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Heterogeneities from the first 100 million years recorded in deep mantle noble gases from the Northern Lau Back-arc Basin

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ABSTRACT

Heavy noble gases can record long-lasting heterogeneities in the mantle, because Ne, Ar, and Xe isotopes are produced from extant (U, Th, K) and extinct (^{129}I and ^{244}Pu) radionuclides. However, the presence of ubiquitous atmospheric contamination in basalts, particularly for ocean island basalts (OIBs) that sample the Earth's deep mantle, have largely hampered precise characterization of the mantle source compositions. Here we present new high-precision noble gas data from gas-rich basalts erupted along the Rochambeau Rift (RR) in the northwestern corner of the Lau Basin. The strong influence of a deep mantle plume in the Rochambeau source is apparent from low ^{4}He/^{3}He ratios down to 25,600 (^{3}He/^{4}He of 28.1R_A).

We find that the Rochambeau source is characterized by low ratios of radiogenic to non-radiogenic nuclides of Ne, Ar, and Xe (i.e., low ^{21}Ne/^{22}Ne, ^{40}Ar/^{36}Ar, and ^{129}Xe/^{130}Xe) compared to the mantle source of mid-ocean ridge basalts (MORBs). High-precision xenon isotopic measurements indicate that the lower ^{129}Xe/^{130}Xe ratios in the Rochambeau source cannot be explained solely by mixing atmospheric xenon with MORB-type xenon; nor can fission-produced Xe be added to MORB Xe to produce the compositions seen in the Rochambeau basalts. Deconvolution of fissiogenic xenon isotopes demonstrate a higher proportion of Pu- fission derived Xe in the Rochambeau source compared to the MORB source. Therefore, both I/Xe and Pu/Xe ratios are different between OIB and MORB sources. Our observations require heterogeneous volatile accretion and a lower degree of processing for the plume source compared to the MORB source. Since differences in ^{129}Xe/^{130}Xe ratios have to be produced while ^{129}I is still alive, OIB and MORB sources must have been processed at different rates for the first 100 million years (Myr) of Solar System history, and subsequent to this period, the two reservoirs have not been homogenized.

In combination with recent results from the Iceland plume, our noble gas observations require the formation and preservation of less-degassed, early-formed (pre-4.45 Ga) heterogeneities in the Earth's deep mantle. Consequently, the primitive noble gas reservoir sampled by mantle plumes cannot be created solely through sequestration of recycled slabs or undegassed melts at the base of the mantle during the past 4.4 Ga. Finally, if the more primitive, less degassed heterogeneities reside in the Large Low Shear Wave Velocity Provinces (LLSVPs), then LLSVPs must be long-lasting features of the deep mantle and are not composed exclusively of recycled material.

1. Introduction

The noble gas compositions of mantle-derived basalts provide information on the degassing history, style of mantle convection, and volatile exchange between the deep Earth and the atmosphere. Compared to mid-ocean ridge basalts (MORBs), ocean island basalts (OIBs) from Iceland, Hawaii, Galapagos, Réunion and Samoa are characterized by lower ratios of radiogenic to primordial isotopes such as ^{4}He/^{3}He, ^{21}Ne/^{22}Ne and ^{40}Ar/^{36}Ar (e.g., Hanyu et al., 2001; Honda et al., 1993a; Mukhopadhyay, 2012; Poreda and Farley, 1992; Raquin and Moreira, 2009; Trieloff et al., 2000; Trieloff et al., 2002). Likewise, lower ratios of radiogenic to non-radiogenic Xe isotopes (^{129}Xe/^{130}Xe) are found in Hawaii, Samoa, Iceland and Reunion (e.g., Mukhopadhyay, 2012; Poreda and Farley, 1992; Trieloff et al., 2000; Trieloff et al., 2002; Hopp and Trieloff, 2005). These noble gas signatures in OIBs are commonly attributed to sampling parts of Earth's mantle that are significantly less degassed than the MORB source (e.g., Allègre et al., 1987, 1996; Graham, 2002; Gonnermann and Mukhopadhyay, 2009; Kurz et al., 1982; Kurz et al., 2009; Porcelli and Wasserburg,

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1995; Staudacher and Allègre, 1982). Shallow-level atmospheric contamination, however, often makes it difficult to decipher whether the lower measured Ar and Xe isotopic ratios in OIBs are indeed reflective of the mantle source composition. Additionally, the low $^{40}Ar/^{36}Ar$ and $^{129}Xe/^{130}Xe$ ratios in OIBs may arise from recycled atmospheric Ar and Xe and not from a less degassed reservoir (Holland and Ballentine, 2006: Kendrick et al., 2011; Trieloff and Kunz, 2005).

If the low $^{129}Xe/^{130}Xe$ ratios in OIBs are indeed from a less degassed reservoir, then the OIB and MORB reservoirs must be partially isolated from each other since 4.45 Ga as ^{129}I, which produces ^{129}Xe, became extinct 100 Myr after the start of the Solar System. Such long-term separation would invalidate many models put forth to explain the chemical and dynamical evolution of the mantle. On the other hand, if the differences in $^{129}Xe/^{130}Xe$ ratios between OIBs and MORBs arise solely from recycling of atmospheric Xe, long-term separation of the two sources is not required and extensive mixing between the sources may be allowed. Hence, addressing the origin of the low $^{40}Ar/^{36}Ar$ and $^{129}Xe/^{130}Xe$ ratios observed in OIBs compared to MORBs is of fundamental importance in understanding whether compositional heterogeneities dating back to Earth's accretion are still preserved. The preservation of old heterogeneities in the deep mantle can in turn provide important constraints on long-term mixing rates and mass flow in the mantle.

Recently, Mukhopadhyay (2012) and Tucker et al. (2012) demonstrated that the lower $^{40}Ar/^{36}Ar$ and $^{129}Xe/^{130}Xe$ in the Iceland plume compared to depleted MORBs cannot be generated solely through recycling of atmospheric noble gases. To investigate whether the composition of the Iceland plume is representative of other mantle plumes, we present combined He–Ne–Ar–Xe measurements in gas-rich basaltic glasses from the Rochambeau Rift in the northern Lau Back-arc Basin with $^4He/^3He$ ratios as low as 25,600 ($28.1R_A$, where R_A is the $^3He/^4He$ ratio normalized to the atmospheric ratio of 1.39×10^{-6}).

The RR is located in the northwestern flank of the Lau Back-arc Basin, behind the Tonga arc, in the western Pacific (Fig. 1). Shear-wave splitting analyses suggest a fast direction of anisotropy that is oriented north to south in the Lau back-arc spreading center (Smith et al., 2001). If this anisotropy is interpreted in terms of mantle flow, it would suggest southward flow of the Pacific mantle (Smith et al., 2001). Slab rollback could induce the southward flow, which would consequently introduce Samoan plume material into the northern Lau back-arc region (Smith et al., 2001; Regelous et al. 2008; Jackson et al., 2010) through a tear in the Tonga slab beneath the Vitiaz lineament (Millen and Hamburger, 1998).

The flow of Samoan plume material into the northern Lau Basin is consistent with observations of low $^4He/^3He$ ratios along the RR, while $^4He/^3He$ ratios in the central and southern Lau Basin are consistently MORB-like (Poreda and Craig, 1992; Lupton et al., 2009; Turner and Hawkesworth, 1998: Hahm et al., 2012; Honda et al., 1993b; Hilton et al., 1993). For example, $^4He/^3He$ ratios along the RR are as low as 32,700–25,600 ($22–28.1R_A$; Hahm et al., 2012; Poreda and Craig, 1992; Lupton et al., 2009). These values are similar to the lowest reported $^4He/^3He$ ratio of 21,000 from Samoa ($34.2R_A$, Jackson et al., 2007; Farley et al., 1992). $^{40}Ar/^{36}Ar$ and $^{129}Xe/^{130}Xe$ ratios of up to $11,988\pm156$ and 7.04 ± 0.1, respectively, have been measured in Samoan mantle xenoliths (Poreda and Farley, 1992). Consequently, if Samoan plume material influences the He isotopic composition of basalts along the RR, non-atmospheric, but low $^{40}Ar/^{36}Ar$ and $^{129}Xe/^{130}Xe$ ratios should be expected in these basalts. Thus, basaltic glasses from the RR could be ideal for characterizing the heavy noble gas composition of a low $^4He/^3He$ mantle plume. In this study, we use combined He–Ne–Ar–Xe measurements in basaltic glass samples

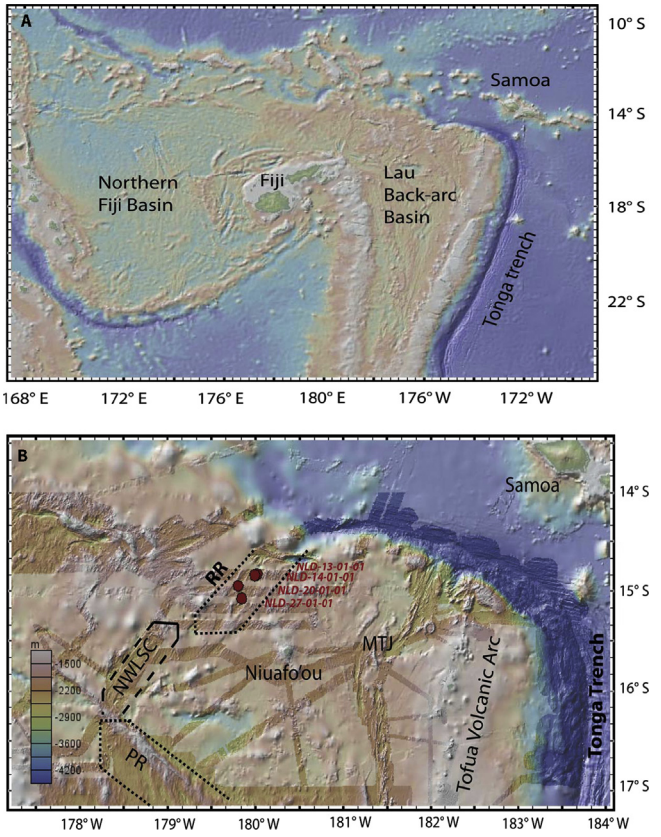

Fig. 1. (A) Regional bathymetric map of the Western Pacific and (B) bathymetric map of the Lau Basin showing the location of the four studied samples (RR=Rochambeau Rift, NWLSC=Northwest Lau Spreading Center, PR=Peggy Ridge, MTJ=Mangatolu Triple Junction).

to constrain the Ne, Ar and Xe isotopic composition of the RR mantle. We use the mantle source composition from Rochambeau to investigate whether the lower $^{40}Ar/^{36}Ar$ and $^{129}Xe/^{130}Xe$ ratios measured in plumes can be assigned to recycled atmospheric noble gases. Additionally, we utilize our Xe isotopic measurements to constrain the age of heterogeneities sampled by deep mantle plumes, and test whether dynamical and chemical evolution models of the mantle are consistent with our new observations.

2. Analytical methods

We analyzed four basaltic glass samples from the Rochambeau Rift: NLD-13-01-01, NLD-14-01-01, NLD-20-01-01 and NLD-27-01-01 (abbreviated as NLD-13, NLD-14, NLD-20, and NLD-27 in the following text; Fig. 1). The samples were pillow lavas that were collected by dredging during the voyage SS07/2008 of the R/V *Southern Surveyor* (Lupton et al., 2009; Lytle et al., 2012). $^4He/^3He$ ratios of the four samples were previously measured by Lupton et al. (2009) and range between 25,600 and 46,700 ($15.4R_A–28.1R_A$). Glass chunks were carefully selected to avoid phenocrysts. In order to remove surface alteration, glasses were leached in 2% nitric acid for 10–20 min, and then ultrasonically cleaned in distilled water and acetone. Single pieces of basaltic glass (3.2–6.8 g) were baked under vacuum for 24 h at 100 °C and were pumped for an additional 6–12 days. Samples were crushed in vacuo using a hydraulic ram to release magmatic gases trapped in vesicles. The released gases were purified by sequential exposure to hot and cold SAES getters and a small split of the gas was let into a quadrupole mass spectrometer to determine the