *Geochim. Cosmochim. Acta* 34, 781–824.
- McCubbin, F.M., Elardo, S.M., Shearer Jr, C.K., Smirnov, A., Hauri, E.H., Draper, D.S., 2013. A petrogenetic model for the comagmatic origin of chassignites and nakhlites: Inferences from chlorine-rich minerals, petrology, and geochemistry. *Meteorit. Planet. Sci.* 48, 819–853.
- Meshik, A., Hohenberg, C., Pravdivtseva, O., Burnett, D., 2014. Heavy noble gases in solar wind delivered by Genesis mission. *Geochim. Cosmochim. Acta* 127, 326–347.
- Mizuno, H., Nakazawa, K., Hayashi, C., 1980. Dissolution of the primordial rare gases into the molten earth's mantle. *Earth Planet. Sci. Lett.* 50, 202–210.
- Mohapatra, R.K., Schwenger, S.P., Herrmann, S., Murty, S.V.S., Ott, U., Gilmour, J.D., 2009. Noble gases and nitrogen in Martian meteorites Dar al Gani 476, Sayh al Uhaymir 005 and Lewis Cliff 88516: EFA and extra neon. *Geochim. Cosmochim. Acta* 73, 1505–1522.
- Moreira, M., 2013. Noble gas constraints on the origin and evolution of Earth's volatiles. *Geochim. Perspect.* 2, 229–403.
- Mukhopadhyay, S., 2012. Early differentiation and volatile accretion recorded in deep mantle Neon and Xenon. *Nature* 486, 101–104.
- Mukhopadhyay, S., Parai, R., 2019. Noble Gases: A Record of Earth's Evolution and Mantle Dynamics. *Annu. Rev. Earth Planet. Sci.* 47, 389–419.
- Nagao, K., Park, J., Choi, J., Baek, J.M., Haba, M.K., Mikouchi, T., Zolensky, M.E., Herzog, G.F., Park, C., Lee, J.I., Lee, M.J., 2019. Genetic Relationship Between Martian Chassignites and Nakhlites Revealed from Noble Gases, 82nd Annual Meeting of The Meteoritical Society, p. 6183.
- Nagao, K., Park, J., Choi, H.G., 2008. Noble gases of the Yamato 000027 and Yamato 000097 iherzolitic shergottites from Mars. *Polar Sci.* 2, 195–214.
- Nier, A.O., 1950. A Redetermination of the Relative Abundances of the Isotopes of Carbon, Nitrogen, Oxygen, Argon, and Potassium. *Phys. Rev.* 77, 789–793.
- O'Brien, D.P., Walsh, K.J., Morbidelli, A., Raymond, S.N., Mandell, A.M., 2014. Water delivery and giant impacts in the 'Grand Tack' scenario. *Icarus* 239, 74–84.
- Ott, U., 1988. Noble gases in SNC meteorites: Shergotty, Nakhla, Chassigny. *Geochim. Cosmochim. Acta* 52, 1937–1948.
- Ott, U., Swindle, T.D., Schwenger, S.P., 2019. Chapter 3 - Noble Gases in Martian Meteorites: Budget, Sources, Sinks, and Processes. In: Filiberto, J., Schwenger, S.P. (Eds.), *Volatiles in the Martian Crust*. Elsevier, pp. 35–70.
- Ozima, M., Podosek, F.A., 2002. Noble Gas Geochemistry. Cambridge University Press.
- Pahlevan, K., Schaefer, L., Elkins-Tanton, L.T., Desch, S.J., Buseck, P.R., 2022. A primordial atmospheric origin of hydrospheric deuterium enrichment on Mars. *Earth Planet. Sci. Lett.* 595, 117772.
- Paquet, M., Sossi, P.A., Moynier, F., 2023. Origin and abundances of volatiles on Mars from the zinc isotopic composition of Martian meteorites. *Earth Planet. Sci. Lett.* 611, 118126.
- Parai, R., 2022. A dry ancient plume mantle from noble gas isotopes. *Proc. Natl. Acad. Sci.* 119, e2201815119.
- Pepin, R.O., 2000. On the isotopic composition of primordial xenon in terrestrial planet atmospheres. *Space Sci. Rev.* 92, 371–395.
- Pepin, R.O., 2003. On noble gas processing in the solar accretion disk. *Space Sci. Rev.* 106, 211–230.
- Pepin, R.O., Porcelli, D., 2002. Origin of noble gases in the terrestrial planets. *Rev. Mineral. Geochem.* 47, 191–246.
- Péron, S., Mukhopadhyay, S., 2022. Krypton in the Chassigny meteorite shows Mars accreted chondritic volatiles before nebular gases. *Science* 377, 320–324.
- Péron, S., Moreira, M., Agraniér, A., 2018. Origin of light noble gases (He, Ne, and Ar) on earth: a review. *Geochim. Geophys. Geosyst.* 19, 979–996.
- Péron, S., Mukhopadhyay, S., Huh, M., 2020. A new dual stainless steel cryogenic trap for efficient separation of krypton from argon and xenon. *J. Anal. At. Spectrom.* 35, 2663–2671.
- Péron, S., Mukhopadhyay, S., Kurz, M.D., Graham, D.W., 2021. Deep-mantle krypton reveals Earth's early accretion of carbonaceous matter. *Nature* 600, 462–467.
- Peslier, A.H., Schönbächler, M., Busemann, H., Karato, S.-I., 2017. Water in the earth's interior: distribution and origin. *Space Sci. Rev.* 212, 743–810.
- Piani, L., Marrocchi, Y., Rigaudier, T., Vacher, L.G., Thomassin, D., Marty, B., 2020. Earth's water may have been inherited from material similar to enstatite chondrite meteorites. *Science* 369, 1110.
- Reedy, R.C., 1992. Solar-Proton Production of Neon and Argon. *Lunar and Planetary Science Conference* 1133–1134.
- Roth, A.S.G., Trappitsch, R., Metzler, K., Hofmann, B.A., Leya, I., 2017. Neon produced by solar cosmic rays in ordinary chondrites. *Meteorit. Planet. Sci.* 52, 1155–1172.
- Rubin, M., Altwegg, K., Balsiger, H., Bar-Nun, A., Berthelier, J.-J., Brioso, C., Calmonte, U., Combi, M., De Keyser, J., Fiethe, B., Fuselier, S.A., Gasc, S., Gombosi, T.I., Hansen, K.C., Kopp, E., Korth, A., Laufer, D., Le Roy, L., Mall, U., Marty, B., Mousis, O., Owen, T., Rème, H., Sémon, T., Tzou, C.-Y., Waite, J.H., Wurz, P., 2018. Krypton isotopes and noble gas abundances in the coma of comet 67P/Churyumov-Gerasimenko. *Science Advances* 4.
- Sano, Y., Marty, B., Burnard, P., 2013. Noble Gases in the Atmosphere. In: *Burnard, P. (Ed.), The Noble Gases as Geochemical Tracers*. Springer, Berlin Heidelberg, pp. 17–31.
- Schwenger, S.P., Herrmann, S., Ott, U., 2009. Noble gases in two shergottites and one nakhlite from Antarctica: Y000027, Y000097, and Y000593. *Polar Sci.* 3, 83–99.
- Swindle, T.D., 2002. Martian Noble Gases. *Rev. Mineral. Geochem.* 47, 171–190.
- Swindle, T.D., Jones, J.H., 1997. The xenon isotopic composition of the primordial Martian atmosphere: Contributions from solar and fission components. *J. Geophys. Res. Planets* 102, 1671–1678.
- Swindle, T.D., Caffee, M.W., Hohenberg, C.M., 1986. Xenon and other noble gases in shergottites. *Geochim. Cosmochim. Acta* 50, 1001–1015.
- Tang, H., Dauphas, N., 2014. 60Fe–60Ni chronology of core formation in Mars. *Earth Planet. Sci. Lett.* 390, 264–274.
- Taylor, G.J., 2013. The bulk composition of Mars. *Geochemistry* 73, 401–420.
- Taylor, G.J., Boynton, W.V., McLennan, S.M., Martel, L.M.V., 2010. K and Cl concentrations on the Martian surface determined by the Mars Odyssey Gamma Ray Spectrometer: Implications for bulk halogen abundances in Mars. *Geophys. Res. Lett.* 37.
- Udry, A., Day, J.M.D., 2018. 1.34 billion-year-old magmatism on Mars evaluated from the co-genetic nakhlite and chassignite meteorites. *Geochim. Cosmochim. Acta* 238, 292–315.
- Udry, A., Howarth, G.H., Herd, C.D.K., Day, J.M.D., Lapen, T.J., Filiberto, J., 2020. What Martian Meteorites Reveal About the Interior and Surface of Mars. *J. Geophys. Res. Planets* 125, e2020JE006523.
- Wang, H., Weiss Benjamin, P., Bai, X.-N., Downey Brynna, G., Wang, J., Wang, J., Suavet, C., Fu Roger, R., Zucolotto Maria, E., 2017. Lifetime of the solar nebula constrained by meteorite paleomagnetism. *Science* 355, 623–627.
- Wanke, H., Dreibus, G., Wright, I.P., 1994. Chemistry and Accretion History of Mars [and Discussion]. *Philosophical Transactions: Physical Sciences and Engineering* 349, 285–293.
- Welten, K.C., Lindner, L., Van Der Borg, K., Loeken, T., Scherer, P., Schultz, L., 1997. Cosmic-ray exposure ages of diogenites and the recent collisional history of the howardite, eucrite and diogenite parent body/bodies. *Meteorit. Planet. Sci.* 32, 891–902.
- Wieler, R., Huber, L., Busemann, H., Seiler, S., Leya, I., Maden, C., Masarik, J., Meier, M.M., Nagao, K., Trappitsch, R., Irving, A.J., 2016. Noble gases in 18 Martian meteorites and angrite Northwest Africa 7812—Exposure ages, trapped gases, and a re-evaluation of the evidence for solar cosmic ray-produced neon in shergottites and other achondrites. *Meteorit. Planet. Sci.* 51, 407–428.
- R. Wieler, R., 2002. Cosmic-Ray-Produced Noble Gases in meteorites. In *Noble gases in geochemistry and cosmochemistry, reviews in Mineralogy and Geochemistry* 47, 125–170.
- Williams, C.D., Mukhopadhyay, S., 2018. Capture of nebular gases during Earth's accretion is preserved in deep-mantle neon. *Nature*.
- Yoshizaki, T., McDonough, W.F., 2020. The composition of Mars. *Geochim. Cosmochim. Acta* 273, 137–162.
- Zahnle, K.J., 1993. Xenological constraints on the impact erosion of the early Martian atmosphere. *J. Geophys. Res. Planets* 98, 10899–10913.