

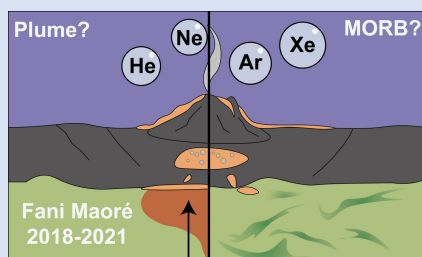
Xenon isotopes in the Fani Maoré lavas: Implications for upper mantle heterogeneity

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Abstract



Xenon isotopes provide unique constraints on mantle evolution but remain rarely investigated in oceanic intraplate lavas due to pervasive atmospheric contamination. The 2018–2021 Fani Maoré eruption (Mayotte) produced gas-rich lavas, allowing the first investigation of xenon in the Comoros. While helium, neon, and argon systematics are MORB-like, consistent with derivation from a depleted upper mantle, xenon displays a distinct behaviour: the Fani Maoré mantle $^{129}\text{Xe}/^{130}\text{Xe}$ is below 7.1, potentially consistent with a mantle plume contribution. Deconvolution of fissiogenic Xe isotopic signatures, however, reveals (1) substantial contribution from recycled air, and (2) nearly pure ^{238}U spontaneous fission pattern ($\text{Xe}_{\text{Pu}}/\text{Xe}_{\text{U}} \sim 0$), arguing against derivation from a deep primordial plume reservoir. Instead, it supports a shallow origin, perhaps involving ancient, U-rich, strongly degassed recycled lithologies that have pervasively metasomatised the Comorian lithosphere. The low $^{129}\text{Xe}/^{130}\text{Xe}$ of the Comoros mantle may reflect a higher contribution of a recycled atmospheric component in the local mantle. Together, this points toward a shallow origin for the archipelago and shows that recycled volatiles in the upper mantle are spatially variable and not fully homogenised.

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Introduction

Noble gases are atmophile elements characterised by their chemical inertness, which, combined with their ultra-trace concentrations in the mantle, makes them particularly sensitive tracers of mantle evolution and mass transfer between planetary reservoirs. Their isotopic compositions are strongly influenced by nucleogenic and radiogenic production, providing a sensitive record of mantle outgassing and evolution through time. Some xenon (Xe) isotopes record the decay of short lived ^{129}I (half-life = 17 Myr; ^{129}Xe) and ^{244}Pu (half-life = 80 Myr; $^{131-132-134-136}\text{Xe}$), providing insights into the early history of terrestrial planets.

Noble gas isotopes distinguish end member volatile signatures associated with mid-ocean ridge basalt (MORBs) and oceanic island basalts (OIBs), the latter bearing lower radiogenic to primordial Ne, Ar and Xe ratios consistent with a lesser degree of outgassing than the MORB source (e.g., Parai, 2025 and references therein). Recent investigations, however, highlight that significant isotopic heterogeneity may exist among upper-mantle derived samples on a local scale (e.g., Zhang *et al.*, 2026), highlighting the limits of a simple MORB *vs.* plume mantle reservoir view. Resolving Xe contributions is more challenging than for Ne or Ar because mantle Xe is dominated by recycled atmospheric Xe owing to the high Xe/light noble gas ratios of subducted materials relative to the mantle (Parai, 2025). This, combined with pervasive secondary atmospheric contamination, has historically hampered precise Xe measurements, motivating specific analytical approaches (Péron and

Moreira, 2018; Parai, 2023). Two main strategies exist: (i) measuring isotopic excesses relative to air that are, most of the time small, with high precision using large quantities of gas from natural springs (Bekaert *et al.*, 2024), and (ii) measuring the largest possible excesses with lower precision, usually from pillow lavas (e.g., Moreira *et al.*, 1998; Mukhopadhyay, 2012). The latter is often limited by pre-quenching degassing, which fractionates elemental ratios (Lux, 1987), and leaves low gas concentrations. In rare cases, however, gas-rich pillow rims, or “popping rocks,” retain high concentrations of unfractionated noble gases, allowing precise isotopic analyses representative of the mantle. The Fani Maoré lavas, erupted 50 km offshore Mayotte in the Mozambique Channel between 2018 and 2021 (Feuillet *et al.*, 2021), represent one such rare case.

Methods and Sample Information

We performed a total of 19 crushing steps on three glassy rims from the Fani Maoré lavas for their He-Ne-Ar and Xe isotopic compositions; full details of the analytical and data reduction procedures are provided in the [Supplementary Information](#). The fragments we used are part of the “DR08” dredge from the MAYOBS2 cruise (Rinnert *et al.*, 2019), previously investigated for He-Ne-Ar isotopes (Sauvalle *et al.*, 2026). Details about the samples can be found in the [Supplementary Information](#) and the entire data set is presented in [Tables S-1, S-2 and S-3](#).

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Results

Elemental ratios. Measured noble gas production ratios ($^4\text{He}/^{40}\text{Ar}^*$ and $^4\text{He}/^{21}\text{Ne}^*$) agree with theoretical mantle production ratios (Graham, 2002), indicating negligible elemental fractionation during degassing. In contrast, some crushing steps yield extremely low Xe abundances, resulting in anomalously high $^3\text{He}/^{130}\text{Xe}$ ratios (Fig. 1). This behaviour is not systematic: most steps follow the array defined by the N. Atlantic popping-rock 2PID43 in $^{129}\text{Xe}/^{130}\text{Xe}$ versus $^3\text{He}/^{130}\text{Xe}$ space (Fig. 1). No corresponding fractionation is observed in other elemental ratios (e.g., $^{36}\text{Ar}/^{22}\text{Ne}$ or $^3\text{He}/^{22}\text{Ne}$; Table S-3), suggesting a Xe specific effect. Air standards are unaffected, confirming that this feature is sample specific (Fig. S-4). Consequently, individual Xe measurements display variable and sometimes large analytical uncertainties due to low concentrations.

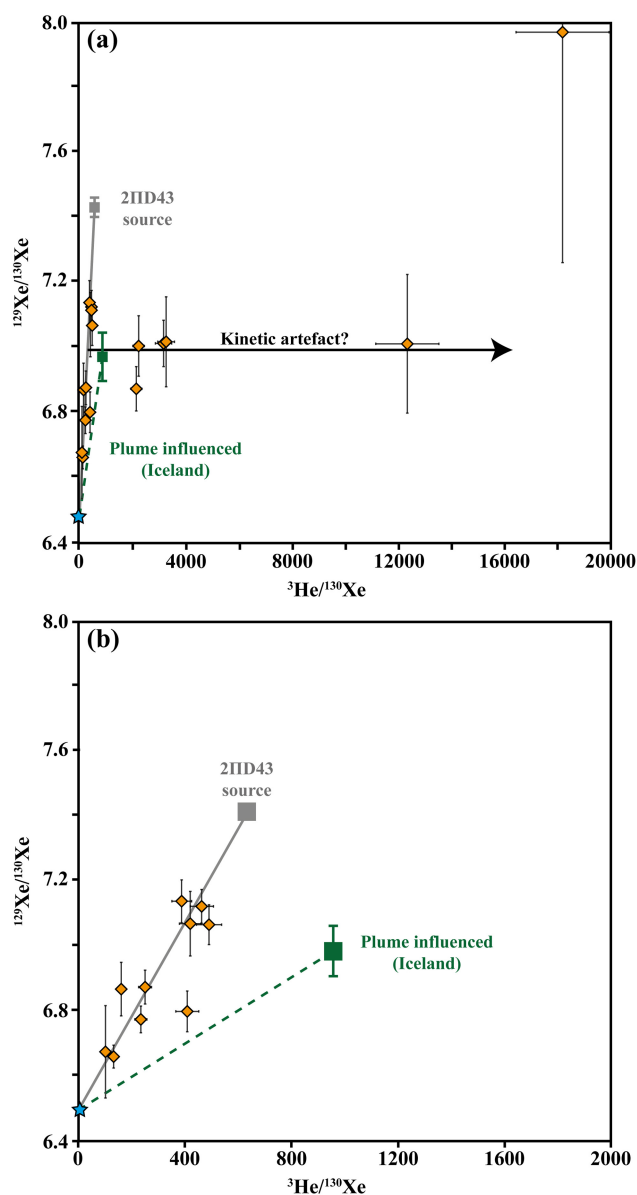


Figure 1 (a) $^{129}\text{Xe}/^{130}\text{Xe}$ against $^3\text{He}/^{130}\text{Xe}$, with a zoomed in view in (b). Most of the crushing steps plot along the 2PID43 array (Parai and Mukhopadhyay, 2021), whereas a subset deviates toward high $^3\text{He}/^{130}\text{Xe}$ values, indicative of elemental fractionation. The plume influenced array shown is that of Iceland (Mukhopadhyay, 2012).

He-Ne-Ar isotopes. The He-Ne-Ar results obtained in this study are in excellent agreement with previously reported data (Sauvalle *et al.*, 2026). The analysed fragments are gas-rich, containing $>10^{-5}$ cc STP/g of ^4He . Helium measurements yield an average $^3\text{He}/^4\text{He}$ of 6.98 ± 0.05 Ra (1σ ; Ra = 1.384×10^{-6} , the atmospheric ratio) across the crushing steps. This value falls at the lower end of the canonical MORB range (8 ± 1 Ra; Moreira, 2013).

Ne and Ar isotopic compositions define mixing arrays between air and mantle derived components (Fig. 2). Most of the crushing steps (11 out of 19) define a coherent mantle cluster characterised by consistently high $^{20}\text{Ne}/^{22}\text{Ne}$ and $^{40}\text{Ar}/^{36}\text{Ar}$ ratios (Fig. 2). The $^{20}\text{Ne}/^{22}\text{Ne}$ isotopic ratio reaches mantle-like values, with $^{20}\text{Ne}/^{22}\text{Ne}$ up to ~ 12.3 and the $^{21}\text{Ne}/^{22}\text{Ne}$ ratio reaches values up to 0.057, overlapping the MORB array (Fig. 2). One crushing step yields a $^{20}\text{Ne}/^{22}\text{Ne}$ ratio significantly below air (9.06 ± 0.02 ; $^{21}\text{Ne}/^{22}\text{Ne} = 0.0284 \pm 0.0001$ vs. 9.80 and 0.0290 for air, respectively), the origin of which is discussed later. The $^{40}\text{Ar}/^{36}\text{Ar}$ isotopic ratio reaches values up to $\sim 17,000$, well above the atmospheric ratio (295.5; Fig. 2). Extrapolation toward the mantle end member (assuming $^{20}\text{Ne}/^{22}\text{Ne} = 12.5$ for DMM; Moreira *et al.*, 1998) yields a $^{21}\text{Ne}/^{22}\text{Ne}_{\text{extrap}}$ of 0.0593 ± 0.0009 (1σ), a value close to the depleted upper mantle (0.06; Moreira *et al.*, 1998). The extrapolated $^{40}\text{Ar}/^{36}\text{Ar}$ (Fig. 2) to a $^{20}\text{Ne}/^{22}\text{Ne}$ of 12.5 is $19,980 \pm 1,110$ (1σ) with a curvature parameter of 1.22 ± 0.33 (1σ). This is lower than expected for the DMM

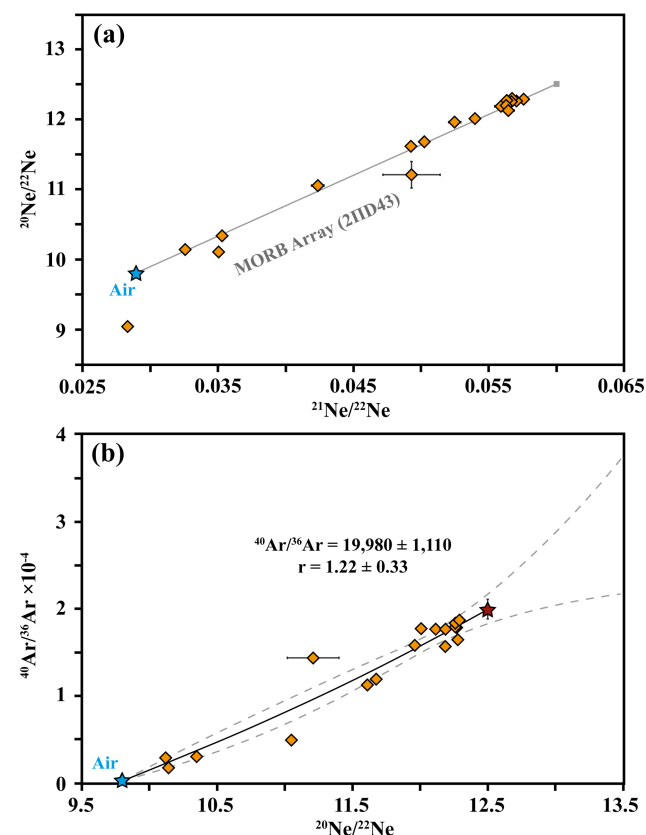


Figure 2 Air-mantle mixing systematics from step crushing of Fani Maoré lavas for Ne and Ar isotopes. (a) $^{20}\text{Ne}/^{22}\text{Ne}$ vs. $^{21}\text{Ne}/^{22}\text{Ne}$; crushing steps extend from air and align on the MORB array defined by 2PID43 (Moreira *et al.*, 1998). (b) $^{40}\text{Ar}/^{36}\text{Ar}$ vs. $^{20}\text{Ne}/^{22}\text{Ne}$; data define a positive mixing hyperbola ($r = 1.22 \pm 0.33$), yielding $^{40}\text{Ar}/^{36}\text{Ar} = 19,980 \pm 1,110$ (1σ) at $^{20}\text{Ne}/^{22}\text{Ne} = 12.5$. The 2σ envelope on the hyperbola is represented as the dotted grey lines.

(~27,000; Moreira *et al.*, 1998). More details on the extrapolation procedure are provided in the [Supplementary Information](#).

Xenon isotopes. Several crushing steps show a clear excess in terms of Xe isotopic composition compared to air. This is particularly evident for the heavier, fissiogenic Xe isotopes ($^{131}\text{--}^{132}\text{--}^{134}\text{--}^{136}\text{Xe}$), which are much more abundant than the primordial Xe isotopes in the mantle ($^{124}\text{--}^{126}\text{--}^{128}\text{--}^{130}\text{Xe}$). The very low abundances of ^{124}Xe , ^{126}Xe , and ^{128}Xe result in comparatively large analytical uncertainties that preclude robust interpretation; accordingly, these data are reported in [Table S-3](#) but not further discussed.

Xe isotopic compositions define mixing arrays between air and a mantle-derived end member that largely overlap the field of MORBs ([Fig. 3a](#)). Measured $^{129}\text{Xe}/^{130}\text{Xe}$ ratios reach 7.14 ± 0.07 , lower than the 2PID43 mantle source value of 7.41 ± 0.03 (measured from [Péron and Moreira, 2018](#); extrapolated from [Parai and Mukhopadhyay, 2021](#)). Normalisation to ^{132}Xe , the most abundant Xe isotope, enables extrapolation toward an air-free mantle composition and subsequent deconvolution of U and Pu fission contributions while minimising the impact of analytical uncertainties ([Parai and Mukhopadhyay, 2015](#); see [SI](#)). The mantle $^{129}\text{Xe}/^{132}\text{Xe}$ ratio is determined by fitting the mixing relationship in the $^{129}\text{Xe}/^{132}\text{Xe}\text{--}^{40}\text{Ar}/^{36}\text{Ar}$ space ([Fig. 3b](#)). The resulting mixing hyperbola displays a curvature of $r = 0.148^{+0.103}_{-0.064}$, such that variations of $^{40}\text{Ar}/^{36}\text{Ar}$ within its

uncertainty produce only negligible changes in the extrapolated mantle $^{129}\text{Xe}/^{132}\text{Xe}$ ratio ([Fig. 3a](#)). Accordingly, the $^{129}\text{Xe}/^{132}\text{Xe}$ ratio for Fani Maoré mantle is 1.053 ± 0.008 (1 σ ; [Fig. 3b](#)) by extrapolation to the previously constrained mantle $^{40}\text{Ar}/^{36}\text{Ar}$ value (19,980; [Fig. 2](#)). This best fit mantle value is then used as a fixed reference to determine the remaining $^{130,131,134,136}\text{Xe}/^{132}\text{Xe}$ ratios by York regression ([Fig. S-6](#)).

The present-day mantle $^{131}\text{--}^{132}\text{--}^{134}\text{--}^{136}\text{Xe}$ inventory can be modelled as a mixture of four components ([Caffee *et al.*, 1999](#)): (1) the initial mantle (assumed as average carbonaceous chondrite-like, AVCC; [Péron and Moreira, 2018](#)), (2) recycled atmospheric Xe, (3) Pu derived Xe, and (4) U derived Xe. The system is over determined, and end member fractions are obtained by least squares inversion under the constraint $X_{\text{init}} + X_{\text{atm}} + X_{\text{U}} + X_{\text{Pu}} = 1$. Mixing proportions are reported as the median of 10^6 Monte Carlo realisations, with 16th–84th percentile uncertainties. Accordingly, the fissiogenic Xe signature of the Fani Maoré mantle is best explained by $19.4^{+14.0}_{-7.8}$ % AVCC, $78.4^{+8.0}_{-15.1}$ % recycled air, $0.0^{+3.3}_{-0.0}$ % Pu derived fission and $1.7^{+0.4}_{-1.7}$ % U derived fission. The Pu derived contribution is statistically indistinguishable from zero, indicating that ^{244}Pu fission is not required to explain the Xe isotopic composition. The U fission dominance is independently supported by comparison with expected fission spectra ([Fig. 4b](#); [Bekaert *et al.*, 2019](#)).

Discussion and Conclusions

Sample scale heterogeneity. One crushing step yielded a $^{20}\text{Ne}/^{22}\text{Ne}$ ratio of 9.06 ± 0.02 ([Table S-1](#)), significantly lower than air. Similarly, ratios have been reported in glassy rims and attributed to fractionated air ([Harrison *et al.*, 2003](#)). Although ultra-high vacuum pumping prior to analysis evacuates cracks and open vesicles, extremely narrow conduits can drastically reduce permeability, effectively isolating portions of trapped gas. Under such conditions, kinetic fractionation may occur during pumping, preferentially removing lighter species and isotopes. The anomalous step also displays elevated $^{36}\text{Ar}/^{22}\text{Ne}$ (24.1) and $^{40}\text{Ar}/^{36}\text{Ar}$ (469) but low $^4\text{He}/^{40}\text{Ar}^*$ (1.1; [Tables S-3](#) and [S-4](#)), consistent with elemental and isotopic fractionation of atmospheric gases. These observations highlight the complexity of secondary atmospheric contamination, which may involve air, fractionated air, and seawater derived components ([Harrison *et al.*, 2003](#)). This anomalous analysis is probably unrelated to mantle source processes and is therefore excluded from extrapolation fits ([Figs. 2, 3](#)).

Regarding Xe specifically, some analyses exhibit extremely low abundances (down to 10^{-15} cc/g; [Table S-3](#)) without systematic correlation to the analysed fragment or to other noble gas elemental or isotopic ratios. This Xe specific effect cannot be attributed to degassing since $^4\text{He}/^{40}\text{Ar}$ and $^4\text{He}/^{21}\text{Ne}^*$ ratios closely match theoretical mantle production ratios ([Graham, 2002](#)), indicating negligible degassing related fractionation. A possible explanation is that rapid vesicle nucleation during fast magma ascent allowed insufficient time for dissolved Xe to equilibrate with newly formed bubbles. Indeed, the Fani Maoré lavas ascended rapidly, perhaps related to their low viscosity ([Verdume *et al.*, 2025](#)). Noble gas diffusivity in silicate melts decreases with increasing ionic radius ([Lux, 1987](#)); consequently, Xe diffuses more slowly than He, Ne, or Ar. Selective Xe depletion may therefore occur in vesicles that did not fully equilibrate with the melt. These Xe-poor steps occur almost exclusively among analyses isotopically distinct from air, consistent with a sample-intrinsic origin. Importantly, crushing steps with anomalously low Xe abundances yield Xe isotopic ratios indistinguishable, within analytical uncertainty, from those with

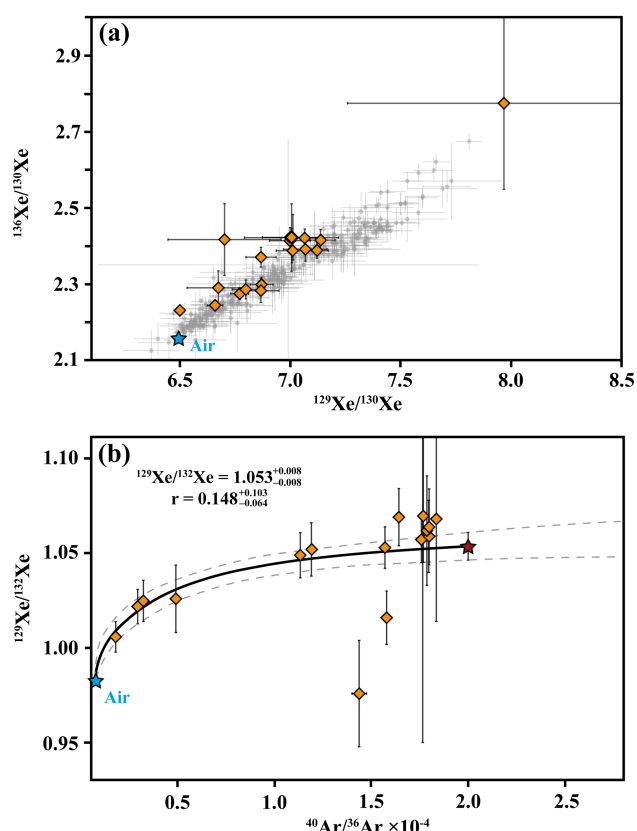


Figure 3 Air-mantle mixing systematics for Xe. (a) $^{136}\text{Xe}/^{130}\text{Xe}$ vs. $^{129}\text{Xe}/^{130}\text{Xe}$; crushing steps extend from air and align on the global MORB array (grey symbols; [Moreira *et al.*, 1998](#); [Kunz *et al.*, 1998](#); [Parai *et al.*, 2012](#); [Tucker *et al.*, 2012](#); [Parai and Mukhopadhyay, 2015, 2021](#); [Péron and Moreira, 2018](#)). (b) $^{129}\text{Xe}/^{132}\text{Xe}$ vs. $^{40}\text{Ar}/^{36}\text{Ar}$; data define a positive mixing hyperbola ($r = 0.148^{+0.103}_{-0.064}$, 1 σ). The resulting extrapolated $^{129}\text{Xe}/^{132}\text{Xe}$ ratio is 1.053 ± 0.008 . The 1 σ envelope on the hyperbola is represented as the dotted grey lines.

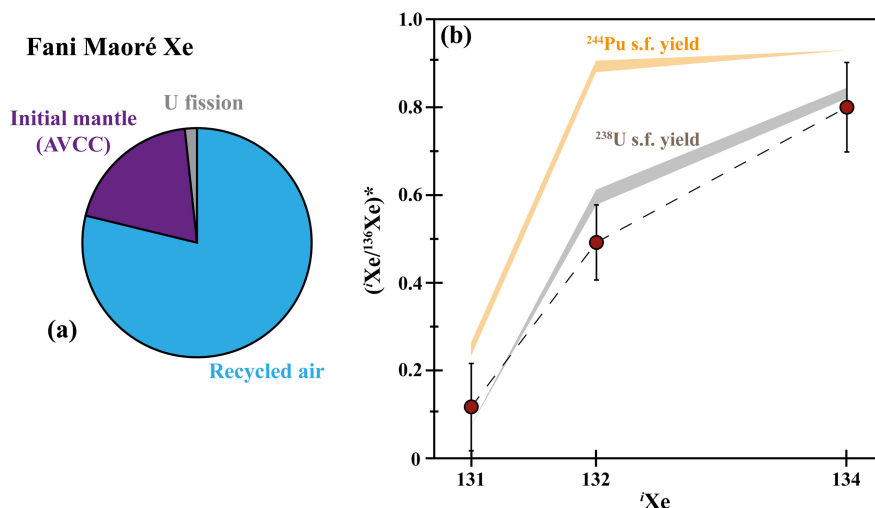


Figure 4 Fissiogenic Xe excesses deconvolution. (a) Pie chart showing the median relative contribution of the four end members (AVCC, air, U fission, Pu fission) to the present day ^{132}Xe in the Fani Maoré lavas. The median contribution from Pu fission is 0 %. (b) Fission spectra of the Fani Maoré lavas compared with theoretical fission spectra from pure ^{238}U and ^{244}Pu fission (Ozima and Podosek, 2002), illustrating the predominance of ^{238}U derived fissiogenic Xe.

higher concentrations. This behaviour supports a kinetic, vesicle scale origin rather than mantle source heterogeneity.

Both observations highlight that significant variability can arise from vesicle scale kinetic and contamination processes for noble gases, independent of mantle source composition.

The Fani Maoré Mantle: a He-Ne-Ar-Xe Perspective. The Comoros archipelago has traditionally been interpreted as a hot spot track (Class *et al.*, 1998), although inconsistencies between volcanic alignment and Somalian plate motion have challenged this view (Morgan and Morgan, 2007). Alternative models invoke plume material ponding beneath the lithosphere (Dongmo Wamba *et al.*, 2023), potentially explaining the lithophile isotopic signatures of Comorian lavas through the involvement of old recycled oceanic crust (Chauvel *et al.*, 2024).

Noble gases provide constraints on the origin of magmatism in the Comoros. Light noble gases from Fani Maoré are consistent with a DMM-like source (Sauvalle *et al.*, 2026). High extrapolated radiogenic to primordial ratios for Ne and Ar (Fig. 2) are characteristic of the MORB source (Moreira *et al.*, 1998), contrasting with the lower ratios typical of less degassed reservoirs, including several HIMU localities (e.g., Zhang *et al.*, 2024). One exception is the HIMU influenced equatorial Atlantic MORBs of Tucker *et al.* (2012), which show similar Ne-Ar signatures.

Xe isotopes provide a more ambiguous signal. The relatively low extrapolated mantle $^{129}\text{Xe}/^{130}\text{Xe}$ value (7.00 ± 0.07 ; $^{129}\text{Xe}/^{132}\text{Xe} = 1.053 \pm 0.008$) could reflect either a less degassed mantle contribution or enhanced atmospheric Xe recycling into the mantle source. Fissiogenic Xe provide a decisive constraint: plume influenced mantle sources generally preserve a substantial ^{244}Pu derived fission component relative to the DMM. Because ^{244}Pu has a short half-life (~ 80 Myr), a significant Pu contribution implies early isolation and limited subsequent degassing (Parai, 2025). In contrast, deconvolution of the Fani Maoré Xe isotopic composition yields a median Pu derived contribution of 0 %. This result is supported by the fissiogenic Xe isotope pattern, which is consistent with a dominant ^{238}U fission contribution (Fig. 4). This argues against involvement of a preserved, less degassed mantle reservoir, and supports derivation from a more processed mantle. Consistently, most unfractionated crushing steps ($^3\text{He}/^{130}\text{Xe} < 1000$) align with the 2TID43

array in $^{129}\text{Xe}/^{130}\text{Xe}$ versus $^3\text{He}/^{130}\text{Xe}$ space (Fig. 1). The low extrapolated $^{129}\text{Xe}/^{130}\text{Xe}$ (7.00 ± 0.07) is therefore best explained by enhanced recycling of atmospheric Xe into the local mantle, rather than sampling of a primitive plume reservoir. We consequently favour a shallow origin for the recent Fani Maoré paroxysm and volcanism across the Comoros archipelago, consistent with recent geophysical and geochemical constraints (e.g., Bordenca *et al.*, 2023; Boymond *et al.*, 2025). Notably, HIMU-type Atlantic MORBs of Tucker *et al.* (2012), despite similar Ne-Ar signatures, show a substantial Pu derived Xe contribution. The origin of this Xe specific contrast between HIMU influenced reservoirs with similar Ne-Ar and lithophile signatures, such as Fani Maoré and the Tucker *et al.* (2012) HIMU-MORBs, remains unclear. This warrants further investigation and may point to heterogeneity within the HIMU reservoir itself.

Inferences on Upper Mantle Heterogeneity from the Fani Maoré Paroxysm. As discussed above, enhanced incorporation of recycled atmospheric volatiles into a DMM-like mantle source beneath the Comoros can account for the Xe isotopic systematics of the Fani Maoré lavas. Noble gas signatures previously reported in mantle xenoliths from Grande Comore (Ne-Ar; Bordenca *et al.*, 2023) further suggest that these characteristics reflect regional mantle properties rather than processes restricted to the recent Fani Maoré paroxysm.

Ne and Ar systematics independently support this interpretation: low $^{40}\text{Ar}/^{36}\text{Ar}_{\text{extrap}}$ and $^{20}\text{Ne}/^{22}\text{Ne}$ clustering at ~ 12.3 (slightly below the MORB value of ~ 12.5 ; Moreira *et al.*, 1998) could indicate a minor recycled atmospheric contribution (Sauvalle *et al.*, 2026; this study). A median Pu contribution of 0 % is lower than the upper mantle estimate of 31 ± 11 % (relative to total fission; Parai *et al.*, 2019), though recently questioned by recent measurements of Etna and Eifel spring gases yielding similarly negligible Pu contributions (Bekaert *et al.*, 2024). This may reflect extensive early mantle degassing followed by long term convective processing of the local mantle, resulting in a high time integrated $\text{Xe}_U/\text{Xe}_{\text{Pu}}$ ratio. This absence of Pu is nevertheless puzzling given the large ^{129}Xe excesses observed, since ^{129}I (half-life ~ 17 Myr) became extinct well before ^{244}Pu (~ 80 Myr). Alternatively, it may indicate the involvement of subduction derived fluids or ancient, U-rich recycled components, consistent with the radiogenic Pb and Os signatures reported in Comorian lavas (Chauvel *et al.*, 2024).

Recycled lithologies are expected to be strongly depleted in noble gases relative to ambient peridotitic mantle, as most He, Ne, Ar, and Xe are efficiently expelled from slabs during subduction (Staudacher and Allègre, 1988). Consequently, low degree melts sampling recycled components may inherit radiogenic lithophile isotopic signatures while being noble gas-poor. The Comorian lithosphere appears pervasively metasomatised by C-rich melts, as documented by metasomatic textures in ultramafic xenoliths from Grande Comore (Coltorti *et al.*, 1999). This process could have modified the lithosphere's lithophile isotopic composition (Jiang *et al.*, 2026), shifting it toward the HIMU-like signatures observed (Chauvel *et al.*, 2024). Low degree melting of this fertilised lithosphere, triggered by local rifting and/or edge driven convection (Sauvalle *et al.*, 2026), can produce the observed basanitic compositions. Lithophile isotopes could therefore record the metasomatic overprint, while noble gases isotopes remain mostly controlled by the original lithospheric budget, owing to the noble gas-poor character of the metasomatising agent. These melts and fluids, of recycled origin, should carry a predominantly air-like noble gas signature reflecting subduction recycling efficiencies, which may account for the elevated atmospheric noble gas component proposed for the Fani Maoré mantle. Xe is uniquely sensitive to recycled atmospheric contributions because it is both extremely scarce in the mantle (Parai, 2025) and highly soluble in seawater (Ozima and Podosek, 2002), promoting efficient recycling of atmospheric Xe during subduction. The systematic $\text{He} < \text{Ne} < \text{Ar} < \text{Xe}$ progression in atmospheric contributions reflects the differential recycling efficiencies of noble gases during subduction, which scale with ionic radius and seawater solubility (Wang *et al.*, 2020). Xe isotopes therefore provide the most sensitive tracer of recycled atmospheric contributions, as reflected by the anomalously low extrapolated $^{129}\text{Xe}/^{130}\text{Xe}$ ratio of 7.00 ± 0.07 in the Fani Maoré mantle (Fig. 3).

Our results suggest that the low $^{129}\text{Xe}/^{130}\text{Xe}$ ratios observed in the region do not require mixing with a primitive deep mantle reservoir but can instead be explained by heterogeneous recycling of atmospheric volatiles within a long term processed, upper mantle domain. More broadly, the Fani Maoré case suggests that the volatile composition of the upper mantle may not be globally homogeneous, but instead preserves persistent regional heterogeneities inherited from long term recycling of surface derived volatiles.

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Additional Information

Supplementary Information accompanies this letter at <https://www.geochemicalperspectivesletters.org/article2639>.



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Xenon isotopes in the Fani Maoré lavas: implications for upper mantle heterogeneity

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Supplementary Information

The Supplementary Information includes:

- Material and Methods
- Tables S-1 to S-6
- Figures S-1 to S-6
- Supplementary Information References

Material and Methods

Samples used

The samples were recovered in 2019 during the MAYOBS2 oceanographic cruise (Jorry, 2019). The analysed lava flows are associated with the second eruptive phase of the Fani Maoré volcano (Berthod *et al.*, 2021). Glassy rims formed during emplacement of the flows by rapid quenching upon contact with cold deep seawater. Because quenching occurred at ~3000 m water depth, gas is trapped inside the vesicles at high confining pressures (≥ 300 bar). Upon recovery on deck, the large pressure contrast between magmatic gas trapped in vesicles and atmospheric pressure caused many glassy rims to rupture explosively (“popping-rocks”). The lavas are evolved basanites (Berthod *et al.*, 2021) and are predominantly aphyric, containing less than 5% crystals (mainly olivine and oxides). They are highly vesicular, with vesicularities exceeding 30% (Fig. S-1). We used a total of 3 distinct rock fragments for analyses with respective masses of 1.33, 1.74 and 2.77 grams.

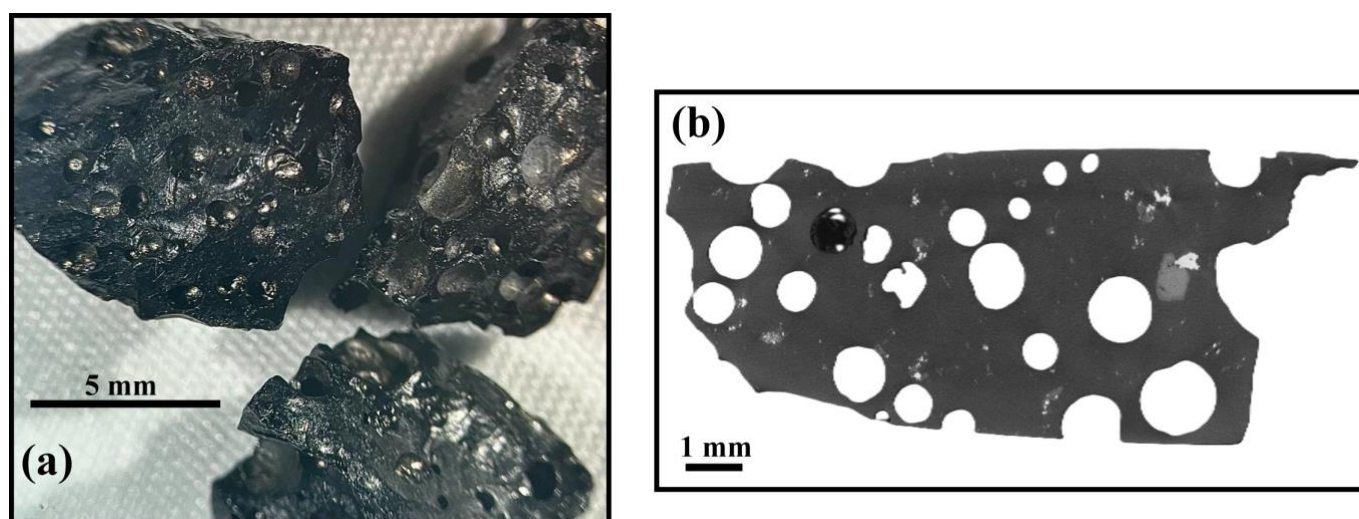


Figure S-1 Glassy lava fragments from the Fani Maoré submarine eruption recovered during dredge DR08 of the MAYOBS2 oceanographic cruise (Jorry, 2019). **(a)** Photograph of representative glassy pillow-lava rims fragments. **(b)** Representative single slice obtained by X-ray microtomography. The contrast corresponds to density variations: vesicles and fractures appear originally in black but here in white for clarity, the glass is dark grey, and olivine appears slightly brighter. Oxides, the densest phase, are shown in white.

Microtomography acquisitions

Preliminary 3D-microtomography was conducted to assess the vesicularity of glassy lavas fragments similar to the ones used for step-crushing. All acquisitions were performed at the Institut des Sciences de la Terre d'Orléans (France) using a Phoenix Nanotom M system equipped with a molybdenum target and a 180 kV X-ray tube operating at voltages up to 120 kV and filament currents ranging from 40 to 170 μA . Data acquisition consisted of a sequence slice corresponding to successive sections of the sample. These slices can subsequently be reconstructed to generate a full three-dimensional volume of each rock fragment. A copper filter was employed to reduce beam-hardening artefacts. An example of a slice is presented in Figure S-1b.

Gas extraction, purification and separation

Gases were extracted from rock fragments by step-crushing using a hand-actuated magnetic crusher. Samples were loaded into a cylindrical crusher that was baked at 120 °C overnight prior to analysis, or until procedural blanks reached levels suitable for accurate measurements. Procedural blanks for ^4He , ^{22}Ne , ^{36}Ar , and ^{130}Xe were on the order of 3.10^{-10} , 6.10^{-13} , 1.10^{-11} , and 1.10^{-15} cc STP, respectively.

During crushing, the pressure within the crusher (isolated from the purification line) was continuously monitored using a Pfeiffer Vacuum D-35614 Asslar manometer.

Following extraction, the released gases were purified using two Ti-getters: first at 1073 K (5 min each), then at room temperature (10 min each). This procedure removes reactive species (*e.g.*, CO₂, H₂O, H₂S) through chemisorption onto titanium sponge.

The noble gases are then cryoseparated using two cold traps: a stainless-steel trap and a charcoal trap. The stainless-steel trap was initially maintained at 40 K to retain Ar, Kr, and Xe, while the remaining gases were exposed to the charcoal trap held at 7 K to trap He and Ne.

Helium was released by heating the charcoal trap to 35 K and subsequently analysed in the mass spectrometer. Neon was then extracted by increasing the charcoal trap temperature to 70 K. Argon was transferred from the stainless-steel trap to the charcoal trap by heating the stainless-steel trap to 60 K, and Ar isotopes were desorbed from the charcoal trap at 220 K for analysis. Krypton was released from the stainless-steel trap at 70 K and adsorbed onto the charcoal trap. Finally, Xe was extracted by heating the stainless-steel trap to 160 K while isolating the charcoal trap from the purification line prior to isotopic analysis.

Noble gas mass spectrometry and analytical standards

All analyses were performed using a Noblesse® 5F 5M mass spectrometer. This instrument is capable of fully resolving ³He from HD in high-resolution mode and of partially resolving ²⁰Ne⁺ from ⁴⁰Ar⁺⁺ and (¹H¹⁹F)⁺ interferences.

All isotopes were measured using electron multipliers in pulse-counting mode, except for ⁴He and ⁴⁰Ar, which were analysed on Faraday cups. Ne, Ar, and Xe isotopes were measured in multicollection. A single multicollection step allows the simultaneous measurement of ²⁰⁻²¹⁻²²Ne as well as ³⁶⁻³⁸⁻⁴⁰Ar.

Xe isotopes required three distinct multicollection steps. The isotopes ¹²⁶⁻¹²⁹⁻¹³²Xe, ¹²⁸⁻¹³¹⁻¹³⁴Xe, and ¹²⁴⁻¹³⁰⁻¹³⁶Xe were measured sequentially by adjusting the magnetic field between each step.

He isotopes were analysed by peak switching due to the large mass difference between ³He and ⁴He. ⁴He was measured first, followed by ³He. The mass position for ³He⁺ was determined relative to the HD⁺ peak, as the mass difference (Δm) between these two peaks on the same detector remains constant.

Interference between ²²Ne⁺ and ⁴⁴(CO₂)⁺⁺ was corrected by monitoring ⁴⁴(CO₂)⁺ during each analytical cycle, using a precisely calibrated (CO₂)⁺⁺/(CO₂)⁺ ionization ratio of 0.012. Each isotope was measured over 15 analytical cycles per analysis.

All measurements presented in the manuscript and in the Supplementary Tables were corrected for procedural blanks and instrumental mass discrimination using standards. Ne, Ar, and Xe isotopic ratios were corrected for mass discrimination using an air standard consisting of two 0.1 cc pipettes extracted from a 2 L reservoir, in which ten 0.1 cc air aliquots had previously been diluted. The air standard is inadequate for He analysis and

a dedicated standard is using consisting of a mixture of 150 cc of fumarole gas sampled in the Þingvallavatn geothermal field (Iceland) and 150 cc of gas sampled from a CO₂ plant located 10 km southeast of the lake Þingvallavatn diluted in a 2L bottle. This He standard was calibrated against air and has a ³He/⁴He isotopic ratio of 22.86 ± 0.21 R/Ra. Each 0.1 cc pipette contains $(9.78 \pm 0.72) \cdot 10^{-8}$ cc of ⁴He. Representative standard analyses during are shown in Figures S-2, S-3, S-4, and S-5.

Standard analyses

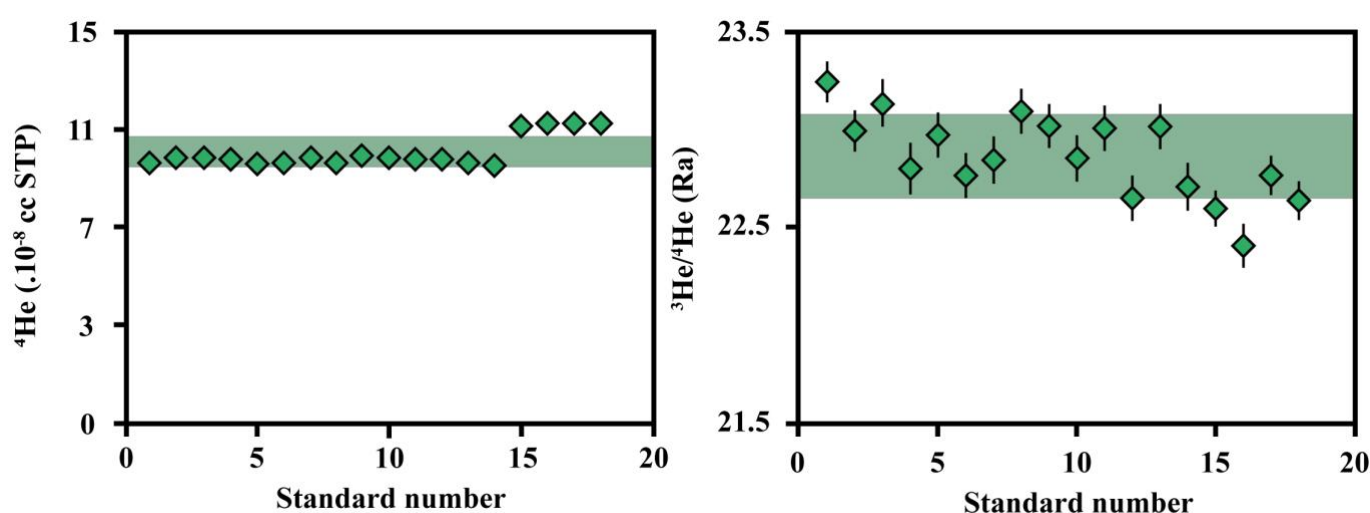


Figure S-2 Representative analyses of the He standards performed during the period where the step-crushing analyses were conducted. The green shaded box represents the 1σ uncertainty around the mean composition of the standards. To account for the true reproducibility of the measurement beyond individual precision, the mean composition and standard deviation of all standards measured over the analytical period were used for sample correction. All errors are 1σ and are not shown if smaller than the symbols.

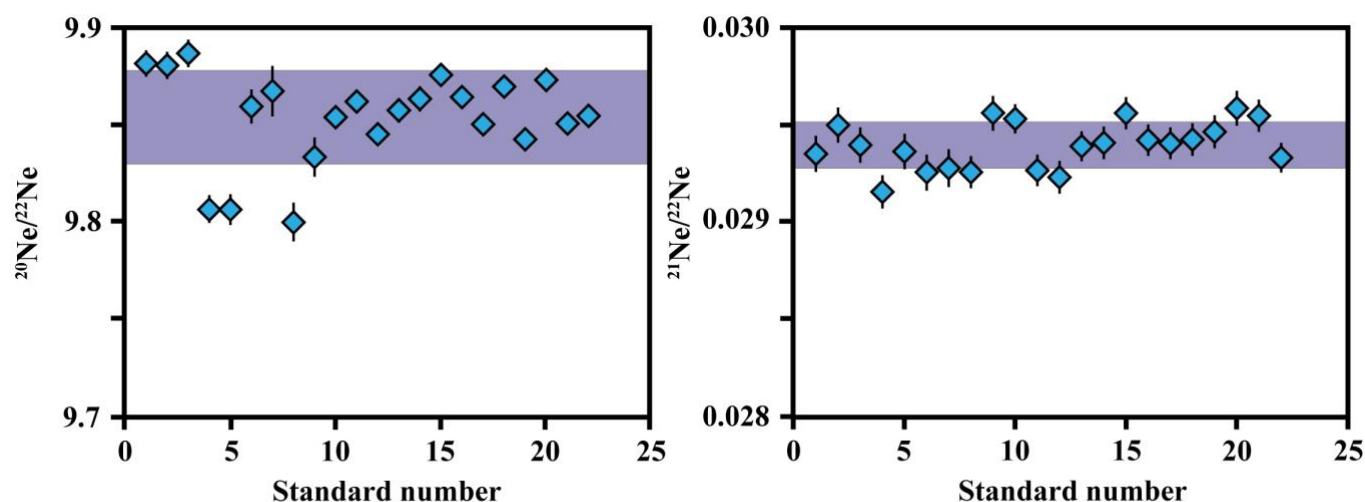


Figure S-3 Representative analyses of Ne isotopes in the air standards performed during the period where the analyses were conducted. The blue shaded box represents the 1σ uncertainty around the mean composition of the standards. To account for the true reproducibility of the measurement, the mean composition and standard deviation of all standards measured over the analytical period were used for sample correction. All errors are 1σ and are not shown if smaller than the symbols.

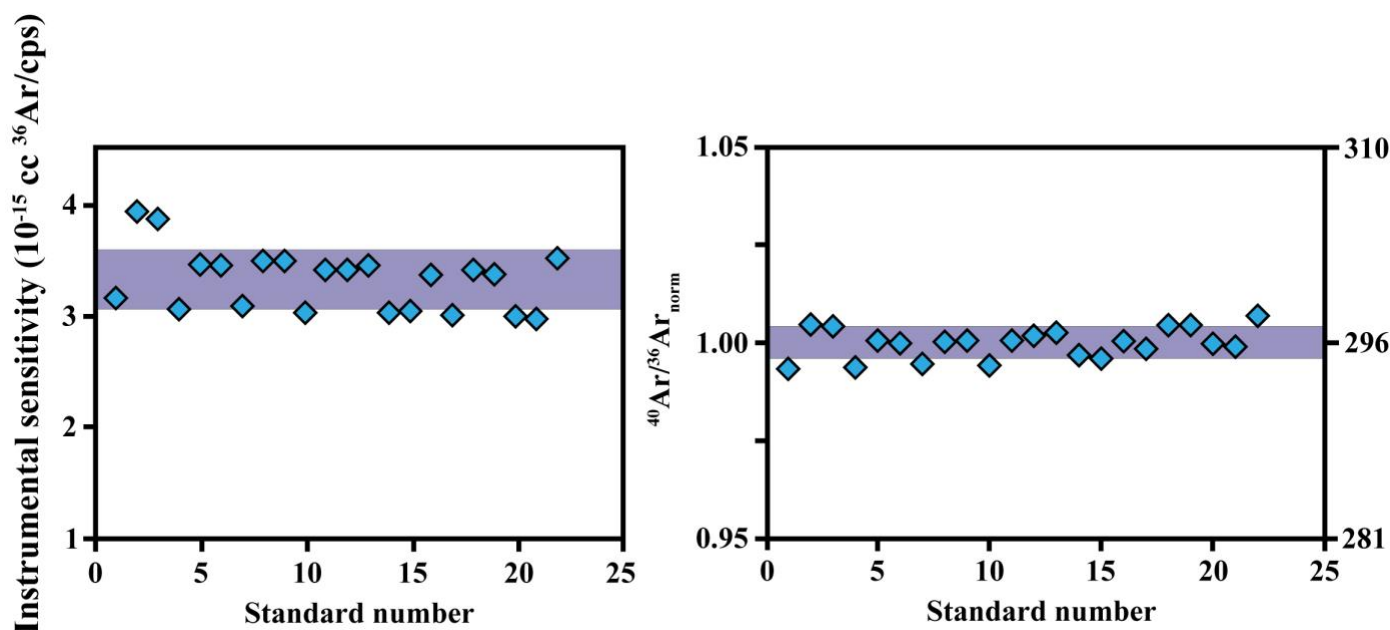


Figure S-4 Representative analyses of Ar isotopes in the air standards performed during the period where the step-crushing were conducted. The instrumental sensitivity for ^{36}Ar is also presented. The blue shaded box represents the 1σ uncertainty around the mean sensitivity or composition of the standards. To account for the true reproducibility of the measurements, the mean composition and standard deviation of all standards measured over the analytical period were used for sample correction. The raw $^{40}\text{Ar}/^{36}\text{Ar}$ measurement (in V/cps) is shown normalized to air, with corresponding absolute values given on the right axis. All errors are 1σ and are not shown if smaller than the symbols.

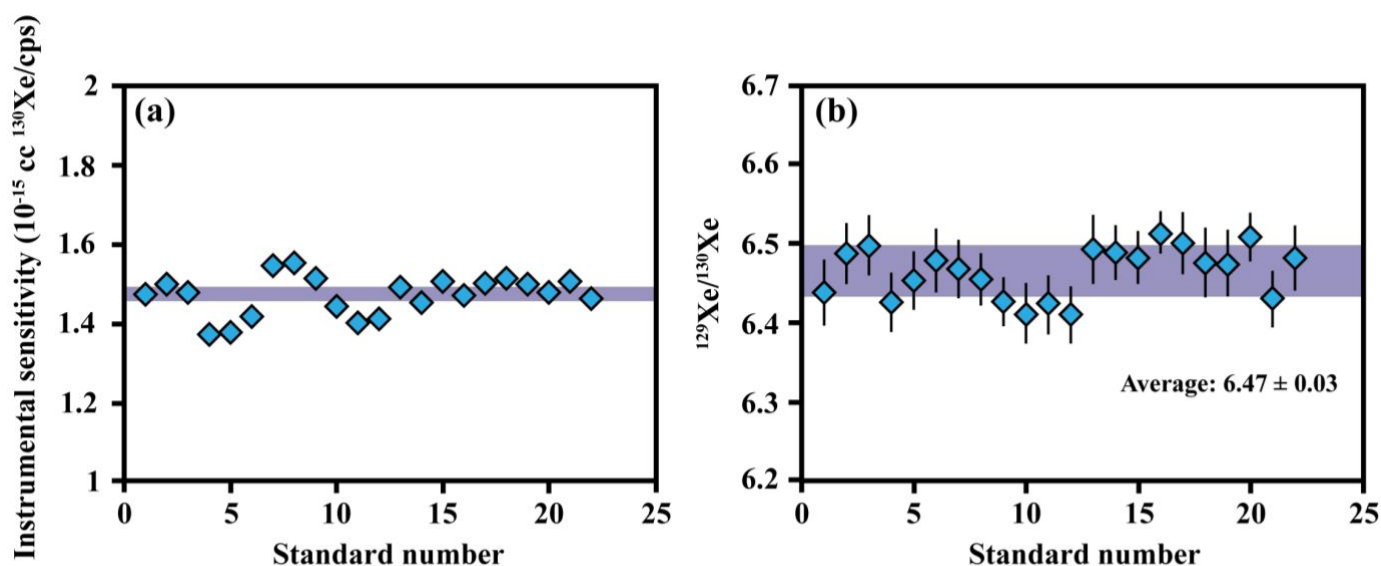


Figure S-5 Representative analyses of Xe isotopes in the air standards performed during the period where the step-crushing analyses were conducted. The instrumental sensitivity across the standards varies only a little suggesting that very low Xe abundances measured for some crushing steps is sample specific (Table S-1). The blue shaded box represents the 1σ uncertainty around the mean sensitivity or composition of the standards. To account for the true reproducibility of the measurement beyond individual cycle-based precision, the mean composition and standard deviation of all standards measured over the analytical period were used for sample correction. All errors are 1σ and are not shown if smaller than the symbols.

Analytical blank and mass discrimination corrections

Blank contribution to the measurement (in cps) is α where $\alpha = ({}^{22}\text{Ne}_{\text{blank}}/{}^{22}\text{Ne}_{\text{measured}})$ (Eq. S-1). The measured isotopic ratio (e.g. ${}^{20}\text{Ne}/{}^{22}\text{Ne}$) of a given individual crushing step is corrected from the blank following:

$$R_{\text{blank corrected}} = (R_{\text{measured}} - \alpha \times R_{\text{blank}})/(1 - \alpha) \quad \text{Eq. S-2}$$

Here, R_{blank} refers to the raw, mass-discrimination-uncorrected isotopic ratio of the procedural blank measured under the same instrumental conditions as the samples.

The associated uncertainty on the corrected isotopic ratio is given by Eq. S-3:

$$\sigma_{R_{\text{blank corrected}}} = \sqrt{\left[\left(\frac{\sigma_{R_{\text{measured}}}}{1 - \alpha}\right)^2 + \left(\frac{\alpha \sigma_{R_{\text{blank}}}}{1 - \alpha}\right)^2 + \left(\frac{R_{\text{measured}} - R_{\text{blank}}}{(1 - \alpha)^2}\right) (d_{\alpha} \alpha)\right]^2}$$

A relative uncertainty of 5% was assigned to α , based on the observed reproducibility of repeated blank measurements during analytical sessions ($d_\alpha = 0.05\alpha$). The individual error on the measured abundances (cps) and on the measured isotopic ratios ($R_{measured}$ and R_{blank}) is calculated as $\sigma/\sqrt{n}$ with n being the number of cycles performed during each analysis (15).

Because the blank correction is performed relative to the measured procedural blank composition, the resulting ratio remains expressed in the instrumental reference frame. Instrumental mass discrimination is therefore corrected in a subsequent step using repeated air standard analyses according to:

$$R_{final} = (R_{blank\ corrected} / R_{standard} \times R_{air}) \quad \text{Eq. S-4}$$

Where R_{air} is the isotopic ratio of air (e.g. 9.8 for $^{20}\text{Ne}/^{22}\text{Ne}$).

The final error on the isotopic ratio is computed as:

$$\sigma_{R_{final}} = \sqrt{\left(\frac{R_{air}}{R_{standard}} \sigma_{R_{blank\ corrected}}\right)^2 + \left(\frac{R_{blank\ corrected} R_{air}}{R_{standard}^2} \sigma_{R_{standard}}\right)^2} \quad \text{Eq. S-5}$$

Internal uncertainties for individual isotopic analyses correspond to the standard error of repeated measurement cycles ($\sigma/\sqrt{n}$, $n = 15$). In contrast, the uncertainty associated with $R_{standard}$ corresponds to the standard deviation (σ) of all repeated standard analyses acquired over the full analytical period (*i.e.*, external reproducibility). Consequently, the propagated uncertainties reported for the samples already account for the long-term reproducibility of the instrumental mass discrimination correction.

Determination of the Fani Maoré mantle $^{40}\text{Ar}/^{36}\text{Ar}$

Individual crushing steps are variably affected by secondary atmospheric contamination. This is expressed by well-defined mixing arrays for each noble gas element when plotting two isotopic ratios, extending from an atmospheric endmember toward mantle-derived compositions (Fig. 2).

As a result, the direct determination of the mantle endmember composition beneath Fani Maoré is not straightforward. A robust approach consists of selecting a well-constrained mantle isotopic ratio and extrapolating the data toward that value in order to extrapolate the mixing array to the mantle component (Moreira *et al.*, 1998).

The $^{20}\text{Ne}/^{22}\text{Ne}$ ratio is often used, as it is relatively well constrained for the upper mantle, and especially for the MORB source. In the $^{40}\text{Ar}/^{36}\text{Ar}$ - $^{20}\text{Ne}/^{22}\text{Ne}$ space, binary mixing between air and mantle produces a positive hyperbolic array due to differences in elemental $^{22}\text{Ne}/^{36}\text{Ar}$ ratios between the two reservoirs. The curvature of this hyperbola (r) is defined by:

$$r = (^{22}\text{Ne}/^{36}\text{Ar})_{\text{mantle}} / (^{22}\text{Ne}/^{36}\text{Ar})_{\text{air}} \quad \text{Eq. S-6}$$

Accordingly, the formula for the hyperbola defining air-mantle mixing in the $^{40}\text{Ar}/^{36}\text{Ar}$ - $^{20}\text{Ne}/^{22}\text{Ne}$ space is:

$$R40(R20) = \frac{(R40_{\text{mantle}} - rR40_{\text{air}})R20 + rR40_{\text{air}}R20_{\text{mantle}} - R20_{\text{air}}R40_{\text{mantle}}}{(1 - r)R20 + rR20_{\text{mantle}} - R20_{\text{air}}} \quad \text{Eq. S-7}$$

Where r is the curvature parameter of the hyperbolic mixing relationship defined above, $R40$ is the $^{40}\text{Ar}/^{36}\text{Ar}$ isotopic ratio and $R20$ the $^{20}\text{Ne}/^{22}\text{Ne}$ isotopic ratio. For the regression, $R20_{\text{air}}$ and $R40_{\text{air}}$ are fixed and $R20_{\text{mantle}}$ was fixed at 12.5.

The hyperbolic mixing equation was fitted to the dataset using nonlinear least-squares minimization, with simultaneous optimization of the curvature parameter r and the mantle $^{40}\text{Ar}/^{36}\text{Ar}$ ratio. Parameter uncertainties (1σ) were estimated from the covariance matrix of the fit. The goodness of fit was assessed using the coefficient of determination ($R^2 = 0.92$).

The best-fit curvature parameter is $r = 1.22 \pm 0.33$ (1σ). Extrapolation of the fitted hyperbola to $^{20}\text{Ne}/^{22}\text{Ne} = 12.5$ yields a mantle $^{40}\text{Ar}/^{36}\text{Ar}$ ratio of $19,980 \pm 1,110$ (1σ) for the Fani Maoré mantle source (Fig. 2b).

Determination of the Fani Maoré mantle Xe isotopic composition

Similarly to Ar, the Xe isotopic composition of the Fani Maoré mantle can be determined by extrapolation toward an air-free composition. For this purpose, we closely followed the method of Parai and Mukhopadhyay (2015), as we also use their method for further deconvolution of the fissiogenic Xe isotopes.

Extrapolation was performed to determine the $^{129}\text{Xe}/^{132}\text{Xe}$ ratio of the Fani Maoré mantle. Normalization over ^{132}Xe allows for subsequent deconvolution of fissiogenic Xe isotopes, as detailed below. Moreover, ^{129}Xe and ^{132}Xe are the most abundant Xe isotopes, which ensures that the fit is minimally affected by analytical uncertainties.

For this, the previously determined $^{40}\text{Ar}/^{36}\text{Ar}$ of the Fani Maoré mantle is used instead of a $^{20}\text{Ne}/^{22}\text{Ne}$ ratio of 12.5. This is because the Ar-Xe mixing hyperbola is often better defined than the Ne-Xe hyperbola, due to the

larger isotopic variation in Ar between air and mantle. The hyperbola in Ar-Xe space is strongly curved and asymptotes rapidly with respect to $^{40}\text{Ar}/^{36}\text{Ar}$, such that uncertainty in the extrapolated $^{40}\text{Ar}/^{36}\text{Ar}$ has only a minimal impact on the final $^{129}\text{Xe}/^{132}\text{Xe}$ estimate (Fig. 3b) and was not considered in the fit. A posteriori propagation of the $\pm 1\sigma$ uncertainty on the mantle $^{40}\text{Ar}/^{36}\text{Ar}$ endmember confirmed its negligible influence, producing changes of $<0.2\%$ in the inferred $^{129}\text{Xe}/^{132}\text{Xe}$ ratio and $<0.7\%$ in the fitted curvature parameter both well below the uncertainty associated with the inferred mantle $^{129}\text{Xe}/^{132}\text{Xe}$ ratio.

Following Parai and Mukhopadhyay (2015), a grid search over r and the mantle $^{129}\text{Xe}/^{132}\text{Xe}$ ratio was performed, calculating χ^2 as the sum of the orthogonal, uncertainty-normalized distances from each data point to the hyperbola. The minimum χ^2 defines the best-fit hyperbola, and the 1σ confidence region was determined using $\Delta\chi^2 \leq 2.30$ for $p = 2$ (curvature parameter and $^{129}\text{Xe}/^{132}\text{Xe}_{\text{mantle}}$).

The best-fit curvature and mantle $^{129}\text{Xe}/^{132}\text{Xe}$ are found to be $r = 0.148^{+0.103}_{-0.064}$ and 1.053 ± 0.008 (1σ), respectively (Fig. 3b). All hyperbolas within the confidence interval pass through the fixed air point, and the fit quality was evaluated using the reduced χ^2 . This approach provides a robust estimate of the mantle $^{129}\text{Xe}/^{132}\text{Xe}$ which is then used to constrain the $^{130-131-134-136}\text{Xe}/^{132}\text{Xe}$ isotopic ratios of the Fani Maoré mantle by York regression (Fig. S-6).

The resulting Fani Maoré mantle extrapolated Xe isotopic composition is reported in Table S-1.

Table S-1 Modelled Xe isotopic composition of the Fani Maoré mantle. The $^{129}\text{Xe}/^{132}\text{Xe}$ is derived from the hyperbolic fit of air-mantle mixing in the Ar-Xe space (Fig. 2b). The $^{130-131-134-136}\text{Xe}/^{132}\text{Xe}$ isotopic ratios of the Fani Maoré mantle are constrained by York regression (Fig. S-6).

$^{129}\text{Xe}/^{132}\text{Xe}$	$^{130}\text{Xe}/^{132}\text{Xe}$	$^{131}\text{Xe}/^{132}\text{Xe}$	$^{134}\text{Xe}/^{132}\text{Xe}$	$^{136}\text{Xe}/^{132}\text{Xe}$
1.053 ± 0.008	0.1500 ± 0.0005	0.7833 ± 0.0035	0.4068 ± 0.0030	0.3567 ± 0.0039

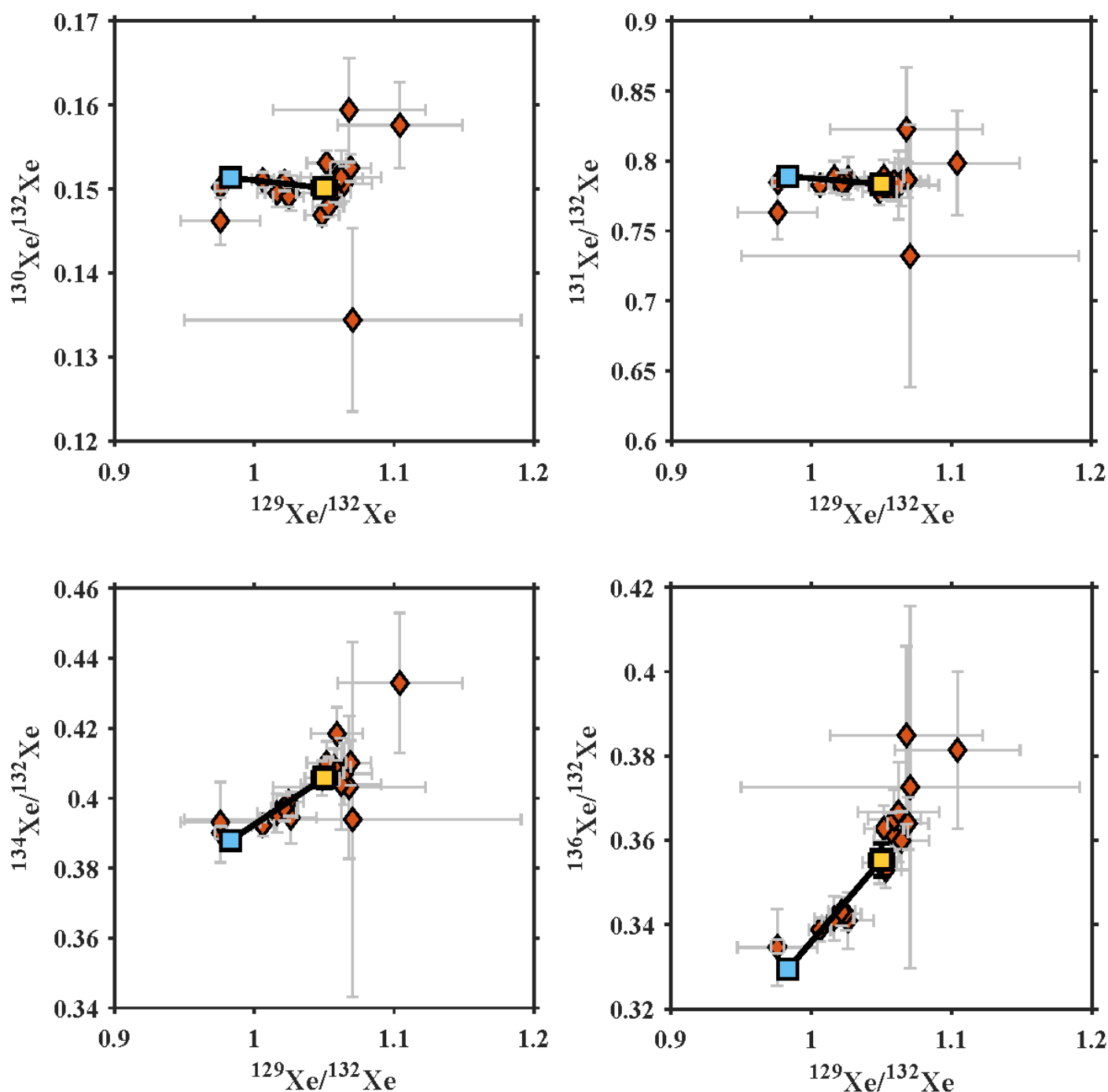


Figure S-6 Plots of measured $^{130-131-134-136}\text{Xe}/^{132}\text{Xe}$ isotopic ratios against $^{129}\text{Xe}/^{132}\text{Xe}$ for the individual crushing steps of Fani Maoré lava fragments. The mantle $^{130-131-134-136}\text{Xe}/^{132}\text{Xe}$ is derived by York regression (black line) between air (blue square) and the mantle (yellow square). For this, the air composition is fixed as well as the $^{129}\text{Xe}/^{132}\text{Xe}$ of the Fani Maoré mantle is constrained by extrapolation to an air-free composition, following the procedure described above. All errors are 1σ and are not shown if smaller than the symbols.

Deconvolution of fissiogenic Xe by linear least squares and Monte Carlo error propagation

For deconvolution of the fissiogenic Xe isotopic signature of the Fani Maoré mantle, we closely follow the procedure described in Parai and Mukhopadhyay (2015), initially developed by Caffee *et al.* (1999). This allows for proper comparison with previously modelled outcomes. The procedure is summarized below.

The present-day mantle composition can be modelled as the mixture of four distinct endmembers: the initial mantle, recycled air, Pu-derived fission Xe and U-derived fission Xe. Accordingly, the mantle $^i\text{Xe}/^{132}\text{Xe}$ can be expressed as (Eq. S-8):

$$^i\text{Xe}/^{132}\text{Xe}_{\text{mantle}} = x_{\text{initial}} ^i\text{Xe}/^{132}\text{Xe}_{\text{initial}} + x_{\text{air}} ^i\text{Xe}/^{132}\text{Xe}_{\text{air}} + x_{\text{Pu}} ^i\text{Xe}/^{132}\text{Xe}_{\text{Pu}} + x_{\text{U}} ^i\text{Xe}/^{132}\text{Xe}_{\text{U}}$$

where i represents 130, 131, 134, or ^{136}Xe , and x denotes the fraction of each endmember. We used the average carbonaceous chondrite (AVCC) composition as the initial mantle Xe isotopic composition (Péron and Moreira, 2018) and the present-day air composition for the recycled atmospheric component. Although the isotopic composition of subducted air may have evolved since the onset of subduction (Pujol *et al.*, 2011), recycling of atmospheric noble gases is expected to become more efficient over time due to secular cooling of the Earth (van Keken *et al.*, 2011). The relative contributions of ancient versus more recent Xe recycling have been specifically explored by Péron and Moreira (2018) and Parai and Mukhopadhyay (2018), supporting the view that the present-day atmospheric composition likely dominates the recycled flux. The composition of the individual components used for calculations are presented in Table S-2.

Table S-2 Individual components used for deconvolution of the fissiogenic Xe isotopic signature of the Fani Maoré lavas. We used the same endmembers isotopic compositions as in Parai and Mukhopadhyay (2015) for internal consistency.

Component	$^{130}\text{Xe}/^{132}\text{Xe}$	$^{131}\text{Xe}/^{132}\text{Xe}$	$^{134}\text{Xe}/^{132}\text{Xe}$	$^{136}\text{Xe}/^{132}\text{Xe}$
AVCC ^a	0.1626	0.8200	0.3836	0.3233
Air ^b	0.1513	0.7895	0.3880	0.3296
Pu-fission ^c	0	0.2777	1.0413	1.1198
U-fission ^d	0	0.1449	1.4370	1.7375

^aAVCC composition from Pepin (1991).

^bPresent-day air Xe isotopic composition from Basford *et al.* (1973).

^cError-weighted average of data from Alexander *et al.* (1971), Lewis (1975), and Hudson *et al.* (1989).

^dError-weighted average of data from Wetherill (1953), Hebeda *et al.* (1987), Eikenberg *et al.* (1993), and Ragetti *et al.* (1994).

A key constraint for this linear system is that all fractions must sum to unity and cannot be negative:

$$x_{AVCC} + x_{air} + x_{Pu} + x_U = 1, \quad 0 \leq x_{AVCC}, x_{air}, x_{Pu}, x_U \leq 1 \quad \text{Eq. S-9}$$

These constraints, together with the measured $^{136}\text{Xe}/^{132}\text{Xe}$ ratios of the Fani Maoré mantle and the known compositions of the endmembers, allow the system to be solved using a χ^2 -weighted linear inversion. In this approach, each isotope ratio is weighted by the inverse of its 1σ uncertainty, so that ratios with smaller uncertainties contribute more strongly to the fit.

The corresponding best-fit fractions are $x_{AVCC} = 0.148$, $x_{air} = 0.832$, $x_{Pu} = 0.000$, $x_U = 0.019$.

To propagate uncertainties, we perform Monte Carlo simulations by randomly sampling the mantle composition within its 1σ uncertainties and solving the constrained linear system for each realization. Each realization strictly respects equality and bound constraints (fractions sum to 1, $0 \leq x \leq 1$). Realizations yielding residuals larger than 2σ for any isotope are rejected. From the accepted realizations (out of $1e6$), median values and 16-84% percentiles are reported as the final fractions with asymmetric uncertainties. Accordingly, the fissiogenic Xe signature of the Fani Maoré mantle is best explained by $19.4^{+14.0}_{-7.8}$ % AVCC, $78.4^{+8.0}_{-15.1}$ % recycled air, $0.0^{+3.3}_{-0.0}$ % Pu-derived fission and $1.7^{+0.4}_{-1.7}$ % U-derived fission.

Supplementary Tables

Table S-3 Elemental abundances measured during individual crushing steps of the Fani Maoré lavas. n.d. = not measured. The $^4\text{He}/^{40}\text{Ar}^*$ ratio represents the elemental $^4\text{He}/^{40}\text{Ar}$ ratio corrected for air contamination, assuming that all ^{36}Ar is atmospheric in origin (Graham, 2002). All errors are 1σ .

Rock fragment-step	^4He (10^{-6} cc/g)	^{22}Ne (10^{-11} cc/g)	^{36}Ar (10^{-10} cc/g)	^{130}Xe (10^{-14} cc/g)	$^4\text{He}/^{40}\text{Ar}^*$	$^3\text{He}/^{22}\text{Ne}$	$^3\text{He}/^{130}\text{Xe}$
DR08-133-1	1.53±0.15	0.77±0.05	1.88±0.16	9.92±0.31	1.76±0.02	1.93±0.22	161±17
DR08-133-2	n.d.	0.95±0.06	0.74±0.06	10.7±0.36	n.d.	4.64±0.54	409±43
DR08-133-3	0.93±0.09	200±1.23	48.0±3.96	151±5.12	1.11±0.01	0.05±0.01	5.96±0.10
DR08-133-4	n.d.	1.25±0.07	0.99±0.08	0.61±0.02	n.d.	n.d.	n.d.
DR08-133-5	6.93±0.67	1.73±0.11	1.48±0.12	n.d.	2.73±0.04	4.19±0.46	n.d.
DR08-133-6	3.06±0.30	n.d.	0.89±0.07	7.68±0.26	2.10±0.03	n.d.	420±40
DR08-133-7	0.23±0.02	0.01±0.01	0.07±0.01	2.17±0.07	2.42±0.04	4.23±0.49	102±11
DR08-174-1	3.89±0.39	0.97±0.06	1.04±0.09	8.44±0.29	2.38±0.03	4.26±0.47	490±41
DR08-174-2	3.86±0.38	1.32±0.08	1.46±0.12	10.3±0.35	2.58±0.04	3.05±0.33	388±37
DR08-174-3	3.60±0.35	0.89±0.06	0.84±0.07	0.21±0.01	2.66±0.04	4.20±0.46	18225±1755
DR08-174-4	4.46±0.43	1.17±0.07	1.27±0.11	10.0±0.34	2.45±0.04	3.95±0.43	463±45
DR08-174-5	5.00±0.49	9.90±0.61	15.0±1.24	36.3±1.23	2.34±0.03	0.52±0.06	133±14
DR08-277-1	5.06±0.49	1.40±0.08	0.65±0.05	0.42±0.01	4.81±0.14	3.74±0.41	12371±1191
DR08-277-2	3.22±0.31	3.57±0.22	4.98±0.41	13.2±0.45	2.35±0.03	0.93±0.10	251±24
DR08-277-3	4.65±0.45	1.24±0.08	1.27±0.11	2.15±0.07	2.22±0.03	3.89±0.43	2240±216
DR08-277-4	5.36±0.52	5.37±0.33	7.38±0.61	23.4±0.79	2.95±0.05	1.02±0.11	235±24
DR08-277-5	7.06±0.69	1.98±0.12	2.20±0.18	2.30±0.08	2.14±0.03	3.69±0.40	3179±306
DR08-277-6	5.19±0.50	1.74±0.11	1.89±0.16	2.48±0.08	2.55±0.04	3.08±0.34	2152±207
DR08-277-7	3.27±0.32	0.89±0.06	0.83±0.07	1.03±0.03	2.40±0.03	3.79±0.41	3277±316

Table S-4 Isotopic ratios measured during individual crushing steps of the Fani Maoré lavas for He, Ne and Ar. n.d. = not measured. The $^3\text{He}/^4\text{He}$ ratios are normalized to Ra, the atmospheric ratio ($1.384 \cdot 10^{-6}$). $^{40}\text{Ar}/^{36}\text{Ar}$ values are reported to four significant figures, consistent with the precision of the atmospheric reference value used for normalisation. All errors are 1σ .

Rock fragment-step	$^3\text{He}/^4\text{He}$ (Ra)	$^{20}\text{Ne}/^{22}\text{Ne}$	$^{21}\text{Ne}/^{22}\text{Ne}$	$^{40}\text{Ar}/^{36}\text{Ar}$
DR08-133-1	7.00±0.06	11.05±0.04	0.0424±0.0005	4920±30
DR08-133-2	n.d.	11.96±0.04	0.0525±0.0004	15800±80
DR08-133-3	7.04±0.06	9.06±0.02	0.0284±0.0001	469±2
DR08-133-4	n.d.	12.26±0.04	0.0567±0.0004	18360±80
DR08-133-5	7.04±0.06	12.29±0.04	0.0575±0.0004	18710±80
DR08-133-6	7.07±0.06	n.d.	n.d.	17990±80
DR08-133-7	6.98±0.06	11.21±0.19	0.0493±0.0021	14380±370
DR08-174-1	6.99±0.05	12.12±0.04	0.0564±0.0004	17620±70
DR08-174-2	6.98±0.05	11.61±0.03	0.0493±0.0004	11350±90
DR08-174-3	7.00±0.05	12.19±0.04	0.0559±0.0005	17660±80
DR08-174-4	7.00±0.05	12.19±0.03	0.0563±0.0004	15720±150
DR08-174-5	6.98±0.06	10.14±0.03	0.0326±0.0002	1821±7
DR08-277-1	6.96±0.05	12.01±0.03	0.0540±0.0003	17690±70
DR08-277-2	6.93±0.05	10.35±0.03	0.0353±0.0002	3250±12
DR08-277-3	6.95±0.05	12.26±0.03	0.0570±0.0004	1797±720
DR08-277-4	6.88±0.05	10.12±0.03	0.0351±0.0002	2947±11
DR08-277-5	6.96±0.05	12.28±0.03	0.0567±0.0003	16430±60
DR08-277-6	6.91±0.05	11.67±0.03	0.0503±0.0003	11920±50
DR08-277-7	6.95±0.05	12.27±0.03	0.0564±0.0004	17870±720

Table S-5 Isotopic ratios measured during individual crushing steps of the Fani Maoré lavas for Xe (normalised to ^{130}Xe). n.d. = not measured. All errors are 1σ .

	$^{124}\text{Xe}/^{130}\text{Xe}$	$^{126}\text{Xe}/^{130}\text{Xe}$	$^{128}\text{Xe}/^{130}\text{Xe}$	$^{129}\text{Xe}/^{130}\text{Xe}$	$^{131}\text{Xe}/^{130}\text{Xe}$	$^{132}\text{Xe}/^{130}\text{Xe}$	$^{134}\text{Xe}/^{130}\text{Xe}$	$^{136}\text{Xe}/^{130}\text{Xe}$
DR08-133-1	0.0214±0.0019	0.0216±0.0018	0.4918±0.0138	6.87±0.08	5.27±0.07	6.69±0.09	2.64±0.03	2.28±0.03
DR08-133-2	0.0219±0.0015	0.0214±0.0015	0.4875±0.0111	6.80±0.06	5.27±0.05	6.69±0.07	2.65±0.02	2.28±0.02
DR08-133-3	0.0228±0.0007	0.0220±0.0005	0.4687±0.0019	6.50±0.02	5.23±0.01	6.66±0.02	2.60±0.01	2.23±0.01
DR08-133-4	0.0257±0.0060	0.0219±0.0055	0.5247±0.0393	6.70±0.26	5.16±0.19	6.28±0.24	2.53±0.08	2.42±0.09
DR08-133-5	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
DR08-133-6	0.0236±0.0021	0.0225±0.0018	0.4904±0.0111	7.07±0.10	5.21±0.09	6.64±0.09	2.70±0.05	2.39±0.03
DR08-133-7	0.0227±0.0041	0.0241±0.0030	0.4870±0.0140	6.67±0.14	5.22±0.09	6.84±0.13	2.69±0.06	2.29±0.04
DR08-174-1	0.0220±0.0015	0.0234±0.0012	0.4768±0.0070	7.06±0.06	5.21±0.03	6.68±0.05	2.73±0.03	2.42±0.02
DR08-174-2	0.0215±0.0010	0.0240±0.0013	0.4922±0.0060	7.14±0.07	5.30±0.05	6.81±0.05	2.76±0.03	2.41±0.01
DR08-174-3	0.0158±0.0144	0.0318±0.0111	0.6306±0.0811	7.97±0.71	5.45±0.54	7.44±0.60	2.93±0.29	2.77±0.23
DR08-174-4	0.0234±0.0012	0.0231±0.0014	0.4738±0.0053	7.12±0.05	5.28±0.04	6.76±0.06	2.75±0.02	2.39±0.02
DR08-174-5	0.0225±0.0008	0.0225±0.0006	0.4678±0.0026	6.66±0.04	5.18±0.03	6.62±0.04	2.60±0.01	2.24±0.01
DR08-277-1	0.0195±0.0042	0.0243±0.0041	0.4901±0.0236	7.01±0.21	5.07±0.17	6.35±0.21	2.75±0.09	2.42±0.09
DR08-277-2	0.0228±0.0012	0.0213±0.0006	0.4792±0.0060	6.87±0.04	5.27±0.04	6.71±0.05	2.68±0.02	2.30±0.02
DR08-277-3	0.0230±0.0021	0.0218±0.0018	0.4698±0.0104	7.00±0.09	5.19±0.06	6.61±0.09	2.77±0.04	2.41±0.03
DR08-277-4	0.0227±0.0008	0.0223±0.0008	0.4713±0.0040	6.77±0.04	5.19±0.04	6.63±0.05	2.63±0.02	2.27±0.02
DR08-277-5	0.0236±0.0020	0.0237±0.0014	0.4836±0.0101	7.01±0.07	5.16±0.06	6.56±0.07	2.69±0.03	2.39±0.03
DR08-277-6	0.0236±0.0017	0.0221±0.0019	0.4723±0.0085	6.87±0.07	5.15±0.06	6.53±0.07	2.68±0.03	2.37±0.03
DR08-277-7	0.0214±0.0033	0.0187±0.0028	0.4859±0.0175	7.01±0.14	5.17±0.12	6.60±0.14	2.67±0.07	2.42±0.06

Table S-6 Isotopic ratios measured during individual crushing steps of the Fani Maoré lavas for Xe (normalised to ^{132}Xe). n.d. = not measured. All errors are 1σ .

Table S-6	$^{129}\text{Xe}/^{132}\text{Xe}$	$^{130}\text{Xe}/^{132}\text{Xe}$	$^{131}\text{Xe}/^{132}\text{Xe}$	$^{134}\text{Xe}/^{132}\text{Xe}$	$^{136}\text{Xe}/^{132}\text{Xe}$
DR08-133-1	1.026±0.018	0.150±0.002	0.788±0.015	0.394±0.007	0.341±0.007
DR08-133-2	1.016±0.014	0.150±0.003	0.788±0.012	0.396±0.005	0.342±0.005
DR08-133-3	0.976±0.004	0.150±0.001	0.785±0.003	0.390±0.002	0.335±0.002
DR08-133-4	1.068±0.054	0.160±0.006	0.823±0.044	0.403±0.020	0.385±0.021
DR08-133-5	n.d.	n.d.	n.d.	n.d.	n.d.
DR08-133-6	1.064±0.020	0.151±0.002	0.785±0.017	0.407±0.009	0.360±0.007
DR08-133-7	0.976±0.028	0.146±0.003	0.763±0.019	0.393±0.011	0.335±0.009
DR08-174-1	1.057±0.012	0.150±0.001	0.779±0.008	0.409±0.005	0.362±0.005
DR08-174-2	1.049±0.012	0.147±0.001	0.778±0.010	0.406±0.005	0.355±0.005
DR08-174-3	1.070±0.120	0.134±0.011	0.732±0.094	0.394±0.051	0.373±0.043
DR08-174-4	1.053±0.011	0.148±0.001	0.781±0.009	0.407±0.004	0.353±0.004
DR08-174-5	1.006±0.008	0.151±0.001	0.783±0.006	0.392±0.003	0.339±0.003
DR08-277-1	1.104±0.045	0.158±0.005	0.799±0.037	0.433±0.020	0.381±0.019
DR08-277-2	1.025±0.011	0.149±0.001	0.785±0.009	0.399±0.004	0.343±0.004
DR08-277-3	1.059±0.019	0.151±0.002	0.785±0.013	0.418±0.008	0.365±0.007
DR08-277-4	1.022±0.009	0.151±0.001	0.784±0.008	0.397±0.004	0.343±0.003
DR08-277-5	1.069±0.015	0.153±0.002	0.786±0.013	0.410±0.006	0.364±0.006
DR08-277-6	1.052±0.014	0.153±0.002	0.789±0.012	0.410±0.006	0.363±0.005
DR08-277-7	1.062±0.029	0.151±0.003	0.783±0.024	0.404±0.013	0.367±0.012

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