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Neon and helium isotopes as tracers of mantle reservoirs and mantle dynamics

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Abstract

He isotopes are usually used as tracers for the identification of mantle reservoirs and mantle dynamics. High $^3\text{He}/^4\text{He}$ ratios are thought to represent deep mantle material, whereas ratios around $8 R_A$ (R_A stands for the atmospheric $^3\text{He}/^4\text{He}$ ratio of 1.39×10^{-6}) are thought to be representative of the upper mantle. Based on He, Ne and Ar fusion data from fresh, submarine volcanic glasses of several Mid-Atlantic Ridge off-axis seamounts we show that He isotopes can be susceptible to interferences during melt formation and evolution resulting in the decoupling of He from other elements, such as e.g. Ne or Pb. All obtained He data are indistinguishable from that of the MORB range. In contrast, Ne isotopic compositions are much more primitive than MORB. Combined He, Ne and Ar systematics show that

the source region of these seamounts have experienced a preferential loss of He compared to Ne and Ar. This He loss, combined with subsequent ^4He production, resulted in the decoupling of the He isotope systematics from Ne and Pb. Thus, when considering He and Ne, only Ne has preserved the evidence that a primitive mantle component contributed to the formation of the investigated seamounts. As these seamounts are not fed from a mantle plume being derived from the deep mantle, the primitive Ne component resides within the upper mantle, implying that primitive noble gases are not necessarily indicative of deep mantle material.

Keywords: $^3\text{He}/^4\text{He}$, neon, mantle tracer, mantle sources, decoupling

1. Introduction

He and Ne isotopic and abundance studies of mid-ocean ridge basalts (MORB) and ocean island basalts (OIB) have provided important insights into the formation, evolution and composition of the Earth's mantle. Basic concepts on mantle structure and evolution, such as two-layer mantle convection or any other "layered mantle model", are primarily based on the interpretation of mantle ^3He and ^{22}Ne as reflecting primordial, undegassed mantle material [e.g. 1, 2]. Primordial He and Ne isotopic ratios in terrestrial samples are largely thought to be solar-like, with the deviation from those solar-like ratios increasing during Earth's history caused by the coupled production of radiogenic ^4He and nucleogenic ^{21}Ne . ^4He is produced in the radioactive decay chains of ^{238}U , ^{235}U and ^{232}Th , whereas ^{21}Ne is mainly produced by nuclear reactions of α particles with ^{18}O . As the α particles needed for these reactions are derived from U and Th decay and O is thought to be homogeneously distributed within the Earth's mantle, the production of radiogenic ^4He and nucleogenic ^{21}Ne has

to be coupled [e.g. 3]. Since mantle ^3He , ^{20}Ne and ^{22}Ne are dominantly primordial in origin, mantle He and Ne isotopic ratios are controlled by the ratios of [primordial ^3He]/[U+Th] and [primordial Ne]/[U+Th], respectively. In this context, OIBs with high $^3\text{He}/^4\text{He}$ ratios denoting high ratios of [primordial ^3He]/[U+Th] and solar-like Ne isotopic compositions implying high ratios of [primordial Ne]/[U+Th], relative to MORB, are mainly thought to reflect undegassed lower mantle material. However, this interpretation of noble gas data is not only at conflict with trace element and Sr-Nd-Pb-Hf isotope data, showing that mantle plume sources do not represent less degassed, primitive mantle [see review by 4], but also with the geophysical evidence for whole-mantle convection [see review by 5]. Furthermore, studies on e.g. the He and Pb isotope systematics of different OIB settings have revealed that He can be susceptible to changes during melt production and evolution making $^3\text{He}/^4\text{He}$ ratios amenable for secondary interferences, resulting in a decoupling of He and Pb isotopic compositions [e.g. 6, 7-9]. In addition, it has been shown that the isotopic systematics of He and Ne may also be decoupled, e.g. that basaltic lavas may have primitive Ne isotopic ratios but $^3\text{He}/^4\text{He}$ ratios that are much lower than expected from the associated Ne data [e.g. 10, 11, 12]. Nevertheless, He is still used as the main noble gas tracer for mantle reservoirs and mantle evolution. In this study the status of He and Ne isotopes as tracers of specific mantle reservoirs is re-evaluated based on the investigation of noble gas isotopic compositions of fresh, submarine basaltic glasses from the Mid-Atlantic Ridge (MAR) and adjacent seamounts.

2. Sample set and geological setting

The studied sample set comprises fresh, submarine basaltic glasses that are variably enriched in incompatible trace elements, and show a range of $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ ratios from MORB-like to much more radiogenic [13, 14]. The glasses were dredged during the Meteor cruises M42/1 and M64/1 along the neovolcanic zone of the MAR between 7 and 11°S bounded by the Ascension and Bode Verde Transform Faults, and on three off-axis seamounts 20, 40 and 120 km east of the ridge axis (Seamount E, Grattan Seamount, and Seamount D) [15]. Ascension Island is located at 7.9° S, approximately 80 km west of the MAR (Fig. 1). The MAR in this area consists of four different segments (A1 to A4 from N to S) bounded by non-transform offsets, two of which, segments A2 and A3, are unusual considering ridge structure and the composition of the erupted magmas [13, 14]. Lavas erupted along A2 and A3 are enriched in incompatible elements, have elevated $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ ratios and are relatively fractionated (lowest MgO content is around 4 wt.%) compared to normal MORB [13, 14]. The most enriched, radiogenic and fractionated lavas erupted adjacent to Seamount E, at approximately 9.7°S [13, 14]. The MAR spreading axis also becomes unusually shallow within this area (1200 m), forming a volcanic ridge rather than an axial valley, as would be typical for a slowly spreading mid-ocean ridge system [16]. The bathymetric data correspond well with seismic and gravity data indicating a crustal thickness of 10 to 11 km on segment A3, which decreases to 6 km on segment A1, a value common for oceanic crust [16, 17]. Grattan Seamount and Seamount D are the largest ones of the three investigated seamounts. Grattan Seamount has a basal diameter of 25 km whereas Seamount D has a basal diameter of around 35 km and a height of about 3160 m above seafloor [15, 18]. Both seamounts are bigger than typical abyssal seamounts produced off-axis near a MOR [18]. Even

though the seamount sizes as well as the unusual depth and crust thickness of segment A3 seem to require a larger melting anomaly, no hotspot track is related to either seamount or to Ascension Island. Nonetheless, it has been postulated that a mantle plume is responsible for the formation of these seamounts and the geophysical and geochemical anomaly produced along the MAR [15, 18, 19]. However, Minshull [17] as well as Haase et al. [14] have shown that the seamounts, as well as the anomalous ridge segments, are created by a small chemical mantle heterogeneity residing in the upper mantle in the vicinity of the shallowest ridge segment.

3. Sample preparation and analytical procedures

The glass samples were crushed and sieved into 500 to 1000 μm fractions. Samples were hand-picked under a microscope to insure purity. Glass fragments displaying evidence of alteration were discarded. The glass separates were ultrasonically cleaned using acetone before being wrapped in Al foil and placed into the sample carousel of the extraction furnace. To achieve a better separation of magmatic from atmospheric noble gas components, the glasses were degassed in three temperature steps (400°, 800° and 1500°C), using an all-metal, double-walled resistance-heated furnace with a vacuum-tight Ta crucible and a Nb liner fitted into the Ta crucible. After gas extraction, gas purification was achieved following the procedure described by Niedermann et al. [10]. Analytical blanks were run routinely between sample measurements and their noble gas values depend on the history of the crucible and on extraction temperature. Typical blank values in $10^{-12} \text{ cm}^3 \text{ STP}$ are: ^4He 1-270, ^{20}Ne 0.5-2.8 and ^{40}Ar 480-4200, where the maximum values correspond to the highest extraction step. Noble gases were analysed in a VG 5400 mass spectrometer having a mass resolution of ≥ 600 . With this resolution isobaric

interferences such as $^{40}\text{Ar}^{++}$ at $m/e=20$ or $^{12}\text{C}^{16}\text{O}_2^{++}$ at $m/e=22$ cannot be resolved, and were corrected for by using the method described in Niedermann et al. [10]. For more detailed information on the equipment and analytical procedures used during this study see Niedermann et al. [10].

4. He, Ne and Ar isotopic and elemental systematics of the sample suite

As shown in Fig. 2a and b (see Table 1 for the complete data set), almost all of the He isotopic data fall within the range typical for MORBs, except for sample 184DS4, which exhibits a significantly lower than MORB $^3\text{He}/^4\text{He}$. Sample 184DS4 has an unusually low gas content compared to the other samples and the $^3\text{He}/^4\text{He}$ ratios of this sample might have been affected by radiogenic ingrowth of ^4He . Therefore, sample 184DS4 will be omitted from the following discussion. Slight covariations can be observed between $^3\text{He}/^4\text{He}$ ratios and other isotopic ratios, such as $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{21}\text{Ne}/^{22}\text{Ne}_{\text{ext}}$. $^{21}\text{Ne}/^{22}\text{Ne}_{\text{ext}}$ is the $^{21}\text{Ne}/^{22}\text{Ne}$ ratio corrected for atmospheric contamination by extrapolation to the solar $^{20}\text{Ne}/^{22}\text{Ne}$ ratio of 13.8 [20]. An alternative extrapolation to the Ne-B $^{20}\text{Ne}/^{22}\text{Ne}$ ratio of 12.5 [21] would not affect the conclusions of the study presented here. The Ne isotopic data of the investigated glasses lie on or near either of two trends in a Ne three-isotope diagram (Fig. 3), irrespective of the fact that the error limits of individual data points are relatively large. Error-weighted linear regressions through all non-atmospheric seamount and on-ridge data yield fits which agree within error limits with the Loihi-Kilauea and MORB lines as defined by Honda et al. [22] and Sarda et al. [23], respectively (Fig. 3). Even though the studied MORB data are shown for comparison in every figure the focus of the discussion will be on the seamount data and thus the calculated regression through the MORB data is not shown in Fig. 3. The calculated Ne correlation line

clearly indicate the existence of a primitive mantle component in the seamount source, which is not detectable in the He isotopic data. This apparent He/Ne decoupling becomes even more obvious by calculating the $^3\text{He}/^4\text{He}$ ratios corresponding to the observed Ne isotopic compositions. One of the fundamental axioms of the solar hypothesis formulated by Honda et al. [24] is that He and Ne isotopic systematics should be coupled. Thus, for a given He isotopic composition, a corresponding Ne isotopic composition can be calculated and vice versa. The $^3\text{He}/^4\text{He}$ ratios calculated from the extrapolated $^{21}\text{Ne}/^{22}\text{Ne}$ ratios using the error weighted linear regression and the algorithm of Honda et al. [24] are much higher (weighted mean of 18, total range being between 12 and 37 R_A) than the measured values (7.84 ± 0.05) from this study.

The relative elemental abundances of He, Ne and Ar can be used as tracers to assess the reasons for the observed He/Ne decoupling in these basalt glasses. Ne and Ar are variably affected by atmospheric contamination, thus their measured abundances cannot be used directly. In the following discussion, the calculated amounts of nucleogenic (Ne^*) and solar Ne (Ne_S) and of radiogenic Ar (Ar^*) of each glass will be related to the measured ^4He abundances. Nucleogenic Ne and radiogenic Ar have been calculated using the method described by Graham [2]. As shown in Figs. 4 and 5 the investigated sample suite is characterised, similar to other MORB or OIB suites, by large ranges in $^4\text{He}/^{21}\text{Ne}^*$, $^3\text{He}/^{22}\text{Ne}_S$ and $^4\text{He}/^{40}\text{Ar}^*$ ratios. Some of the seamount samples have $^4\text{He}/^{21}\text{Ne}^*$ and $^3\text{He}/^{22}\text{Ne}_S$ lower than the corresponding production and primordial ratios and all but two seamount samples have $^4\text{He}/^{40}\text{Ar}^*$ lower than the production ratio. These samples indicate that He has been preferentially lost from the source region of the seamount glasses prior to eruption or any source mixing processes. Such preferential He loss makes the initial $^3\text{He}/^4\text{He}$ ratios of the seamount source susceptible for changes caused by radioactive decay,

diffusion or source mixing. Samples with $^4\text{He}/^{21}\text{Ne}^*$, $^3\text{He}/^{22}\text{Ne}_s$ and $^4\text{He}/^{40}\text{Ar}^*$ higher than the corresponding production and primordial ratios indicate a He enrichment relative to Ne and Ar. This He enrichment is typical for degassing processes, which is also shown e.g. by the decrease in Ar concentration with increasing $^4\text{He}/^{40}\text{Ar}^*$ (Fig. 5a) and the positive correlations between $^4\text{He}/^{40}\text{Ar}^*$ and $^3\text{He}/^{22}\text{Ne}_s$ (Fig. 5b) [e.g. 25, 26], and is not intrinsic to the source.

5. He/Ne decoupling: consequences for He and Ne as mantle tracers

Existing He/Ne data indicate that the decoupling of He/Ne isotopic systematics, as observed in the investigated sample suite, seems to be more the rule than the exception; the majority of OIB studies show that $^3\text{He}/^4\text{He}$ ratios calculated using the approach of Honda et al. [24] are significantly different from the measured ones. This discrepancy has been noted before by e.g. Niedermann et al. [10], Moreira et al. [11] and Madureira et al. [12]. In general, two different models have been proposed to explain this apparent discrepancy in He/Ne isotopic systematics: (1) a closed system evolution of a mantle having heterogeneous $^3\text{He}/^{22}\text{Ne}$ ratios and (2) different mixing processes. Model 1 is in contradiction to the “solar hypothesis” [24] and the “steady-state upper mantle model” [27]. In their “solar hypothesis” Honda et al. [24] argue that “primordial He and Ne would all be solar” and have only been changed by production of radiogenic ^4He and nucleogenic ^{21}Ne , implying that the $^3\text{He}/^{22}\text{Ne}$ in the mantle should have remained constant over time, provided that He cannot be fractionated from Ne during mantle melting and subductive recycling of light noble gases is negligible. In the “steady-state upper mantle model” it has been proposed that the $^3\text{He}/^{22}\text{Ne}$ ratios of the upper and lower mantle are similar and are related to a steady state flow of He and Ne from the lower to the upper mantle. In

196 contrast, a mantle with heterogeneous $^3\text{He}/^{22}\text{Ne}$ ratios would develop different
 197 $^3\text{He}/^4\text{He}$ and $^{21}\text{Ne}/^{22}\text{Ne}$ ratios with time for different source regions. Using the
 198 approach of Moreira et al. [11] the He and Ne isotopic evolution of different
 199 reservoirs with the same initial He and Ne isotopic compositions (solar) but varying
 200 initial $^3\text{He}/^{22}\text{Ne}$ ratios can be traced. Fig. 6a shows the time-dependent isotopic
 201 evolution of different reservoirs with varying initial $^3\text{He}/^{22}\text{Ne}$ ratios in a plot of
 202 $^4\text{He}/^3\text{He}$ vs. $^{21}\text{Ne}/^{22}\text{Ne}_{\text{ext}}$. The He/Ne isotopic systematics of the investigated samples
 203 from this study are reproduced by this model. The model results indicate that the
 204 initial $^3\text{He}/^{22}\text{Ne}$ composition of the MORB source might be about 10, whereas that of
 205 the seamount source would be between 1 and 3.

206 The alternative “mixing model” is again evaluated in a plot of $^4\text{He}/^3\text{He}$ vs.
 207 $^{21}\text{Ne}/^{22}\text{Ne}_{\text{ext}}$ (Fig. 6b). The endmember compositions used in this mixing model are as
 208 follows: for the enriched, primitive plume component we have chosen solar-like He
 209 and Ne isotopic ratios ($^4\text{He}/^3\text{He} = 4800$, $^{21}\text{Ne}/^{22}\text{Ne} = 0.032$), whereas for the depleted
 210 MORB source average upper-mantle He and Ne isotopic ratios have been used
 211 ($^4\text{He}/^3\text{He} = 90000$, $^{21}\text{Ne}/^{22}\text{Ne} = 0.076$) [2]. The mixing lines in our model are defined
 212 by “ r_{mix} ”, where “ r_{mix} ” is the ratio of $^3\text{He}/^{22}\text{Ne}$ in MORB to $^3\text{He}/^{22}\text{Ne}$ in the primitive
 213 source. The hyperbolic mixing lines require large differences between the $^3\text{He}/^{22}\text{Ne}$
 214 ratios of the two sources involved in the mixing process in order to reproduce the
 215 He/Ne isotopic systematics of the data presented here as well as of the hotspot data
 216 from Iceland [28, 29], Loihi [22, 30-32] and Kerguelen [33] shown for comparison
 217 (Fig. 6b). Thus, these mixing relations seem to suggest that the mantle is
 218 heterogeneous in terms of $^3\text{He}/^{22}\text{Ne}$ ratios. However, Moreira et al. [11] have argued
 219 that such mixing relations can also be produced by assuming variable degrees of
 220 degassing of the MORB magmas prior to mixing with magmas from the primitive

source. Generally, this scenario appears to be plausible, however it would require that OIB magmas are much less or even undegassed, which is not the case when taking the many published $^4\text{He}/^{21}\text{Ne}^*$ vs. $^3\text{He}/^{22}\text{Ne}$ patterns of different OIBs into account [e.g. 2]. In addition, OIB melts are thought to be much more volatile-rich compared to MORB melts, thus solubility limits of OIB melts might be reached at greater depth resulting in higher degrees of degassing of these melts. Considering our seamount samples the mixing model seems to be consistent with our data; however, $^3\text{He}/^{22}\text{Ne}$ ratios 250 times higher in the MORB magmas than in the seamount-source magmas would be necessary to produce the He/Ne isotopic systematics of the seamount samples by binary mixing between a melt derived from an enriched mantle source and an upper mantle melt. These high $^3\text{He}/^{22}\text{Ne}$ ratios are neither measured in our MORB samples (Fig. 4) nor can a $^3\text{He}/^{22}\text{Ne}_s$ ratio of 250 be produced by normal degrees of degassing. To produce such high ratios very large degrees of degassing would be necessary. The He and Ne concentrations of our sample suite are similar to other published MORB and hotspot data (Table 1), indicating that extremely high degrees of degassing can be ruled out.

The seamount and MORB He and Ne data presented here can be best explained by assuming inherited differences in the $^3\text{He}/^{22}\text{Ne}$ ratios of the two sources. The low $^4\text{He}/^{21}\text{Ne}^*$ ratios (compared to the production ratio) of some of the seamount samples indicate that the difference in the $^3\text{He}/^{22}\text{Ne}$ ratio must have been acquired relatively recently, presumably by a preferential loss of He compared to Ne prior to the main melting phase, otherwise the $^4\text{He}/^{21}\text{Ne}^*$ ratios of the samples would be closer to the $^4\text{He}/^{21}\text{Ne}$ production ratio. This preferential He loss made the $^3\text{He}/^4\text{He}$ source ratio more susceptible to changes in such a way that subsequent nuclear processes had a larger impact on the He than on the Ne isotopic ratios. Model calculations show that

a lowering of the He content of the seamount source by about two orders of magnitude would be enough to lower the $^3\text{He}/^4\text{He}$ ratios by about 11 R_A in less than 100,000 a, assuming a fertile mantle source. It has been shown by Haase et al. [14] that the seamount source most likely consists of fertile, incompatible element-enriched garnet peridotite. In this context, Kurz and Geist [34] have shown that the decoupling of He from Sr in magmas from Galápagos could be caused by deep incipient, low degree melting at the hydrous solidus prior to the main melt production phase, assuming that He is more incompatible than Sr. Similar processes could be visualised for the source of the off-axis seamounts. In addition, Kurz et al. [35] confirmed a similar but less extreme decoupling of He from Ne for the East-Pacific-Rise (EPR) near 17°S, that was earlier reported by Niedermann et al. [10]. Kurz et al. [35] concluded: “The spatial relationships between the isotopic systems, [...], are interpreted as relating to *preferential extraction of He* from the entrained heterogeneity. [...] This is probably related to bulk partition coefficients during melting and would require that the order of incompatibility be $\text{He} < \text{Ne} < \text{Sr}, \text{Nd}, \text{Pb}$.”

He isotope fractionation caused by diffusion processes during melt formation and ascent can be ruled out as being responsible for the He/Ne isotopic decoupling, since Burnard [36] has shown that the $^3\text{He}/^4\text{He}$ ratio of a melt can be lowered by at most 2 R_A by diffusion processes during melt ascent. Our data would require a lowering of the calculated initial $^3\text{He}/^4\text{He}$ ratios by $\sim 11 R_A$. A post-eruptive diffusive He loss could not have produced the observed He/Ne isotope patterns because diffusion coefficients of He in glass (see compilation by Ozima and Podosek [3]) are much too small to account for the substantial He loss required to explain the observed isotope patterns in these young glasses. Furthermore the differences in ^3He and ^4He diffusivity are not large enough to lower the initial $^3\text{He}/^4\text{He}$ ratios by $\sim 11 R_A$ to the

ratios observed today [37], thus post-emplacement radiogenic ^4He production would be required. ^{21}Ne would also be produced along with the radioactive decay of U and Th, and as the Ne content in the residual melt from which the glasses have formed is lowered more drastically by degassing than the He content, the Ne isotopic ratios would be even more susceptible to changes in this scenario than the He ratios, in contrast to our observations. Thus, even though diffusion processes may have the ability to alter He/Ne or He/Ar ratios, they cannot account for the apparent He loss and the MORB-like He isotopic ratios compared to primitive Ne isotopic ratios observed in the investigated samples.

Even though the model described in the previous paragraph seems to be the best and most likely one to reproduce the source systematics of the investigated region, a final “proof” for the reliability of this model cannot be given. This is based on the problem of acquiring reliable, consistent partition coefficients for He and Ne under consideration of the full petrologic composition of the mantle. The majority of published partition coefficients have high analytical uncertainties making it quite difficult to decide which are the “right or wrong” values. Furthermore, they show a relatively large range with He being either more or less compatible than Ne, and with He and Ne being either more or less compatible than U. This is a critical point in terms of mantle evolution, which is largely controlled by melt extraction. However, using the latest partition coefficients obtained by Heber et al. [38], modelling partial melting of a fertile mantle source indicates that even small differences in He and Ne partition coefficients can result in fractionation of He from Ne during melting (Fig. 7). The modelling results also show that the modal composition of the mantle has a critical influence on the behaviour of He and Ne. In this context, our data might also be taken as an indication that He is at least more incompatible than Ne. However, if

He is indeed more incompatible than Ne during melt formation, the differences in $^3\text{He}/^{22}\text{Ne}$ ratios necessary to reproduce most hotspot data could be explained by differences in melting processes. Assuming further that Ne is more compatible than U could explain how primitive, solar-like Ne can survive in depleted residues of mantle melting. Recently Brooker et al. [39] as well as Parman et al. [40] have proposed, based on experimental data and model calculations, that even He might be more compatible in olivine than U and Th. Assuming that the bulk partition coefficient of He is higher than that of U and Th would just change the time-scales for the inheritance of the different $^3\text{He}/^{22}\text{Ne}$ ratios of the investigated mantle sources, because more time would be needed to lower the $^3\text{He}/^4\text{He}$ ratio of the seamount source by $\sim 11 R_A$, but it would still be required that He is more incompatible than Ne to explain our data. On the other hand, Haase et al. [14] have shown that the source of the seamounts consists most likely of fertile peridotite and is not depleted in incompatible trace elements. This indicates that the source has not only lost He preferentially relative to Ne but also to U and Th. Taking this into account it could be argued that He is more incompatible than U and Th. In either case, our data clearly indicate that Ne is a more reliable tracer than He for mantle formation, mantle evolution and source characterization.

6. He and Ne: always indicators for a lower mantle source?

High $^3\text{He}/^4\text{He}$ and primitive Ne isotopic ratios are usually interpreted as evidence for the contribution of deep, relatively undegassed mantle material to a sample, despite the fact that other indicatives (e.g. seismic data, hotspot trace) might be missing [e.g. 12]. Taking our data into consideration, we are left with the same dilemma of finding relatively primitive Ne isotopic ratios in samples derived from an

area where no indication of a deep mantle plume has been reported [17]. Instead it is inferred that the geochemical anomaly observed along this section of the MAR as well as the seamounts found in this area, have been produced by a small mantle heterogeneity residing in the upper mantle [13, 17]. However, considering the differences of melt formation processes at hotspot and mid-ocean ridge settings (point sources compared to broad melting regime) it is not difficult to visualise that it depends on the size and the fertility of an enriched “mantle blob” whether it can escape homogenisation during melting along a mid-ocean ridge. Thus, it can also be argued that the primitive Ne signal resides in the upper mantle and is not related to a deep mantle plume.

7. Conclusions

We have presented the first He, Ne and Ar data from the MAR between 7 and 12°S and from adjacent seamounts lying to the east of the ridge axis. We have shown, based on the Ne isotope data, that the source responsible for the seamount formation and the geochemical anomaly along the MAR must contain relatively primitive mantle material. Based on the He isotope data alone this primitive aspect of the source would have been completely missed and the source of those seamounts would have been interpreted as representing a recycled component. We have also shown that the differences in $^3\text{He}/^{22}\text{Ne}$ ratios required to explain the apparent decoupling of He and Ne isotopes cannot be accounted for by mixing processes between a degassed MORB magma and a less or non-degassed magma from the enriched source. These isotopic patterns can only be produced by a preferential loss of He compared to Ne, indicating that He is more incompatible than Ne. The He loss was most likely caused by incipient, low degree melting processes at the hydrous solidus prior to the main melt

production phase. The timing of this He loss greatly depends on the partition coefficients of He in relation to U and Th, for which no consistent data currently exist. Our study points out the necessity of obtaining neon data for the modelling of mantle formation and evolution and correct source characterisation.

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Figure captions

Fig. 1: Map of the working area.

Fig. 2: $^{206}\text{Pb}/^{204}\text{Pb}$ vs. $^3\text{He}/^4\text{He}$ (a) and $^{21}\text{Ne}/^{22}\text{Ne}_{\text{ext}}$ (see section 4 for further explanation) vs. $^3\text{He}/^4\text{He}$ (b) for the entire sample suite. $^3\text{He}/^4\text{He}$ ratios represent the weighted averages of all temperature steps whereas the Ne isotope data represent the weighted averages of all temperature steps showing a Ne excess. Note that only Ne data which are different from the atmospheric value at the 1σ uncertainty level have been considered in this study. Pb isotope data are from Möller [13]. Stars denote the seamount samples, polygons denote the MORB samples. 1σ uncertainties are shown where larger than the symbol.

Fig. 3: Neon three-isotope diagram. Ne isotope data represent all temperature steps having an excess in mantle Ne. Ne data of the seamount samples define a trend line agreeing, within error limits, with the Loihi-Kilauea (L-K) line [22], whereas the Ne isotope data from the ridge-axis samples define a trend line consistent with the MORB line [23]. The dashed line denotes the error-weighted linear regression line ($y = 264 (\pm 50) x + 2.15 (\pm 1.48)$) through the non-atmospheric seamount data, the shaded area represents the uncertainty range of this regression. The diamonds denote the seamount samples the squares the MORB samples. 1σ uncertainties are shown where larger than the symbol.

Fig. 4: $^4\text{He}/^{21}\text{Ne}^*$ vs. $^3\text{He}/^{22}\text{Ne}_s$ diagram. $^3\text{He}/^{22}\text{Ne}_s$ and $^4\text{He}/^{21}\text{Ne}^*$ were calculated using the algorithms compiled by Graham [2], based, in the case of He on the totals of

all temperature steps and in the case of Ne on the totals of all temperature steps showing a significant excess in $^{20}\text{Ne}/^{22}\text{Ne}$. As a result of He loss some of the seamount samples plot below the solar/primordial mantle and production values (dashed lines), whereas those samples plotting above the solar/primordial mantle and production values are relatively enriched in He as a result of degassing. Symbols are the same as in Fig. 2. 1σ uncertainties are shown where larger than the symbol.

Fig. 5: In panel (a) $^{40}\text{Ar}^*$ vs. $^4\text{He}/^{40}\text{Ar}^*$ is shown. $^4\text{He}/^{40}\text{Ar}^*$ ratios were calculated using the algorithms compiled by Graham [2], based on the totals of all temperature steps. The brought negative correlation observed between $^4\text{He}/^{40}\text{Ar}^*$ and $^{40}\text{Ar}^*$ is typical for degassing and is caused by the greater melt solubility of He compared to Ar [25, 26]. The samples lying below the production ratio have preferentially lost He. Panel (b) shows the $^3\text{He}/^{22}\text{Ne}_s$ vs. $^4\text{He}/^{40}\text{Ar}^*$ systematics of the sample set. Again samples lying below the solar/primordial mantle and production values have lost He, whereas the others are relatively enriched in He. The positive correlation between $^4\text{He}/^{40}\text{Ar}^*$ and $^3\text{He}/^{22}\text{Ne}_s$ again suggests that the effects of magmatic degassing are superimposed on the effects of mantle melting and or source heterogeneity. The dashed line represents the error-weighted linear regression ($y = 0.868 (\pm 0.199) x - 0.913 (\pm 0.454)$) through the seamount data. Symbols are the same as in Fig. 2. 1σ uncertainties are shown where larger than the symbol.

Fig. 6: Plots of $^{21}\text{Ne}/^{22}\text{Ne}_{\text{ext}}$ vs. $^4\text{He}/^3\text{He}$. In panel (a) the straight lines represent the temporal evolution of reservoirs having the same initial isotope ratios but different initial $^3\text{He}/^{22}\text{Ne}$ ratios (as denoted by r_s on the diagram). Panel (b) represents a binary

mixing model between a solar and a MORB-type mantle end-member. The seamount
 data can only be fitted by a hyperbolic mixing line with an unrealistically high r_{mix}
 value ($r_{\text{mix}} = (^3\text{He}/^{22}\text{Ne}_{\text{MORB}}) / (^3\text{He}/^{22}\text{Ne}_{\text{primitive source}})$) of about 250. For comparison
 data from Iceland (crosses) [28, 29], (grey triangles) [22, 30-32] and Kerguelen (grey
 circles) [33] are shown. 1σ uncertainties are shown for the samples presented in this
 study where larger than the symbol.

Fig. 7: Modelled evolution of He (black curves) and Ne (grey curves) source
 concentrations with the degree of melting. The residual source concentrations have
 been calculated using the non-modal batch melting equation of Shaw [41] and the
 mantle and melt modes of van Westrenen et al. [42] for garnet peridotite (solid black
 and grey curves) and garnet pyroxenite (dashed black and grey curves) respectively as
 well as the mantle and melt modes of Johnson et al. [43] for garnet peridotite (dotted
 black and grey curves). To exclusively demonstrate the influence of the partition
 coefficients and the modal mantle and melt compositions on the evolution of He and
 Ne in the source the initial He and Ne source concentrations have been arbitrarily set
 to 10 ppm. The partition coefficients have been taken from Heber et al. [38], the
 uncertainties of those partition coefficients have not been included in our model
 calculations.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Table 1: Concentration and isotope data of He, Ne and Ar of the entire sample suite, sample IDs written in italics denote the seamount samples.

Sample ID	Lat [°S]	Long [°W]	Depth [m]	Temp Steps [°C]	^4He $10^{-8}\text{cm}^3/\text{g}$	Error [+/-]	^{20}Ne $10^{-12}\text{cm}^3/\text{g}$	Error [+/-]	^{40}Ar $10^{-8}\text{cm}^3/\text{g}$	Error [+/-]	$^3\text{He}/^4\text{He}$ $\times 10^{-6}$	Error [+/-]	$^{20}\text{Ne}/^{22}\text{Ne}$ Error [+/-]	$^{21}\text{Ne}/^{22}\text{Ne}$ Error [+/-]	$^{40}\text{Ar}/^{36}\text{Ar}$ Error [+/-]			
122 DS-5 I	6.66	11.29	4080	400	60.36	2.15	4.35	1.35	0.92	0.06	12.85	0.76	9.10	0.55	0.02913	0.00637	305	6
122 DS-5 I	6.66	11.29	4080	800	1150.91	40.69	108.11	5.80	112	6	12.36	0.25	11.17	0.16	0.05055	0.00153	3003	24
122 DS-5 I	6.66	11.29	4080	1500	28.27	1.41	8.85	1.48	17.88	1.22	11.55	1.08	9.03	0.27	0.03246	0.00332	2296	551
122 DS-5 I	6.66	11.29	4080	Total	1239.54	40.77	121.30	6.14	131	6	12.36	0.24	10.90	0.16	0.04804	0.00153	2720	24
130 DS-3	7.58	13.47	3925	400	19.74	0.70	0.87	0.76	8.78	0.45	11.80	0.40	9.16	1.27	0.02840	0.01850	7963	954
130 DS-3	7.58	13.47	3925	800	252.49	8.93	15.51	1.22	0.12	0.01	11.52	0.24	11.71	0.26	0.05082	0.00424	365	13
130 DS-3	7.58	13.47	3925	1500	478.13	16.91	106.16	6.15	268	18	11.06	0.20	11.48	0.13	0.05260	0.00282	16020	408
130 DS-3	7.58	13.47	3925	Total	750.37	19.14	122.54	6.32	277	18	11.23	0.15	11.48	0.26	0.05216	0.00424	15247	408
142DS2	8.02	13.43	3576	400	134.15	4.74	3.63	0.46	0.33	0.04	11.81	0.14	9.63	0.36	0.03113	0.00447	505	42
142DS2	8.02	13.43	3576	800	286.91	10.14	136.45	7.05	40.61	2.05	11.39	0.16	10.17	0.07	0.03369	0.00102	1702	23
142DS2	8.02	13.43	3576	1500	5.71	0.29	12.48	0.90	13.96	0.76	10.03	0.74	10.56	0.27	0.03904	0.00475	6602	1751
142DS2	8.02	13.43	3576	Total	426.78	11.20	152.56	7.13	54.90	2.18	11.50	0.11	10.19	0.27	0.03405	0.00475	2061	1751
158 DS-1	8.84	13.50	2139	400	137.061	4.846	31.84	1.74	0.24	0.04	10.60	0.22	9.81	0.17	0.02890	0.00290	323	9
158 DS-1	8.84	13.50	2139	800	198.237	7.009	107.60	5.58	6.48	0.34	9.93	0.14	9.95	0.10	0.03216	0.00204	372	4
158 DS-1	8.84	13.50	2139	1500	0.079	0.011	1.29	0.38	0.18	0.15	11.83	8.74	8.87	0.55	0.02661	0.01062	2280	12550
158 DS-1	8.84	13.50	2139	Total	335.38	8.52	140.73	5.86	6.90	0.38	10.20	0.12	9.91	0.10	0.03136	0.00204	378	4
173 DS-1	9.64	13.19	1477	400	44.75	1.58	36.35	1.95	0.12	0.03	10.80	0.44	9.80	0.15	0.03000	0.00267	342	18
173 DS-1	9.64	13.19	1477	800	36.01	1.27	5.93	0.60	0.24	0.07	10.02	0.36	10.04	0.45	0.03585	0.00602	368	27
173 DS-1	9.64	13.19	1477	1500	0.131	0.010	0.85	0.33	1.95	0.17	9.89	8.08	8.80	1.08	0.03365	0.01420	312	5
173 DS-1	9.64	13.19	1477	Total	80.889	2.031	43.13	2.07	2.31	0.19	10.45	0.29	9.81	0.45	0.03087	0.00602	319	27
174 DS-2	9.70	13.16	1539	400	1.220	0.062	10.73	0.91	1.51	0.08	11.55	4.03	9.45	0.32	0.02872	0.00416	300	2
174 DS-2	9.70	13.16	1539	800	420.66	14.89	876	44	52.15	2.62	10.79	0.18	9.95	0.06	0.02979	0.00056	322	1
174 DS-2	9.70	13.16	1539	1500	5.939	0.297	75.83	4.19	5.90	0.57	9.91	1.80	9.68	0.13	0.02969	0.00157	346	5
174 DS-2	9.70	13.16	1539	Total	427.82	14.89	962	45	59.56	2.68	10.78	0.18	9.92	0.06	0.02977	0.00056	323	1
14DS1	9.73	12.88	981	400	0.00070	0.0026/0.0007	0.10	1.9/0.1	<0.028		60.00	220/60	7.00	30/7	0.04000	0.14/0.04	>310	
14DS1	9.73	12.88	981	800	21.30	1.10	710	36	8.06	0.45	10.95	0.59	9.90	0.04	0.02940	0.00092	836	24
14DS1	9.73	12.88	981	1500	0.0199	0.0052	108.20	6.30	22.40	1.40	13.70	8.70	9.80	0.08	0.02920	0.00240	318	2
14DS1	9.73	12.88	981	Total	21.30	1.10	818	37	30.50	1.50	10.95	0.59	9.89	0.04	0.02938	0.00086	380	6
179 DS-2	9.73	12.88	1241	400	24.61	0.87	2230	113	169.97	11.59	11.26	0.63	9.91	0.08	0.02923	0.00053	307	4
179 DS-2	9.73	12.88	1241	800	720.02	25.46	4582	233	423	29	11.06	0.18	10.29	0.34	0.03091	0.00144	510	22
179 DS-2	9.73	12.88	1241	1500	0.0139	0.0054	2.96	2.86	15.58	1.07	19.13	22.68	8.25	2.23	0.02921	0.00638	319	4
179 DS-2	9.73	12.88	1241	Total	744.64	25.48	6815	259	608	31	11.07	0.17	10.16	0.34	0.03035	0.00144	425	22
183 DS-5	9.71	12.14	2297	400	20.030	0.709	722.51	36.52	13.09	0.66	11.37	0.54	9.91	0.05	0.02936	0.00067	330	3

Sample ID	Lat [°S]	Long [°W]	Depth	Temp Steps [°C]	⁴ He 10 ⁻⁸ cm ³ /g	Error [+/-]	²⁰ Ne 10 ⁻¹² cm ³ /g	Error [+/-]	⁴⁰ Ar 10 ⁻⁸ cm ³ /g	Error [+/-]	³ He/ ⁴ He x 10 ⁻⁶	Error [+/-]	²⁰ Ne/ ²² Ne Error [+/-]	²¹ Ne/ ²² Ne Error [+/-]	⁴⁰ Ar/ ³⁶ Ar Error [+/-]
183 DS-5	9.71	12.14	2297	800	83.021	2.936	329.71	19.93	54.77	2.78	10.52	0.33	9.84	0.05	0.02982 0.00057 448 3
183 DS-5	9.71	12.14	2297	1500	0.129	0.010	1.03	0.45	0.74	0.08	11.68	5.48	8.55	1.07	0.03121 0.01242 428 18
183 DS-5	9.71	12.14	2297	Total	103.18	3.02	1053.25	41.60	68.60	2.86	10.68	0.28	9.89	0.05	0.02952 0.00067 421 3
184DS4	9.73	12.13	1529	400	0.0072	0.0065	32.30	4.00	1.21	0.11	9.30	8.50	9.90	0.27	0.02850 0.00350 293 5
184DS4	9.73	12.13	1529	800	2.63	0.13	5130	260	311	21	5.74	0.72	9.75	0.02	0.02896 0.00031 311 2
184DS4	9.73	12.13	1529	1500	0.689	0.035	<4		1.49	0.28	10.90	1.00			448 42
184DS4	9.73	12.13	1529	Total	3.33	0.13	5160	260	314	21	6.82	0.61	9.75	0.27	0.02896 0.00350 311 2
188ROV4				400	2.389	0.088	44.57	2.62	3.34	0.18	11.13	0.68	9.69	0.28	0.02906 0.00289 294 5
188ROV4				800	55.12	1.96	17.30	1.32	1.10	0.06	10.97	0.46	10.83	0.33	0.03222 0.00305 331 8
188ROV4				1500	2.54	0.09	14.32	1.75	1.07	0.28	9.92	0.62	10.20	0.32	0.03164 0.00443 338 8
188ROV4				Total	60.05	1.96	76.20	3.42	5.51	0.33	10.94	0.42	10.02	0.33	0.03020 0.00305 309 8
188ROV7				400	1.283	0.046	49.71	2.73	3.69	0.19	10.98	1.13	9.51	0.07	0.02843 0.00292 296 5
188ROV7				800	14.95	0.53	28.80	1.88	3.64	0.85	11.01	0.50	9.99	0.35	0.02982 0.00305 303 5
188ROV7				1500	0.379	0.019	4.68	1.19	0.71	0.21	9.98	2.61	10.19	0.64	0.02911 0.00840 377 9
188ROV7				Total	16.61	0.53	109.67	3.52	8.04	0.90	10.98	0.46	9.70	0.35	0.02893 0.00305 305 9

Table 1: Continued