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# Noble gases in the Martian meteorite Northwest Africa 2737: A new chassignite signature

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**Abstract–**We report noble gas data for the second chassignite, Northwest Africa (NWA) 2737, which was recently found in the Moroccan desert. The cosmic ray exposure (CRE) age based on cosmogenic $^{3}$He, $^{21}$Ne, and $^{38}$Ar around 10–11 Ma is comparable to the CRE ages of Chassigny and the nakhlites and indicates ejection of meteorites belonging to these two families during a discrete event, or a suite of discrete events having occurred in a restricted interval of time. In contrast, U-Th/He and K/Ar ages <0.5 Ga are in the range of radiometric ages of shergottites, despite a Sm-Nd signature comparable to that of Chassigny and the nakhlites (Misawa et al. 2005). Overall, the noble gas signature of NWA 2737 resembles that of shergottites rather than that of Chassigny and the nakhlites: NWA 2737 does not contain, in detectable amount, the solar-like xenon found in Chassigny and thought to characterize the Martian mantle nor apparently fission xenon from $^{244}$Pu, which is abundant in Chassigny and some of the nakhlites. In contrast, NWA 2737 contains Martian atmospheric noble gases trapped in amounts comparable to those found in shergottite impact glasses. The loss of Martian mantle noble gases, together with the trapping of Martian atmospheric gases, could have occurred during assimilation of Martian surface components, or more likely during shock metamorphism, which is recorded in the petrology of this meteorite.

## INTRODUCTION

The Chassigny meteorite, which fell close to the village of Chassigny (Haute Saône, France) in 1815, is unique among the 34 Shergotty-Nakhla-Chassigny (SNC) meteorites found so far. It is the only olivine-rich (>89% Ol) SNC while the others are mineral assemblages that range from basaltic to pyroxenitic (e.g., Meyer 2004). Noble gases in Chassigny are thought to be mostly derived from the Martian mantle. Xenon trapped in Chassigny has a solar-like composition (Mathew et al. 1998; Ott 1988) whereas Xe in nakhlites and shergottites is dominated by a mixture of Martian atmospheric and terrestrial atmospheric Xe. The occurrence of a solar noble gas component in the Martian mantle has important implications for the formation of terrestrial planets and is in line with the occurrence of solar-like neon in the terrestrial mantle (Hiyagon et al. 1992; Honda et al. 1991). Furthermore, Chassigny and some of the SNCs contain Xe isotopes that have been produced by the fission of extinct $^{244}$Pu ($T_{1/2}$ = 82 Ma) (Mathew and Marti 2001; Ott 1988). The amount of fissiogenic Xe in Chassigny is close to chondritic values, suggesting that, if this meteorite has sampled gases from the Martian mantle, then this reservoir has experienced moderate degassing and therefore limited magmatism (Marty and Marti 2002) compared to the terrestrial mantle, which is highly depleted in fissiogenic Xe from $^{244}$Pu as a result of mantle convection (Yokochi and Marty 2005). All these properties make Chassigny a unique meteorite for understanding the early evolution of terrestrial planets.

Recently, a second olivine-rich (89.7% Ol) meteorite has been found in the Moroccan desert. Northwest Africa (NWA) 2737 is a stone of 611 g that has a $\Delta^{17}$O of +0.305, demonstrating its membership to the SNC clan (Beck et al. 2005a). Its rare earth element (REE) pattern (Beck et al. 2005b), and its initial $\varepsilon^{143}$Nd value (Misawa et al. 2005) are similar to those of Chassigny, leaving little doubt that NWA 2737 represents the second chassignite. With respect to Chassigny, NWA 2737 is more Mg-rich, suggesting that the parent magma experienced less differentiation and is therefore an even better candidate for representing the

Martian mantle source. Despite being a desert find, the trace element composition of NWA 2737 indicates limited, if any, terrestrial weathering (Beck et al. 2005b). We present here the results of a noble gas study, aimed to document 1) its cosmic ray exposure (CRE) age, 2) its gas retention age, and 3) the nature of the trapped noble gas component(s).

## ANALYTICAL

Two aliquots of NWA 2737 were analyzed at ETH Zürich by single and stepwise heating extraction for He, Ne, and Ar (10.11 mg; NWA 2737 #1) and He, Ne, Ar, Kr, and Xe (143.12 mg; NWA 2737 #2) isotopes, respectively. Stepwise heating was carried out in four temperature steps. Noble gases were calibrated using standard gas volumes with atmospheric isotopic composition. For details of gas extraction, noble gas separation, and cleaning procedure, as well as mass spectrometric techniques and data reduction, see Graf et al. (1990). All step data are corrected for their respective blanks. Blank contribution in the stepwise heating runs was <1% for $^{4}$He, ≤0.1 for $^{22}$Ne (except for the 600 °C step with ~5%) and <30% (600 °C, 1000 °C), or ≤10% (1200 °C, 1600 °C) for $^{36}$Ar. Blank $^{84}$Kr and $^{132}$Xe contributed ≤20% and ≤30%, except for 1200 °C with <10% and <20%, respectively. The blank at 1000 °C was somewhat higher than at 1200 °C, presumably because the furnace had been reheated from room temperature for the 1000 °C step but only from 400 °C for the 1200 °C step. Note that exactly the same protocol as for the blank was applied when analyzing the sample for the 1000 °C and 1200 °C steps.

Due to a high background pressure in the mass spectrometer during the Kr-Xe analysis of the 600 °C step, the Kr and Xe data might be corrupted. Blank contribution in the single extraction analysis was <1% for $^{4}$He and $^{22}$Ne and ~50% for $^{36}$Ar. Uncertainties given for gas amounts take into account counting statistics and errors due to blank reduction, interference correction, and calibration. Uncertainties on the isotopic ratios include errors due to blank reduction, counting statistics, and the error due to mass discrimination correction. He, Ne, and Ar data are given in Table 1, Kr data is given in Table 2, and Xe data is given in Table 3.

### CRE Ages

$^{3}$He is dominated by the cosmogenic component, as indicated by $^{3}$He/$^{4}$He ratios around 0.15, much higher than potential trapped end-members or terrestrial atmospheric He (Table 1). In computing the CRE ages based on $^{3}He_{c}$ (Table 4), we therefore assume a purely cosmogenic origin for this isotope. All $^{20}$Ne/$^{22}$Ne ratios but the one of the 600 °C extraction step are <0.9, indicating that neon isotopes are mostly cosmogenic in origin. Using the $^{22}$Ne/$^{21}$Ne ratio (in the range of 1.14–1.19) as a shielding indicator according to Leya et al. (2000) indicates that the analyzed aliquots were located at depths less than approximately 10 cm during exposure to cosmic rays, thus giving confidence that CRE ages are representative of the transit time of the meteorite since ejection from Mars. In a Ne three-isotope diagram (not shown), the data point of the 600 °C extraction falls on a mixing line between a cosmogenic end-member ($^{20}$Ne/$^{22}$Ne ≤ 1.0) and terrestrial or Martian atmospheric Ne ($^{20}$Ne/$^{22}$Ne = 9.8 and ~10, respectively; cf. Swindle 2002 and references therein for Martian atmospheric Ne). For this temperature step data, a correction for trapped Ne has been made, assuming a terrestrial $^{20}$Ne/$^{22}$Ne ratio. For other temperature steps, a purely cosmogenic origin for $^{21}$Ne has been assumed when computing CRE ages. For computing the amount of $^{38}Ar_{c}$, we assumed $^{36}$Ar/$^{38}$Ar values of 0.63 and 5.32 for the cosmogenic and trapped end-members, respectively (Ott 1988). Note that lower $^{36}$Ar/$^{38}$Ar values than 5.32 down to 4.0 have been inferred for Martian atmospheric argon, and one cannot make an a priori assumption about the nature of the trapped Ar component. Taking a value of 4.0 for trapped $^{36}$Ar/$^{38}$Ar would lower the computed $^{38}Ar_{c}$ exposure age by 0.4 Ma and 1.5 Ma for NWA 2737 #1 and NWA 2737 #2, respectively. However, we argue later that trapped $^{38}$Ar and $^{36}$Ar are dominated by a terrestrial, or Mars interior, end member rather than by Martian atmospheric argon. Cosmic ray production rates for $^{3}$He, $^{21}$Ne, and $^{38}$Ar were computed with elemental production rates of Eugster and Michel (1995) and using the NWA 2737 chemical composition given by Beck et al. (2005b). To facilitate intercomparison, we also re-computed CRE ages of Chassigny, given in Table 4, following the same procedure, using noble gas data from Ott (1988) and chemical composition from compilation in Meyer (2004). Two examples of CRE ages of nakhlites are also given in Table 1: NWA 817 (Mathew et al. 2003) and Nakhla (the compilation in Eugster et al. 1997).

Clearly, CRE ages of NWA 2737 are similar within uncertainties to those of Chassigny and of the nakhlites (Table 4), confirming a probable link between NWA 2737 and these meteorites. All these meteorites appear to have been ejected during a common event that occurred 10–11 Ma ago, or— less likely—to a suite of discrete events that were close in time compared to the uncertainty (1~2 Ma) of CRE ages.

We also searched for possible neutron capture effects in NWA 2737. As demonstrated in Fig. 1, which is a $^{80}$Kr/$^{83}$Kr versus $^{86}$Kr/$^{83}$Kr mixing diagram between a cosmogenic Kr end-member (defined with data from Lavielle and Marti 1988) and two potential Kr end-members, terrestrial atmosphere, and Martian atmosphere (a Martian mantle component is unlikely, as indicated by Xe isotope data; see below), there is no apparent effect for NWA 2737, except perhaps in the 1200 °C step. This is similar to Chassigny, for which no neutron-capture effect has been observed, but contrasts with the case of Nakhla for which there is evidence of n-capture effects on $^{79}$Br (Ott 1988). If excess $^{80}$Kr was due to incorporation of an atmospheric component enhanced in

Table 1. Helium, neon, and argon data. Abundances are in $10^{-10}$ $cm^3$ STP/g.

| Sample no. | Release T (°C) | $^{3}He$ | ± | $^{4}He$ | ± | $^{3}He/^{4}He$ | ± | $^{21}Ne$ | ± | $^{20}Ne/^{22}Ne$ | ± | $^{21}Ne/^{22}Ne$ | ± | $^{22}Ne/^{21}Ne$ | ± |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NWA 2737 #1 | 1600 | 2208 | 24 | 14,281 | 156 | 0.1546 | 0.0024 | 402 | 5 | 0.876 | 0.003 | 0.877 | 0.003 | 1.141 | 0.004 |
| NWA 737 #2 | 600 | 41 | 0.7 | 247 | 1 | 0.1660 | 0.0029 | 0.51 | 0.03 | 5.61 | 0.25 | 0.426 | 0.018 | 2.348 | 0.102 |
| | 1000 | 1263 | 7 | 9022 | 35 | 0.1400 | 0.0009 | 70.5 | 0.8 | 0.85 | 0.008 | 0.873 | 0.009 | 1.146 | 0.012 |
| | 1200 | 682 | 5 | 4044 | 15 | 0.1686 | 0.0014 | 238 | 3 | 0.823 | 0.013 | 0.841 | 0.009 | 1.189 | 0.015 |
| | 1600 | 15 | 0.2 | 84 | 1 | 0.1786 | 0.0032 | 54.2 | 0.9 | 0.867 | 0.006 | 0.862 | 0.013 | 1.16 | 0.018 |
| | Total | 2001 | 9 | 13,397 | 38 | 0.1494 | 0.0008 | 363 | 3 | 0.835 | 0.0089 | 0.85 | 0.011 | 1.176 | |

| Sample no. | Release T (°C) | $^{36}Ar$ | ± | $^{40}Ar/^{36}Ar$ | ± | $^{38}Ar/^{36}Ar$ | ± |
|---|---|---|---|---|---|---|---|
| NWA 2737 #1 | 1600 | 84.1 | 2.0 | 363.6 | 5.0 | 0.529 | 0.005 |
| NWA 2737 #2 | 600 | 2.53 | 0.05 | 340 | 22 | 0.241 | 0.002 |
| | 1000 | 19.3 | 0.4 | 509 | 7 | 0.761 | 0.020 |
| | 1200 | 13.7 | 0.2 | 209.4 | 2.1 | 1.205 | 0.017 |
| | 1600 | 5.72 | 0.09 | 203.7 | 2.6 | 0.857 | 0.003 |
| | Total | 41.2 | 0.5 | 356.7 | 8 | 0.890 | 0.011 |

Table 2. Krypton data for NWA 2737 #2 analysis. Krypton-84 abundance is in $10^{-12}$ $cm^3$ STP/g.

| Release T (° C) | $^{84}Kr$ | ± | $^{78}Kr/^{84}Kr$ | ± | $^{80}Kr/^{84}Kr$ | ± | $^{82}Kr/^{84}Kr$ | ± | $^{83}Kr/^{84}Kr$ | ± | $^{86}Kr/^{84}Kr$ | ± |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 600 | 5.82 | 0.10 | 0.0037 | 0.0006 | 0.042 | 0.002 | 0.203 | 0.008 | 0.210 | 0.007 | 0.311 | 0.008 |
| 1000 | 17.3 | 0.2 | 0.0231 | 0.0006 | 0.087 | 0.003 | 0.261 | 0.004 | 0.266 | 0.004 | 0.289 | 0.003 |
| 1200 | 12.7 | 0.2 | 0.0088 | 0.0004 | 0.050 | 0.001 | 0.217 | 0.006 | 0.210 | 0.005 | 0.302 | 0.004 |
| 1600 | 7.91 | 0.12 | 0.0078 | 0.0004 | 0.041 | 0.003 | 0.209 | 0.005 | 0.208 | 0.008 | 0.304 | 0.007 |
| Total | 43.7 | 0.3 | 0.0136 | 0.0003 | 0.062 | 0.001 | 0.231 | 0.003 | 0.232 | 0.003 | 0.298 | 0.002 |

Table 3. Xenon data for NWA 2737 #2 analysis. Xenon-132 abundance is in $10^{-12}$ $cm^3$ STP/g.

| Release T (°C) | $^{132}Xe$ | ± | $^{124}Xe/^{132}Xe$ | ± | $^{126}Xe/^{132}Xe$ | ± | $^{128}Xe/^{132}Xe$ | ± | $^{129}Xe/^{132}Xe$ | ± | $^{130}Xe/^{132}Xe$ | ± | $^{131}Xe/^{132}Xe$ | ± | $^{134}Xe/^{132}Xe$ | ± | $^{136}Xe/^{132}Xe$ | ± |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 600 | 1.23 | 0.04 | 0.0059 | 0.0024 | 0.008 | 0.002 | 0.076 | 0.006 | 1.051 | 0.028 | 0.168 | 0.011 | 0.847 | 0.032 | 0.421 | 0.022 | 0.333 | 0.013 |
| 1000 | 1.49 | 0.05 | 0.0925 | 0.0047 | 0.155 | 0.005 | 0.285 | 0.012 | 1.769 | 0.041 | 0.263 | 0.013 | 1.049 | 0.030 | 0.383 | 0.013 | 0.306 | 0.012 |
| 1200 | 1.11 | 0.04 | 0.0227 | 0.0025 | 0.030 | 0.002 | 0.108 | 0.006 | 1.825 | 0.045 | 0.164 | 0.013 | 0.816 | 0.041 | 0.399 | 0.013 | 0.346 | 0.015 |
| 1600 | 0.65 | 0.02 | 0.0055 | 0.0024 | 0.007 | 0.002 | 0.059 | 0.018 | 1.359 | 0.050 | 0.160 | 0.011 | 0.765 | 0.055 | 0.401 | 0.027 | 0.288 | 0.020 |
| Total | 4.48 | 0.08 | 0.0389 | 0.0019 | 0.062 | 0.002 | 0.151 | 0.005 | 1.527 | 0.020 | 0.197 | 0.006 | 0.895 | 0.017 | 0.400 | 0.008 | 0.321 | 0.006 |
| Data corrected for spallation | | | | | | | | | | | | | | | | | | |
| Release T (°C) | $^{132}Xe$ | ± | $^{124}Xe/^{132}Xe$ | ± | $^{126}Xe/^{132}Xe$ | ± | $^{128}Xe/^{132}Xe$ | ± | $^{129}Xe/^{132}Xe$ | ± | $^{130}Xe/^{132}Xe$ | ± | $^{131}Xe/^{132}Xe$ | ± | $^{134}Xe/^{132}Xe$ | ± | $^{136}Xe/^{132}Xe$ | ± |
| 600 | 1.22 | 0.04 | 0.0036 | 0.0036 | 0.0038 | 0.0007 | 0.0708 | 0.0106 | 1.050 | 0.030 | 0.164 | 0.012 | 0.839 | 0.033 | 0.421 | 0.022 | 0.3334 | 0.0140 |
| 1000 | 1.30 | 0.05 | 0.0090 | 0.0051 | 0.0038 | 0.0007 | 0.0753 | 0.112 | 1.793 | 0.079 | 0.140 | 0.065 | 0.758 | 0.180 | 0.391 | 0.029 | 0.3490 | 0.0210 |
| 1200 | 1.09 | 0.04 | 0.0203 | 0.0036 | 0.0038 | 0.0007 | 0.05723 | 0.0206 | 1.829 | 0.052 | 0.143 | 0.017 | 0.766 | 0.050 | 0.401 | 0.014 | 0.3539 | 0.0180 |
| 1600 | 0.65 | 0.02 | 0.0031 | 0.0036 | 0.0038 | 0.0007 | 0.0544 | 0.0196 | 1.359 | 0.056 | 0.157 | 0.011 | 0.759 | 0.055 | 0.402 | 0.027 | 0.2877 | 0.0200 |
| Total | 4.26 | 0.08 | 0.0094 | 0.0021 | 0.0038 | – | 0.066 | 0.035 | 1.523 | 0.030 | 0.150 | 0.021 | 0.783 | 0.057 | 0.404 | 0.011 | 0.336 | 0.009 |

Table 4. CRE ages (Ma) of NWA 2737, Chassigny NWA 817, and Nakhla.

| | NWA 2737 #1 | NWA 2737 #2 | Chassigny[a] | NWA 817[b] | Nakhla[c] |
|---|---|---|---|---|---|
| $T_{3c}$ | 13.4 | 12.7 | 12.5 | 8.7 | 12.5 |
| $T_{21c}$ | 9.3 | 8.9 | 11.8 | 9.3 | 12.5 |
| $T_{38c}$ | 9.6 | 9.7 | 7.3 | 11.7 | 9.8 |
| Mean | 10.8 | 10.4 | 10.6 | 10.0 | 11.6 |
| ± | 2.3 | 2.0 | 2.9 | 1.3 | 1.8 |

[a]CRE age computed with noble gas data from Ott (1988) and chemical composition from Meyer (2004).
[b]Data from Mathew et al. (2003).
[c]Compilation in Eugster et al. (1997).

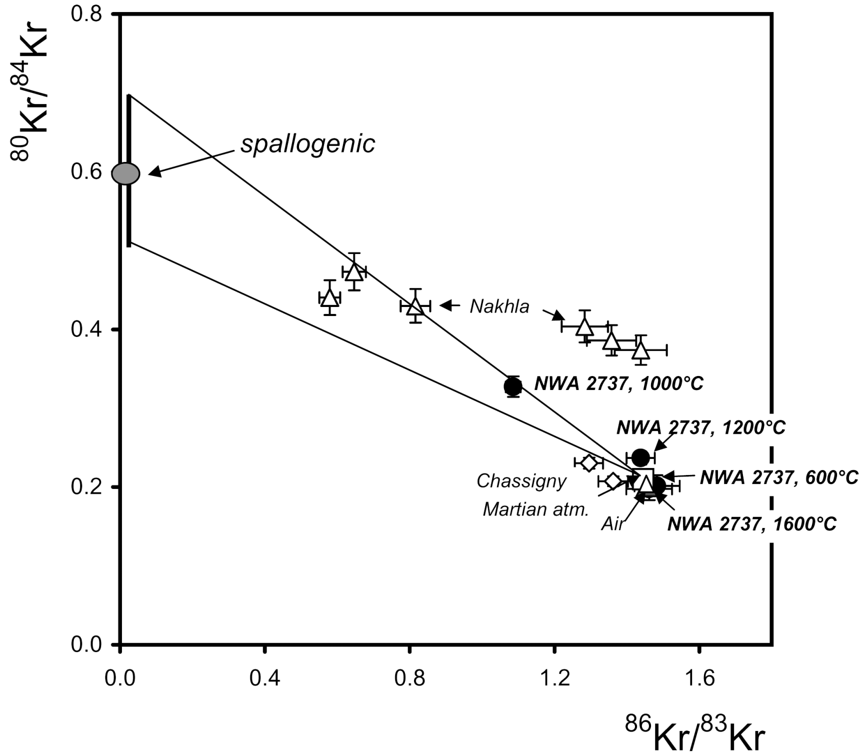


Fig. 1. The search for possible neutron capture effects on Kr isotopes, using the format of and Nakhla and Chassigny data from Ott (1988). Lines represent mixing between Mars atmosphere (Swindle 2002) (terrestrial atmosphere would not change significantly the end member) and cosmogenic Kr (value and uncertainty from Lavielle and Marti 1988). There is no clear evidence for excess $^{80}$Kr (above the mixing domain) from neutron capture reaction on $^{79}$Br, contrary to the case of Nakhla.

$^{80}$Kr as suggested previously, but not unanimously accepted (see review by Swindle 2002 and references therein for pro and con arguments), this excess should be most prominent in meteorites presenting Xe isotope evidence for incorporation of Martian atmospheric noble gases. The observation that NWA 2737 does not show such an excess despite $^{129}$Xe/$^{132}$Xe ratios up to 1.8 is not consistent with a Martian atmospheric origin for such a component. An in situ origin (production through neutron capture on $^{79}$Br) is consistent with the fact that Chassigny and NWA 2737, which are dunites, are likely to contain less Br than nakhlites and shergottites. Although one cannot dismiss that halogens measured in Martian meteorites may partly be terrestrial in origin, the measured Br content of Chassigny (~100 ppb) (Dreibus and Wänke 1987) is much lower than that of Nakhla (3,000–4,000 ppb) (Dreibus and Wänke 1987). The Br content of NWA 2737 has not yet been measured.

## Gas Retention Ages

In the following, we use Ar isotope data corrected for cosmogenic contribution. Upper limits for K-Ar ages computed assuming in situ decay of $^{40}$K as an exclusive source of $^{40}$Ar are 0.7 Ga and 1.2 Ga for the two aliquots, respectively. These upper limits are lower than the radiometric ages in the range 1.3–1.4 Ga that characterize Chassigny and the nakhlites (e.g., Nyquist et al. 2001). The $^{40}$Ar/$^{36}$Ar ratios of all steps are lower than the Mars atmospheric ratio ($^{40}$Ar/$^{36}$Ar = 1900–2400; Swindle 2002 and references therein), despite evidence for Mars atmosphere contribution from Xe isotopes (see next subsection). In addition to a potentially trapped Mars atmosphere Ar component and to radiogenic $^{40}$Ar from the in situ decay of $^{40}$K, there must be significant Ar with lower $^{40}$Ar/$^{36}$Ar. The latter could be either Mars interior argon ($^{40}$Ar/$^{36}$Ar ≤ 200) (Mathew and Marti 2001), and/or terrestrial atmospheric argon ($^{40}$Ar/$^{36}$Ar = 295.5).

In order to attempt correction of in situ produced $^{40}$Ar for addition of inherited Ar, we tentatively use a mixing diagram approach:

$$\left(\frac{^{40}\mathrm{Ar}}{^{36}\mathrm{Ar}}\right)_{\mathrm{obs}} \approx \left(\frac{^{40}\mathrm{Ar}^*}{^{36}\mathrm{Ar}_A}\right) + \left(\frac{^{40}\mathrm{Ar}}{^{36}\mathrm{Ar}}\right)_A \quad (1)$$

This equation describes the case of mixing between an $^{40}$Ar component in constant proportion and alien argon inherited either from Mars reservoir(s) or added during terrestrial residence or laboratory handling. The suffixes “obs” and “A” stand for “observed” and “alien,” respectively, and “*” represents radiogenic $^{40}$Ar from in situ production.

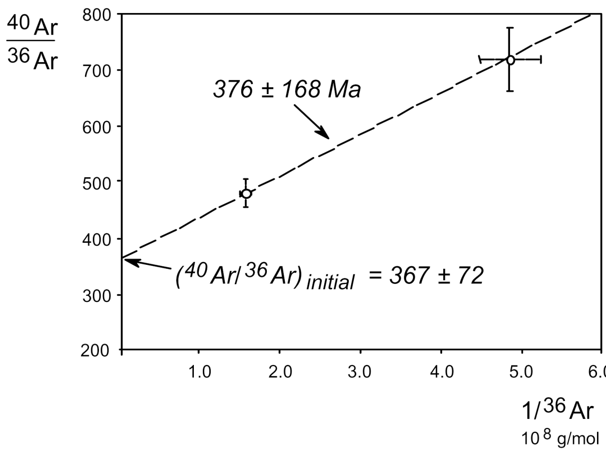


Fig. 2. A mixing diagram for NWA 2737 (see the text for explanations and comments on the validity of the mixing approach). The age is computed with the K content of the meteorite given in Beck et al. (2005b) and the $^{40}$Ar* content computed from the slope of the line passing through the two data points (Ar data are corrected for cosmogenic contribution). The ordinate intersects indicates the $^{40}$Ar/$^{36}$Ar ratio of the diluting Ar component.

In an ($^{40}$Ar/$^{36}$Ar) versus 1/$^{36}$Ar plot (Fig. 2), the equation yields a straight line with slope $^{40}$Ar* if the mixing hypothesis is verified. The two data points allow one to infer a radiometric age of 376 ± 168 Ma (2σ) as computed from the regression slope and with a K content of 415 ppm for NWA 2737 (Beck et al. 2005b). The ordinate intercept of the regression line yields ($^{40}$Ar/$^{36}$Ar)$_i$ = 367 ± 72 (2σ), which is consistent with the terrestrial atmospheric value of 295.5. Thus the presently available data are consistent with variable atmospheric contamination of a $^{40}$Ar* component dominated by in situ production. Such terrestrial contamination is expected in the case of desert finds, even if NWA 2737 appears to be among the least altered meteorites found in the desert (Beck et al. 2005b). A K-Ar age of 376 ± 168 Ma is consistent with $^{39}$Ar–$^{40}$Ar ages <500 Ma for the same meteorite (Bogard and Garrison 2005) and is much younger than radiometric ages of Chassigny and the nakhlites (Nyquist et al. 2001 and references therein).

The K-Ar age of 376 ± 168 Ma is in the range of ages characterizing basaltic shergottites (165–475 Ma, Nyquist et al. 2001 and references therein). However, the NWA 2737 age is probably a metamorphic one because the Sm-Nd systematics of this meteorite yield an age within the range of those of Chassigny and the nakhlites (Misawa et al. 2005). This low K-Ar age could be due to either loss of $^{40}$Ar during Martian metamorphism or during the shock ejection event, a possibility consistent with mineralogical evidence for shock metamorphism in this meteorite. The (U, Th)/He age of 0.12 Ga (computed by assuming that all $^4$He is from in situ accumulation and with U and Th data from Beck et al. 2005b) is even lower than the K-Ar age, strongly suggesting that the K-Ar age of NWA 2737 lower that those of Chassigny and the nakhlites is due to metamorphic loss.

**Origin of Trapped Noble Gases**

The xenon content of NWA 2737 is the lowest one recorded among Martian meteorites. It is lower than that of Chassigny by one order of magnitude and by a factor of ≥2 compared to Nakhla and other nakhlites. The low Xe content resulted in relatively large uncertainties in the measured Xe isotopic ratios (Table 3). Data were corrected for addition of spallation xenon, using the $^{126}$Xe/$^{132}$Xe ratio as an index of spallation contribution. For the spallation $^{i}$Xe/$^{132}$Xe ratios, we used values from Mathew and Marti (2002) for Martian meteorites except for the $^{129}$Xe/$^{132}$Xe ratio, which was not given by these authors and for which we instead used the value given by Kim and Marti (1992). The production of $^{136}$Xe by spallation is very small and was not given by Mathew and Marti (2002). After renormalization to $^{132}$Xe (the original values were normalized to $^{126}$Xe in Mathew and Marti 2002), the spallation ratios we used are: $^{124}$Xe/$^{132}$Xe = 0.61 ± 0.29, $^{126}$Xe/$^{132}$Xe = 1.18 ± 0.35, $^{128}$Xe/$^{132}$Xe = 2.60 ± 0.77, $^{129}$Xe/$^{132}$Xe = 1.60 ± 0.38, $^{130}$Xe/$^{132}$Xe = 1.09 ± 0.30, $^{131}$Xe/$^{132}$Xe = 3.05 ± 0.96, and $^{134}$Xe/$^{132}$Xe = 0.33 ± 0.16. For the $^{136}$Xe/$^{132}$Xe ratio, we took the $^{136}$Xe/$^{132}$Xe ratio of 0.02 ± 0.01 for computation purpose. Errors are somewhat inflated because the normalizing $^{132}$Xe/$^{126}$Xe ratio has a relative uncertainty of 29.4% (Mathew and Marti 2002). In diagrams, $^{126}$Xe/$^{132}$Xe versus $^{i}$Xe/$^{132}$Xe (where $i$ = 124, 128, 129, 130, 131, 134, and 136), the regression lines defined by the spallogenic end-member and the observed data points allows one to compute the $^{i}$Xe/$^{132}$Xe trapped ratio by inputting a value for the trapped ($^{126}$Xe/$^{132}$Xe)$_T$ in the regression equation. For ($^{126}$Xe/$^{132}$Xe)$_T$, we adopted a value of 0.0038 ± 0.0007, which is the mean isotopic ratio between solar, Mars atmosphere, and Earth atmosphere. Results are rather insensitive to this uncertainty because the relative spallogenic contribution at mass 126 is maximum among Xe isotopes. We computed the regression lines and propagated errors following the program of Ludwig (1999).

Xe isotopic ratios corrected for spallation are given in Table 3. The composition of the 1200 °C extraction is compared to potential end-member compositions (terrestrial atmosphere, solar, and Martian atmosphere) in Fig. 3. For the 600 °C extraction, the overall Xe isotope pattern (not shown) demonstrates that terrestrial Xe dominates. For the 1600 °C step, the low Xe amount does not allow one to be conclusive about the origin of xenon, but we note that a $^{129}$Xe/$^{132}$Xe ratio of 1.36 indicates the presence of Martian atmospheric Xe. For the two other temperature steps (1000 °C and 1200 °C), contribution from the Martian atmosphere is evident from large $^{129}$Xe excesses, with $^{129}$Xe/$^{132}$Xe ratios up to 1.83 ± 0.05 (1200 °C step). Such high values are only matched among SNC by shergottite glasses and by few temperature steps of Nakhla and Allan Hills (ALH) 84001 (e.g., Bogard et al. 2001 and references therein). The occurrence of Mars atmospheric Xe in the steps >600 °C is consistent with most of the Xe isotope patterns, and is best seen in the 1200 °C step release

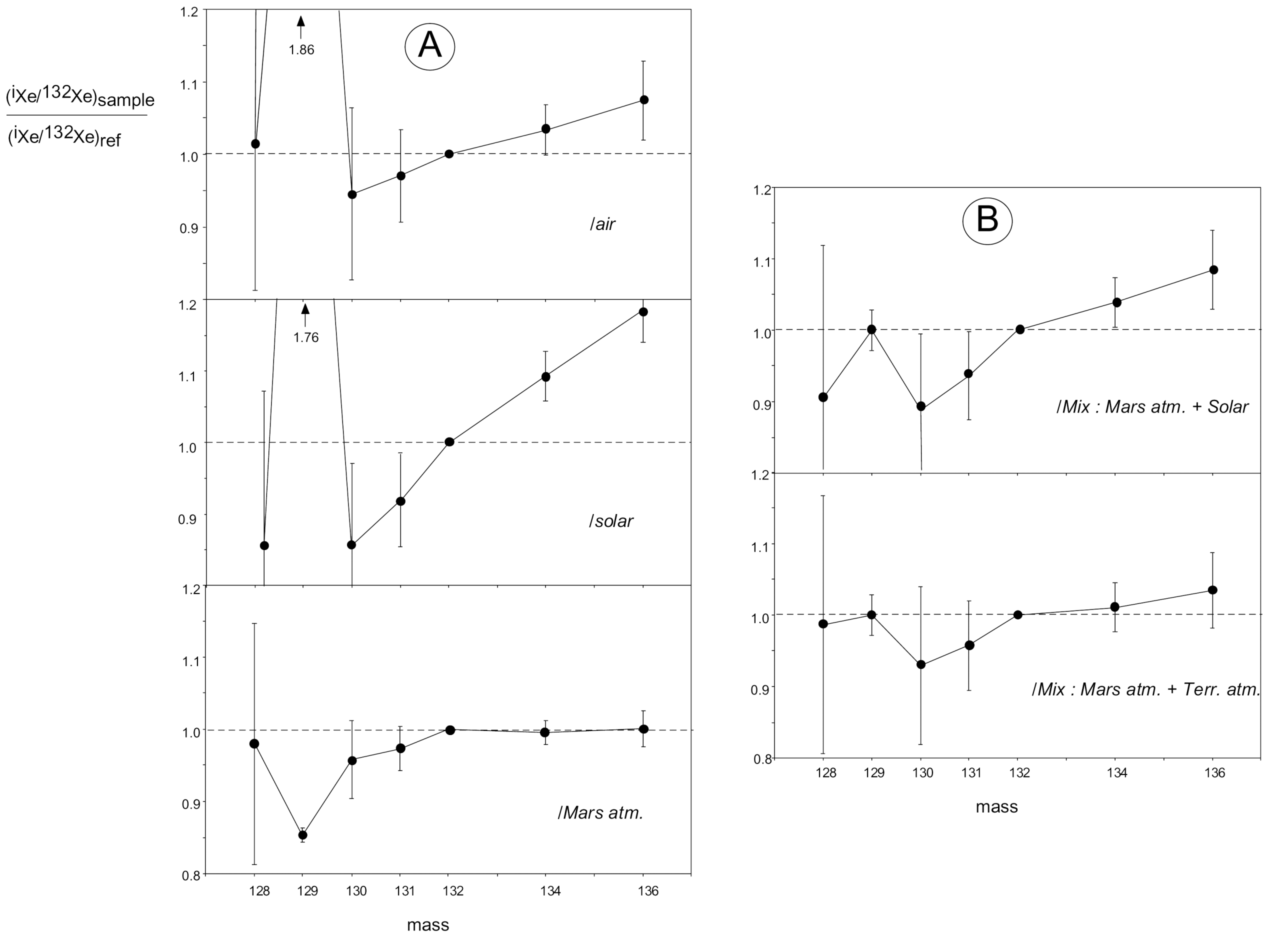


Fig. 3. The Xe isotopic composition corrected for spallation compared to potential end-member compositions. Only the 1200 °C data are represented, but the conclusion drawn from these data are also supported by the 1000 °C data. The 600 °C step is dominated by atmospheric xenon. The Xe content of the 1600 °C is lower and data have higher uncertainties. The normalizing compositions are: terrestrial atmosphere (Ozima and Podosek 2002), Martian atmosphere (Swindle 2002), and solar (Wieler 2002). a) Xe isotopic ratios normalized to pure reference components. Normalization to both air (terrestrial atmosphere) and solar cannot account for the $^{129}Xe$ excess. Normalization to Martian atmospheric Xe induces a deficit of $^{129}Xe$. b) Normalization to mixtures of Martian atmospheric Xe bearing the $^{129}Xe$ excess and either solar or air Xe. In each case the mixing ratio has been computed to yield no excess of $^{129}Xe$. Both mixtures can account for trapped Xe within errors.

pattern where normalization to the Mars atmosphere composition gives the best results in term of normalized ratios being close to 1 (Fig. 3a). In Fig. 3b, we have normalized the observed Xe pattern to a mixture of Mars atmosphere and solar (top) and Mars atmosphere and terrestrial atmosphere (bottom). The mixing ratio was set as to account for the observed $^{129}Xe/^{132}Xe$ ratio (normalized ratio = 1). Both mixtures can account for the observed pattern. In case the mixture involves solar (Mars interior) Xe, an excess of $^{136}Xe$ marginally significant at 1σ uncertainty appears, leaving open the occurrence of fission Xe in this meteorite. This fission excess disappears when a mixture of Mars atmosphere and terrestrial atmosphere is considered. Further high-precision analysis of xenon in NWA 2737 will be required to definitely make any conclusions about the possible occurrence of fission xenon in NWA 2737, which was otherwise detected in Chassigny and the nakhlites.

The presence of Martian atmospheric gases is also evident in a $^{129}Xe/^{132}Xe$ versus $^{84}Kr/^{132}Xe$ diagram for Martian meteorites which permits identification of several potential Martian end-members (Fig. 4). Chassigny represents the Martian interior component characterized by a strong enrichment of Xe relative to other noble gases (e.g., Kr, $^{84}Kr/^{132}Xe$ ratio = 1.2 [Ott 1988]) and a low $^{129}Xe/^{132}Xe$ ratio of <1.07, (Mathew and Marti 2001; Ott 1988). Both the Mars atmosphere and the terrestrial atmosphere are enriched in $^{84}Kr$ but the former is also strongly enriched in $^{129}Xe$ ($^{129}Xe/^{132}Xe$ = 2.6, e.g., Garrison and Bogard 1998). Shergottite data for impact glasses (represented here by EET 9001 and Zagami) are consistent with a ternary mixing and represent the samples that have trapped the largest amount of Mars atmosphere. The nakhlites (Nakhla, NWA 817) and ALH 84001 are characterized by lower $^{84}Kr/^{132}Xe$ ratios whatever the corresponding $^{129}Xe/^{132}Xe$ ratios.

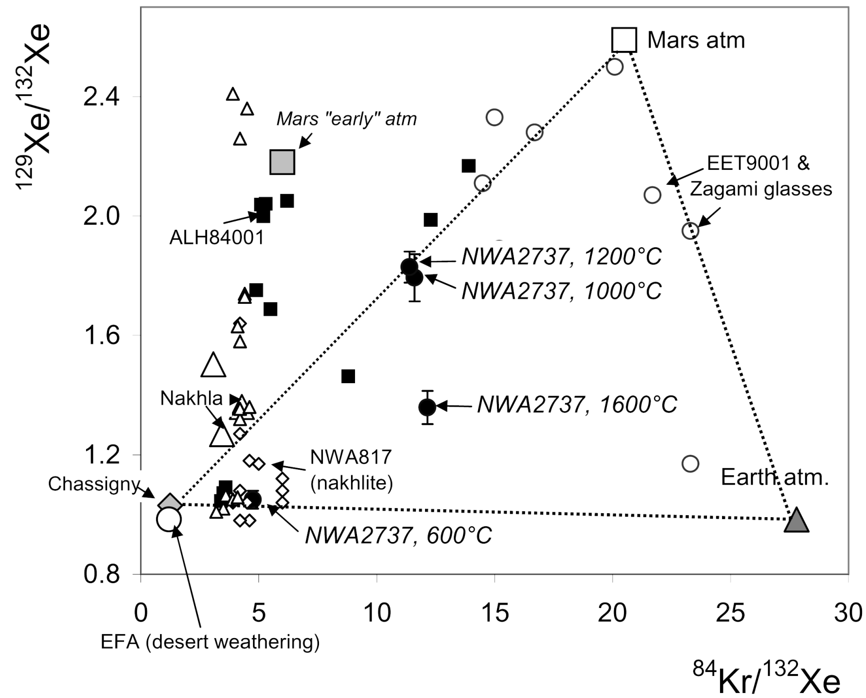


Fig. 4. $^{129}Xe/^{132}Xe$ versus $^{84}Kr/^{132}Xe$ for a selection of representative Martian meteorite noble gas compositions. NWA 2737: I (this work); Chassigny (diamond): Ott (1988); Nakhla bulk rock (large open triangles): Ott (1988); Nakhla stepwise heating (small open triangles): Ott (1988); ALH 84001 stepwise heating (black squares): Mathew and Marti (2001); NWA 817 stepwise heating (open diamonds) (this nakhlite is also a desert find): Mathew et al. (2003); EET 9001 and Zagami glasses (circles): Garrison and Bogard (1998) and references therein; elementally fractionated air (EFA), representing the effect of desert weathering, large dot: Schwenzer et al. (2005); Mars "early atmosphere": Mathew and Marti (2001); Mars atmosphere: Swindle (2002), Earth atmosphere: Ozima and Podosek (2002).

The composition of the high $^{129}Xe/^{136}Xe$, low $^{84}Kr/^{132}Xe$ end-member of ALH 84001 has been interpreted as due to trapping of an "ancient" atmospheric Xe component (Mathew and Marti 2001), or due to fractionation of the Martian atmosphere through preferential solubility of Xe in liquid water and incorporation in weathering products (Drake et al. 1994), or due to adsorption of Xe in Martian crust and its incorporation during either magma assimilation (Gilmour et al. 1999), or shock implantation (Bart et al. 2001). A totally different explanation has been recently proposed in the case of Martian meteorites found in deserts. Although the low $^{84}Kr/^{132}Xe$, low $^{129}Xe/^{132}Xe$ end-member could represent the Mars interior component, the Xe isotopic compositions of many SNC falling in this category are not solar-like but rather display evidence of terrestrial contamination. This component has been observed notably in the low temperature release of desert finds which otherwise present stable isotope data (H, C, N) indicative of a terrestrial origin (Mohapatra et al. 2002), and has been labeled as elementally fractionated air (EFA). Furthermore, stochiometric calcite from the surface of a desert SNC and desert soil have been found to present even lower $^{84}Kr/^{132}Xe$ ratios than EFA (Schwenzer et al. 2005). In line with this explanation, the 600 °C step extraction of NWA 2737 has $^{129}Xe/^{132}Xe$ and $^{84}Kr/^{132}Xe$ ratios close to the EFA end-member (Fig. 4), which is consistent with a terrestrial contamination for gases released at this temperature advocated in the case of Ne and Xe isotopes. Remarkably, the other temperature steps display $^{84}Kr/^{132}Xe$ ratios higher by a factor of ~2–3 than those of nakhlites, and also of many shergottites found in desert area (e.g., NWA 480, NWA 856, NWA 1068, SaU 005; Mathew et al. 2003). This observation, together with the fact that this meteorite shows one of the highest $^{129}Xe/^{136}Xe$ ratios observed in SNC desert finds, suggests strongly that NWA 2737 is among the least altered SNC finds, which is fully consistent with its trace element signature indicating very limited alteration (Beck et al. 2005b).

## Processes of Gas Incorporation

NWA 2737 differs from Chassigny and nakhlites by its scarcity of fissiogenic Xe, its apparent lack of Mars interior Xe, and its relatively high level of Mars atmosphere Xe. In this respect, it shares similarities with shergottites that are also depleted in fission Xe relative to Chassigny and nakhlites and which can contain relatively high amounts of Mars atmosphere Xe (e.g., Mathew et al. 2003; Ott 1988).

The lack of Martian mantle gases together with the occurrence of Martian atmospheric gases could reflect degassing of the parent magma and assimilation of a crustal component saturated in atmospheric noble gases, as it is the case for terrestrial magmas during assimilation, fractional crystallization, and degassing (AFCD) (Marty and Zimmermann 1999). In this case, the NWA 2737 parent magma should be more evolved than the Chassigny parent magma. However, magnesium is higher in NWA 2737 (Mg# = 78) compared to Chassigny (Mg# = 69), indicating that this is not the case. Alternatively, noble gas exchange on Mars could have taken place during the shock event that ejected the meteorite. The black color of NWA 2737 interpreted by Beck et al. (2005a) as due to Fe and Si speciation during a strong shock as well as the occurrence of melt veins attest that this meteorite is indeed highly shocked. An important step forward will be to determine if the K-Ar age in the range of shergottite ones is coincidental (partial loss of radiogenic $^{40}Ar$ during the ejection event) or reflects a regional event that could be linked with the setting of shergottite chronometers.

## CONCLUSIONS

NWA 2737 is unique among Martian meteorites. It presents mineralogical similarities with Chassigny and a CRE age similar to those of Chassigny and of the nakhlites, suggesting that it derives from the same region and was ejected during the same event. In contrast, it displays an apparent K-Ar age younger than those of Chassigny and nakhlites and in the range of shergottite ages. Its heavy noble gas signature is different from that of Chassigny and is more akin to those of some of the shergottites. These noble gas characteristics are suggestive of extensive exchange with the Martian atmosphere, probably during the shock event that modified its mineralogy.

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