



Geochemistry (Cosmochemistry)

The origin of rare gases on Earth: The noble gas ‘subduction barrier’ revisited

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Abstract

The origin of the Earth's atmosphere can be constrained by the study of noble gases in oceanic basalts. If it is clear that the mantle is degassed and formed part of the present atmosphere, it has been proposed that an important subduction of atmospheric noble gases in the mantle occurred during Earth's history, altering the primordial signature of the solid Earth. This subduction process has been suggested on the basis of the measurements of light xenon isotopes in CO₂ well gases. Moreover, the fact that the ³⁸Ar/³⁶Ar ratio is atmospheric in all oceanic basalts, even for uncontaminated samples (e.g. with high ²⁰Ne/²²Ne), may also suggest that a massive subduction of atmospheric argon occurred, if the primitive Earth had a solar-like ³⁸Ar/³⁶Ar. This also implies that the atmosphere suffered a massive gas loss accompanied by mass fractionation (e.g. hydrodynamic escape) after mantle degassing or that a late veneer with an atmospheric composition occurred. Such a hypothesis is explored for rare gases, by developing a model in which degassing and subduction of atmospheric noble gases started ~4.4 Ga ago. In the model, both radiogenic and non-radiogenic isotopic ratios are used (e.g. ³⁸Ar/³⁶Ar and ⁴⁰Ar/³⁶Ar; ¹²⁴Xe/¹³⁰Xe and ¹²⁹Xe/¹³⁰Xe) to constrain the subduction flux and the degassing parameters. It is shown that subduction and massive contamination of the entire mantle is possible, but implies that the ⁴⁰Ar/³⁶Ar and the ¹²⁹Xe/¹³⁰Xe ratios were higher in the past than today, which is not observed in Archean samples. It also implies that the sediments and the altered oceanic crust did not lose their noble gases during subduction or that the contaminated mantle wedge is mixed by the convective mantle. Moreover, such a model has to apply to the oceanic island source, since this later shows the same signature of argon and xenon non-radiogenic isotopic ratios. A scenario where the isotopic compositions of the argon and xenon were settled before or during accretion is therefore preferred to the subduction. **To cite this article: M. Moreira, A. Raquin, C. R. Geoscience 339 (2007).**

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Résumé

L'origine des gaz rares sur Terre : la barrière à la subduction des gaz nobles revisitée. L'origine de l'atmosphère terrestre peut être contrainte par l'étude des gaz rares dans les basaltes océaniques. S'il est clair que le manteau est dégazé et a formé une partie de l'atmosphère, il a été suggéré qu'une partie importante des gaz rares atmosphériques avait été recyclée dans le manteau terrestre par subduction durant toute l'histoire de la Terre. La subduction aurait alors modifié la signature primordiale des gaz rares du manteau terrestre. Ce processus a été évoqué sur la base des analyses isotopiques précises des isotopes légers du xénon dans les puits de CO₂. De plus, le fait que les rapports ³⁸Ar/³⁶Ar de tous les basaltes océaniques soient atmosphériques et différents de la

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valeur solaire, même pour les échantillons dont on est sûr que la contamination atmosphérique est négligeable, pourrait suggérer qu'une subduction d'argon atmosphérique se soit produite. En effet, si l'on considère que le manteau était initialement solaire pour le rapport isotopique $^{38}\text{Ar}/^{36}\text{Ar}$, et que l'atmosphère a perdu de l'argon avec fractionnement de masse après le dégazage massif des premiers millions d'années de la Terre, un recyclage atmosphérique est nécessaire. Nous avons exploré cette hypothèse en développant un modèle de dégazage/subduction qui commence il y a 4,4 Ga. Nous utilisons à la fois les isotopes non radiogéniques et les isotopes radiogéniques ($^{38}\text{Ar}/^{36}\text{Ar}$ et $^{40}\text{Ar}/^{36}\text{Ar}$; $^{124}\text{Xe}/^{130}\text{Xe}$ et $^{129}\text{Xe}/^{130}\text{Xe}$) pour contraindre les paramètres du modèle (flux de subduction et taux de dégazage). Les résultats du calcul montrent que la subduction est possible dans tout le manteau, mais ils impliquent que les rapports $^{40}\text{Ar}/^{36}\text{Ar}$ et $^{129}\text{Xe}/^{130}\text{Xe}$ étaient plus élevés à l'Archéen que maintenant. Ceci n'est pas observé dans les échantillons archéens dont la source est le manteau. De plus, le taux de gaz rares à subduire est relativement important, et il implique que la plaque plongeante ne perde pas beaucoup de ceux-ci lors de sa descente. Par ailleurs, la subduction doit également contaminer la source des points chauds, supposée être primitive pour les signatures isotopiques des gaz rares, ce qui pose donc un problème majeur dans l'interprétation des données de gaz rares. Nous préférons donc un modèle d'origine des gaz rares sur terre dans lequel les fractionnements isotopiques des gaz rares ont lieu lors de l'accrétion des planétésimaux plutôt qu'après que l'atmosphère se fut formée et qu'une partie fut subduite dans le manteau. **Pour citer cet article : M. Moreira, A. Raquin, C. R. Geoscience 339 (2007).**

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Keywords: Noble gases; Mantle degassing; Atmosphere; Subduction

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1. Introduction

The origin of volatile elements on Earth can be addressed using the noble gas systematics in oceanic basalts by comparing their isotopic compositions to those of the atmosphere, of the meteorites and of the solar wind. Noble gases (He, Ne, Ar, Kr and Xe) are inert gases, have both radiogenic and non-radiogenic isotopes and can fractionate during physical processes (e.g. diffusion, adsorption...). Therefore, they are excellent tracers of atmosphere formation. If it is clear that a degassing of the mantle occurred to form part of the atmosphere [2,7,42], there is some debate about the possibility of the atmospheric noble gases returning back into the mantle through subduction, masking the primordial rare gas composition. This process has to be understood if one wants to constrain the isotopic composition of the primitive Earth, the nature of the parent bodies and the process of volatile acquisition by terrestrial planets.

The issue of the noble gas subduction in the mantle has been addressed in different ways. Staudacher and Allègre have postulated the existence of a 'noble gas subduction barrier' in order to preserve the ^{129}Xe anomalies in the Mid Oceanic Ridge source mantle [43]. Sarda et al. [41], based on the Ar–Pb negative correlation on MORB, have suggested that the 'high μ ' component (high $^{206}\text{Pb}/^{204}\text{Pb}$) has also an atmospheric $^{40}\text{Ar}/^{36}\text{Ar}$ ratio consistent with recycling of altered oceanic crust in the mantle. Sarda has also suggested that the air component observed in MORB and OIB reflects a recycled altered material [39]. More recently,

based on xenon measurements on CO_2 well gases, in particular the light isotopes of the xenon ($^{124(130)}\text{Xe}$), Holland and Ballentine [14] have suggested massive subduction of xenon and of other heavy noble gases in the mantle, in the form of seawater. Indeed, they explain the position of the CO_2 well gases in

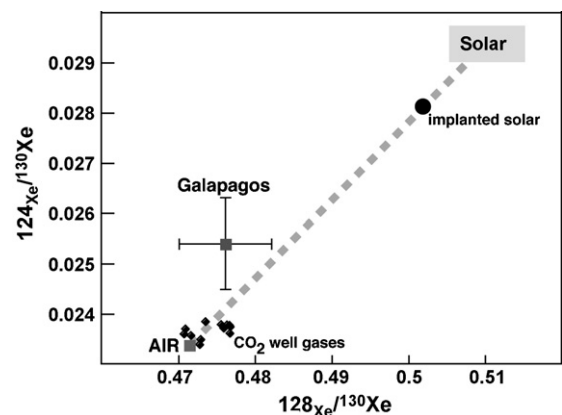


Fig. 1. Xenon isotopic diagram showing the CO_2 well gases presenting a small proportion of solar xenon [14]. Implanted solar is the composition that will have a material that is exposed to a solar wind. The Galapagos sample has the most primitive neon signature and the xenon corresponds to crushing steps with high $^{20}\text{Ne}/^{22}\text{Ne}$, reflecting little air contamination.

Fig. 1. Diagramme isotopique du xénon représentant des échantillons de puits de CO_2 [14]. Une faible proportion de xénon solaire ou de xénon solaire implanté et fractionné isotopiquement pourrait expliquer la différence avec les valeurs de l'air. L'échantillon provenant des îles Galapagos est un verre basaltique sous-marin montrant un rapport $^{20}\text{Ne}/^{22}\text{Ne}$ de $\sim 12,5$, et qui a la signature la plus primitive en néon observée dans les basaltes océaniques.

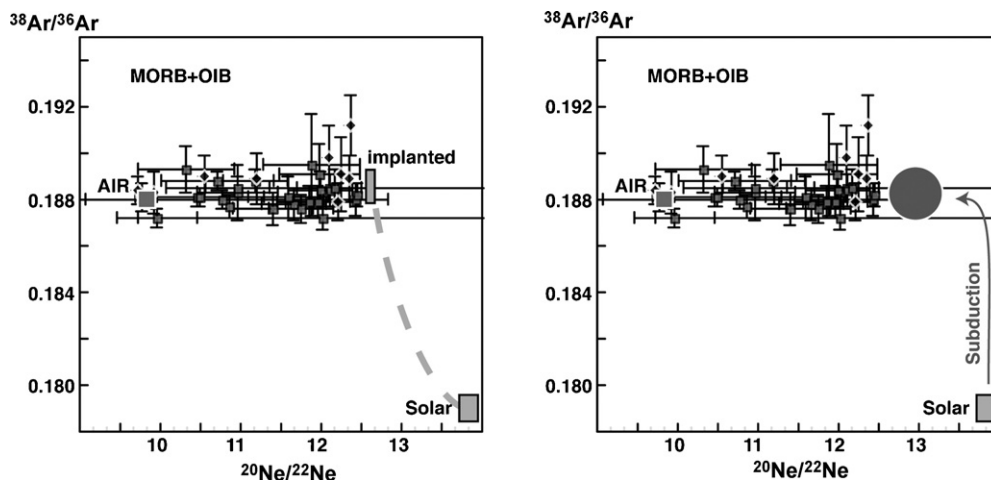


Fig. 2. Ne–Ar systematics in oceanic basalts. Two extreme scenarios can be proposed for the origin of the air-like $^{38}\text{Ar}/^{36}\text{Ar}$ ratio in MORB and OIB. One is that the parent bodies of the Earth were exposed to a solar wind. Solar wind implantation is fractionating the isotopic ratios [12]. Another hypothesis is the subduction of air argon, after the isotopic fractionation of the atmospheric argon following the major degassing in the Hadean [35]. Data are unpublished data from Raquin and Moreira.

Fig. 2. Systématique Ne–Ar dans les basaltes océaniques. Deux scénarios extrêmes peuvent être proposés pour expliquer le fait que le rapport $^{38}\text{Ar}/^{36}\text{Ar}$ est atmosphérique dans le manteau (et non solaire). Un des scénarios est que le rapport atmosphérique reflète la composition de l'argon solaire implanté dans les corps parents de la Terre, avec fractionnement de masse dépendant de la masse [12]. Une autre hypothèse est la subduction massive d'argon atmosphérique, celui-ci ayant été fractionné isotopiquement peu de temps après un événement majeur de dégazage à l'Hadéen [35]. Les données proviennent de Raquin et Moreira (non publiées).

$^{124-126}/^{130}\text{Xe}$ – $^{128}/^{130}\text{Xe}$ diagrams (Fig. 1) – close to the air ratios, by a mixture between air and solar end-members (similarly to [8]).

The $^{38}\text{Ar}/^{36}\text{Ar}$ ratio can also bring clues on the possible subduction of noble gases in the mantle. The $^{38}\text{Ar}/^{36}\text{Ar}$ ratio appears to be atmospheric in both MORB and OIB sources (Fig. 2), even for samples that are uncontaminated by air or seawater (i.e. high neon isotopic ratio) [20,45,46]. The atmospheric value is different from the solar value and may suggest recycling of atmospheric argon in order to give air-like argon in the mantle.

The use of both radiogenic and stable isotopic ratios of the argon and xenon ($^{40}\text{Ar}/^{36}\text{Ar}$ and $^{38}\text{Ar}/^{36}\text{Ar}$ and $^{124-128}\text{Xe}/^{130}\text{Xe}$ and $^{129}\text{Xe}/^{130}\text{Xe}$) should give constraints on the possible noble gas subduction in the mantle. We propose a model of degassing–subduction for these isotopic ratios and demonstrate that argon and xenon subduction appears to be difficult to consider, and that the peculiar noble gas signatures of the Earth probably reflect processes that occurred during the formation of parent bodies.

2. Noble gas isotopic ratios in the mantle and of early Earth ('stable' isotopes)

We present here only the case of the non-radiogenic isotopic ratios of the noble gases. The cases of the

radiogenic ratios are relatively well known and the discussions about their origin can be found in [3,28,38,44,48–50]. Values of the isotopic ratios are given in Table 1.

It is relatively clear now that the $^{20}\text{Ne}/^{22}\text{Ne}$ ratio is solar-like in the mantle, different from the atmospheric value, although its precise value is not known [15,23,27,29,30,40]. This difference between the mantle and the atmosphere is certainly due to an escape of the neon from the atmosphere with mass fractionation [17]. To enter in more details, there is a debate on the exact $^{20}\text{Ne}/^{22}\text{Ne}$ ratio of the mantle. It has been suggested that the neon ratio is similar to the solar wind value ($=13.84$ [12]) [13,48]. On the other hand, some authors suggest that the $^{20}\text{Ne}/^{22}\text{Ne}$ ratio is similar in the mantle to a component called 'neon B' (~ 12.5) [6] that is sampled in gas-rich meteorites and in lunar soils [4,44–46]. The origin of this component is now clear since the samples returned from the Genesis mission have shown that mass fractionation occurs during solar wind implantation, with a deeper implantation of the heavier isotope ^{22}Ne (or ^{38}Ar) [12]. Assuming this fractionation during implantation and sputtering of the surface, one can easily show that after a short time of irradiation, a steady state is obtained with a $^{20}\text{Ne}/^{22}\text{Ne}$ ratio of ~ 12.6 , similar to the 'neon B' component. Therefore, it appears that the process of incorporation of neon in parent body precursors was solar irradiation, probably during the

Table 1

Concentration and isotopic ratios of the rare gases in the atmosphere, in the present-day MORB reservoir and in the primitive Earth, assuming that the isotopic compositions were solar after its formation

Tableau 1

Concentrations et rapports isotopiques des gaz rares dans l'atmosphère, dans le manteau source des basaltes de dorsales et dans la Terre primitive, si on suppose que la Terre avait une composition isotopique solaire lors de sa formation

Gas	Atmosphere	MORB source	Solar
^4He	2.08×10^{19} ccSTP	10^{-5} ccSTP/g	
$^4\text{He}/^3\text{He}$	722 500	90 000	2800
^{22}Ne	6.64×10^{18} ccSTP	2.3×10^{-11} ccSTP/g	
$^{20}\text{Ne}/^{22}\text{Ne}$	9.8	12.6	13.80
$^{21}\text{Ne}/^{22}\text{Ne}$	0.029	0.06	0.0328
^{36}Ar	1.24×10^{20} ccSTP	2.7×10^{-10} ccSTP/g	
$^{38}\text{Ar}/^{36}\text{Ar}$	0.1880	0.1880	0.1790
$^{40}\text{Ar}/^{36}\text{Ar}$	295.5	25,000	
^{84}Kr	2.57×10^{18} ccSTP	7.9×10^{-12} ccSTP/g	
^{130}Xe	1.4×10^{16} ccSTP	1.5×10^{-13} ccSTP/g	
$^{124}\text{Xe}/^{130}\text{Xe}$	0.02337	~0.023	0.02939
$^{128}\text{Xe}/^{130}\text{Xe}$	0.4715	~0.47	0.51
$^{129}\text{Xe}/^{130}\text{Xe}$	6.5	7.5	6.27

Concentrations and isotopic ratios of the rare gases in the MORB source are taken from [28], assuming a $^{20}\text{Ne}/^{22}\text{Ne}$ of 12.5. Air isotopic ratios and abundances are from [32]. Solar isotopic ratios are from [47].

Les concentrations et les rapports isotopiques dans la source des MORB sont tirés de [28], en supposant un $^{20}\text{Ne}/^{22}\text{Ne}$ de 12,5. Les valeurs de l'air sont tirés de [32]. Les valeurs solaires sont de [47].

T-Tauri phase of the Sun, and that the solubilisation of solar neon in the mantle during a magma ocean episode was not necessary.

Atmospheric $^{38}\text{Ar}/^{36}\text{Ar}$ (~0.188) is very different from the solar ratio (0.179 [5,36]) either resulting from fractionated implantation in parent bodies [25,44] or from hydrodynamic escape with mass fractionation of the atmosphere with initially a solar composition [17,33]. However, in this last case, the mantle had to be solar also, whereas it appears that it has presently an air-like signature [20,45,46]. This could either suggest a subduction of atmospheric argon in the mantle or reflect the initial argon composition of the parent bodies ('argon B').

There are only few precise $^{124-128}\text{Xe}/^{130}\text{Xe}$ measurements in mantle-derived rocks due to very low abundance of these isotopes ($\sim 10^{-17}$ g/g). Only CO_2 well gases allow relatively precise measurements. [8] and [14] have produced data of quality showing small excesses relative to air of the $^{124-128}\text{Xe}/^{130}\text{Xe}$ ratios (Fig. 1). These data suggest a solar xenon contribution in the mantle. It has been suggested that the Earth was initially solar for the isotopic compositions and that the atmosphere was isotopically fractionated by a hydrodynamic escape [34]. Subduction of this atmospheric xenon would then have modified the primitive mantle composition.

We have seen that both argon and xenon isotopic ratios in the mantle can be interpreted as the result of subduction of atmospheric argon and xenon, previously

isotopically fractionated by a hydrodynamic escape or by a late veneer. We, therefore, propose to evaluate this hypothesis by developing the following model of degassing/subduction of Ar and Xe.

3. Degassing–subduction model for the noble gases

We will assume that subduction started 4.4 Ga ago, after the major geological event that modified the atmosphere (hydrodynamic escape, large impacts, late veneer. . .) Fig. 3. We therefore assume a simple first-order degassing process, associated with a subduction of atmospheric rare gases. The hypotheses for the developed model are the following:

- Fractions g_{Ar} and g_{Xe} of the present argon and xenon budgets of the atmosphere are in the mantle after the first stage of degassing. This first stage of degassing is certainly due to impacts (Moon formation?) or to the presence of a magma ocean and is required by the $^{129}\text{I}-^{129}\text{Xe}$ or $^{244}\text{Pu}-^{136}\text{Xe}$ systematics [3]. We now consider the second stage of degassing, which can be called the 'plate tectonic degassing', reflecting the oceanic crust formation, and then magma degassing to the atmosphere.
- The $^{38}\text{Ar}/^{36}\text{Ar}$ and the $^{124-128}\text{Xe}/^{130}\text{Xe}$ ratios of the atmosphere are fractionated compared to solar value – and the mantle value – due to a hydrodynamic escape

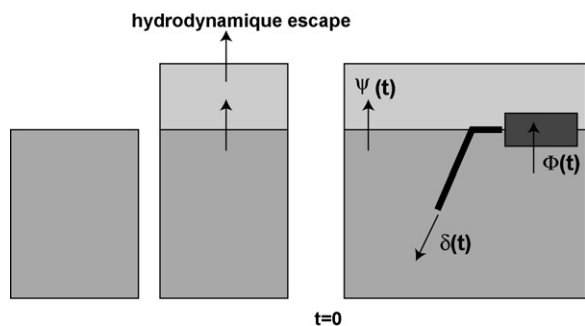


Fig. 3. Sketch showing the proposed model. The basic ideas are that a mass fractionation occurs just after the first stage of mantle degassing (for example by a hydrodynamic escape, increasing the $^{38}\text{Ar}/^{36}\text{Ar}$, and decreasing the $^{124-128}\text{Xe}/^{130}\text{Xe}$ ratios, of the atmosphere from the solar values to the present-day ratio. Following this fractionation, plate tectonics begin and then atmospheric rare gases can be subducted. In parallel, continental crust pumps the K.

Fig. 3. Schéma illustrant le modèle proposé dans cet article. L'idée est qu'un fractionnement de masse s'est produit juste après le dégazage massif du manteau (par exemple grâce à un processus d'échappement hydrodynamique), augmentant ainsi le rapport $^{38}\text{Ar}/^{36}\text{Ar}$ et diminuant les rapports $^{124-128}\text{Xe}/^{130}\text{Xe}$ de l'atmosphère à partir d'une valeur solaire. Après ce fractionnement, la tectonique des plaques commence et permet un recyclage de gaz rares atmosphériques dans le manteau. En parallèle, la croûte continentale pompe le K.

or a late veneer with material having an atmospheric composition (comets?) (e.g. [9,17,24]).

- The mantle was initially solar for the $^{38}\text{Ar}/^{36}\text{Ar}$ and the $^{124-128}\text{Xe}/^{130}\text{Xe}$ ratios. Noble gas compositions vary with time due to subduction of atmospheric argon and xenon.
- The continental crust was extracted continuously over time. This concerns the ^{40}K extraction of the mantle. The crust extraction time is given by the present concentration in the MORB source compared to the bulk Earth concentration, which reflects the depletion of the mantle. We neglect the iodine extraction.
- The present degassing rate is given by the helium isotopes. The ^3He flux at ridges is 1000 mol/year [10].
- The subduction term is proportional to the total quantity in the atmosphere. It has an isotopic composition similar to the atmospheric one (e.g. not fractionated isotopically).

The equations describing the evolution of the different isotopes are the following: for a stable isotope in the mantle

$$\frac{dS}{dt} = -\Psi(t)S + \delta(t) \cdot S_a(t);$$

for a stable isotope in the atmosphere:

$$\frac{dS_a}{dt} = +\Psi(t)S - \delta(t) \cdot S_a(t);$$

for a radiogenic isotope in the mantle:

$$\frac{dF}{dt} = -\Psi(t)F + \delta(t) \cdot F_a(t) + \lambda P;$$

for a radiogenic isotope in the atmosphere:

$$\frac{dF_a}{dt} = +\Psi(t)F - \delta(t) \cdot F_a(t);$$

for a radioactive isotope in the mantle:

$$\frac{dP}{dt} = -\Phi(t)P - \lambda P;$$

for a stable isotope of the parent in the mantle:

$$\frac{dP_s}{dt} = -\Phi(t)P_s.$$

$\Psi(t)$ is the degassing term (for the rare gases). $\Phi(t)$ is the continental crust extraction term for the parent isotopes. $\delta(t)$ is a parameter for each gas that corresponds to the annual fraction of the total atmospheric budget that is subducted. λ is the decay constant of the parent isotope. The isotopic ratios are therefore $R(t) = F(t)/S(t)$ in the mantle and $R_a(t) = F_a(t)/S_a(t)$ for the atmosphere. The initial isotopic conditions are the solar isotopic compositions for the mantle and the atmospheric compositions for the atmosphere (Table 1) since we assume the model starts after the major degassing event and the associated hydrodynamic escape that fractionated the isotopic ratios.

The initial quantity of rare gas isotopes in the mantle left after the first degassing event is supposed to be a fraction g of the total atmospheric quantity. The total primitive budget of the atmosphere is assumed to be the same as today. The differential equations were solved using Matlab[®].

For xenon, since ^{129}I has a short half-life (17 Ma), it is important to know the time of the first degassing event. The ^{129}I in the mantle at the moment T_1 of the first degassing event is $^{129}\text{I}(T_1) = [^{129}\text{I}/^{127}\text{I}]_i \cdot e^{-\lambda T_1} \cdot ^{127}\text{I}$ where $[^{129}\text{I}/^{127}\text{I}]_i = 1.1 \times 10^{-4}$. T_1 is taken as 100 My for the calculations (\sim degassing at 4.47 Ga). The iodine content of the primitive mantle is 10 ppb [22]. The $^{129}\text{Xe}/^{130}\text{Xe}$ ratio of the mantle when the model start, is

$$\left(\frac{^{129}\text{Xe}}{^{130}\text{Xe}}\right)_0 \approx \left(\frac{^{129}\text{Xe}}{^{130}\text{Xe}}\right)_{\text{air}} + \frac{^{129}\text{I}(T_1)}{^{130}\text{Xe}_0}$$

where $^{130}\text{Xe}_0$, which is the initial xenon content in the mantle after the first degassing event (=fraction g of the present-day atmospheric budget), is a free parameter.

This isotopic ratio can be extremely high if the mantle was strongly degassed ($= 240$ if $g = 0.001$).

In the present model, since we start from after the first degassing step, which is a ‘tectonic’ stage, $\Psi(t)$ is supposed to follow the potential mantle temperature, given in Labrosse and Jaupart [21], interpreted in terms of mean melting rate using the following equation: $\bar{F} = 0.006(T_0 - 1150)/12$ [19]. To determine the present-day Ψ , one can use helium. For a ^3He concentration in the mantle of 10^{-10} ccSTP/g [28] and for a degassing mantle size of 10^{27} g (e.g. upper mantle), the degassing constant Ψ_{actual} is 2×10^{-10} an^{-1} . $\Phi(t)$ is a constant in this model and is determined by the fact that the present-day MORB K concentration is 4 times lower than the primitive K content of the bulk Earth. Therefore, $\Phi(t) = \Phi = -\ln(1/4)/4.5 \times 10^9 = 3.1 \times 10^{-10}$ yr^{-1} . For reasons of mass conservation, $\delta(t)$ has to follow the same law (versus time) than $\Psi(t)$.

4. Results and discussion

Examples of results are represented on Figs. 4 and 5. A model of mantle degassing without any atmospheric recycling is able to explain the $^{40}\text{Ar}/^{36}\text{Ar}$ ratio with a remaining argon fraction in the mantle of 0.65% after

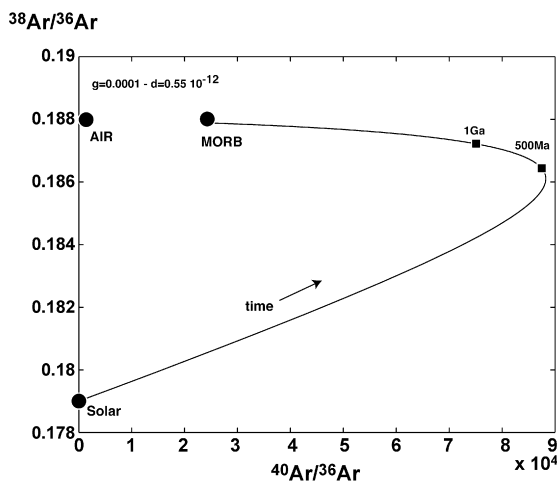


Fig. 4. Example of mantle evolution with atmospheric noble gas recycling. This was calculated using the following parameters: $\Psi = 2 \times 10^{-10}$ yr^{-1} , $g = 0.01\%$ (actual). The subduction constant δ is 0.55×10^{-12} yr^{-1} .

Fig. 4. Exemple d'évolution de la composition isotopique de l'argon dans le manteau, avec recyclage de gaz atmosphériques. Dans cet exemple, les paramètres suivants ont été obtenus pour expliquer la composition isotopique actuelle du manteau source des basaltes de dorsale : $\Psi = 2 \times 10^{-10}$ an^{-1} , $g = 0,01\%$, $\delta = 0,55 \times 10^{-12}$ an^{-1} (valeurs actuelles).

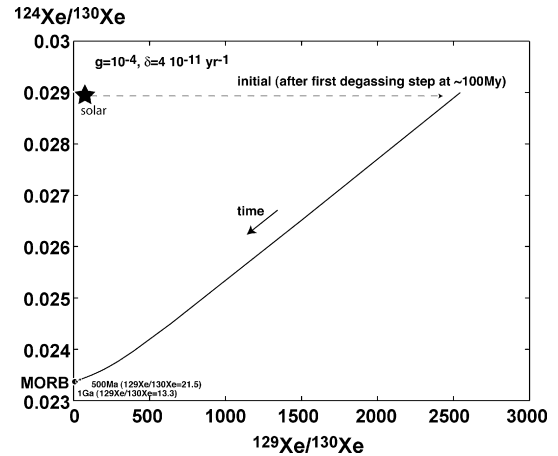


Fig. 5. Result of the subduction model for xenon with a remaining fraction of 10^{-4} for the ^{130}Xe after the first degassing event (here at 100 My after CAI formation) and a present-day fraction of the total atmospheric budget that is subducted of 4×10^{-11} yr^{-1} . Note that the $^{129}\text{Xe}/^{130}\text{Xe}$ ratio was, in this model, higher in the Archean (~ 13 – 21).

Fig. 5. Résultats du modèle de subduction de xénon atmosphérique dans le manteau. La même proportion de xénon restant dans le manteau après le grand événement de dégazage (100 Ma après les CAI) que pour l'argon est utilisée (10^{-4}). Pour expliquer les rapports isotopiques, un taux de subduction actuel de 4×10^{-11} an^{-1} est nécessaire. Notez que le rapport $^{129}\text{Xe}/^{130}\text{Xe}$ à l'Archéen est compris entre 13 et 21.

the first stage of degassing. It is, however, not possible to get the present-day $^{40}\text{Ar}/^{36}\text{Ar}$ ratio (24 000) if there is a recycling with such a remaining fraction. With a remaining fraction g of 10^{-4} and a present-day δ of 0.55×10^{-12} yr^{-1} , it is possible to obtain both the $^{38}\text{Ar}/^{36}\text{Ar}$ and the $^{40}\text{Ar}/^{36}\text{Ar}$ of the present-day MORB source (after 4.4 Ga of subduction). The value of δ of 0.55×10^{-12} yr^{-1} corresponds to a total ^{36}Ar of subducted argon in the convecting mantle equal to $\sim 7 \times 10^7$ ccSTP/yr. Higher subduction proportion leads to $^{40}\text{Ar}/^{36}\text{Ar}$ ratios of only few thousands, much lower than the MORB present-day value. Higher residual fraction of ^{36}Ar left after the first degassing event leads to a lower $^{38}\text{Ar}/^{36}\text{Ar}$ ratio than that of the air.

The results are identical for the xenon in the sense that an important first-step degassing is required. Fig. 5 shows the $^{124}\text{Xe}/^{130}\text{Xe}$ versus $^{129}\text{Xe}/^{130}\text{Xe}$ as a function of time. It is possible to get to present-day $^{129}\text{Xe}/^{130}\text{Xe}$ for a fraction of remaining ^{130}Xe in the mantle of 10^{-4} , the value required for argon. To get MORB-like $^{129}\text{Xe}/^{130}\text{Xe}$ ratio (~ 8), a minimum present-day δ of 4×10^{-11} yr^{-1} is necessary, which corresponds to a subduction flux of 6×10^5 ccSTP/yr of ^{130}Xe . It is important to note that the $^{129}\text{Xe}/^{130}\text{Xe}$ ratio in the Early Archean is of a few hundreds. 3.5 Ga ago, this ratio was ~ 13 .

The flux of subducting oceanic crust is $\sim 5 \times 10^{16}$ g/yr. The mass flux of subducting sediment is ~ 10 times lower. Staudacher and Allègre have estimated the mean concentration of ^{36}Ar and ^{130}Xe in altered oceanic crust and sediments [43]. They obtained $^{36}\text{Ar} = 2.7 \times 10^{-8}$ ccSTP and $^{130}\text{Xe} = 4.3 \times 10^{-11}$ ccSTP for oceanic sediments and $^{36}\text{Ar} = 3.2 \times 10^{-9}$ ccSTP and $^{130}\text{Xe} = 7.4 \times 10^{-12}$ ccSTP for the oceanic crust. Without loss from the slab, the total flux of subduction ^{36}Ar would be $\sim 3 \times 10^8$ ccSTP/yr and $\sim 6 \times 10^5$ ccSTP/yr for ^{130}Xe (if all the oceanic crust is similar to altered pillows).

From our calculations, we estimated a minimum flux of ^{36}Ar and ^{130}Xe of 7×10^7 and 6×10^5 ccSTP/yr, respectively. This suggests that the dehydration, and the associated loss of noble gases from the subducting slab, or from the mantle wedge if this one is re-injected in the convecting mantle, is small ($\sim 80\%$ for Ar and 0% for Xe) and that an important proportion of the rare gases from the oceanic crust and the sediments has to be re-injected into the mantle if one wants to ‘mask’ the solar argon and xenon primordial composition.

4.1. Comparison with Archean rocks

One of the major results of this model is that both the $^{40}\text{Ar}/^{36}\text{Ar}$ and the $^{129}\text{Xe}/^{130}\text{Xe}$ were much higher in the Archean than today. There are only few noble gas data on Archean rocks due to alteration and radiogenic production problems. Diamonds, cherts and fluid inclusions in hydrothermal deposits are the only few samples with mantle-like signatures [11,16,31,37]. For the $^{129}\text{Xe}/^{130}\text{Xe}$ ratio, it has been argued that it can derive from neutron capture by ^{128}Te , giving ^{129}I , and then decaying into ^{129}Xe . However, Moreira [26] has shown that in this case, due to the double beta decay of the ^{130}Te (having the same abundance as ^{128}Te), the $^{129}\text{Xe}/^{130}\text{Xe}$ ratio will decrease, rather than increase. Therefore, the use of the $^{129}\text{Xe}/^{130}\text{Xe}$ ratio is appropriate for Archean samples.

As we said, there are only few reliable noble gas data on Archean rocks. Archean cherts from Australia have been analyzed for xenon isotopes [37]. Although it is not clear how cherts acquired a mantle signature for the xenon, these samples show a $^{129}\text{Xe}/^{130}\text{Xe}$ of 7.5 and fall on the MORB line on a $^{129}\text{Xe}/^{130}\text{Xe}$ - $^{136}\text{Xe}/^{130}\text{Xe}$ isotopic diagram. $^{128}\text{Xe}/^{130}\text{Xe}$ are not precise enough to distinguish between air and solar compositions. Fluid inclusions in 3.5-Ga hydrothermal deposits from the North Pole area (Pilbara Craton, Australia) have been analyzed [31]. Using the correlation between $^{40}\text{Ar}/^{36}\text{Ar}$ and the $\text{SO}_4^{2-}/\text{Na}^+$, these authors were able to derive the $^{40}\text{Ar}/^{36}\text{Ar}$ of the mantle at this epoch around 16 000.

However, the $^{38}\text{Ar}/^{36}\text{Ar}$ ratios are not published and cannot be used to constrain the possibility of argon subduction (Fig. 4). Although the ages of diamonds are questionable, it has been argued that they may be as old as 3 Ga and certainly older than 1 Ga. All the diamonds analyzed so far do not show any $^{129}\text{Xe}/^{130}\text{Xe}$ ratio higher than ~ 8 [11,16]. They also show atmospheric $^{128}\text{Xe}/^{130}\text{Xe}$.

An anorthosite from Greenland, dated from 3.5 Ga, has been analyzed for xenon and also show MORB-like xenon with $^{129}\text{Xe}/^{130}\text{Xe}$ of 7.02 ± 0.09 and a $^{136}\text{Xe}/^{130}\text{Xe}$ of 2.27 ± 0.02 [18]. The $^{131}\text{Xe}/^{130}\text{Xe}$ and $^{132}\text{Xe}/^{130}\text{Xe}$ ratios show clear excesses compared to air, suggesting little atmospheric contamination. Again, it seems that the $^{129}\text{Xe}/^{130}\text{Xe}$ ratio in the Early Archean was not higher than the present-day MORB ratio.

The few precisely measured $^{128}\text{Xe}/^{130}\text{Xe}$ ratios do not show a solar signature (the anorthosite from Greenland has a ratio of 0.477, similar to the present-day air ratio, as well as the diamonds).

From all these results on Archean samples, deriving from a mantle source, it appears that the $^{129}\text{Xe}/^{130}\text{Xe}$ ratio was not very different from the present-day MORB ratio, suggesting that the model of xenon subduction is not appropriate.

4.2. Subduction of noble gases in the OIB source?

Our calculation was applied to the MORB source. However, it has been shown that the OIB source also has atmospheric $^{38}\text{Ar}/^{36}\text{Ar}$ argon [45,46]. The case of the $^{124-126}\text{Xe}/^{130}\text{Xe}$ ratios is not solved yet due to the inadequate precision of the data. However, unpublished data from Galapagos, the hotspot having the most primitive neon on Earth, do not show clear ^{128}Xe excess compared to air. Iceland samples do not show excesses either [45]. Therefore, we will have to admit that the OIB sources also have argon and xenon stable isotopic ratios similar to the air ratio (and not solar). The subduction of atmospheric rare gases in the OIB source is also a possibility. The model we have developed could apply to OIB. Nevertheless, if one assumes the OIB source is less degassed than the MORB source by a factor 10 or 100 [1], it appears much harder to subduct atmospheric noble gases in these sources (it requires very important subduction fluxes).

5. Conclusions

The subduction of noble gases in the mantle, although possible under some extreme hypothesis (e.g. high proportion of subduction, important first-

stage degassing), does not explain the apparent atmospheric noble gas signatures in the mantle, especially in the oceanic island source. If subduction of atmospheric noble gas occurred, the $^{129}\text{Xe}/^{130}\text{Xe}$ ratios and the $^{40}\text{Ar}/^{36}\text{Ar}$ in mantle derived rocks would have been higher in the Archean than the present-day MORB source value. This is not observed in Archean rocks deriving from the mantle. Therefore, the scenario the most probable is that the rare gas isotopic fractionation (leading from solar to air ratios) occurred before or during Earth's accretion, either by solar wind implantation (Ne, Ar) or by adsorption (Kr, Xe) on the parent bodies.

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