



Hybrid mantle plumes with recycled and primordial nitrogen: Insights from plume-influenced basaltic glasses from Reykjanes Ridge and Rochambeau Bank

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ABSTRACT

Sources of nitrogen (N) in the plume mantle source remains hotly debated between a primordial origin (i.e., acquired during Earth's formation) and a recycled origin associated with subduction of surficial material. Although N isotope data for plume-derived magmas are limited, the available data show clear differences in N isotope compositions between plume ($\delta^{15}\text{N} > -2\text{‰}$) and the depleted mid-ocean-ridge basalt mantle sources (i.e., DMM; $\delta^{15}\text{N} = -5 \pm 2\text{‰}$). Here we present N-isotope and noble gas isotope data from two suites of well-characterized plume-influenced submarine basaltic glasses with high $^3\text{He}/^4\text{He}$: 1) the Rochambeau Bank in the northeastern Lau backarc basin (up to $\sim 23 R_A$, where R_A refers to the atmospheric $^3\text{He}/^4\text{He}$ ratio), and 2) the Reykjanes Ridge (up to $\sim 18 R_A$) south of Iceland. These sample suites are associated with different tectonic settings: the Tonga subducting slab interacts with the Samoan plume beneath the Lau backarc basin, whereas the Mid-Atlantic Ridge interacts with the Icelandic plume at the Reykjanes Ridge. The contrasting tectonic settings provide a unique opportunity to decipher both the origin of N in plume mantle sources and the interaction of the plume mantle with other mantle components, including recycled material from subducting slabs and the DMM. Our results show that Rochambeau Bank ($\delta^{15}\text{N}$ from $+1.3\text{‰}$ to $+2.8\text{‰}$) and Reykjanes Ridge samples ($\delta^{15}\text{N}$ from -2.3‰ to $+0.1\text{‰}$) are both characterized by $\delta^{15}\text{N}$ values that are enriched relative to the DMM. Rochambeau Bank data are consistent with ternary mixing between the DMM ($\delta^{15}\text{N} = -5 \pm 2\text{‰}$; $\text{N}_2/^{40}\text{Ar}^* = 3.7 \pm 1.2 \times 10^6$; $\text{N}_2/^{40}\text{Ar}^* = 138 \pm 65$), a subduction component from the adjacent Tonga slab with recycled N ($\delta^{15}\text{N} = +3\text{‰}$; $\text{N}_2/^{40}\text{Ar}^* = \sim 10^9$; $\text{N}_2/^{40}\text{Ar}^* = \sim 5 \times 10^6$), and a third component with $\delta^{15}\text{N} = \sim 0\text{‰}$, $\text{N}_2/^{40}\text{Ar}^* = \sim 2 \times 10^5$ and $\text{N}_2/^{40}\text{Ar}^* = \sim 40$, which we attribute to the Samoan plume component enriched in primordial N. In contrast, Reykjanes Ridge data, combined with Iceland data, are consistent with ternary mixing among the DMM, plume components with recycled N ($\delta^{15}\text{N}$ from 0‰ to $+6\text{‰}$; $\text{N}_2/^{40}\text{Ar}^* = \sim 10^9$; $\text{N}_2/^{40}\text{Ar}^* = \sim 5 \times 10^6$) and primordial N ($\delta^{15}\text{N}$ from -2‰ to $+2\text{‰}$; $\text{N}_2/^{40}\text{Ar}^* = \sim 2 \times 10^5$; $\text{N}_2/^{40}\text{Ar}^* = \sim 40$) endmembers in deep Icelandic mantle plumes. This is consistent with the presence of both recycled and primordial N being intrinsic to the Icelandic mantle plume. By integrating N data from other global plume-influenced samples (i.e., Society, Hawaii, and Central Indian Ridge), we show that the global dataset is consistent with ternary mixing among the DMM, and plume components entrained with both recycled N and primordial N. Nitrogen in deep plume sources is therefore likely hybrid in composition, containing both recycled N from subducting slab and primordial N retained from Earth's early stages of formation. The heavier $\delta^{15}\text{N}$ of an apparent primordial N component within plume mantle sources (-2‰ to $+2\text{‰}$) relative to that of the convecting MORB mantle ($\sim -5\text{‰}$) potentially requires an addition of ^{15}N -rich carbonaceous material from the outer solar system to the early accreting Earth.

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1. Introduction

Earth's mantle is chemically heterogeneous and composed of various components formed from recycling of lithospheric materials and mixing of variably degassed mantle reservoirs (e.g., Hart, 1988). Early studies based on geochemical systematics (e.g., major/trace element and Sr-Nd-Pb isotopes) revealed four principal isotopic components in oceanic basalts, including the depleted MORB (mid ocean ridge basalt) mantle (DMM), high U/Pb mantle (HIMU), and two enriched mantle components (EMI and EMII; Hart, 1988). An additional component, primarily identified by high $^3\text{He}/^4\text{He}$, likely represents a less-degassed (primordial) source sampled by ocean island basalts (OIB) (Kurz et al., 1982). MORBs, formed by the partial melting of ascending mantle beneath spreading centers, are generally thought to sample the convecting upper mantle (e.g., Hart, 1988). In contrast, OIBs represent the upwelling of heterogeneous material from the deep mantle (i.e., mantle plume; White, 2010). The heterogeneous geochemical signatures of OIBs suggest they originate from a 'hybrid' reservoir comprising deeply-subducted components, primordial mantle domains, and potentially material sourced from Earth's core (e.g., Kurz et al., 1982; Jackson et al., 2017, 2020; Dottin et al., 2020; Koppers et al., 2021; Ranta et al., 2022; Horton et al., 2023).

The recycling of volatile elements (including carbon, heavy noble gases and halogens) to the deep mantle has been suggested based on similarities in the elemental and isotope composition of volatile elements between plume-derived magmas and variable surficial components (e.g., Parai and Mukhopadhyay, 2015; Kendrick et al., 2017; Broadley et al., 2019). Flux estimates further suggest that the mantle is in a current state of net ingassing for most of these volatiles (e.g., Bekaert et al., 2021). However, Earth's deep nitrogen (N) cycle remains debated, particularly the extent to which surficial N carried by subducting slabs can be deeply recycled to plume sources (e.g., Bekaert et al., 2021; Labidi, 2022; Li and Li, 2022; Hudak et al., 2024).

Geochemical investigations of N isotopes in various terrestrial reservoirs have revealed a discernible N isotopic contrast between surficial reservoirs and the mantle. For example, subducting slabs, including modern seafloor sediments and altered oceanic lithosphere are characterized by $\delta^{15}\text{N}$ values between -1‰ and $+10\text{‰}$ (Li et al., 2023 and references therein). The DMM sampled by MORBs is characterized by $\delta^{15}\text{N}$ values of $-5 \pm 2\text{‰}$ (e.g., Javoy et al., 1986; Marty and Zimmermann, 1999; Bekaert et al., 2024a). In contrast, the plume mantle source has positive $\delta^{15}\text{N}$ values of $+3 \pm 2\text{‰}$, which may indicate the recycling of surficial N - enriched in ^{15}N - to the plume mantle sources of the Kola magmatic province (Dauphas and Marty, 1999), Loihi Seamount, the Society Islands (Marty and Dauphas, 2003), Iceland (Halldórsson et al., 2016), and the Central Indian Ridge (CIR) influenced by Réunion plume (Barry and Hilton, 2016). However, similar $\delta^{15}\text{N}$ values of $\sim 0\text{‰}$, still higher than the DMM, have also been associated with a primordial component in Earth's interior as sampled by the volcanic gases from Yellowstone (Labidi, 2022; Broadley et al., 2025).

The overlap of $\delta^{15}\text{N}$ values between recycled materials and a possible primordial component make it difficult to use these data to determine the origins of N in plume mantle sources. Instead, the coupled isotopic and elemental ratios of N and noble gases can provide more meaningful insights into volatile exchange between Earth's surface and its interior (e.g., Marty and Dauphas, 2003; Barry and Hilton, 2016; Halldórsson et al., 2016; Barry and Broadley, 2021; Labidi, 2022; Bekaert et al., 2024b; Broadley et al., 2025). Subducted material is generally enriched in N relative to the mantle and is associated with high $\text{N}_2/^3\text{He}$ (up to $\sim 10^{12}$) relative to the DMM ($3.7 \pm 1.2 \times 10^6$) (Labidi, 2022). Accordingly, the coupled elevation of $\text{N}_2/^3\text{He}$ and $\delta^{15}\text{N}$ values (up to $\sim +6\text{‰}$) in Icelandic subglacial glasses could be the result of addition of subducted N to the source of the Icelandic mantle plume source (Halldórsson et al., 2016), although some of these samples may be contaminated by air (Labidi, 2022). Similarly, a combination of elevated $\text{N}_2/^3\text{He}$, higher-than-DMM $\delta^{15}\text{N}$, and low $^3\text{He}/^4\text{He}$ in Society Islands

submarine glasses could also potentially indicate the involvement of recycled material in the plume mantle source (Labidi, 2022). In contrast, DMM-like $\text{N}_2/^3\text{He}$ and $\text{N}_2/^{36}\text{Ar}$ as well as near-zero $\delta^{15}\text{N}$ values of Yellowstone volcanic gases are likely from a primordial component (Labidi et al., 2020; Labidi, 2022; Broadley et al., 2025). These studies suggest that the deep sources of individual mantle plumes could vary significantly from one another, comprising both recycled and primordial N components. The compositions, and therefore the contributions, of primordial and recycled N to plume-derived magmas remains poorly constrained.

Here, we present new high-precision N and noble gas isotope data for two suites of plume-influenced submarine basaltic glasses (Fig. 1) with high $^3\text{He}/^4\text{He}$ above the DMM of $8 \pm 1 R_A$ (Graham, 2002), where R_A is the atmospheric $^3\text{He}/^4\text{He}$ ratio of 1.384×10^{-6} (Clarke et al., 1976). The Rochambeau Bank sample suite from the northeastern Lau backarc basin ($^3\text{He}/^4\text{He}$ up to $23 R_A$; Fig. 1A) records the interaction of the Samoan plume with the Tonga subducting slab (e.g., Turner and Hawkesworth, 1998). In contrast, the suite from the Reykjanes Ridge records plume-ridge interactions ($^3\text{He}/^4\text{He}$ up to $18 R_A$), where Icelandic mantle plume interacts with the Mid-Atlantic ridge (e.g., Thirlwall et al., 2004, 2006). Both primordial and recycled mantle components were identified in these two mantle plumes (e.g., Jackson et al., 2007, 2014, 2020; Mukhopadhyay, 2012; Petó et al., 2013; Parai and Mukhopadhyay, 2015; Dottin et al., 2020; Mundl-Petermeier et al., 2020; Ranta et al., 2022; Kaare-Rasmussen et al., 2023), however the Icelandic plume appears to be least modified by deep crustal recycling (Jackson et al., 2020). These two sample suites from complex and contrasting tectonic settings thus provide unique insights into the contributions of mantle components from the deep mantle plume, recycled material from subducting slab, and the DMM. By leveraging N and noble gas data of these two sample suites, we provide improved constraints on the composition of recycled and primordial N in deep mantle plume sources.

2. Geological background and samples

2.1. Rochambeau bank, Lau basin

Nine submarine glasses analyzed for N isotopes are from northeastern Lau backarc basin located behind the Tonga arc in the southwest Pacific (Fig. 1B). The latitudes and longitudes of these samples are presented in Hawkins (1989), and the geological setting of the Lau backarc basin is presented in Supplementary Material Text S1-1. In brief, early studies of lavas from Lau Basin have revealed the interaction of different mantle components, including the Indian-type DMM, mantle sources influenced by recycled material released from the Tonga slab at shallow depths beneath the Lau backarc basin (termed as "subduction component" hereafter), and plume material from the adjacent Samoan plume (termed as "plume component" hereafter) (Tian et al., 2011). The plume component is characterized by high $^3\text{He}/^4\text{He}$ (up to $23 R_A$) and enrichment of light rare Earth elements (LREE) and high field strength elements (HFSE) (Tian et al., 2011; Hahn et al., 2012). In contrast, the subduction component is characterized by enrichment of large ion lithophile elements (LILE) (e.g., Tian et al., 2011). In this part of the Lau Basin, the Samoan plume infiltrates the Tonga mantle wedge through a slab tear (e.g., Turner and Hawkesworth, 1998). All the glassy samples have been analyzed for their major/trace elements by Tian et al. (2011) and seven of our nine samples (except PPTU4-24-1 and PPTU4-24-3) have been previously analyzed for their He-Ne-Ar isotope compositions (Hahn et al., 2012). PPTU4-24-1 and PPTU4-24-3 were analyzed for He-Ne-Ar isotopes compositions and MGLN8-D8-3 was also selected to be re-run for He-Ne-Ar isotope compositions to confirm the reproducibility of previous measurements.

2.2. Reykjanes Ridge

Ten submarine glasses analyzed for N isotopes are from the

Reykjanes Ridge between 57°N to 63°N, which is a ~900 km long slow spreading segment of the Mid-Atlantic ridge located between the Bight fracture zone at 57°N and the Reykjanes Peninsula on Iceland at 64°N. The new dataset supplements N isotope compositions of seven glasses from Reykjanes Ridge reported by Barry et al. (2012) (Table 1). The latitude and longitude of the analyzed samples are presented in Murton (1995) and the geological setting and summary of previous studies are presented in Supplementary Material Text S1-2. In brief, early studies based on trace element and radiogenic Pb-Sr-Nd isotope compositions of Reykjanes Ridge lavas revealed the involvement of multiple mantle components sourced from Icelandic mantle plume in generating the geochemically heterogeneous lava compositions across Reykjanes Ridge and Iceland (e.g., Kempton et al., 2000; Murton et al., 2002; Thirlwall et al., 2004, 2006; Peate et al., 2010; Koornneef et al., 2012; Harðardóttir et al., 2022; Supplementary Material Text S1-2 and S2). The high $^3\text{He}/^4\text{He}$ ratios of basaltic glasses from the Reykjanes Ridge (11 to ~18 R_A ; Fig. S1), compared to DMM ($8 \pm 1 R_A$), indicate that the Atlantic MORB mantle has been affected by the Icelandic mantle plume at least ~1000 km south of Iceland (Hilton et al., 2000). The sample suite used in this study has been previously analyzed for He-Ne-Ar isotope compositions (Hilton et al., 2000; de Leeuw, 2007) and Pb-Sr-Nd-O isotopes and trace element chemistry (e.g., Murton et al., 2002; Thirlwall et al., 2004, 2006).

The detailed methods of measuring contents and isotope compositions of N (i.e., $\delta^{15}\text{N} = [^{15}\text{N}^{14}\text{N}/^{14}\text{N}^{14}\text{N}]_{\text{sample}}/([^{15}\text{N}^{14}\text{N}/^{14}\text{N}^{14}\text{N}]_{\text{air}} - 1) \times 1000$) and noble gases (He-Ne-Ar) were previously presented in

Bekaert et al. (2024a) and Kurz et al. (2009), respectively, and are briefly summarized in Supplementary Material Text S2.

3. Results

3.1. Nitrogen contents and isotope compositions

The nine Rochambeau Bank samples have N_2 contents and $\delta^{15}\text{N}$ values varying from $2.4 \times 10^{-6} \text{ cm}^3 \text{ STP/g}$ to $148.8 \times 10^{-6} \text{ cm}^3 \text{ STP/g}$, and $-0.1 \pm 0.3 \text{ ‰}$ to $+2.8 \pm 0.5 \text{ ‰}$, respectively (Table 1). The ten Reykjanes Ridge samples have N_2 contents and $\delta^{15}\text{N}$ values ranging from $8.4 \times 10^{-6} \text{ cm}^3 \text{ STP/g}$ to $442.1 \times 10^{-6} \text{ cm}^3 \text{ STP/g}$, and $-2.3 \pm 0.6 \text{ ‰}$ to $+0.1 \pm 0.7 \text{ ‰}$, respectively (Table 1). Samples 96D1G and 66D3G analyzed in this study have higher N_2 contents (222.8×10^{-6} and $308.2 \times 10^{-6} \text{ cm}^3 \text{ STP/g}$, respectively) than those reported by Barry et al., (2012) (7.5×10^{-6} and $41.9 \times 10^{-6} \text{ cm}^3 \text{ STP/g}$, respectively), likely due to significant entrainment of air-derived N_2 (see Section 4.1.1).

3.2. He-Ar-Ne contents and isotope compositions

All three of the Rochambeau Bank samples analyzed in this study have high $^3\text{He}/^4\text{He}$ ratios of 20.2 to 22.6 R_A . PPTU4-24-1 and PPTU4-24-3 both have air-like $^{20}\text{Ne}/^{22}\text{Ne}$ and $^{21}\text{Ne}/^{22}\text{Ne}$ ratios, unlike MGLN8-D8-3, which has elevated ratios of 10.51 ± 0.08 and 0.0318 ± 0.0006 , respectively (Table 1). PPTU4-24-1 and PPTU4-24-3 also have low $^{40}\text{Ar}/^{36}\text{Ar}$ ratios (299 to 308), while MGLN8-D8-3 has a higher

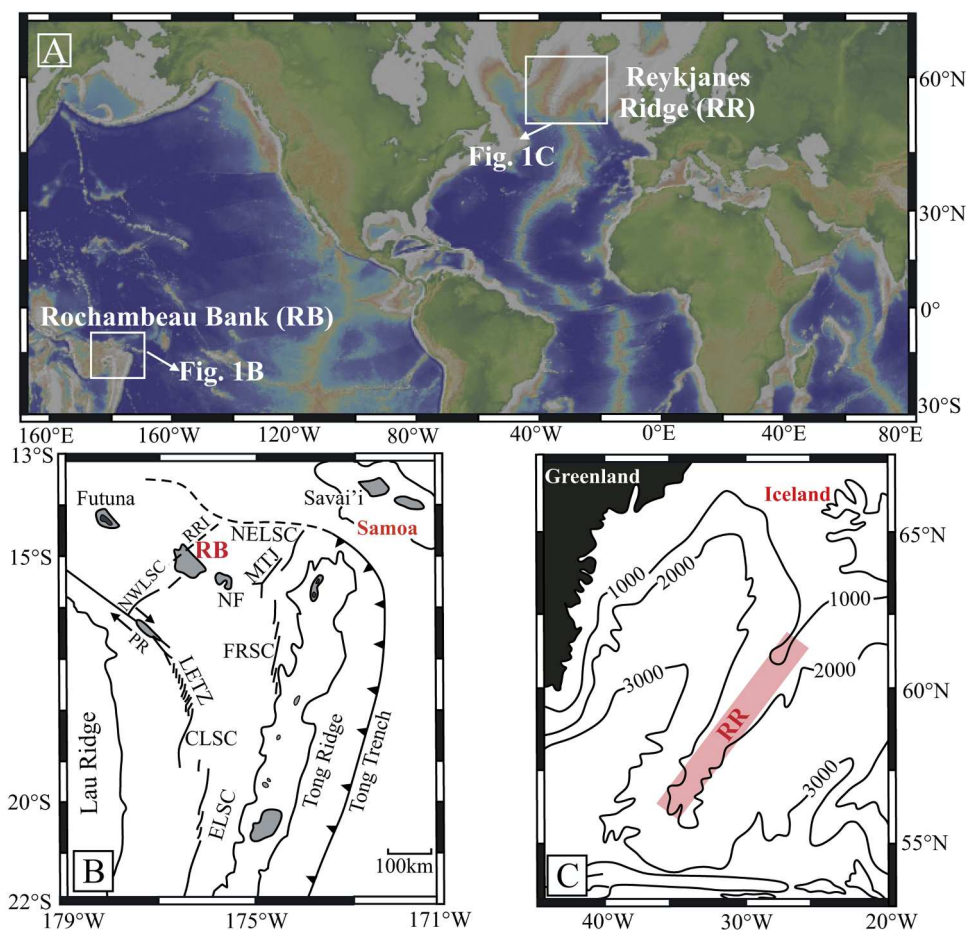


Fig. 1. (A) Locations (white squares) of Rochambeau Bank (RB) at Lau Basin and Reykjanes Ridge (RR) at the south of Iceland. (B) Schematic map of the Lau Basin (after Tian et al., 2011). Abbreviations: CLSC: central Lau spreading center; ELSC: eastern Lau spreading center; LETZ: Lau extensional transform zone; PR: Peggy ridge; RRI: Rochambeau rifts; NWLSC: northwestern Lau spreading center; FRSC: Fonualei rift and spreading center; MTJ: Mangatolu triple junction; NELSC: northeastern Lau spreading center; NF: Niuafu'ou; RB: Rochambeau Bank. (C) Location of the study area along the Reykjanes Ridge, showing isobaths every 1000 m (modified after Murton et al., 2002).

Table 1
Nitrogen and noble gas (He-Ne-Ar) isotope compositions of oceanic glasses from Rochambeau Bank and Reykjanes Ridge.

Sample ID	[N ₂] μ cm ³ STP/g	δ ¹⁵ N (‰) ^b	[⁴ He] μ cm ³ STP/g	³ He/ ⁴ He (× R _A)	[⁴⁰ Ar] n cm ³ STP/g ^e	⁴⁰ Ar/ ³⁶ Ar	[²⁰ Ne] n cm ³ STP/g ^f	²⁰ Ne/ ²² Ne	²¹ Ne/ ²² Ne	⁴ He/ ⁴⁰ Ar ^{*c}	(La/Sm) _N Ba/Nb	X ^d	N ₂ / ³ He ⁺	N ₂ / ⁴⁰ Ar [*]
Rochambeau Bank														
MGLN8-D11-8	14.2	+1.17±0.43	0.41	12.1 ± 0.1	629.0	302±6	1.72	9.74±0.03	0.0290±0.0002	30.4	0.178	753	1.5 × 10 ⁷	1048
MGLN8-D7-25	8.6	+1.08±0.80	0.02	15.3 ± 0.2	135.3	298±6	0.40	10.06±0.10	0.0291±0.0002	20.9	0.117	186	9.9 × 10 ⁷	7552
MGLN8-D9-9	8.8	+2.82±0.50	0.61	12.1 ± 0.1	275.8	541±11	0.30	10.23±0.21	0.0300±0.0002	4.9	0.038	6469	1.9 × 10 ⁶	70
MGLN8-D10-2	46.9	+1.26±0.33	4.59	10.0 ± 0.1	525.0	728±15	0.52	10.18±0.23	0.0304±0.0002	14.7	0.095	27,972	3.4 × 10 ⁶	150
MGLN8-D14-2	9.0	+2.54±0.53	3.41	7.5 ± 0.1	118.4	584±12	0.12	10.32±0.14	0.0314±0.0005	58.3	0.075	88,621	2.9 × 10 ⁶	154
MGLN8-D12-1	107.2	+1.25±0.35	0.04	16.0 ± 0.1	3141.0	294±6	5.45	9.74±0.16	0.0295±0.0007	n.d	0.045	21	n.d	n.d
MGLN8-D8-3 ^a	2.4	+1.41±0.90	1.09	22.3 ± 1.4	43.3	990±18	0.07	10.51±0.08	0.0318±0.0006	36.0	0.128	51,973	5.9 × 10 ⁵	79
PPTU4-24-1 ^a	26.3	-0.11±0.34	0.08	20.2 ± 1.2	187.5	308±2	0.93	9.83±0.07	0.0290±0.0005	13.9	0.212	280	5.2 × 10 ⁷	4423
PPTU4-24-3 × 1 [‡]	148.8	+1.45±0.29	0.001	22.6 ± 0.9	5.5	297±1	0.02	9.76±0.11	0.0293±0.0007	n.d	0.160	126		
PPTU4-24-3 × 20 [‡]			0.05	22.4 ± 0.9	596.9	299±1	1.28	9.55±0.04	0.0289±0.0004	n.d		123		
PPTU4-24-3 × 20 [‡]			0.03	22.4 ± 0.8	67.5	302±1	0.28	9.78±0.09	0.0291±0.0004	31.8		283		
PPTU4-24-3 [‡]			Average:	22.5 ± 0.5		299±1		9.70±0.13	0.0291±0.0003			177	n.d	n.d
Reykjanes Ridge														
185D4G	20.5	-1.85±0.88	0.03	15.4 ± 0.8	81.0	284±2	0.04	10.48±0.16	0.0279±0.0021	n.d	0.248	2513	n.d	n.d
160D4G	8.4	-1.85±0.88	0.08	16.4 ± 0.3	130.5	301±3	0.07	10.60±0.07	0.0307±0.0022	19.9	0.138	4090	2.5 × 10 ⁷	3228
157D3G ^e	41.6	-0.39±0.52	0.15	15.9 ± 0.3	99.6	292±1	0.08	10.28±0.10	0.0286±0.0026	n.d	0.147	6244	n.d	n.d
136D2G	66.8	-1.33±0.76	0.43	15.0 ± 0.3	133.6	373±2	0.06	10.37±0.14	0.0284±0.0045	3.7	0.056	22,451	1.4 × 10 ⁷	2383
131D3G ^e	11.8	-1.69±0.58	0.61	16.0 ± 0.3	112.7	509±7	0.04	10.44±0.12	0.0308±0.0030	9.1	0.048	43,366	2.9 × 10 ⁶	248
116D6G	373.6	-0.61±0.68	0.67	15.0 ± 0.3	195.7	723±17	0.03	10.41±0.24	0.0316±0.0032	6.4	0.070	71,915	7.1 × 10 ⁷	3220
96D1G	222.8	-0.27±0.72	1.92	15.5 ± 0.3	586.5	468±3	1.36	9.63±0.11	0.0290±0.0004	4.1	0.073	4429	1.1 × 10 ⁷	1025
80D1G	214.4	+0.14±0.66	0.33	15.6 ± 0.3	40.2	547±14	0.15	10.28±0.10	0.0296±0.0015	10.1	0.101	6919	1.1 × 10 ⁸	11,549
75D10G ^e	17.0	-1.57±0.40	2.77	14.4 ± 0.2	122.7	582±7	0.02	10.74±0.15	0.0357±0.0039	8.0	0.076	482,349	9.5 × 10 ⁵	280
66D3G	308.2	-0.56±0.53	3.89	12.7 ± 0.2	1648.4	550±4	0.95	9.83±0.11	0.0298±0.0005	4.0	0.070	12,907	8.7 × 10 ⁶	402
50D3G	186.3	-2.33±0.56	1.29	13.9 ± 0.2	355.3	627±9	0.12	10.49±0.15	0.0343±0.0015	8.7	0.073	33,507	2.4 × 10 ⁷	988
46D5G ^e	31.5	-0.39±0.32	2.70	11.6 ± 0.2	1188.0	706±6	0.77	9.92±0.09	0.0299±0.0004	2.7	0.077	11,078	1.1 × 10 ⁶	45
40D3G ^e	61.0	-0.44±0.60	4.90	11.5 ± 0.2	2794.9	804±9	1.26	9.96±0.12	0.0302±0.0004	2.1	0.050	12,206	9.7 × 10 ⁵	34
33aD1G	342.6	-0.49±0.64	3.94	11.0 ± 0.2	1193.9	1339±36	0.27	10.17±0.11	0.0300±0.0007	2.2	0.070	45,787	7.4 × 10 ⁶	368
17D1G	442.1	-1.46±0.62	2.50	17.6 ± 0.3	714.2	1030±18	0.45	10.60±0.05	0.0309±0.0011	1.4	0.058	17,321	6.9 × 10 ⁶	866

^a Only MGLN8-D8-3, PPTU4-24-1 and PPTU4-24-3 were analyzed for their noble gas abundances and isotope compositions (i.e., He, Ne and Ar) in this study. The noble gas data of the other Rochambeau Bank and Reykjanes Ridge samples are from [Hahm et al. \(2012\)](#) (He-Ne-Ar data of Rochambeau Bank samples), [Hilton et al. \(2000\)](#) (He data of Reykjanes Ridge samples) and [de Leeuw. \(2007\)](#) (Ar-Ne data of Reykjanes Ridge samples).

^b The analytical uncertainties of δ¹⁵N values are given in 1σ.

^c ⁴He/⁴⁰Ar* of MGLN8-D8-3, PPTU4-24-1 and PPTU4-24-3 were calculated based on data from this study. ⁴He/⁴⁰Ar* of the other Rochambeau Bank and Reykjanes Ridge samples were from [Hahm et al. \(2012\)](#) and [de Leeuw. \(2007\)](#), respectively.

^d X = (⁴He/²⁰Ne)_{sample}/(⁴He/²⁰Ne)_{air}.

^e The N₂ contents and δ¹⁵N values of these Reykjanes Ridge samples are from [Barry et al. \(2012\)](#).

⁺ Corrected N₂/³He (Supplementary Material Text S3). 'n.d' indicates N₂/⁴⁰Ar* and corrected N₂/³He values are not determined due to the air-like ⁴⁰Ar/³⁶Ar ratios.

[‡] Sample PPTU4-24-1 was measured three times following 1 stroke, 20 strokes and 20 strokes again. The three measurements give air-like ²⁰Ne/²²Ne and ²¹Ne/²²Ne ratios and consistent ³He/⁴He ratios. Average ²⁰Ne/²²Ne ²¹Ne/²²Ne and ³He/⁴He ratios were used in the discussion.

$^{40}\text{Ar}/^{36}\text{Ar}$ ratio of 990, consistent with the observation of non-atmospheric $^{20}\text{Ne}/^{22}\text{Ne}$ (10.16 ± 0.16) and $^{40}\text{Ar}/^{36}\text{Ar}$ (526 ± 182) for MGLN8-D8-3 by Hahm et al. (2012). The noble gas contents of these three samples are presented in Table 1.

We combined N contents and noble gas data from this study with previously published data on the different sets of the same samples (Hilton et al., 2000; de Leeuw, 2007; Barry et al., 2012; Hahm et al., 2012) to calculate $\text{N}_2/^{3}\text{He}$ and $\text{N}_2/^{40}\text{Ar}^*$ ratios (where $^{40}\text{Ar}^*$ is the radiogenic ^{40}Ar ; calculated following equation 5 in Graham, 2002). All $\text{N}_2/^{3}\text{He}$ data discussed below have been corrected for degassing-induced fractionation between N_2 and ^3He , using a $^4\text{He}/^{40}\text{Ar}^*$ mantle production ratio of 1.5 (see Supplementary Material Text S3 for method). Overall, $\text{N}_2/^{3}\text{He}$ values range from 5.9×10^5 to 9.9×10^7 and $\text{N}_2/^{40}\text{Ar}^*$ values from 70 to 4423 for Rochambeau Bank samples. $\text{N}_2/^{3}\text{He}$ values range from 9.8×10^5 to 7.1×10^7 and $\text{N}_2/^{40}\text{Ar}^*$ values from 34 to 11,549 for Reykjanes Ridge Samples.

4. Discussions

4.1. Integrity of data

Since air contamination, magmatic degassing, and shallow-level crustal contamination can fractionate or modify the original $\delta^{15}\text{N}$ values of the mantle source (e.g., Barry and Hilton, 2016; Halldórsson et al., 2016), we thus firstly evaluate each of these processes in the following sections.

4.1.1. Air contamination

For the 9 Rochambeau Bank and 15 Reykjanes Ridge samples (Table 1), those with air-like $^{40}\text{Ar}/^{36}\text{Ar}$ and/or air-like $^{20}\text{Ne}/^{22}\text{Ne}$ are excluded from further discussion of their N characteristics due to extensive contamination by present-day air. ‘Air-like’ means that the reported isotope values (i.e., $^{40}\text{Ar}/^{36}\text{Ar}$ and $^{20}\text{Ne}/^{22}\text{Ne}$) are within 1σ of air (air $^{40}\text{Ar}/^{36}\text{Ar} = 298.6$; $^{20}\text{Ne}/^{22}\text{Ne} = 9.8$). Using this approach, five Rochambeau Bank samples (i.e., MGLN8-D11-8, MGLN8-D12-1, MGLN8-D7-25, PPTU4-24-1, and PPTU4-24-3) and five Reykjanes Ridge samples (i.e., 185D4G, 157D3G, 160D4G, 96D1G and 66D3G) were filtered out (Fig. 2A–2C) (see discussions in Supplementary Material Text S4-1). After filtering samples based on Ar-Ne isotope systematics, five out of nine Reykjanes Ridge samples still exhibit air-like $\delta^{15}\text{N}$ values of $\sim 0\text{‰}$ (i.e., 116D6G, 80D1G, 46D5G, 40D3G, 33D1G) (Fig. 2). These samples were not excluded because their $\delta^{15}\text{N}$ values of $\sim 0\text{‰}$ could be a fortuitous mixture of ^{15}N enriched and depleted sources (Sections 4.2 and 4.3).

The samples were further filtered based on $^{40}\text{Ar}/^{36}\text{Ar}$ and $\text{N}_2/^{3}\text{He}$ ratios. Since ^3He is not recycled, the elevated $\text{N}_2/^{3}\text{He}$ of basaltic glasses can be used as an index to infer the recycling of surficial N into the plume mantle sources (e.g., Halldórsson et al., 2016; Labidi, 2022; discussions in Sections 4.2 and 4.3 of this study). However, $\text{N}_2/^{3}\text{He}$ ratios could be easily contaminated by an air component with high $\text{N}_2/^{3}\text{He}$ of $\sim 10^{11}$ relative to mantle (e.g., DMM; $\text{N}_2/^{3}\text{He} = 3.7 \pm 1.2 \times 10^6$) (Labidi, 2022). Labidi (2022) showed that MORB samples with $^{40}\text{Ar}/^{36}\text{Ar}$ ratios >500 could largely retain the $\text{N}_2/^{3}\text{He}$ of the uncontaminated DMM endmember without significant contribution from air component (Fig. 2D). Similarly, in Fig. 2D, three Reykjanes Ridge (i.e., 160D4G, 136D2G and 96D1G) and three Rochambeau Bank samples (i.e., MGLN8-D7-25, MGLN8-D11-8 and PPTU4-24-1) with $^{40}\text{Ar}/^{36}\text{Ar} <500$ fall on the vertical section of the mixing curves between mantle source and air component, showing that their $\text{N}_2/^{3}\text{He}$ ratios could be significantly elevated by air contamination. Since most samples with $^{40}\text{Ar}/^{36}\text{Ar} <500$ show air-like $^{40}\text{Ar}/^{36}\text{Ar}$ and/or air-like $^{20}\text{Ne}/^{22}\text{Ne}$ and have already been excluded (Fig. 2A–2C), only sample 136D2G ($^{40}\text{Ar}/^{36}\text{Ar} = 373$) from Reykjanes Ridge was excluded based on $^{40}\text{Ar}/^{36}\text{Ar}$ grounds. Notably, the Iceland data from Halldórsson et al. (2016) are combined with Reykjanes Ridge data in Section 4.3.1 for discussion of N signatures in the Icelandic plume. Some of these Iceland samples also show

significant elevation of $\text{N}_2/^{3}\text{He}$ with $^{40}\text{Ar}/^{36}\text{Ar} <500$ (in the range of 303 to 419; Fig. 2D). This could be a result of air contamination or deep recycling of atmosphere-derived Ar and N to the plume mantle source, as proposed by Halldórsson et al. (2016) (see discussions in Section 4.3.1).

Overall, four Rochambeau Bank samples (i.e., MGLN8-D9-9, -D10-2, -D14-2, -D8-3) and nine Reykjanes Ridge samples (i.e., 131D3G, 116D6G, 80D1G, 75D10G, 50D3G, 46D5G, 40D3G, 33aD1G, and 17D1G) (Table 1) are included in the discussion of the intrinsic N isotope compositions of Reykjanes Ridge and Rochambeau Bank mantle sources (Sections 4.2 and 4.3). These samples, together with Iceland samples with $^{40}\text{Ar}/^{36}\text{Ar} >500$, clearly suggest that their mantle sources have variable $\text{N}_2/^{3}\text{He}$ ($\sim 2 \times 10^5$ to $\sim 1 \times 10^8$), encompassing and extending beyond the DMM value ($3.7 \pm 1.2 \times 10^6$) (Fig. 2D), potentially indicating contributions of N from different sources (see discussion in Section 4.3.1). They are also characterized by $(^4\text{He}/^{20}\text{Ne})_{\text{sample}}/(^4\text{He}/^{20}\text{Ne})_{\text{air}}$ over 3 orders of magnitude higher than air (Fig. S4; Table 1), suggesting only minor modification of $\delta^{15}\text{N}$ values of these samples by air contamination (Barry and Hilton, 2016).

4.1.2. Magmatic degassing

Magmatic degassing may also affect isotope ratios through mass-dependent N isotope fractionation, where ^{14}N could be preferentially exsolved from a basaltic melt versus ^{15}N , therefore leading to a progressive enrichment of ^{15}N in the residual melt (Cartigny et al., 2001). As degassing proceeds, the $^4\text{He}/^{40}\text{Ar}^*$ ratio of the residual melt increases because of the roughly ten-fold lower solubility of Ar than He in basaltic magmas (Jambon et al., 1986). As such, a positive correlation between $^4\text{He}/^{40}\text{Ar}^*$ and $\delta^{15}\text{N}$ can be used to assess the effect of magmatic degassing on $\delta^{15}\text{N}$ (e.g., Barry and Hilton, 2016).

For the Rochambeau Bank samples, comparable $\delta^{15}\text{N}$ values (i.e., $+2.8\text{‰}$ vs. $+2.5\text{‰}$) for two samples (MGLN8-D9-9 and MGLN8-D14-2, respectively) with markedly different $^4\text{He}/^{40}\text{Ar}^*$ (i.e., 4.9 vs. 58.3, respectively) suggests that the effect of magmatic degassing on the intrinsic $\delta^{15}\text{N}$ values is minimal (Fig. 3A). For the Reykjanes Ridge samples, an early study by Hilton et al. (2000) showed progressive degassing of He with the decrease of eruption depths from ~ 2000 m at the southern Reykjanes Ridge to <1000 m at the northern Reykjanes Ridge. The broad northward increase in $^4\text{He}/^{40}\text{Ar}^*$ (Fig. 3B) and decrease in N_2 concentrations (Fig. 3C) is consistent with progressive degassing from south to north. When $^4\text{He}/^{40}\text{Ar}^*$ values are plotted against N_2 concentrations (Fig. 3D), a broad negative correlation ($R^2=0.3$) between N_2 concentrations and $^4\text{He}/^{40}\text{Ar}^*$ is observed. This trend is also observed in the plot between eruption depths and N_2 concentrations, whereby low N_2 concentrations are generally associated with shallow eruption depths (Fig. 3E). However, the lack of correlation between $\delta^{15}\text{N}$ and $^4\text{He}/^{40}\text{Ar}^*$ values (Fig. 3A), and between $\delta^{15}\text{N}$ values and latitude (Fig. 3F), suggest degassing did not significantly affect the intrinsic $\delta^{15}\text{N}$ values of the Reykjanes Ridge mantle source.

4.1.3. Crustal contamination

The lack of correlations between N characteristics (N_2 concentrations and $\delta^{15}\text{N}$ values) and $\text{N}_2/^{40}\text{Ar}^*$ and $\text{Cl}/\text{K}_2\text{O}$ ratios, which were employed by early studies as indexes to test the effect of shallow-level crustal contamination (i.e., seawater, altered oceanic crust and brines; Hahm et al., 2012; Barry and Hilton, 2016; Halldórsson et al., 2016), indicate no modification of the intrinsic $\delta^{15}\text{N}$ value of mantle by potential crustal contamination (see discussions in Supplementary Material S3-2 and S5).

4.2. Enrichment of ^{15}N in Rochambeau Bank and Reykjanes Ridge mantle sources

The $\delta^{15}\text{N}$ values of the Rochambeau Bank ($+1.3\text{‰}$ to $+2.8\text{‰}$) and Reykjanes Ridge (-2.3‰ to $+0.1\text{‰}$) samples are higher than the global DMM range ($-5 \pm 2\text{‰}$; e.g., Javoy et al., 1986; Marty and Zimmermann, 1999; Marty and Dauphas, 2003; Bekaert et al., 2024a). In this section, we combine trace elements with N-He-Ar elemental and isotopic

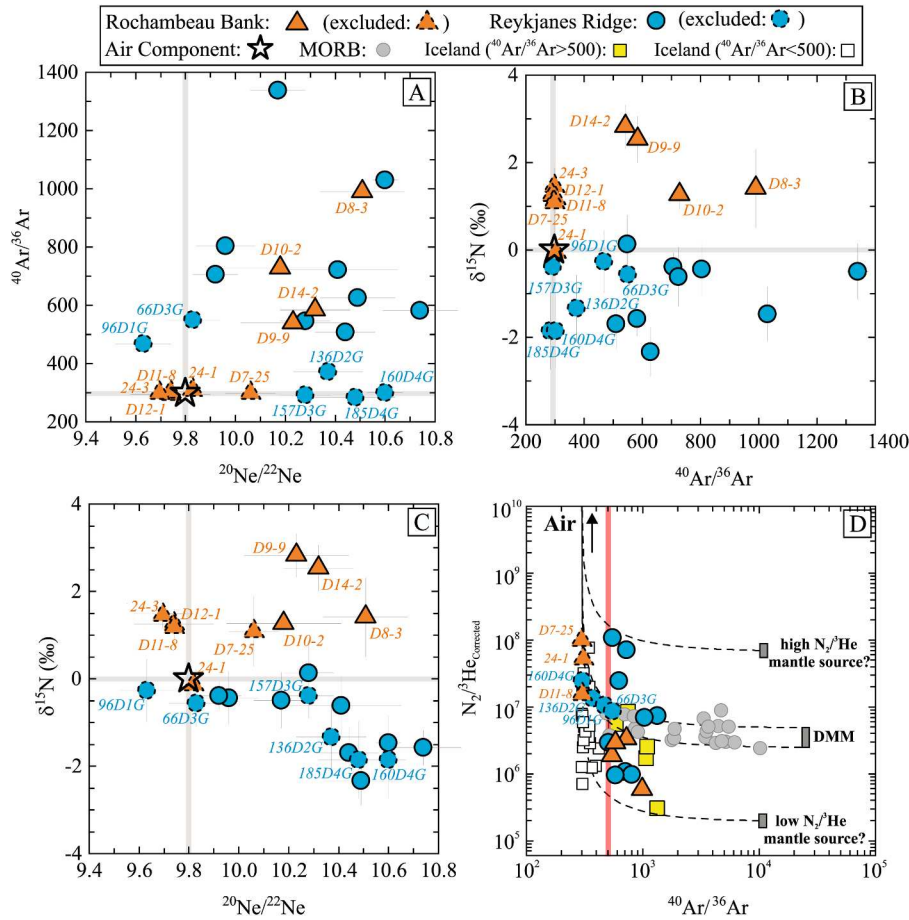


Fig. 2. Relationships between $^{20}\text{Ne}/^{22}\text{Ne}$ and $^{40}\text{Ar}/^{36}\text{Ar}$ ratios (A), $\delta^{15}\text{N}$ values and $^{40}\text{Ar}/^{36}\text{Ar}$ ratios (B), $^{20}\text{Ne}/^{22}\text{Ne}$ and $\delta^{15}\text{N}$ values (C), and $^{40}\text{Ar}/^{36}\text{Ar}$ and $\text{N}_2/{}^3\text{He}$ ratios (corrected for degassing-induced fractionation; see main text for details) (D). The dashed curves in Fig. 2D represent the mixing between an air component ($^{40}\text{Ar}/^{36}\text{Ar} = 298.6$ and $\text{N}_2/{}^3\text{He} = 10^{11}$) and mantle endmembers with variable $\text{N}_2/{}^3\text{He}$ ratios from $\sim 2 \times 10^5$ to $\sim 1 \times 10^8$. Mixing between a DMM endmember ($^{40}\text{Ar}/^{36}\text{Ar} = 25,000$ and $\text{N}_2/{}^3\text{He} = 3.7 \pm 1.2 \times 10^6$) and air explains the majority of MORB data (Labidi, 2022). Assuming a typical $^{40}\text{Ar}/^{36}\text{Ar}$ ratio of $\sim 10,000$ for plume-influenced mantle sources, most of the Reykjanes Ridge and Rochambeau Bank samples with $^{40}\text{Ar}/^{36}\text{Ar} > 500$ fall along the horizontal mixing trend between air and mantle endmembers, suggesting minimal effect of air contamination on their $\text{N}_2/{}^3\text{He}$. The vertical red line marks the $^{40}\text{Ar}/^{36}\text{Ar}$ of 500. The dashed blue-filled circles and dashed orange-filled triangles represent samples excluded due to air contamination. The Iceland data are from Halldórsson et al., (2016).

systematics to assess the source(s) of ^{15}N enrichment in the Rochambeau Bank and Reykjanes Ridge mantle sources.

4.2.1. Contribution of ^{15}N enrichment in Rochambeau Bank mantle source from Tonga subducting slab and Samoan plume

Ba/Nb and $(\text{La}/\text{Sm})_{\text{N}}$ ratios in Rochambeau Bank lavas can be used to identify 1) subduction components from the adjacent Tonga subducting slab, which devolatilized at shallow depths beneath the Lau backarc basin, and 2) Samoan plume mantle components from the Samoan plume (e.g., Tian et al., 2011). Barium is a highly fluid mobile element that – unlike HFSEs (e.g., Nb, REEs) – readily partitions into dehydration fluids from subducting slabs. The dehydration of fluids from a subducting slab is therefore expected to produce high Ba/Nb ratios. On the other hand, plume components typically show enrichment of LREEs (e.g., high $(\text{La}/\text{Sm})_{\text{N}}$; Hofmann and White, 1982).

Rochambeau Bank sample MGLN8-D9-9 shows elevated Ba/Nb ($=16.9$) and is depleted in $(\text{La}/\text{Sm})_{\text{N}}$ ($=0.6$) pointing to a major contribution from subduction-related fluids (Fig. 4A). This is consistent with the geochemistry of Tonga arc magmas, where high Ba/Nb were observed (Fig. 4A; Turner et al., 1997). However, the influence of plume components in Rochambeau Bank samples is also observed, especially sample MGLN8-D11-8 with a higher $(\text{La}/\text{Sm})_{\text{N}}$ ($=1.9$; Fig. 4A), although the slightly higher Ba/Nb ($=10.5$) of this sample may also suggest the influence of subduction components. Because $(\text{La}/\text{Sm})_{\text{N}}$ and Ba/Nb

ratios can be respectively used as indexes for the influence of plume and subduction components, we employ the $(\text{La}/\text{Sm})_{\text{N}}/(\text{Ba}/\text{Nb})$ ratio (Table 1) as an index to infer the relative contribution from plume and subduction components in Rochambeau Bank samples. This means that a higher $(\text{La}/\text{Sm})_{\text{N}}/(\text{Ba}/\text{Nb})$ ratio corresponds to a greater contribution from plume components.

Importantly, a negative correlation between $\delta^{15}\text{N}$ values and $(\text{La}/\text{Sm})_{\text{N}}/(\text{Ba}/\text{Nb})$ is observed for the four Rochambeau Bank samples (Fig. 4B). In particular, the lowest $(\text{La}/\text{Sm})_{\text{N}}/(\text{Ba}/\text{Nb})$ ($=0.038$) of sample MGLN8-D9-9 indicates a significant contribution from subduction components, suggesting that this sample ($\delta^{15}\text{N} = \sim +3\text{‰}$) may best represent the value of the subduction components. This value is compatible with the $\delta^{15}\text{N}$ value of subducting seafloor sediments and altered oceanic crust with $\delta^{15}\text{N}$ values both varying from $\sim -1\text{‰}$ to $\sim +10\text{‰}$ (Li et al., 2023). Among all Rochambeau Bank samples, sample PPTU4-24-1 has the highest $(\text{La}/\text{Sm})_{\text{N}}/(\text{Ba}/\text{Nb})$ ratio of 0.21 (Fig. 4A), suggesting that this sample may best represent the $\delta^{15}\text{N}$ value of the plume endmember. Although PPTU4-24-1 ($\delta^{15}\text{N} = -0.1 \pm 0.3\text{‰}$) was excluded due to air contamination, based on its low $^{40}\text{Ar}/^{36}\text{Ar}$ ratio ($= 308 \pm 2$; Table 1 and Section 4.1), a linear extrapolation based on the relationship of $(\text{La}/\text{Sm})_{\text{N}}/(\text{Ba}/\text{Nb})$ versus $\delta^{15}\text{N}$ determined for the four Rochambeau Bank samples in Fig. 4B yields $\delta^{15}\text{N}$ of $0 \pm 1\text{‰}$ for this sample. This extrapolation suggests that the deep plume components influencing the Rochambeau Bank mantle source are also likely to be

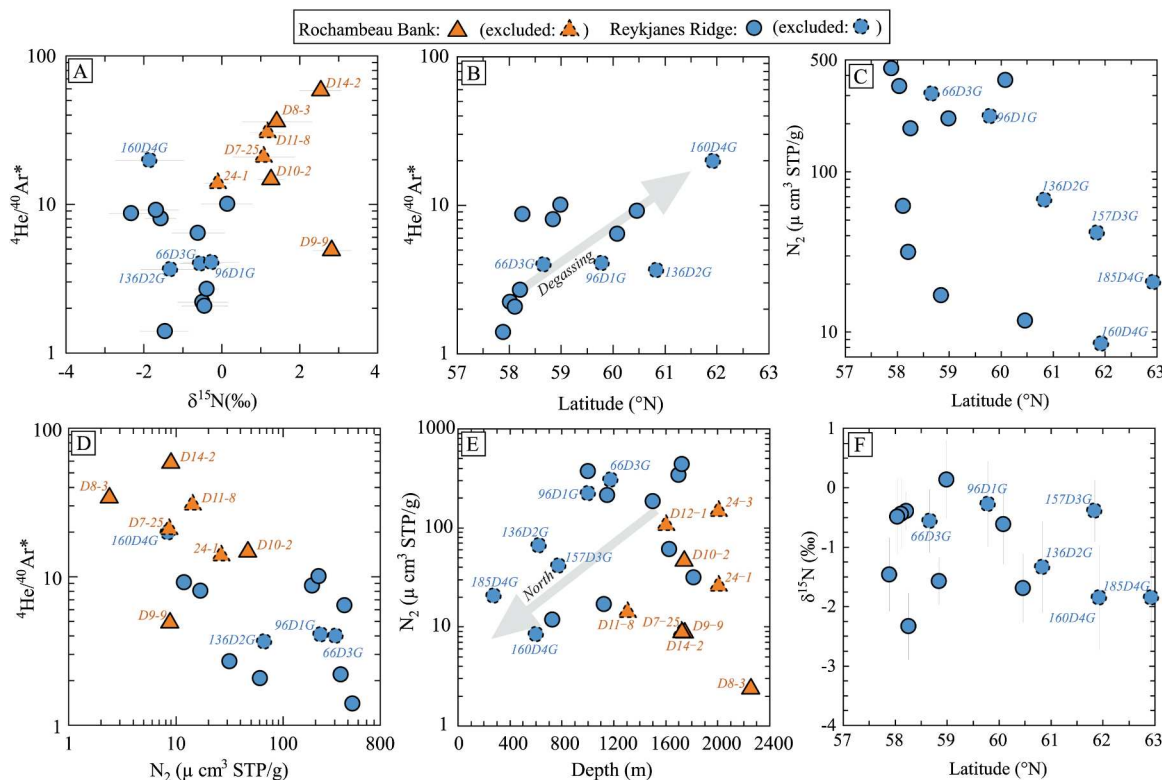


Fig. 3. (A) The relationship between $^4\text{He}/^{40}\text{Ar}^*$ ratios and $\delta^{15}\text{N}$ values of Reykjanes Ridge and Rochambeau Bank glass samples. (B) and (C) The relationship between latitude and $^4\text{He}/^{40}\text{Ar}^*$ ratios, and latitude and N_2 concentrations of Reykjanes Ridge samples. Note the progressive increase of $^4\text{He}/^{40}\text{Ar}^*$ ratios and broad decrease of N_2 concentrations from south to north. (D) The relationship between N_2 concentrations and $^4\text{He}/^{40}\text{Ar}^*$ ratios of Reykjanes Ridge and Rochambeau Bank samples. Note the broad negative correlation between N_2 concentrations and $^4\text{He}/^{40}\text{Ar}^*$ ratios for Reykjanes Ridge samples. (E) The relationship between eruption depth and N_2 concentrations of Reykjanes Ridge and Rochambeau Bank samples. (F) The relationship between latitude and $\delta^{15}\text{N}$ values of Reykjanes Ridge samples. The dashed blue-filled circles and dashed orange-filled triangles represent samples excluded due to air contamination.

enriched in heavy ^{15}N (~ 0 ‰) relative to the DMM. Overall, the array of $\delta^{15}\text{N}$ and $(\text{La}/\text{Sm})_{\text{N}}/(\text{Ba}/\text{Nb})$ observed for Rochambeau Bank samples is consistent with mixing between N derived from both subduction and plume components associated with different $\delta^{15}\text{N}$ values in the Rochambeau Bank backarc mantle source.

4.2.2. Icelandic mantle plume ^{15}N enrichment in the Reykjanes Ridge mantle source

In contrast to Rochambeau Bank samples, Reykjanes Ridge samples display no correlation between $(\text{La}/\text{Sm})_{\text{N}}/(\text{Ba}/\text{Nb})$ and $\delta^{15}\text{N}$ (Figs. 4B). High precision Pb-Sr-Nd isotope data from Reykjanes Ridge lavas (the same samples employed in this study) have previously been used to infer the presence of multiple mantle components in the Reykjanes Ridge mantle source (see Supplementary Material Text S1-2 and Fig. S2 for a summary of previous studies; e.g., Thirlwall et al., 2004). One of the intriguing features of these mantle components is that they are characterized by negative $\Delta^{207}\text{Pb}$ and elevated $\Delta^{208}\text{Pb}$ relative to MORB (percentage deviations of $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ from the Northern Hemisphere Reference Lines; Hart, 1984) (Thirlwall et al., 2004). This is also observed in many Icelandic lavas from the Icelandic plume mantle (Thirlwall et al., 2004). Additionally, the low $\delta^{18}\text{O}$ values of olivine (as low as $+4.2$ ‰; Kokfelt et al., 2006; Thirlwall et al., 2006; Rasmussen et al., 2022) compared to the typical mantle range of $+5.1 \pm 0.3$ ‰ (Eiler, 2001) and the elevated $^3\text{He}/^4\text{He}$ relative to the DMM (11 to ~ 18 R_A along the Reykjanes Ridge and 5 to 47.5 R_A in Iceland; e.g., Hilton et al., 2000; Harðardóttir et al., 2022) were both identified in Icelandic and Reykjanes Ridge lavas. These features consistently indicate that melts from 50°N to 70°N are predominantly derived from the Icelandic plume source that has incorporated relatively young (e.g., Phanerozoic) recycled oceanic crust (e.g., Thirlwall et al., 2004) and

primordial ^3He from a deep less-degassed mantle (e.g., Jackson et al., 2020). Accordingly, while no correlations were observed between $\delta^{15}\text{N}$ values and $^{206}\text{Pb}/^{204}\text{Pb}$, $^{87}\text{Sr}/^{86}\text{Sr}$, or $^{143}\text{Nd}/^{144}\text{Nd}$ ratios of the nine Reykjanes Ridge samples (Fig. S3 and Supplementary Material Text S1-2), the heavier-than-DMM $\delta^{15}\text{N}$ of these Reykjanes Ridge samples suggest that the enrichment of ^{15}N is sourced from the Icelandic plume, consistent with a ^{15}N -enriched signature previously inferred for the Icelandic plume mantle from Icelandic lavas (Halldórsson et al., 2016).

4.3. Constraining possible N compositions in Icelandic and Samoan plume mantle sources

Variable enrichments of ^{15}N in mantle sources could result from the presence of primordial N (Labidi et al., 2020; Labidi, 2022; Bekaert et al., 2024b; Broadley et al., 2025) or the existence of recycled N from ancient subducted slabs (e.g., Dauphas and Marty, 1999; Halldórsson et al., 2016; Labidi, 2022).

4.3.1. Presence of recycled N in the Icelandic plume mantle source

In this study, the Reykjanes Ridge samples show a large spread in $\text{N}_2/^3\text{He}$ ratios, from 9.5×10^5 to 1.1×10^8 (Fig. 5A). Importantly, most Reykjanes Ridge samples are consistent with mixing between DMM and an endmember with recycled N marked by high $\text{N}_2/^3\text{He}$ ($\sim 10^9$) and positive $\delta^{15}\text{N}$ of ~ 0 to $+6$ ‰ (Fig. 5A). Similarly, in the plot of $\text{N}_2/^{40}\text{Ar}^*$ against $\delta^{15}\text{N}$ values, most Reykjanes Ridge data are also consistent with binary mixing between the DMM and a recycled N endmember with positive $\delta^{15}\text{N}$ of ~ 0 to $+6$ ‰ and high $\text{N}_2/^{40}\text{Ar}^*$ ($\sim 5 \times 10^6$) (Fig. 5B). The high $\text{N}_2/^{40}\text{Ar}^*$ of the recycled N endmember is consistent with young (e.g., Phanerozoic) subducted material (Halldórsson et al., 2016). Notably, some Iceland data from Halldórsson et al. (2016) also fit the

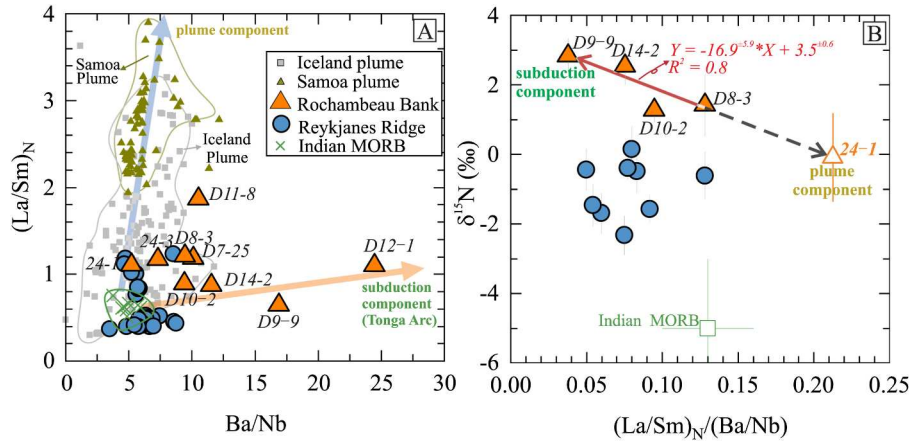


Fig. 4. (A) The relationship between Ba/Nb and (La/Sm)_N ratios of all Reykjanes Ridge and Rochambeau Bank samples. Reykjanes Ridge data is from Murton et al. (2002) and Rochambeau Bank data is from Tian et al. (2011). The trace element compositions of Iceland plume (Kempton et al., 2000), Samoa plume (Workman et al., 2004) and the Indian MORB (Rehkämper and Hofmann, 1997) are also shown in the diagram. The orange arrow points to the subduction components with high Ba/Nb ratios, consistent with the Tonga arc magma geochemistry (Tian et al., 2011). Note that the trace element compositions of all Reykjanes Ridge and Rochambeau Bank samples are plotted in panel A. (B) Relationship between (La/Sm)_N/(Ba/Nb) ratios and δ¹⁵N values of Reykjanes Ridge and Rochambeau Bank samples that are identified to have limited air contamination. A negative correlation (equations are shown in the diagram) is observed for four Rochambeau Bank samples that are identified to be mostly unaffected by air contamination. The δ¹⁵N value of PPTU4-24-1 is extrapolated to be 0 ± 1 ‰ (empty orange triangle) based on the negative correlation observed for the four Rochambeau Bank samples. The Indian MORB composition with (La/Sm)_N/(Ba/Nb) ratio of 0.13 ± 0.03 (Rehkämper and Hofmann, 1997) and an assumed δ¹⁵N value of -5 ± 2 ‰ is also shown in the diagram.

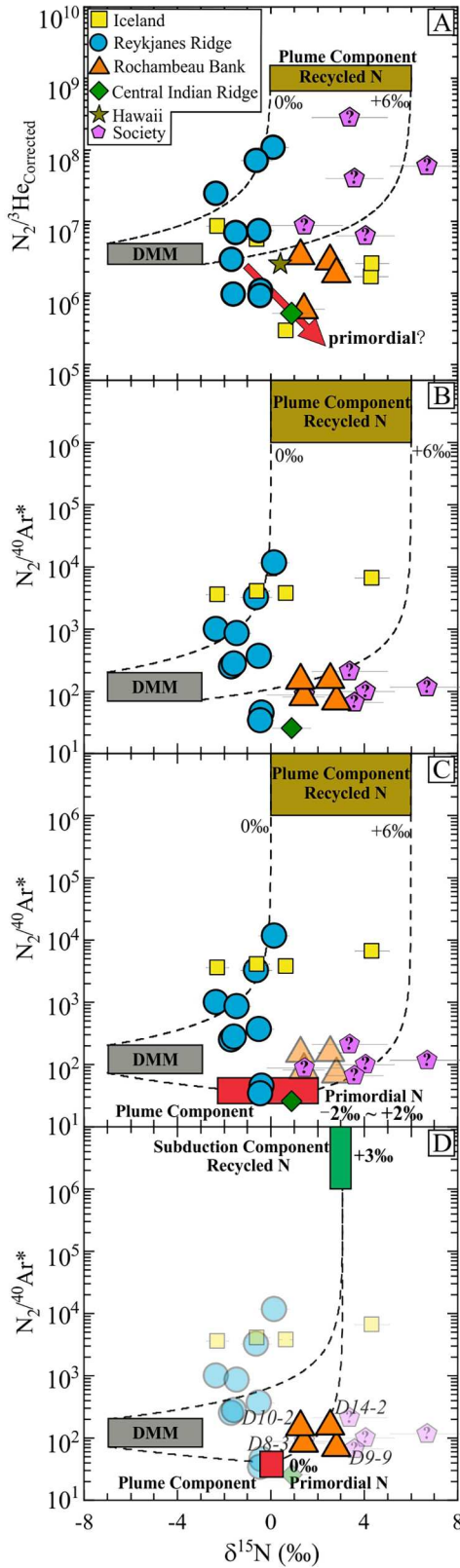
Reykjanes Ridge binary mixing model (Fig. 5A and 5B), including those with low ⁴⁰Ar/³⁶Ar < 500 (Fig. S6A and S6B in Supplementary Material). This may further indicate that the samples with low ⁴⁰Ar/³⁶Ar, elevated N₂/³He, and elevated N₂/⁴⁰Ar* could be an intrinsic signature of the Icelandic plume, and plumes more broadly, as a result of deep recycling of atmospheric components (Halldórsson et al., 2016). Nevertheless, the high N₂/⁴⁰Ar* observed in both Reykjanes Ridge and Iceland lavas, combined with the Pb-Sr-Nd-O isotope systematics from previously published studies (Section 4.2.2; Thirlwall et al., 2004, 2006), suggest the entrainment of young recycled oceanic crust in the Icelandic plume mantle. This supports a scenario of the Icelandic plume being enriched in ¹⁵N because of deep subduction of surficial N.

4.3.2. Presence of primordial N in Samoan and Icelandic plume mantle source

Not all samples can be explained by the addition of a high N₂/³He-high δ¹⁵N recycled component (Fig. 5A). Instead, some samples from Reykjanes Ridge, Iceland and all the Rochambeau Bank samples require contribution from a source with lower N₂/³He and higher δ¹⁵N compared to the DMM, which we suggest reflects a primordial component (Fig. 5A). In the plot of ³He/⁴He versus N₂/³He, Rochambeau Bank data show a negative correlation (R²=0.9) and trend toward an end-member with high ³He/⁴He and low N₂/³He (Fig. 6A). A broad negative correlation (R²=0.3) between ³He/⁴He and N₂/³He also exists for the Iceland data. Using N₂/³⁶Ar and ³He/³⁶Ar elemental ratios assumed for the Iceland plume, Labidi (2022) estimated the primordial N₂/³He to be between 7 × 10⁵ and 3.5 × 10⁶. As demonstrated in Fig. 2D, Reykjanes Ridge, Iceland, and Rochambeau Bank data require mantle sources with N₂/³He as low as ~2 × 10⁵, which is lower than - but within an order or magnitude of - the lower bound estimated by Labidi (2022). This end-member with a low N₂/³He (~2 × 10⁵) but higher δ¹⁵N and ³He/⁴He than the DMM (Figs. 6A) could correspond to a primordial N component from an undegassed (or less-degassed) mantle reservoir in the plume source. Binary mixing between an endmember with recycled N and an ultra-depleted DMM-like endmember with extremely low N₂/³He of ~1 × 10⁵, as proposed by Halldórsson et al. (2016), could also explain the data from Reykjanes Ridge, Iceland and Rochambeau Bank. This is, however, inconsistent with the negative trend between ³He/⁴He versus N₂/³He observed for Rochambeau Bank samples, which requires an endmember with low N₂/³He but higher than DMM ³He/⁴He (Fig. 6A).

As demonstrated in Section 4.2.1, the Rochambeau Bank mantle source contains subduction components from the adjacent Tonga subducting slab and plume components from the Samoan plume, with δ¹⁵N of ~+3 ‰ and ~0 ‰, respectively (Fig. 4B). We suggest that the δ¹⁵N and N₂/³He (Fig. 6B) of Rochambeau Bank can be readily explained by ternary mixing among DMM, a plume component with primordial N (δ¹⁵N = ~0 ‰; N₂/³He = 2 × 10⁵), and a subduction component with recycled N (δ¹⁵N = ~+3 ‰; N₂/³He = ~10⁹). This ternary mixing model also explains Rochambeau Bank data in δ¹⁵N versus ³He/⁴He space (Fig. 7A). In this case, the plume mantle component from the Samoan hotspot shows an enrichment of ¹⁵N relative to the DMM, which is likely inherited from a primordial N component. In both Figs. 6B and 7A, Rochambeau Bank data mostly fall along a mixing trend between subduction and plume components, without requiring any significant contribution from the DMM. For example, in Fig. 6B, the highest DMM contribution is found for sample MGLN8-10-2 (13 %), contrasting with the other three samples that have DMM contributions of <3 % (Supplementary Material Text S5 and Table A1). This is consistent with the correlation observed in Fig. 4B, where DMM falls off the negative trend observed in δ¹⁵N versus (La/Sm)_N/(Ba/Nb) space. Since the infiltration of the Samoan plume component beneath the Lau Backarc basin occurred later than the initiation of the Tonga subduction system (Chang et al., 2016), we interpret these mixing trends as reflecting the interaction between a plume component and a DMM mantle that has been modified by subduction inputs.

The δ¹⁵N of ~0 ‰ of the primordial N determined for the Samoan plume component in Rochambeau Bank mantle source is consistent with a δ¹⁵N of -2 ‰ to 0 ‰ of primordial N in plume mantle sources derived by Labidi (2022) and Broadley et al. (2025). However, it remains uncertain whether the primordial N in the plume mantle source could exhibit positive δ¹⁵N values. If we extend the potential range of its δ¹⁵N to +2 ‰ following Bekaert et al. (2024b), a ternary mixing plot between DMM, a plume component with primordial N (δ¹⁵N from -2 ‰ to +2 ‰; N₂/³He = ~2 × 10⁵), and a plume component with recycled N (δ¹⁵N from 0 ‰ to +6 ‰; N₂/³He = ~10⁹) could explain the compositions of all Reykjanes Ridge and Iceland data (Fig. 6C). In this ternary mixing model, we note that the combined Reykjanes Ridge and Iceland data show that the N in the Icelandic mantle plume may be hybrid, containing both recycled and primordial sources. Similarly, if the plume component entrained with primordial N is associated with a N₂/⁴⁰Ar* of ~40, at the



(caption on next column)

Fig. 5. (A) Binary mixing between the DMM and plume component with recycled N ($N_2/{}^3\text{He} \sim 10^9$; $\delta^{15}\text{N} \sim -0\text{‰}$ to $+6\text{‰}$) best explains most Reykjanes Ridge and some Iceland data. The red arrow points to a possible end-member (primordial N) with lower $N_2/{}^3\text{He}$ and higher $\delta^{15}\text{N}$ than the DMM. (B) Binary mixing between the DMM and plume component with recycled N ($N_2/{}^{40}\text{Ar}^* \sim 5 \pm 5 \times 10^6$; $\delta^{15}\text{N} \sim -0\text{‰}$ to $+6\text{‰}$; Halldórsson et al., 2016) in $N_2/{}^{40}\text{Ar}^*$ and $\delta^{15}\text{N}$ and space. (C) Ternary mixing among the DMM, a plume component with recycled N ($N_2/{}^{40}\text{Ar}^* \sim 5 \pm 5 \times 10^6$; $\delta^{15}\text{N} \sim -0\text{‰}$ to $+6\text{‰}$) and a plume component with primordial N ($N_2/{}^{40}\text{Ar}^* \sim 40$; $\delta^{15}\text{N} \sim -2\text{‰}$ to $+2\text{‰}$). The global plume-influenced dataset including Society and Central Indian Ridge is consistent with the ternary mixing model. The Rochambeau Bank data are shown with transparency for comparison. (D) Ternary mixing among the DMM, a plume component with primordial N ($\delta^{15}\text{N} \sim -0\text{‰}$; $N_2/{}^{40}\text{Ar}^* \sim 40$), and a subduction component with recycled N ($\delta^{15}\text{N} \sim +3\text{‰}$; $N_2/{}^{40}\text{Ar}^* \sim 5 \pm 5 \times 10^6$) of Rochambeau Bank data. Only samples with ${}^{40}\text{Ar}/{}^{36}\text{Ar} > 500$ from Iceland, Society, Hawaii and Central Indian Ridge are shown for comparison. The plot involving Iceland samples with ${}^{40}\text{Ar}/{}^{36}\text{Ar} < 500$ is shown in Fig. S6 in Supplementary Material. The question marks associated with the Society data symbols suggest that these samples may be contaminated by crustal material, as indicated by their low ${}^3\text{He}/{}^4\text{He}$ ratios. Data source of N and noble gas isotope compositions: Marty and Dauphas, 2003; de Leeuw, 2007; Hahn et al., 2012; Barry and Hilton, 2016; Halldórsson et al., 2016; Labidi, 2022.

lower end of the $N_2/{}^{40}\text{Ar}^*$ range (74 ± 34) proposed for the plume mantle source (Marty and Dauphas, 2003), ternary mixing among DMM, a plume component with recycled N ($\delta^{15}\text{N}$ from 0‰ to $+6\text{‰}$; $N_2/{}^{40}\text{Ar}^* \sim 5 \times 10^6$), and a plume component with primordial N ($\delta^{15}\text{N}$ from -2‰ to $+2\text{‰}$; $N_2/{}^{40}\text{Ar}^* \sim 40$) also explains most Reykjanes Ridge and Iceland data (Fig. 5C and Fig. S6C). The Rochambeau Bank data also fit in the ternary mixing model among DMM, a plume component with primordial N ($\delta^{15}\text{N} \sim -0\text{‰}$; $N_2/{}^{40}\text{Ar}^* \sim 40$), and a subduction component with recycled N ($\delta^{15}\text{N} \sim +3\text{‰}$; $N_2/{}^{40}\text{Ar}^* \sim 5 \times 10^6$) (Fig. 5D). In these models, the low $N_2/{}^{40}\text{Ar}^*$ of the plume component with primordial N could be a result of radiogenic ingrowth of ${}^{40}\text{Ar}$ by ${}^{40}\text{K}$ decay over Earth's history (Marty and Dauphas, 2003).

5. Implications

5.1. Hybrid mantle plumes revealed by global plume dataset

Including other plume-influenced samples worldwide (i.e., Society, Hawaii and CIR) indicates that their N data can also be readily explained by the ternary mixing models presented in Fig. 5C ($\delta^{15}\text{N}$ vs. $N_2/{}^{40}\text{Ar}^*$) and Fig. 6C ($\delta^{15}\text{N}$ vs. $N_2/{}^3\text{He}$). This suggests the common presence of primordial N in global plume mantle sources, which have been variably overprinted by deeply recycled N. The identification of recycled N in plume mantle sources supports the view that surficial N can be subducted to the deep Earth beyond the depth of magma generation at subduction zones (Marty and Dauphas, 2003; Bekaert et al., 2021; Li and Li, 2022; Hudak et al., 2024). In the plot of $\delta^{15}\text{N}$ versus ${}^3\text{He}/{}^4\text{He}$ (Fig. 7B), the global dataset is also consistent with mixing between DMM and plume components with $\delta^{15}\text{N}$ values from -2‰ to $+6\text{‰}$ (i.e., primordial N: -2‰ to $+2\text{‰}$; recycled N: 0‰ to $+6\text{‰}$). Notably, data from the Society plume fall outside of the mixing envelopes defined by the samples derived from high- ${}^3\text{He}/{}^4\text{He}$ plumes (Fig. 7B). The $N_2/{}^3\text{He}$ and $\delta^{15}\text{N}$ values of the Society islands samples (Fig. 6A) may indicate the recycling of subducted N to the low- ${}^3\text{He}/{}^4\text{He}$ Society plume mantle source (Labidi, 2022). Instead, the extremely low ${}^3\text{He}/{}^4\text{He}$ values (down to $\sim 1.3 R_A$) of some of these Society data could also be a result of crustal contribution (Marty and Dauphas, 2003).

Nevertheless, this study highlights the hybrid nature of N in the plume mantle (i.e., primordial and recycled N), with the co-occurrence of both components in a single mantle plume (i.e., Iceland). We surmise that this could also be the case for other plumes globally. The hybrid nature of N compositions is consistent with other isotope systematics (e.g., He, Xe, S and ${}^{182}\text{Hf}$ - ${}^{182}\text{W}$) and elemental abundances (e.g., halogens)

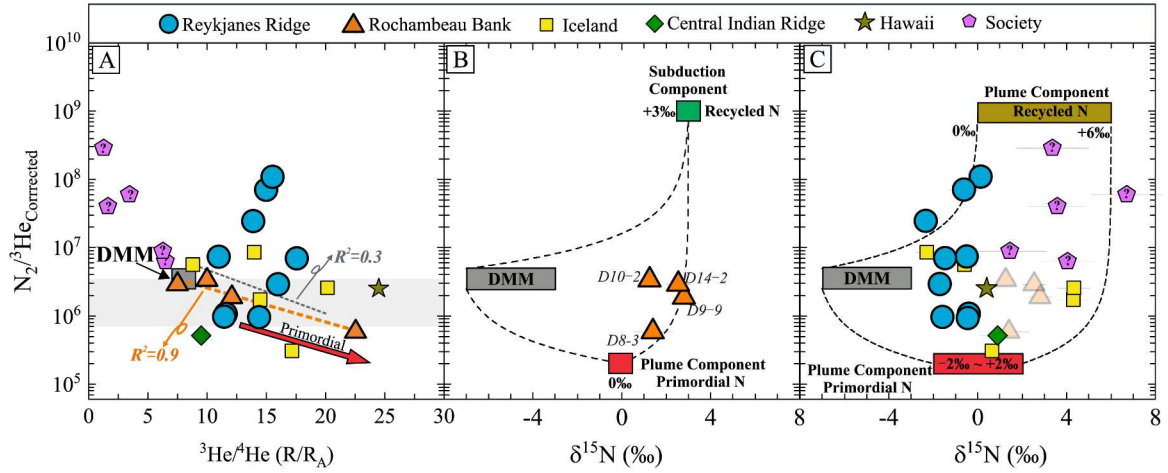


Fig. 6. (A) The relationship between ${}^3\text{He}/{}^4\text{He}$ and $N_2/{}^3\text{He}$ ratios for global plume-influenced dataset from Reykjanes Ridge, Iceland, Rochambeau Bank, Central Indian Ridge, Hawaii, and Society (data source: Marty and Dauphas, 2003; de Leeuw, 2007; Hahm et al., 2012; Barry and Hilton, 2016; Halldórsson et al., 2016; Labidi, 2022). Only samples with ${}^{40}\text{Ar}/{}^{36}\text{Ar} > 500$ from Iceland, Society, Hawaii and Central Indian Ridge are shown for comparison. The grey band shows the possible range of primordial $N_2/{}^3\text{He}$ ratios ($0.7 - 3.5 \times 10^6$) estimated by Labidi (2022). Note that the Rochambeau Bank data show a negative trend (dashed orange line) between ${}^3\text{He}/{}^4\text{He}$ and $N_2/{}^3\text{He}$ ratios, pointing to an endmember with a low $N_2/{}^3\text{He}$ ratio of $\sim 2 \times 10^5$ (red arrow). A broad negative trend (dashed grey line) between ${}^3\text{He}/{}^4\text{He}$ and $N_2/{}^3\text{He}$ ratios also exist for Iceland data. The question marks associated with the Society data symbols suggest that these samples may be contaminated by crustal material, as indicated by their low ${}^3\text{He}/{}^4\text{He}$ ratios (see discussion in main text). (B) Ternary mixing among the DMM ($\delta^{15}\text{N} = -3\text{‰}$ to -7‰ , $N_2/{}^3\text{He} = 3.7 \pm 1.2 \times 10^6$), plume component with primordial N ($\delta^{15}\text{N} = -2\text{‰}$ to $+2\text{‰}$, $N_2/{}^3\text{He} = 2 \times 10^5$) and subduction component with recycled N ($\delta^{15}\text{N} = 0\text{‰}$ to $+6\text{‰}$, $N_2/{}^3\text{He} = 10^9$) for Rochambeau Bank samples. (C) Ternary mixing among the DMM, a plume component with primordial N ($\delta^{15}\text{N} = -2\text{‰}$ to $+2\text{‰}$, $N_2/{}^3\text{He} = 2 \times 10^5$) and a plume component with recycled N ($\delta^{15}\text{N} = 0\text{‰}$ to $+6\text{‰}$, $N_2/{}^3\text{He} = 10^9$) for global plume-influenced dataset. Note that a larger range of $\delta^{15}\text{N}$ value is considered for primordial N (-2‰ to $+2\text{‰}$) in plume component when the global plume-influenced dataset is involved in discussion.

of lavas derived from volcanic hotspots worldwide (e.g., Iceland, Samoa and Hawaii) that show evidence for the coexistence of recycled and primordial components (e.g., Mukhopadhyay, 2012; Jackson et al., 2014, 2017, 2020; Parai and Mukhopadhyay, 2015; Broadley et al., 2019; Dottin et al., 2020; Mundl-Petermeier et al., 2020; Ranta et al., 2022; Kendrick et al., 2025). The co-occurrence of both primordial and recycled components in plume mantle sources is also potentially in line with a stratified lowermost mantle, composed of both primordial domains and recycled components (e.g., Koppers et al., 2021).

5.2. Origin of Earth's primordial N

Enstatite chondrite (EC)-like materials, carbonaceous chondrite (CC)-like materials, differentiated planetary bodies, and comets are considered as potential sources of Earth's volatile inventory (e.g., Broadley et al., 2022; Grewal et al., 2022). The invariant $\delta^{15}\text{N}$ ($\sim -5\text{‰}$; Javoy et al., 1986; Marty and Zimmermann, 1999; Bekaert et al., 2024b) across MORB samples arguably comprising variable contributions from recycled material has led recent studies to suggest that the N budget of the MORB mantle is minimally impacted by recycled N (Barry and Hilton, 2016; Labidi, 2022; Bekaert et al., 2024b). This would imply that

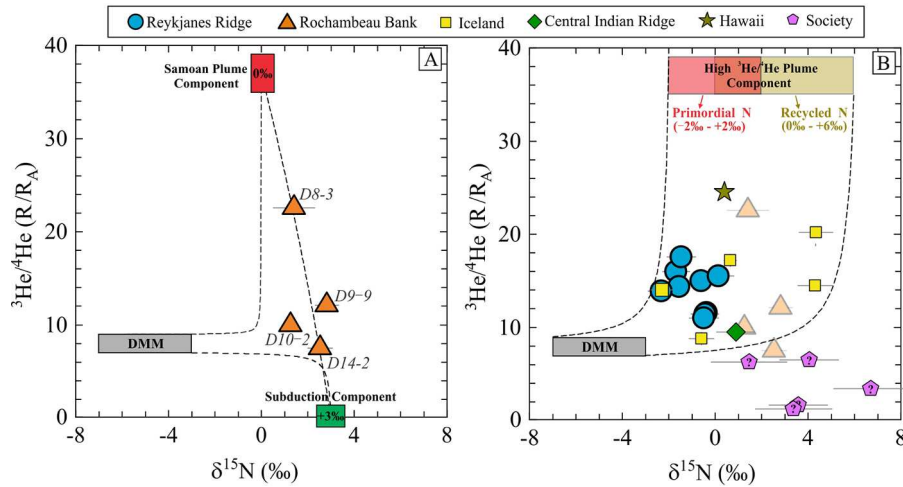


Fig. 7. (A) Ternary mixing among DMM, Samoan plume component ($\delta^{15}\text{N} = 0\text{‰}$; ${}^3\text{He}/{}^4\text{He} = 37 \pm 2 R_A$; Halldórsson et al., 2016), and subduction component ($\delta^{15}\text{N} = +3\text{‰}$; ${}^3\text{He}/{}^4\text{He} = \sim 0.1 R_A$). (B) Relationships between ${}^3\text{He}/{}^4\text{He}$ ratios and $\delta^{15}\text{N}$ values of global plume-influenced dataset from Reykjanes Ridge, Iceland, Central Indian Ridge, Hawaii and Society. Only samples with ${}^{40}\text{Ar}/{}^{36}\text{Ar} > 500$ from Iceland, Society, Hawaii and Central Indian Ridge are shown for comparison. Rochambeau Bank samples are shown with transparency for comparison. Mixing between the depleted MORB mantle (DMM; $\delta^{15}\text{N} = -5 \pm 2\text{‰}$; ${}^3\text{He}/{}^4\text{He} = 8 \pm 1 R_A$), and high ${}^3\text{He}/{}^4\text{He}$ plume components ($37 \pm 2 R_A$; Halldórsson et al., 2016) containing both the recycled (0‰ to $+6\text{‰}$) and primordial N components (-2‰ to $+2\text{‰}$) explain the data from Reykjanes Ridge, Iceland, Central Indian Ridge, and Hawaii. The question marks associated with the Society data symbols suggest that these samples may be contaminated by crustal material, as indicated by their low ${}^3\text{He}/{}^4\text{He}$ ratios (see discussion in main text).

the N characteristics of this reservoir was primarily established early in Earth history. Taken at face value, the higher $\delta^{15}\text{N}$ (-2‰ to $+2\text{‰}$) of primordial N in the plume mantle endmember relative to the MORB mantle ($\sim -5\text{‰}$) could then reflect a greater contribution of ^{15}N -rich outer Solar System bodies, such as comets (Bekaert et al., 2020) and carbonaceous chondrites (Grewal et al., 2022). However, the relative contribution and timing of CC-like ($\delta^{15}\text{N}$ values in the range $\sim -40\text{‰}$ to $\sim 0\text{‰}$; Piani et al., 2020) versus EC-like materials ($\delta^{15}\text{N}$ values in the range $\sim 0\text{‰}$ to $\sim +60\text{‰}$; Piani et al., 2020) contributions to the terrestrial N budget, remains uncertain (e.g., Shi et al., 2022). Some models for example suggest that ^{15}N -enriched CC-like materials could have contributed to an EC-like Earth during main stage accretion or perhaps during the later veneer (e.g., Piani et al., 2020).

If the N isotope composition of the plume mantle does not reflect a contribution of CC-like materials, additional mechanisms are required to explain its $\delta^{15}\text{N}$ range of -2‰ to $+2\text{‰}$. Recent studies for example showed that ^{14}N may preferentially partition into metal phases during core-mantle differentiation versus ^{15}N (Li et al., 2016; Dalou et al., 2019; Grewal et al., 2022), leaving a silicate phase comparatively enriched in ^{15}N . In this case, N partitioning into metal phases during core-mantle differentiation could have played a role in establishing the heavier $\delta^{15}\text{N}$ of the plume mantle (directly present at the core-mantle boundary) compared to the convecting MORB mantle (Broadley et al., 2025). However, the potential isotope consequences of core-mantle formation remain debated. Extreme N isotope fractionation of $\sim 20\text{‰}$ during core mantle fractionation has been proposed by Dalou et al. (2019), but whether these results truly reflect equilibrium conditions between metal and silicate or not (rather than kinetic fractionation during the experiments) remains to be seen (Grewal et al., 2022). Other experimental results suggest that the extent of N isotope fractionation between metal and silicate mantle during core formation could be limited ($+1.1\text{‰}$ to $+5.5\text{‰}$; Li et al., 2016; Grewal et al., 2022). This led Broadley et al. (2025) suggest that the $\delta^{15}\text{N}$ value of the plume source mantle could broadly reflect the N isotope compositions of accretionary material, requiring the contribution of CC-like contributions to the plume mantle. Additional constraints on the origin(s) of the plume mantle N may be gained from elemental ratios. For example, the lower $\text{N}_2/{}^3\text{He}$ of primordial N in the plume mantle sources compared to the convecting MORB mantle could (at least partially) result from greater partitioning of N_2 into the core relative to ${}^3\text{He}$ during Earth's differentiation. While such a scenario remains highly speculative, it is also consistent with the lower $\text{N}_2/{}^{36}\text{Ar}$ observed in the Yellowstone plume mantle source relative to the DMM (Broadley et al., 2025).

The exact proportions of primordial and recycled N into Earth's mantle, as well as the extents to which different reservoirs could have been fractionated from their original compositions due to processes like core formation, remain unknown. In addition to core-mantle differentiation, the diffusion of core material to the potentially stratified lowermost mantle, as evidenced by ${}^{182}\text{Hf}$ - ${}^{182}\text{W}$ and He and Tl isotope systematics of lavas from volcanic hotspots (e.g., the Iceland mantle plume) (e.g., Mundl-Petermeier et al., 2020; Horton et al., 2023; Kaar-e-Rasmussen et al., 2023), could have also affected the N isotope compositions of the plume mantle sources.

5.3. Future work

Compared to other global hotspots, the Icelandic mantle plume appears to be least modified by deeply recycled components (Jackson et al., 2020). However, we show that the Icelandic plume mantle has elevated $\text{N}_2/{}^3\text{He}$ and $\text{N}_2/{}^{40}\text{Ar}^*$, suggesting some deep recycling of crustal N in addition to primordial N. Rochambeau Bank data from this study suggest primordial N rather than deeply recycled N in the Samoan plume mantle, which is at odds with previous findings, which associated enriched mantle components with deep crustal recycling in the Samoan plume (Jackson et al., 2007, 2014). Importantly, plume mantle sources are compositionally heterogeneous, consisting of both recycled and

primordial components (e.g., Jackson et al., 2020; Koppers et al., 2021; this study). This is particularly true for the Samoan plume with both components being clearly identified (Jackson et al., 2007, 2014). Therefore, the absence of a deeply recycled N signature in the Samoan plume mantle source based on Rochambeau Bank N-noble gas data does not imply that the Samoan plume mantle source is entirely composed of primordial N - especially given the lack of N isotope data from lavas directly derived from the Samoan plume. Further studies incorporating high-quality N isotope data (combined with ${}^{182}\text{Hf}$ - ${}^{182}\text{W}$ and noble gas isotope analysis) from lavas of global hotspots (e.g., Samoa) are needed to better constrain the N characteristics of plume mantle sources, particularly those from the least modified mantle domains that may best preserve primordial components from early Earth (Jackson et al., 2020). Attention should also be given to kimberlite and HIMU samples that may originate from the deep mantle, potentially preserving primordial components from the early Earth and containing deeply recycled components from ancient subducted slabs (Zhang et al., 2024; Giuliani et al., 2025).

6. Conclusions

We present new N isotope data from two geochemically well-characterized suites of high ${}^3\text{He}/{}^4\text{He}$ basaltic glasses: Reykjanes Ridge and Rochambeau Bank. Both Rochambeau Bank samples ($+1.3\text{‰}$ to $+2.8\text{‰}$) and Reykjanes Ridge samples (-2.3‰ to $+0.1\text{‰}$) are characterized by $\delta^{15}\text{N}$ values above the DMM ($\sim -5\text{‰}$). The combined trace element, noble gas and N isotope compositions show that Rochambeau Bank data are consistent with ternary mixing among the DMM, Samoan plume component entrained with primordial N, and a subduction component from the Tonga slab. The combined Reykjanes Ridge and Iceland data is consistent with a ternary mixing among the DMM, Icelandic plume components entrained with both recycled and primordial N. This suggests that the Icelandic plume is hybrid in nature composed of both recycled and primordial N. When incorporating a global plume-influenced dataset from Society, Hawaii, and Central Indian Ridge, we highlight that the global plume dataset is also consistent with ternary mixing among DMM, recycled N and primordial N endmembers in deep mantle plumes. This suggests a hybrid nature of N in deep mantle plumes globally. The primordial N with $\delta^{15}\text{N}$ of -2‰ to $+2\text{‰}$ in plume mantle sources potentially requires the addition of ^{15}N -enriched carbonaceous material from the outer solar system.

CRedit authorship contribution statement

Kan Li: Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation, Formal analysis, Data curation, Conceptualization. **Michael R. Hudak:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Michael W. Broadley:** Writing – review & editing. **Molly K. Anderson:** Writing – review & editing. **David V. Bekaert:** Writing – review & editing, Methodology. **John A. Krantz:** Writing – review & editing, Investigation, Formal analysis, Conceptualization. **Namitha Kumar:** Writing – review & editing. **Manuel Pimenta Silva:** Writing – review & editing. **Doshik Hahn:** Writing – review & editing. **Joshua M. Curtice:** Resources, Investigation, Formal analysis, Writing – review & editing, Methodology. **Mark D. Kurz:** Writing – review & editing, Resources. **Peter H. Barry:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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Data availability

All data are available in the embedded tables.

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