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Geochemistry

Helium isotopes on the Macdonald seamount (Austral chain): constraints on the origin of the superswell

Manuel Moreira *, Claude Allègre

Laboratoire de géochimie et cosmochimie, UMR CNRS 7578, Institut de physique du Globe de Paris, université Denis-Diderot, Paris-7, 4, place Jussieu, 75252 Paris cedex 05, France

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Abstract

We present new helium isotope data from the Macdonald seamount (Austral chain). The helium isotopic ratio varies from $^4He/^3He = 45\,000$ (R/Ra = 16.0) to 200 170 (R/Ra = 3.6). The helium content is between 1.5×10^{-8} and 1.1×10^{-5} ccSTP/g. These helium results show clearly the presence of primitive mantle material in the source of the Austral chain. Macdonald has the lowest $^4He/^3He$ ratio among the Polynesian submarine volcanoes, except Hawaii (Loihi). The simplest explanation for the primitive helium signature is the presence under Macdonald of a mantle plume that derives either from the 670 km or 2900 km boundary layers, or, eventually, from the top of a large mantle dome resulting from a stratified two-layer convection. This plume contains less-degassed material with low $^4He/^3He$ ratio. ***To cite this article: M. Moreira, C. Allègre, C. R. Geoscience 336 (2004).***

Résumé

Isotopes de l'hélium sur le mont sous-marin de Macdonald (Australes) : contraintes sur l'origine du superbombement. Nous présentons des données nouvelles d'hélium obtenues sur des verres frais prélevés sur le mont sous-marin de Macdonald (Australes). Le rapport isotopique de l'hélium $^4He/^3He$ varie de 45 000 (R/Ra = 16,0 où R est le rapport $^3He/^4He$ et Ra le rapport de l'air) à 200 170 (R/Ra = 3,6). Les concentrations sont parmi les plus élevées mesurées dans des basaltes de points chauds (entre $1{,}5 \times 10^{-8}$ et $1{,}1 \times 10^{-5}$ ccSTP/g). Ces résultats d'hélium montrent clairement la présence d'un composant primordial dans la source des Australes. Macdonald a le rapport de l'hélium le plus primitif parmi les volcans sous-marins du Pacifique (à part Loihi). L'explication la plus simple pour cette signature primordiale est la présence d'un panache sous le point chaud de Macdonald. Celui-ci peut provenir, soit de la discontinuité de 670 km, de la limite noyau-manteau, ou bien encore du sommet d'un grand dôme résultant d'une convection à deux étages. Ce panache contient du matériel moins dégazé que la source des MORB. ***Pour citer cet article : M. Moreira, C. Allègre, C. R. Geoscience 336 (2004).***

Keywords: helium; Macdonald; mantle plumes; superswell; Polynesia

Mots-clés : hélium ; Macdonald ; panaches ; superbombement ; Polynésie

* Corresponding auhtor.
E-mail address: moreira@ipgp.jussieu.fr (M. Moreira).

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1. Introduction

The helium isotope systematics give constraints on the mantle structure and its evolution [7,16,17,19]. Helium has two isotopes; ^{4}He is radiogenic and mainly derives from the radioactive decay of uranium and thorium, whereas ^{3}He is primordial and was inherited during the Earth's accretion. Because helium can leave the atmosphere to space, there is almost no helium in air or in seawater, allowing little atmospheric contamination of samples, and especially of submarine samples. The ^{4}He/^{3}He ratios (or the R/Ra ratio where R is ^{3}He/^{4}He measured in the sample and Ra is the atmospheric ratio of 1.4×10^{-6}) are different in Mid Oceanic Ridge Basalts (MORB) and in Oceanic Island Basalts (OIB) [18,19]. The MORB source appears to be homogeneous, the mean MORB ratio being $\sim 90\,000 \pm 10\,000$ (R/Ra $\sim 8 \pm 1$), [2]. This reflects either a well mixed reservoir, due to low viscosity, or high melting rates, allowing melting of a large part of the mantle. On the other hand, the OIB show a much larger range of the ^{4}He/^{3}He ratios, from 15 000 (R/Ra $\sim$ 50) in the Iceland plume [35] to 200 000 (R/Ra $\sim$ 3.6) in Sao Miguel island [27]. The low ^{4}He/^{3}He ratios suggest low time integrated (U + Th)/^{3}He ratios in the source. However, the fact that the OIB sources show, in general, higher uranium and thorium contents than the MORB source implies higher ^{3}He content in the OIB source. This suggests the existence of a relatively little degassed reservoir, probably located in the lower mantle [1], and sampled by mantle plumes that start either at the 670 km or 2900 km boundary layers. The high ^{4}He/^{3}He ratios can be interpreted in two ways. The first proposes that high U/^{3}He material is located in the plume source. This can be recycled oceanic crust (e.g., Tubuai or St Helena) or sediments [10,11]. Another interpretation is shallow level contamination or post degassing radioactive production in the magma chamber [14,37].

The Macdonald seamount is the recent expression of the Austral chain volcanism (Fig. 1). This is one of the most active submarine volcanoes in the Pacific [34]. At least two volcanic events have been identified since 1987 [34]. The Macdonald seamount has a circular base of about 45 km in diameter at a depth of 3900 m and a narrow summit less than 40 m in diameter. The summit is presently about 40 m under water, allowing us to think that an island will emerge soon. The aim of this paper is to estimate the isotopic composition of the helium of the Macdonald seamount and to determine the nature of the Macdonald hotspot.

2. Sample location, analytical procedure and results

Sample locations are given in Fig. 2. Most of the samples have basaltic compositions [13]. All the samples come from depths lower than 2000 m.

Helium was obtained by crushing under vacuum and analyzed with our glass mass spectrometer ARESIBO I, equipped with a Faraday cup and an ion counting system. The ^{4}He blank was $1.9 \pm 0.1 \times 10^{-8}$ ccSTP with R/Ra ratio of $0.7 \pm 0.3 (1\sigma)$. Standards were analyzed daily. The helium standard is a gas from a Reunion island (Cilaos spring), that has a ^{4}He/^{3}He ratio of 56 980 (R/Ra = 12.68). Results are given in Table 1. With the exception of samples SO47 DS2 and SO47 60GTVa3, the helium isotopic ratio is around 60 000 (R/Ra $\sim$ 11.5). Sample SO47 DS2 shows a different helium ratio (45 800; R/Ra = 15.8 ± 0.3) whereas sample SO47 60GTVa3 shows a radiogenic ratio of 203 640 (R/Ra = 3.6 ± 0.5), associated with a helium content of 1.5×10^{-8} ccSTP/g (the lowest). Most of the samples have more primitive ratio than the mean MORB ratio of 90 000 (R/Ra $\sim$ 8) [2]. The lowest helium ratio is similar to those found in some Iceland or Hawaii samples [20–22].

3. Discussion

The Macdonald seamount lava clearly show a 'high ^{3}He' signature (^{4}He/^{3}He < 46 000; R/Ra > 15.8) that may reflect the surface expression of a mantle plume that derives from a 'primitive' reservoir. These low ^{4}He/^{3}He ratios are associated with relatively high helium contents (up to 10^{-5} ccSTP/g) that are still minimum values, since degassing and vesicle bursting occurred during magma eruption or in the lab. Such helium contents are typical of OIB glasses (e.g. the highest Loihi helium content is 4 μccSTP/g). High helium contents have been measured in Iceland (10 μccSTP/g in some sub-glacial gassy samples) [12,21,29] or at Mehetia, Societies (30 μccSTP/g) [33]. These values are still lower than

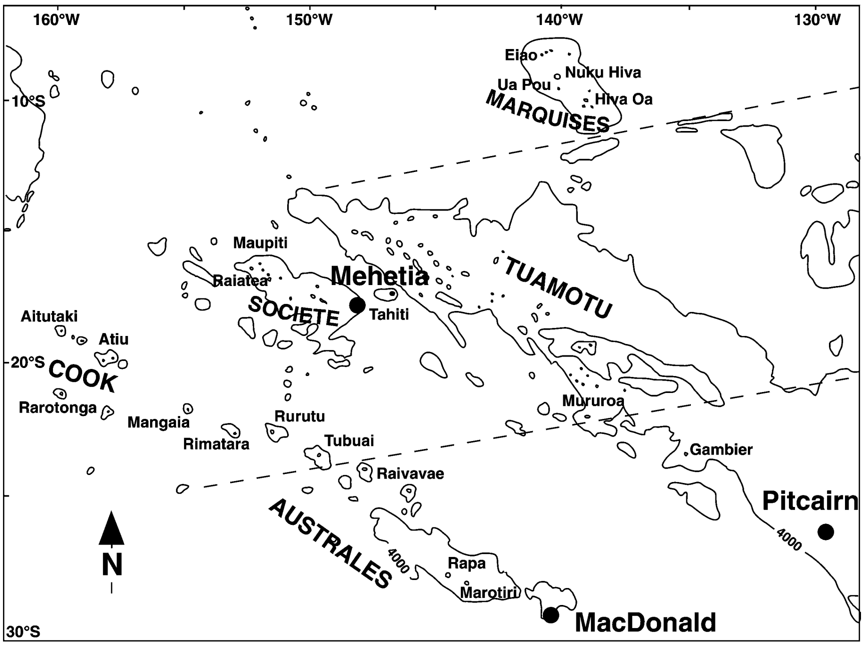

Fig. 1. Map showing the location of three active submarine volcanoes in Polynesia (Mehetia, Pitcairn and Macdonald). The present study concerns the Macdonald seamount, located at the extreme east of the Australes chain.

Fig. 1. Figure montrant la localisation de trois monts sous-marins actifs en Polynésie (Mehetia, Pitcairn et Macdonald). Cette étude concerne le mont sous-marin de Macdonald, situé à l'Extrême-Est de la chaîne des Australes.

Table 1
Helium isotopic ratio and Helium content (in μccSTP/g) of the Macdonald seamount. Note that sample TH28-07 was already analyzed by Marty and Dauphas [23]. They obtained $R/Ra = 11.2 \pm 0.1$, similar to our measurement of 11.3 ± 0.1. Marty and Dauphas [23] analyzed also sample TH30-03 which gives $[^4He] = 0.08$ μccSTP/g and $R/Ra = 5.62 \pm 0.10$. Helium concentrations are in ccSTP/g. Ra is the $^3He/^4He$ ratio of air (1.4×10^{-6})

Tableau 1
Rapport isotopique et teneur en hélium (μccSTP/g) du mont sous-matin de Macdonald. À noter que l'échantillon TH28-07 a déjà été analysé par Marty et Dauphas [23]. Ces auteurs ont obtenu $R/Ra = 11{,}2 \pm 0{,}1$, similaire à notre propre résultat de $11{,}3 \pm 0{,}1$. Marty et Dauphas [23] ont aussi analysé l'échantillon TH30-03, qui donne $[^4He] = 0{,}08$ μccSTP/g et $R/Ra = 5{,}62 \pm 0{,}10$. Les concentrations en He sont fournies en ccSTP/g. Ra est le rapport $^3He/^4He$ de l'air $(1,4 \times 10^{-6})$

Samples	Weight (g)	$^4He/^3He$	±	R/Ra	±	$[^4He]$
SO47 55Ds1J	0.16	60 100	790	12.0	0.2	1.1×10^{-5}
SO47 64DS2	0.23	45 830	920	15.8	0.3	2.3×10^{-7}
SO47 60GTVa3	0.70	203 640	26 400	3.6	0.5	1.5×10^{-8}
SO47 57DS7	0.21	72 840	1270	9.9	0.2	3.6×10^{-7}
SO47 68DS2	0.71	61 100	375	11.8	0.1	2.9×10^{-6}
CY1011 TH28-03	1.77	61 790	485	11.7	0.1	6.4×10^{-7}
CY1011 TH28-07	1.03	64 192	535	11.3	0.1	2.9×10^{-7}
CY1011 TH28-10	0.70	62 320	535	11.6	0.1	3.7×10^{-7}
CY1011 TH28-01 (olivines)	0.59	62 460	550	11.6	0.1	1.2×10^{-7}

MORB concentrations (100 μccSTP/g) [5,24,28,30]. Considering the shallow eruption (< 2000 m), it is legitimate to think that a helium loss occurred by degassing. However, because argon was not measured on these samples, the He/Ar ratio cannot be used to constrain the degassing rate [5,15,24,31].

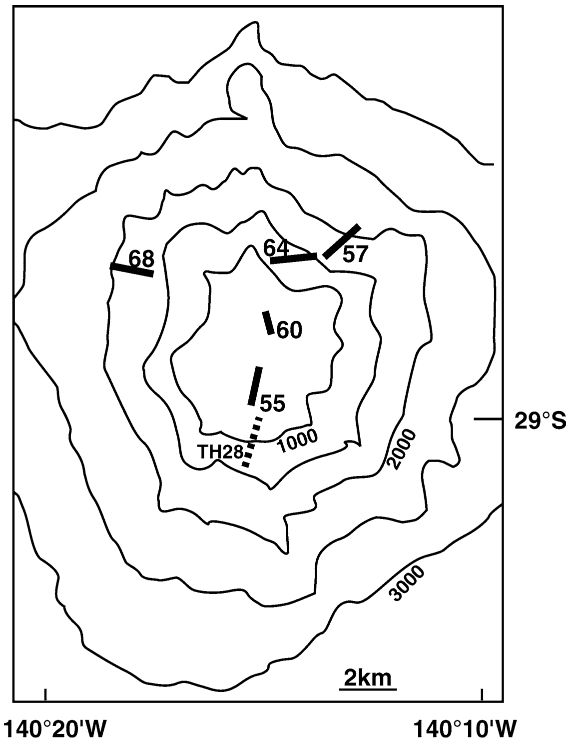

Fig. 2. Sample location in a simplified bathymetric map of Macdonald seamount.

Fig. 2. Localisation des échantillons (carte bathymétrique simplifiée du mont sous-marin de Macdonald).

Moreover, the fact that most samples have a ^{4}He/^{3}He ratio close to 60 000 (except for samples 55DS1J and 60GTVa3) may indicate that either the Macdonald seamount source is homogeneous or that there is a sampling bias of the Macdonald lava, i.e. the surface is very young. Similar observations can be made for other isotopic ratios (^{87}Sr/^{86}Sr $= 0.7037 \pm 0.00008$, ^{143}Nd/^{144}Nd $= 0.51282 \pm 0.00003$, ^{206}Pb/^{204}Pb $= 19.41 \pm 0.06$; ^{207}Pb/^{204}Pb $= 15.62 \pm 0.03$ and ^{208}Pb/^{204}Pb $= 39.19 \pm 0.09$) [13]. This variation is small, considering the variation for the whole Austral chain.

Fig. 3 shows the R/Ra and ^{4}He/^{3}He ratios as a function of the ^{4}He content (in µccSTP/g) in the samples for different submarine volcanoes of the Pacific island chains (Mehetia, Rocard, Teahitia: Societies; Bounty and Adams: Gambier and Macdonald: Austral chain). This figure shows clearly the effect of the degassing and the radioactive decay of U and Th on the helium isotopic ratio. Degassing decreases the mantle-derived helium content and makes the in situ radiogenic helium contribution more important. Only samples with more than 3×10^{-7} ccSTP/g preserve their mantle signature (Fig. 3). This process can be seen on Macdonald lava due to their high uranium and thorium contents ([U] = 1 ppm [13]). For example, for sample SO47 60GTVa3, which has the most radiogenic helium isotopic ratio of the Macdonald samples, it is possible to write the radioactive production equation:

$$\left[\frac{^4\mathrm{He}}{^3\mathrm{He}}\right]_t = \left[\frac{^4\mathrm{He}}{^3\mathrm{He}}\right]_o + 2.8 \times 10^{-8}\left\{4.35 + \frac{\mathrm{Th}}{\mathrm{U}}\right\}\frac{[\mathrm{U}]}{[^3\mathrm{He}]} \cdot t$$

where [U] is in ppm, t in Ma and ^{3}He in ccSTP/g. Note that this equation is valid only for ages lower than 200 Ma, which is the case for Macdonald.

The mean uranium content of Macdonald samples is $\mathrm{U} = 1.0 \pm 0.4$ ppm with $\mathrm{Th/U} = 3.3 \pm 0.8$ [13]. With these values, we get

$$\left[\frac{^4\mathrm{He}}{^3\mathrm{He}}\right]_t = \left[\frac{^4\mathrm{He}}{^3\mathrm{He}}\right]_o + 2.1 \times 10^{-7}\frac{t}{[^3\mathrm{He}]}$$

For sample SO47 60GTVa3, ^{3}He content is 7.5×10^{-14} ccSTP/g. Starting from $(^4\mathrm{He}/^3\mathrm{He})_0 = 45\,000$, the time necessary to obtain ^{4}He/^{3}He = 203 640 is 57 000 years after degassing. This is a realistic time for magma residence in a magma chamber. If the initial ^{4}He/^{3}He ratio is 60 000 (as in most samples), the residence time becomes 51 000 years, almost identical. Therefore, there is no need for another explanation (source, crust assimilation) to explain the radiogenic character of helium in some samples.

4. Constraints on the origin of the superswell

The Macdonald seamount shows a relatively primitive helium signature with a ratio of ∼ 46 000 (R/Ra ∼ 15.8). Davaille [8] and Davaille et al. [9] have suggested that the volcanism from the superswell is the expression at the surface of plumes deriving from the top of a dome rising from the deep mantle. Such a model is consistent with the helium data from active volcanoes from this area. A dome from the lower mantle, containing less-degassed material, produces

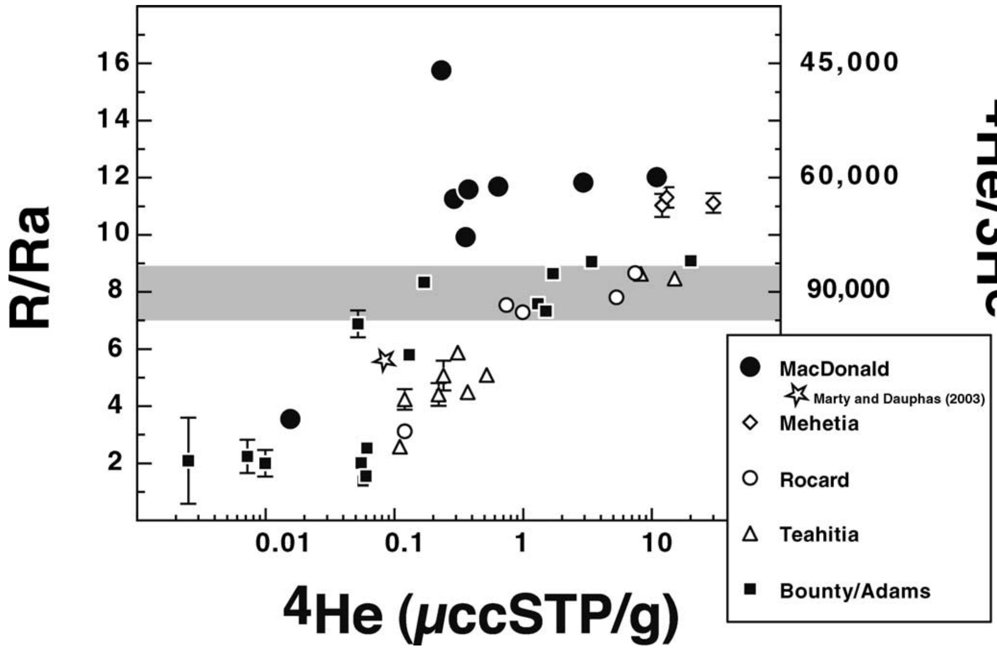

Fig. 3. R/Ra and $^4He/^3He$ ratios as a function of the helium concentration. Other recent submarine volcanoes from Polynesia are shown for comparison. Only Mehetia and Macdonald show clear 'primitive' helium signature. The grey area is the mean MORB ratio. Data below this MORB trend clearly reflect radiogenic ^4He addition in degassed magma chamber. Error bars of Macdonald samples are inside the symbols.

Fig. 3. Rapports R/Ra et $^4He/^3He$ en fonction de la concentration d'hélium. Pour comparaison, d'autres données obtenues sur des monts sous-marins du Pacifique sont montrées. Seuls Mehétia et Macdonald montrent une signature « primitive » claire. La zone grisée montre la moyenne des MORB. Les données situées en dessous de cette valeur moyenne des MORB montrent clairement l'addition d'hélium radiogénique dans une chambre magmatique dégazée. Les barres d'erreur des échantillons de Macdonald sont dans les symboles.

plumes at its top that result in hotspot volcanism at the surface. On the other hand it has also been suggested that this volcanism just reflects shallow features, with no need of mantle plumes. In this case, the primitive helium ratio either reflects a 'stored' ancient mantle helium in the lithosphere [3] or the preferential melting of 'primitive' veins. We exclude the lithospheric hypothesis with the following argument (Fig. 4). Assuming the lithosphere has an age of 100 Ma under the Macdonald seamount, the Anderson's model suggests that the mantle source of the lithosphere had a helium isotopic ratio of 45 000 100 Ma years ago (the lowest measured helium ratio of the Macdonald seamount). To get the present day MORB value of 90 000 [2], the $U/^3He$ ratio of the depleted mantle that is necessary is 2.2×10^5 (mol/mol). Using this ratio and calculating the helium isotopic ratio 500 Ma ago, we get a negative helium isotopic ratio for the depleted mantle (Fig. 4)! Therefore, this U/He ratio is not realistic and this model of stored helium in lithosphere is not correct. Fertile veins with primitive helium that preferentially melt under the thick pacific lithosphere to give hotspot volcanism is a possible model. These veins have to be larger than the characteristic diffusion length of the helium at mantle temperatures, otherwise the helium isotopic ratio would be similar to the MORB ratio (which, in such a model, is a mixture of primitive helium veins and a more radiogenic matrix). With a diffusion coefficient $D = 10^{-8}$ cm^2/s [36] and for $t = 100$ Ma, we get a characteristic length of ~ 50 m (for 1 Ga, we get ~ 200 m). Taking $D = 10^{-7}$ cm^2/s, the characteristic length is ~ 200 m and with $D = 10^{-9}$ cm^2/s, it is ~ 20 m in 100 Ma. This does not change the following interpretations. These veins could be either un-melted parts of the mantle (really primordial helium), pieces of lower mantle (with primordial helium) entrained when the plume forms or ancient subducted material with low $U/^3He$ [6]. From helium measurements only on the Macdonald seamount, it is hard to distinguish between the 'canonical' model and the primitive vein

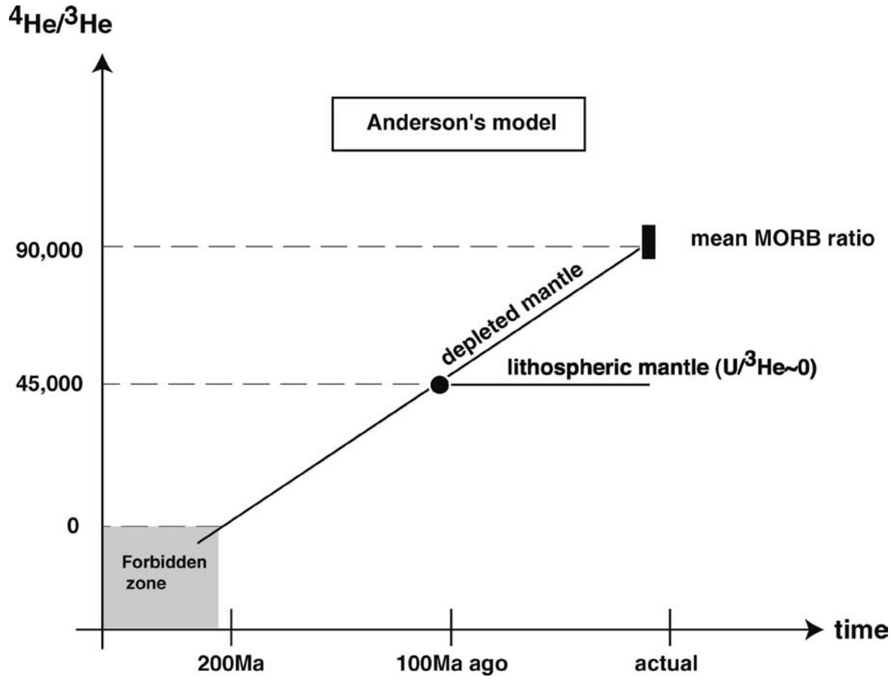

Fig. 4. The perisphere model of Anderson [3]. In this model, the primitive helium ratios observed in some OIB reflect a lithospheric helium rather than a lower mantle derived helium. This is due to an assumed $U/^3He$ ratio of zero in the residual material, allowing freezing an ancient and low $^4He/^3He$ ratio. However, the required $U/^3He$ ratio to increase the isotopic ratio from a ratio of 45 000 to an actual MORB ratio of 90 000 in 100 Ma is 40 times too high compared to the estimate of this ratio in the depleted mantle [1]. This gives a negative helium isotopic ratio 300 Ma years ago in the mantle, which is not possible.

Fig. 4. Le modèle de périsphère de Anderson [3]. Dans ce modèle, le rapport primitif de l'hélium qui est observé dans les points chauds intraplaques, est issu de la lithosphère océanique plutôt que du manteau inférieur. En effet, dans ce modèle, le rapport $U/^3He$ est supposé égal à zéro dans la lithosphère, ce qui permet de « geler » le rapport isotopique du manteau lors de la formation de la lithosphère. Toutefois, le rapport $U/^3He$ qui est nécessaire pour augmenter le rapport isotopique de l'hélium de 45 000 à 90 000 (le rapport moyen des MORB) en 100 Ma est 40 fois trop grand par rapport aux estimations que l'on peut faire de ce rapport [1]. De plus, cela donnerait un rapport isotopique négatif dans le manteau il y a 300 Ma, ce qui n'est pas possible.

model. However, considering the fact that the samples are relatively rich in helium, the subducted material (residual mantle) can be excluded because such a residual mantle does not contain significant helium [4, 25] and is probably not a fertile material that can melt preferentially. Therefore, a model of veins of undegassed material, either due to lower mantle entrainment or to un-melted primitive peridotites, is possible, with the unproven condition that this material melts preferentially to pyroxenites. If such a case is possible, the high ^3He signature observed on some parts of the mid oceanic ridges [26,32] needs to be explained. In such a geodynamic context, the melting rate is certainly higher and therefore, the previous model does not hold.

Therefore, the simplest explanation for Macdonald helium is the presence of a plume derived either from the top of a dome rising from the deep mantle and containing primordial material or a plume derived from either the 670- or 2900-km boundary. In any case, this plume entrains less-degassed material and is mixed with MORB-like material.

5. Conclusion

We have presented new helium isotopic data for the Macdonald seamount (Austral chain). Most of the samples have a $^4He/^3He$ ratio close to 63 000 ($R/Ra \sim 11.5$). One sample shows a very low ratio (45 000: $R/Ra = 15.8$). Another sample has a radiogenic ratio that can be explained by radioactive decay of a degassed uranium rich magma. A residence time of 50 000y is necessary to produce the helium ratio. The simplest explanation of the Macdonald seamount helium signature is the presence of a mantle plume derived from either a dome rising from the lower mantle or from a thermal boundary in the mantle and entraining less-degassed material (∼ 1–5%).

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References

[1] C.J. Allègre, T. Staudacher, P. Sarda, Rare gas systematics, formation of the atmosphere, evolution and structure of the Earth's mantle, Earth Planet. Sci. Lett. 81 (1986) 127–150.

[2] C.J. Allègre, M. Moreira, T. Staudacher, $^4He/^3He$ dispersion and mantle convection, Geophys. Res. Lett. 22 (17) (1995) 2325–2328.

[3] D.L. Anderson, A model to explain the various paradoxes associated with mantle noble gas geochemistry, Proc. Natl Acad. Sci. USA 95 (1998) 9087–9092.

[4] R.A. Brooker, Z. Zu, J.D. Blundy, S.P. Kelley, N.L. Allan, B.J. Wood, E.M. Chamorro, J.A. Wartho, J.A. Purton, The 'Zero charge' partitioning behaviour of noble gases during mantle melting, Nature 423 (2003) 738–741.

[5] P. Burnard, The bubble-by-bubble volatile evolution of two mid-ocean ridge basalts, Earth Planet. Sci. Lett. 174 (1999) 199–211.

[6] N. Coltice, Y. Ricard, Geochemical observations and one layer mantle convection, Earth Planet. Sci. Lett. 174 (1999) 125–137.

[7] H. Craig, J. Lupton, Primordial neon, helium, and hydrogen in oceanic basalts, Earth Planet. Sci. Lett. 31 (1976) 369–385.

[8] A. Davaille, Simultaneous generation of hotspots and superswells by convection in a heterogeneous planetary mantle, Nature 402 (1999) 756–760.

[9] A. Davaille, F. Girard, M. Le Bars, How to anchor hotspots in a convecting mantle? Earth Planet. Sci. Lett. 203 (2002) 621–634.

[10] D.W. Graham, S.E. Humphris, W.J. Jenkins, M.D. Kurz, Helium isotope geochemistry of some volcanic rocks from Saint Helena, Earth Planet. Sci. Lett. 110 (1993) 121–131.

[11] T. Hanyu, I. Kaneoka, The uniform and low $^3He/^4He$ ratios of HIMU basalts as evidence for their origin as recycled materials, Nature 390 (1997) 273–276.

[12] D. Harrisson, P. Burnard, G. Turner, Noble gas behaviour and composition in the mantle: constraints from the Iceland Plume, Earth. Planet. Sci. Lett. 171 (1999) 199–207.

[13] C. Hémond, C.W. Devey, C. Chauvel, Source compositions and melting processes in the Society and Austral plumes (South Pacific Ocean): element and isotope (Sr, Nd, Pb, Th) geochemistry, Chemical Geology 115 (1994) 7–45.

[14] D.R. Hilton, J. Barling, G.E. Wheller, Effect of shallow-level contamination on the helium isotope systematics of ocean-island lavas, Nature 373 (1995) 330–333.

[15] M. Honda, D.B. Patterson, Systematic elemental fractionation of mantle-derived helium, neon, and argon in mid-oceanic ridge glasses, Geochim. Cosmochim. Acta 63 (1999) 2863–2874.

[16] I. Kaneoka, N. Takaoka, Excess ^{129}Xe and high $^3He/^4He$ ratios in olivine phenocrysts of Kapuho lava and xenolithic dunites from Hawaii, Rock Magn. Paleogeophys. 4 (1977) 139–143.

[17] M.D. Kurz, W.J. Jenkins, The distribution of helium in oceanic basalt glasses, Earth Planet. Sci. Lett. 53 (1981) 41–54.

[18] M.D. Kurz, W.J. Jenkins, S.R. Hart, Helium isotopic systematics of oceanic islands and mantle heterogeneity, Nature 297 (1982) 43–47.

[19] M.D. Kurz, W.J. Jenkins, J.-G. Schilling, S.R. Hart, Helium isotopic variation in the mantle beneath the central North Atlantic Ocean, Earth Planet. Sci. Lett. 58 (1982) 1–14.

[20] M.D. Kurz, W.J. Jenkins, S.R. Hart, D. Clague, Helium isotopic variations in volcanic rocks from Loihi Seamount and the island of Hawaii, Earth Planet. Sci. Lett. 66 (1983) 388–406.

[21] M.D. Kurz, P.S. Meyer, H. Sigurdsson, Helium isotopic systematics within the neovolcanic zones of Iceland, Earth. Planet. Sci. Lett. 74 (1985) 291–305.

[22] M.D. Kurz, T.C. Kenn, J.C. Lassiter, D.J. DePaolo, Helium isotopic evolution of Mauna Kea volcano: first results from the 1 km drill core, J. Geophys. Res. 101 (1996) 11 781–11 791.

[23] B. Marty, N. Dauphas, The nitrogen record of crust-mantle interaction and mantle convection from Archean to Present, Earth Planet. Sci. Lett. 206 (2003) 397–410.

[24] M. Moreira, P. Sarda, Noble gas constraints on degassing processes, Earth Planet. Sci. Lett. 176 (2000) 375–386.

[25] M. Moreira, M.D. Kurz, Subducted oceanic lithosphere and the origin of the 'High μ' basalt helium isotopic signature, Earth Planet. Sci. Lett. 189 (2001) 49–57.

[26] M. Moreira, T. Staudacher, P. Sarda, J.-G. Schilling, C.J. Allègre, A primitive plume neon component in MORB: The Shona ridge-anomaly, South Atlantic (51–52°S), Earth Planet. Sci. Lett. 133 (1995) 367–377.

[27] M. Moreira, R. Doucelance, B. Dupré, M. Kurz, C.J. Allègre, Helium and lead isotope geochemistry in the Azores archipelago, Earth Planet. Sci. Lett. 169 (1999) 189–205.

[28] M. Moreira, J. Kunz, C.J. Allègre, Rare gas systematics on popping rock: estimates of isotopic and elemental compositions in the upper mantle, Science 279 (1998) 1178–1181.

[29] M. Moreira, K. Breddam, J. Curtice, M. Kurz, Solar neon in the Icelandic mantle: evidence for an undegassed lower mantle, Earth Planet. Sci. Lett. 185 (2001) 15–23.

[30] P. Sarda, D.W. Graham, Mid-ocean ridge popping rocks: implications for degassing at ridge crests, Earth Planet. Sci. Lett. 97 (1990) 268–289.
[31] P. Sarda, M. Moreira, Vesiculation and vesicle loss in Mid-Oceanic Ridge basalt glasses: He, Ne, Ar elemental fractionation and pressure influence, Geochim. Cosmochim. Acta 66 (2002) 1449–1458.
[32] P. Sarda, M. Moreira, T. Staudacher, J.-G. Schilling, C.J. Allègre, Rare gas systematics on the southernmost Mid-Atlantic Ridge: constraints on the lower mantle and the Dupal source, J. Geophys. Res. 105 (2000) 5973–5996.
[33] T. Staudacher, C.J. Allègre, Noble gases in glass samples from Tahiti: Teahitia, Rocard and Mehetia, Earth Planet. Sci. Lett. 93 (1989) 210–222.
[34] P. Stoffers, R. Botz, J.-L. Cheminée, C.W. Devey, V. Froger, G.P. Glasby, M. Hartmann, R. Hékinian, F. Kogler, D. Laschek, P. Larqué, W. Michaelis, R.K. Muhe, D. Puteanus, H.H. Richnow, Geology of Macdonald Seamount region, Austral islands: Recent hotspot volcanism in the South Pacific, Mar. Geophys. Res. 11 (1989) 101–112.
[35] F.M. Stuart, S. Lass-Evans, J.G. Fitton, R.M. Ellam, High $^{3}He/^{4}He$ ratios in picritic basalts from Baffin Island and the role of a mixed reservoir in mantle plumes, Nature 424 (2003) 57–59.
[36] T.W. Trull, M.D. Kurz, Experimental measurements of ^{3}He and ^{4}He mobility in olivine and clinopyroxene at magmatic temperatures, Geochim. Cosmochim. Acta 57 (1993) 1313–1324.
[37] A. Zindler, S. Hart, Helium: problematic primordial signals, Earth Planet. Sci. Lett. 79 (1986) 1–8.