Geochemical Perspectives Letters

© 2017 European Association of Geochemistry

Solar wind implantation supplied light volatiles during the first stage of Earth accretion

S. Péron[1*], M. Moreira[1], B. Putlitz[2], M.D. Kurz[3]

OPEN ACCESS

doi: 10.7185/geochemlet.1718

Abstract

The isotopic and elemental compositions of noble gases constitute a powerful tool to study volatile origin and evolution, due to their inertness, and can thus provide crucial information about the early stage of planetary formation. Two models are proposed to explain the light noble gas origin on Earth: the solar wind implantation model and the solar nebula gas dissolution model. However, noble gas measurements often show addition of air to the mantle-derived gas, which complicates the determination of mantle isotopic ratios. We analysed the noble gas isotopic compositions of single vesicles in samples from the Galápagos hotspot with laser ablation, in order to understand and remove this atmospheric component, as well as discriminate between the two scenarios. Based on the new high precision results and a new statistical approach, we show that the solar wind implantation model is more likely to explain the terrestrial He, Ne and Ar composition. This scenario could bring important constraints on the solar system environment during the early stage of planetary formation.

Received 12 October 2016 | Accepted 8 February 2017 | Published 13 March 2017

Introduction

The isotopes ^{20}Ne, ^{22}Ne, ^{36}Ar and ^{38}Ar are primordial in the Earth's mantle, the ^{20}Ne/^{22}Ne and ^{38}Ar/^{36}Ar isotopic ratios can thus be used as noble gas source tracers. The major noble gas carriers in the solar system are, among others, the solar wind (^{20}Ne/^{22}Ne = 13.8–14.0, ^{38}Ar/^{36}Ar = 0.1818–0.1828; Heber *et al.*, 2009; Pepin *et al.*, 2012), the component B (^{20}Ne/^{22}Ne = 12.5–12.7, ^{38}Ar/^{36}Ar = 0.1862 or 0.1919; Black, 1972; Raquin and Moreira, 2009; Moreira, 2013; Moreira and Charnoz, 2016), which corresponds to solar wind implantation and is mostly important for light noble gases, and the phase Q for heavy noble gases found in chondrites (^{20}Ne/^{22}Ne = 10.1–10.7, ^{38}Ar/^{36}Ar = 0.1873; Busemann *et al.*, 2000). The lower mantle is one plausible reservoir of primitive noble gases (Allègre *et al.*, 1983), so some Oceanic Island Basalts (OIBs), which are presumed to sample the lower mantle, are of particular interest to determine the Earth's primordial isotopic ratios. Only a limited suite of samples from a few hotspots (Hawaii, Galápagos and Iceland) are suitable because unradiogenic/primitive (He, Ne) isotopic compositions are rare, and because submarine or subglacial glass samples are needed to analyse the primitive noble gas compositions. Such glass samples correspond to magma quenched at high pressures during eruptions and are among the best samples to record the mantle noble gas composition.

However, the ubiquity of an atmospheric component has complicated the determination of mantle source noble gas isotopic compositions. The air component may be derived from post-eruption contamination when samples are recovered from the seafloor (Ballentine and Barfod, 2000). It may also come from atmospheric recycling through subduction for heavy noble gases (Ar, Kr, Xe) (Holland and Ballentine, 2006; Kendrick *et al.*, 2011; Parai and Mukhopadhyay, 2015). Noble gas studies often use step-crushing to analyse samples, and the results yield mixing trends between an atmospheric end-member and a mantle end-member. It is then assumed that the highest measured value is the least air contaminated and corresponds to a lower limit for the mantle. However, this approach does not necessarily completely eliminate atmospheric contamination. In order to avoid the atmospheric component, laser ablation analyses were introduced (Burnard *et al.*, 1997; Burnard, 1999), which involve targeting individual bubbles with a laser. Up to now, no laser ablation study allows us to clearly discriminate between the two scenarios for noble gas origin on Earth because of the scarcity of data and the poor accuracy (Raquin *et al.*, 2008; Colin *et al.*, 2015; Péron *et al.*, 2016).

We analysed by laser ablation the noble gas compositions (He, Ne, Ar) of twenty vesicles of two submarine glass samples from Fernandina volcano (Galápagos), previously imaged via X-ray microtomography to locate the vesicles (Supplementary Information and Table S-1), with the aim of understanding the air contamination mechanisms, and refining the Earth's primordial ^{20}Ne/^{22}Ne and ^{38}Ar/^{36}Ar ratios to evaluate the two models for noble gas origin on Earth; the solar wind implantation model (Trieloff *et al.*, 2000; Raquin and Moreira, 2009) and the solar nebula gas dissolution model (Yokochi and Marty, 2004; Mukhopadhyay, 2012). These OIB samples, AHA-NEMO2-D22A and AHA-NEMO2-D22B, were chosen due to their very primitive He and Ne compositions (Kurz *et al.*, 2009), relatively high gas concentrations and thick glassy rinds (results are in Tables S-2 and S-3).

1. Institut de Physique du Globe de Paris - Sorbonne Paris Cité, UMR CNRS 7154, Université Paris Diderot, 1 Rue Jussieu, 75005 Paris, France
* Corresponding author (email: peron@ipgp.fr)
2. Institute of Earth Sciences, University of Lausanne, Géopolis Building, CH-1015 Lausanne, Switzerland
3. Marine Chemistry and Geochemistry, MS #25, Clark 421, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, United States

Evidence for a Ne-B Component in the Mantle

All the new vesicles analysed show similar isotopic compositions, with only two exceptions (vesicles V4B and V16B; Figs. 1, 2 and Table S-3). Vesicles V4B and V16B may be contaminated by air since their $^{20}Ne/^{22}Ne$ and $^{40}Ar/^{36}Ar$ ratios are lower and tend to atmospheric ratios. Small but subtle cracks are observed just above these bubbles on the X-ray microtomography images (Figs. S-1, S-2, S-3 and S-4) and must have been hit before piercing these vesicles, mixing air with vesicle gases. This is a new evidence of atmospheric contamination mechanisms. These cracks, typically less than 20 µm wide, are difficult to notice. Except those two vesicles, and the vesicles for which the uncertainties are large (V2B, V5B, V6B, V11B and V2A), the $^{20}Ne/^{22}Ne$ ratio is between 12.17 ± 0.13 and 12.83 ± 0.09 (1σ), the vesicles have a $^{38}Ar/^{36}Ar$ ratio similar to air (0.188) and the $^{40}Ar/^{36}Ar$ ratio is between 5809 ± 425 and 8206 ± 695 (Table S-3 and Fig. S-5).

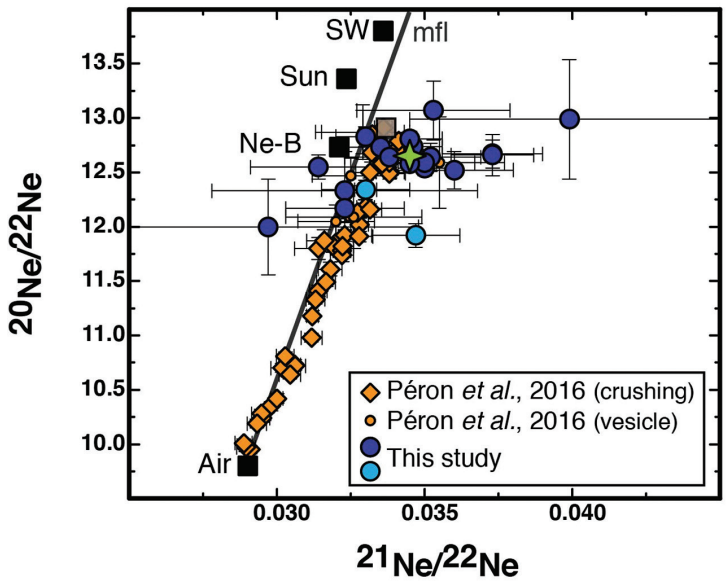

Figure 1 The three neon isotopes plot for the vesicles. Data from the literature for the same samples (Péron *et al.*, 2016) are in orange diamonds and circles. The new data are in blue circles, the two vesicles in light blue (V4B and V16B) are assumed to be air contaminated (Figs. S-1, S-2). The Fernandina source isotopic composition estimated from the statistical analysis with the new data is indicated with the green star, in comparison with the previous one (Péron *et al.*, 2016) indicated with the grey square. Ne-B (Moreira, 2013), Sun (Heber *et al.*, 2012), solar wind SW (Heber *et al.*, 2009), *mfl* mass fractionation line.

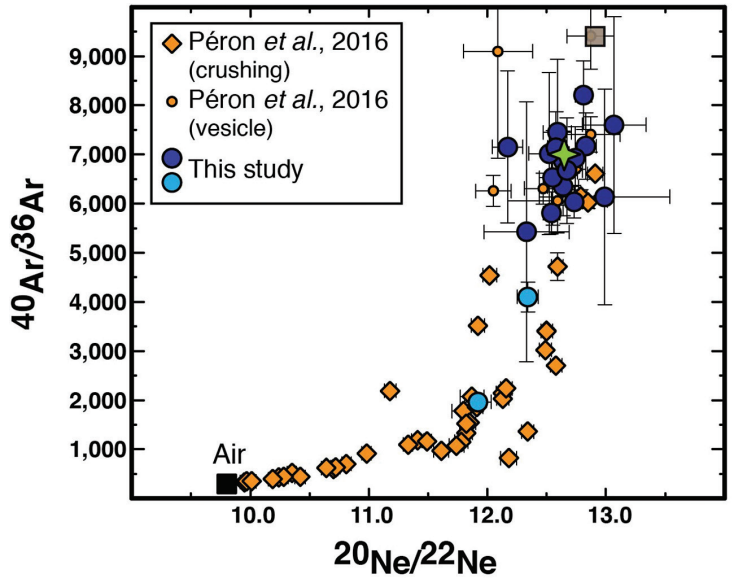

Figure 2 $^{40}Ar/^{36}Ar$ ratio *vs* $^{20}Ne/^{22}Ne$ ratio for the vesicles. The latter are in blue circles (vesicles V2A and V11B have too large uncertainties and are not represented). Previous data are in orange diamonds and circles (Péron *et al.*, 2016). The two vesicles in light blue (V4B and V16B) are assumed to be air contaminated, as indicated by the $^{40}Ar/^{36}Ar$ data, along with distribution of microcracks (Figs. S-1, S-2, S-3, S-4, S-8). The Fernandina source isotopic composition inferred from laser ablation data alone is indicated with the green star, in comparison with the previous one (Péron *et al.*, 2016) indicated with the grey square.

The relatively large dataset (20 vesicles) combined with the fact that all the vesicles have similar isotopic compositions (Figs. 1 and 2), suggests that they all sample the same gas. This allows a statistical analysis (Fig. 3) in order to derive precisely the Fernandina source isotopic ratios. In this new approach, a Gaussian distribution is considered for each vesicle isotopic ratio, where the mean is the measured isotopic ratio and sigma is the associated measurement uncertainty, and then the sum of all these Gaussian distributions for a given isotopic ratio gives a cumulative curve. These cumulative curves are thus fitted to obtain overall means (Supplementary Information). This allows us to weight the mean according to measurement uncertainty. We use all the vesicles except the two contaminated ones (V4B and V16B). By fitting the curves with Gaussian distributions on Figure 3 (and Fig. S-6), we obtained a $^{20}Ne/^{22}Ne$ ratio of 12.65 ± 0.04 (σ/√n), a $^{21}Ne/^{22}Ne$ ratio of 0.0345 ± 0.0004 (σ/√n) and a $^{38}Ar/^{36}Ar$ ratio of 0.1887 ± 0.0006 (σ/√n). The $^{40}Ar/^{36}Ar$ distribution could not be fitted with a Gaussian curve but the data show that this ratio is between 6000 and 7000 in the Fernandina source (Fig. S-7).

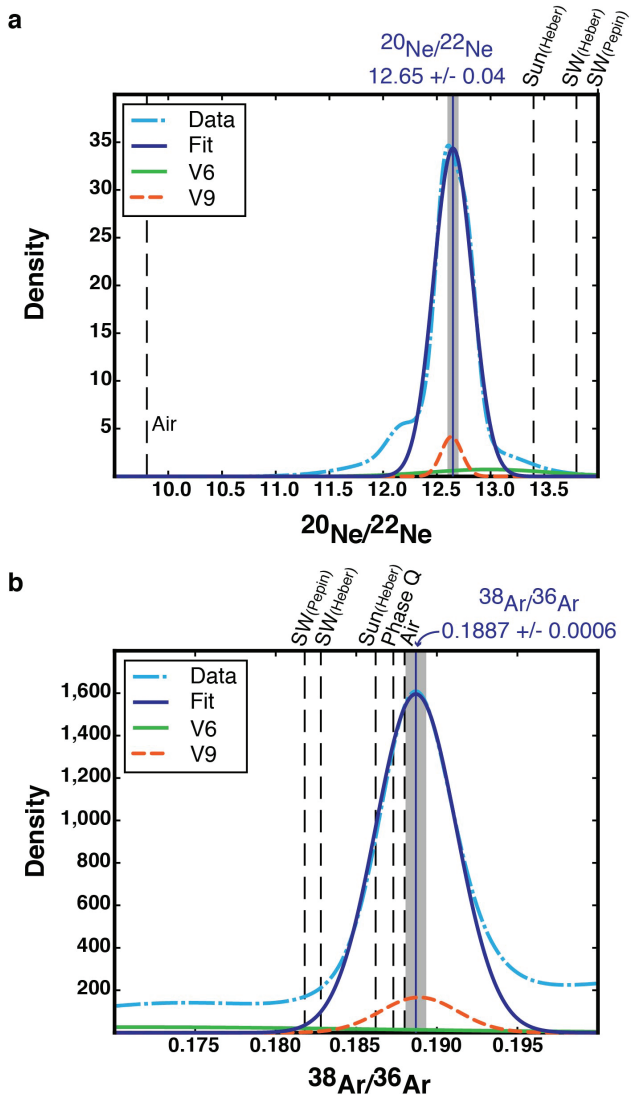

Figure 3 Gaussian curves obtained **(a)** for the $^{20}Ne/^{22}Ne$ ratio and **(b)** for the $^{38}Ar/^{36}Ar$ ratio. The light blue dotted curve is the cumulative curve obtained with the data (except V4B and V16B), the dark blue curve is the Gaussian fit. As an example, the orange dotted curve for vesicle V9 contributes strongly to the cumulative curve, whereas V6 (green curve) is poorly constrained. The mean isotopic ratios, from the statistical analysis, are represented with the blue lines and the corresponding uncertainties ($\sigma/\sqrt{n}$) with the shaded areas. Solar wind (SW) (Heber *et al.*, 2009; Pepin *et al.*, 2012), Sun (Heber *et al.*, 2012), Phase Q (Busemann *et al.*, 2000).

Discussion and Conclusions

The new results are consistent with previous studies about the Hawaii and Iceland hotspots (Trieloff *et al.*, 2000; Mukhopadhyay, 2012; Colin *et al.*, 2015). The highest values of 12.91 ± 0.07 and 9407 ± 672 for the $^{20}Ne/^{22}Ne$ and $^{40}Ar/^{36}Ar$ ratios respectively obtained in a previous study of the same samples (Péron *et al.*, 2016) seem to be slightly too high for the Fernandina mantle source within 2σ uncertainties. Hence, it does not seem appropriate to take the highest values for determining mantle source isotopic ratios. We cannot exclude that isotopic fractionation occurs during bubble formation (Ruzié and Moreira, 2010), which could increase the $^{20}Ne/^{22}Ne$ ratio for a few bubbles, and also that slight sample heterogeneities exist, which could explain the small variability observed between the bubbles. It is thus more suitable to take a mean of the data, provided that the bubbles have similar compositions. The statistical analysis used here provides a new approach for precise determination of isotopic ratios.

As detailed in Supplementary Information, we do not expect contamination of the bubbles. Even if recycling of heavy noble gases (Ar, Kr, Xe) through subduction may occur (Holland and Ballentine, 2006; Kendrick *et al.*, 2011; Parai and Mukhopadhyay, 2015), recycling of He and Ne into the OIB gas-rich source is not significant (Staudacher and Allègre, 1988; Holland and Ballentine, 2006). The $^{20}Ne/^{22}Ne$ ratio of 12.65 ± 0.04 is thus likely to represent the Fernandina source isotopic composition.

The $^{20}Ne/^{22}Ne$ ratio corresponds quite closely to the Ne-B composition. The Ne-B $^{20}Ne/^{22}Ne$ ratio was determined from analyses of gas-rich meteorites and lunar soils, which have been exposed to solar wind irradiation for millions of years (12.52; Black, 1972; 12.8 on average; Eberhardt *et al.*, 1972), and also from numerical simulations (12.73; Raquin and Moreira, 2009; Moreira, 2013; Moreira and Charnoz, 2016). This is the first high precision laser ablation study for Ne, involving enough vesicles for a statistical analysis. The fact that all the vesicles show similar isotopic compositions, in the Ne-B range of values, combined with the lunar soil results, is a strong argument in favour of the solar wind implantation model to explain light noble gas origin on Earth. The new results are consistent with this steady-state (Ne-B) composition and it may not be necessary to invoke non-steady state solar wind implantation onto grains to explain the lower mantle $^{20}Ne/^{22}Ne$ ratio (Péron *et al.*, 2016). Other studies suggest that the $^{38}Ar/^{36}Ar$ ratio is atmospheric in the Earth's mantle (Trieloff *et al.*, 2000; Raquin and Moreira, 2009; Mukhopadhyay, 2012), and lunar soils seem to have a $^{38}Ar/^{36}Ar$ ratio close to the atmospheric value even if the resolution is low (*e.g.*, Eberhardt *et al.*, 1972; Benkert *et al.*, 1993). Hence, the solar wind implantation model could also account for the lower mantle $^{38}Ar/^{36}Ar$ ratio.

Previous step-crushing studies advocated that the early Earth would have captured a primordial atmosphere from solar nebula gas and that noble gases come from the dissolution of this early atmosphere into a magma ocean (Yokochi and Marty, 2004; Mukhopadhyay, 2012). This scenario is problematic for several

reasons. First, the mantle noble gas isotopic composition is different from the solar or solar wind compositions (the Sun $^{20}Ne/^{22}Ne$ ratio would be 13.34; Heber *et al.*, 2012). The solar nebula dissolution model would thus require subduction of atmospheric Ne to lower the $^{20}Ne/^{22}Ne$ ratio from solar to the actual mantle value. However, Ne recycling into the Ne-rich, lower mantle is not significant (Staudacher and Allègre, 1988; Holland and Ballentine, 2006). Finally, this model requires that enough Ne would have been dissolved into the Earth's precursors (Mars-sized objects) because the solar nebula is blown in a few Ma (Wyatt *et al.*, 2003), well before Earth accretion has finished, which may be problematic because those objects cannot capture dense atmospheres.

Implantation of solar wind ions onto grains has also been suggested to explain the very low D/H ratio of the lower mantle (highly negative δD of -218 ‰), measured in olivine-hosted melt inclusions of a Baffin Island sample (Hallis *et al.*, 2015). The solar nebula δD ratio is -870 ‰ and so solar wind irradiation, a mechanism able to enrich grains in heavy isotopes, could explain the lower mantle value and could then be one of the sources of water on Earth (Hallis *et al.*, 2015). This scenario offers a simple alternative to explain light volatiles (H, He, Ne) origin on Earth.

This study has put forward two major implications. First, it is more reliable to consider a mean of laser ablation data rather than taking the highest measured values to determine precisely mantle source compositions. Secondly, this new approach supports the model of solar wind irradiation associated with sputtering to explain He and Ne origin on Earth. Solar wind implantation is also likely a major source of Ar and H on Earth.

Acknowledgements

We thank Lukas Baumgartner for the generous access to the tomography facilities. We also thank Déborah Chavrit, Frédéric Moynier, Alberto E. Saal and John Creech for their constructive comments and discussion on the first versions of this manuscript. We acknowledge the financial support from the UnivEarthS Labex program of Sorbonne Paris Cité (ANR-10-LABX-0023 and ANR-11-IDEX-0005-02). The image for the graphical abstract was designed by Joël Dyon of IPGP.

Editor: Bruce Watson

Additional Information

Supplementary Information accompanies this letter at www.geochemicalperspectivesletters.org/article1718

Reprints and permission information are available online at http://www.geochemicalperspectivesletters.org/copyright-and-permissions

Cite this letter as: Péron, S., Moreira, M., Putlitz, B., Kurz, M.D. (2017) Solar wind implantation supplied light volatiles during the first stage of Earth accretion. *Geochem. Persp. Let.* 3, 151–159.

References

Allègre, C.J., Staudacher, T., Sarda, P., Kurz, M.D. (1983) Constraints on evolution of Earth's mantle from rare gas systematics. *Nature* 303, 762–766.

Ballentine, C., Barfod, D. (2000) The origin of air-like noble gases in MORB and OIB. *Earth and Planetary Science Letters* 180, 39–48.

Benkert, J.-P., Baur, H., Signer, P., Wieler, R. (1993) He, Ne and Ar from the Solar Wind and Solar Energetic Particles in lunar ilmenites and pyroxenes. *Journal of Geophysical Research* 98, 13147–13162.

Black, D.C. (1972) On the origins of trapped helium, neon and argon isotopic variations in meteorites—I. Gas-rich meteorites, lunar soil and breccia. *Geochimica et Cosmochimica Acta* 36, 347–375.

Burnard, P. (1999) The bubble-by-bubble volatile evolution of two mid-ocean ridge basalts. *Earth and Planetary Science Letters* 174, 199–211.

Burnard, P., Graham, D., Turner, G. (1997) Vesicle-specific noble gas analyses of "popping rock": implications for primordial noble gases in the Earth. *Science* 276, 568–571.

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

Colin, A., Moreira, M., Gautheron, C., Burnard, P. (2015) Constraints on the noble gas composition of the deep mantle by bubble-by-bubble analysis of a volcanic glass sample from Iceland. *Chemical Geology* 417, 173–183.

Eberhardt, P., Geiss, J., Graf, H., Grögler, N., Mendia, M.D., Mörgeli, M., Schwaller, H., Stettler, A., Krähenbühl, U., Von Gunten, H.R. (1972) Trapped solar wind noble gases in Apollo 12 lunar fines 12001 and Apollo 11 breccia 10046. *Proceedings of the Third Lunar Science Conference, Supplement 3, Geochimica et Cosmochimica Acta, The MIT press* 2, 1821–1856.

Hallis, L.J., Huss, G.R., Nagashima, K., Taylor, G.J., Halldórsson, S.A., Hilton, D.R., Mottl, M.J., Meech, K.J. (2015) Evidence for primordial water in Earth's deep mantle. *Science* 350, 795–797.

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. *Geochimica et Cosmochimica Acta* 73, 7414–7432.

Heber, V.S., Baur, H., Bochsler, P., McKeegan, K.D., Neugebauer, M., Reisenfeld, D.B., Wieler, R., Wiens, R.C. (2012) Isotopic Mass Fractionation of Solar Wind: Evidence from Fast and Slow Solar Wind Collected by the Genesis mission. *The Astrophysical Journal* 759, 121.

Holland, G., Ballentine, C.J. (2006) Seawater subduction controls the heavy noble gas composition of the mantle. *Nature* 441, 186–191.

Kendrick, M.A., Scambelluri, M., Honda, M., Phillips, D. (2011) High abundances of noble gas and chlorine delivered to the mantle by serpentine subduction. *Nature Geoscience* 4, 807–812.

Kurz, M.D., Curtice, J., Fornari, D., Geist, D., Moreira, M. (2009) Primitive neon from the center of the Galápagos hotspot. *Earth and Planetary Science Letters* 286, 23–34.

Moreira, M. (2013) Noble gas constraints on the origin and evolution of Earth's volatiles. *Geochemical Perspectives* 2, 229–403.

Moreira, M., Charnoz, S. (2016) The origin of the neon isotopes in chondrites and on Earth. *Earth and Planetary Science Letters* 433, 249–256.

Mukhopadhyay, S. (2012) Early differentiation and volatile accretion recorded in deep mantle Neon and Xenon. *Nature* 486, 101–104.

Parai, R., Mukhopadhyay, S. (2015) The evolution of MORB and plume mantle volatile budgets: Constraints from fission Xe isotopes in Southwest Indian Ridge basalts. *Geochemistry, Geophysics, Geosystems* 16, 719–735.

Pepin, R.O., Schlutter, D.J., Becker, R.H., Reisenfeld, D.B. (2012) Helium, neon, and argon composition of the solar wind as recorded in gold and other Genesis collector materials. *Geochimica et Cosmochimica Acta* 89, 62–80.

Péron, S., Moreira, M., Colin, A., Arbaret, L., Putlitz, B., Kurz, M.D. (2016) Neon isotopic composition of the mantle constrained by single vesicle analyses. *Earth and Planetary Science Letters* 449, 145–154.

Raquin, A., Moreira, M. (2009) Atmospheric $^{38}Ar/^{36}Ar$ in the mantle: Implications for the nature of the terrestrial parent bodies. *Earth and Planetary Science Letters* 287, 551–558.

Raquin, A., Moreira, M., Guillon, F. (2008) He, Ne and Ar systematics in single vesicles: Mantle isotopic ratios and origin of the air component in basaltic glasses. *Earth and Planetary Science Letters* 274, 142–150.

Ruzié, L., Moreira, M. (2010) Magma degassing process during Plinian eruptions. *Journal of Volcanology and Geothermal Research* 192, 142–150.

Staudacher, T., Allègre, C.J. (1988) Recycling of oceanic crust and sediments: the noble gas subduction barrier. *Earth and Planetary Science Letters* 89, 173–183.

Trieloff, M., Kunz, J., Clague, D.A., Harrison, D., Allègre, C.J. (2000) The nature of pristine noble gases in mantle plumes. *Science* 288, 1036–1038.

Wyatt, M.C., Dent, W.R.F., Greaves, J.S. (2003) SCUBA observations of dust around Lindroos stars: evidence for a substantial submillimetre disc population. *Monthly Notices of the Royal Astronomical Society* 342, 876–888.

Yokochi, R., Marty, B. (2004) A determination of the neon isotopic composition of the deep mantle. *Earth and Planetary Science Letters* 225, 77–88.